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HUMAN BIOLOGY

EIGHTH EDITION

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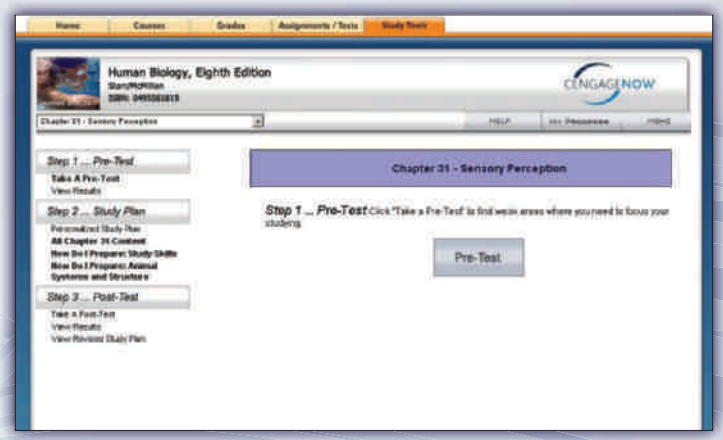

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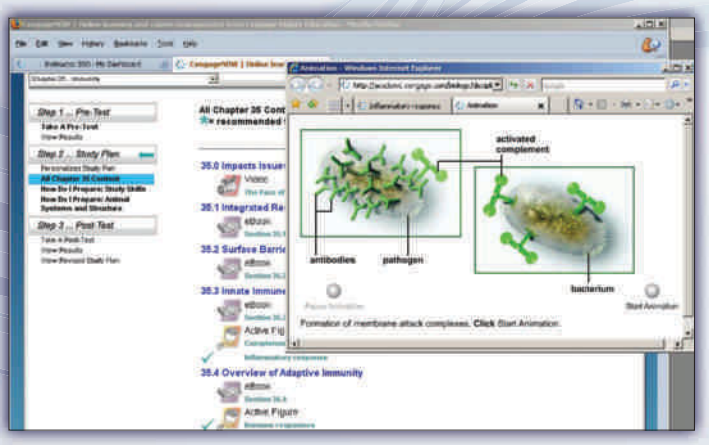

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HUMAN BIOLOGY

EIGHTH EDITION

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BRIEF CONTENTS

DETAILED CONTENTS

Preface

Instructors who teach introductory human biology for non-science majors have long told us that their overall goal for their course is to familiarize students with how the human body works and provide them with tools that will help them make well-informed choices as consumers and voters. This aim makes sense. Most students who use this textbook will never take another science course, yet they will need to make decisions that require a basic understanding of the process of science and fundamental biological principles.

In planning this revision, we asked instructors to review each chapter and suggest changes that would make the text as a whole even more effective in helping to meet the goals of their course. Their responses pinpointed two areas: include even more information on health issues, especially infectious disease and cancer, and reinforce the principle of homeostasis in the functioning of body systems. This excellent advice drove two major changes in this edition. Instead of treating infectious disease as a separate, chapter-length topic, we updated and integrated that information into expanded discussions of diseases and disorders in relevant chapters. In all systems chapters (except Chapter 16 on reproductive systems) we also added a full-page, illustrated *Connections* summary of how each organ system contributes to overall homeostasis in the body.

Several reviewers suggested moving our treatment of digestion so that it immediately precedes the discussion of the urinary system, and that change we have implemented as well. We also split the text's coverage of ecology into two chapters, one focused on basic principles and the second dealing with the impacts of human activities on ecosystems. Highlighted discussions include current thinking about global climate change and alternative energy sources.

We revised the text to make it as clear and straightforward as possible, keeping in mind that English is a second language for a fair number of students. We included new tables to summarize important points, and added more than 165 new photographs and new and simplified diagrams—visual elements that we know help students better understand basic concepts and the health impacts of diseases and disorders.

Changes for This Edition

Links to Key Concepts The previous edition of *Human Biology* included tools that link concepts within and between chapters. For this edition we enhanced these tools, to reinforce the concept that the functioning of tissues, organs, and organ systems are part of an integrated whole. Every chapter introduction has a section-by-section list of *Key Concepts*, each with a simple title. A brief list of *Links to Earlier Concepts* at the beginning of each chapter helps remind students of relevant concepts presented in previous chapters.

Sentence-Form Figure Captions All figure captions in this edition are introduced with a simple sentence that encapsulates the central concept represented by the illustration or photograph.

Take-Home Messages At the end of each chapter section, a *Take-Home Message* question pinpoints the main concept(s) covered in the section. It is followed by bulleted summaries of the section's key concepts.

Media-Integrated Summaries We have always offered a wealth of online media for students. In this edition, chapter summaries integrate even more information about the relevant animations, tutorials, and videos.

Chapter-Specific Changes We scrutinized every chapter for opportunities to make the writing clearer, and we have added dozens of new photographs and other illustrations. We summarize the highlights here.

Chapter 1, Learning about Human Biology New, two-page *Focus on Health* section introduces the topic of infectious disease as a central health concern that will be discussed in relevant chapters throughout the textbook.

Chapter 2, Chemistry of Life New chapter introduction on trans fats. Simplified text and streamlined art on atom structure, structure of carbohydrates and proteins, and the pH scale.

Chapter 3, Cells and How They Work New chapter introduction on the effects of consumed alcohol on liver cells. New illustrations of cell structure, diffusion, osmosis, electron transport chains, and a summary of aerobic cellular respiration. New *Focus on Health* on mitochondrial diseases.

Chapter 4, Tissues, Organs, and Organ Systems Streamlined text and new illustrations on muscle and nervous tissue.

Chapter 5, The Skeletal System New illustration of knee joint. New full-page *Connections* section on the role of the skeletal system in maintaining homeostasis.

Chapter 6, The Muscular System Revised text and added new art on muscle contraction. Expanded discussion of muscle diseases and disorders. New full-page *Connections* section on the role of the muscular system in homeostasis.

Chapter 7, Circulation: The Heart and Blood Vessels New placement of this chapter before blood and the respiratory system, with new chapter introduction. Expanded coverage of cardiovascular diseases and disorders, with a new section on infections, cancer, and heart defects. *Connections* section on the role of the cardiovascular system and blood in homeostasis.

Chapter 8, Blood New placement following the cardiovascular system.

Chapter 9, Immunity and Disease New chapter introduction on cervical cancer. Streamlined/new text and art for sections on antibody-mediated and cell-mediated defenses. New sections on HIV/AIDS and on understanding and avoiding infectious disease.

Chapter 10, The Respiratory System New text and art on breathing controls. Expanded discussion of respiratory diseases and disorders, with a new section on pathogens and lung cancer. *Connections* section on the role of the respiratory system in homeostasis.

Chapter 11, Digestion and Nutrition Updated text/art on dieting and nutritional guidelines. Expanded discussion of digestive system diseases and disorders, with a new section on relevant infectious diseases. *Connections* section on the role of the digestive system in homeostasis.

Chapter 12, The Urinary System Expanded coverage of urinary system diseases and disorders, including cancers, infections, and harm from drugs. *Connections* section on the role of the urinary system in homeostasis.

Chapter 13, The Nervous System Revised text and new art on divisions of the nervous system. Streamlined discussion of psychoactive drugs. Expanded coverage of nervous system diseases and disorders, including cancers, infections, headache, and autism spectrum disorders. *Connections* section on the role of the nervous system in homeostasis.

Chapter 14, Sensory Systems New text/art on olfactory pathways, inner ear structure, visual pigments and processing.

Chapter 15, The Endocrine System New section on growth hormone functions and disorders. Discussion of thyroid, parathyroid hormones now in an integrated section. Expanded text on blood sugar disorders. New text on gonads and reproductive hormones. *Connections* section on the role of the endocrine system in homeostasis.

Chapter 16, Reproductive Systems New chapter introduction on multiple births. New art on the male reproductive system and structure of sperm. New art summary of the menstrual and ovarian cycles. New section on fertilization (moved from development chapter) with accompanying new art. Added section on reproductive cancers.

Chapter 17, Development and Aging New chapter introduction on intersex developmental disorders. New *Focus on Health* on twinning. New photograph of amniocentesis procedure. Shortened discussion of aging effects on major body systems.

Chapter 18, Cell Reproduction New diagrams of chromosome duplication and the cell cycle.

Chapter 19, Introduction to Genetics New chapter introduction on genetics of skin color. New diagram on independent assortment. New text and art on sickle-cell anemia and on ABO blood types as an example of codominance. New subsection on effects of environmental factors on gene expression.

Chapter 20, Chromosomes and Human Genetics New diagrams of gene linkage and mapping of cystic fibrosis gene to chromosome 7. New photographs for X inactivation and example of related disorders. *Science Comes to Life* on pharmacogenetics.

Chapter 21, DNA, Genes, and Biotechnology New chapter introduction on genetically modified foods. New, simplified diagrams of steps of gene transcription and translation. New photograph of DNA fingerprinting. New text on cloning.

Chapter 22, Genes and Disease: Cancer Chapter refocused on cancer causes, diagnosis, treatment, and prevention. New introduction on breast cancer susceptibility genes. New diagram of steps in the development of colorectal cancer. New text on how cancers are categorized and named. Expanded sections on cancer diagnosis and treatments.

Chapter 23, Principles of Evolution New photograph of gene-based variation in human skin color. New diagram of homologous structures (vertebrate limbs). New diagram and photograph for discussion of mass extinction events.

Chapter 24, Principles of Ecology New chapter introduction on global climate change. New food web diagram. Topics concerning human impacts on ecosystems now the focus of Chapter 25.

Chapter 25, Human Impacts on the Biosphere Chapter introduction on sea level rise. New section on the concept of "ecological footprint" and renewable versus nonrenewable resources. Expanded section on climate change and global warming. New illustrations of thermal inversion, acid rain damage, location of the ozone layer, retreating glaciers due to warming, groundwater depletion/contamination, water pollution, recycling, desertification, deforestation, loss of biodiversity, other chapter topics. New *Explore on Your Own* urges students to find ways to reduce their personal carbon footprint.

Appendices New Appendix VI showing maps of human genes and a selection of associated functions and diseases.

Acknowledgments

This edition of *Human Biology* incorporates thoughtful comments and critiques of dozens of instructors, listed on the following page, who are committed to excellence in teaching science to non-science majors. Our bright new design, *Key Concepts*, *Impacts/Issues* essays, *Take-Home Messages*, custom videos and online learning resources—such features are responses to their insights from the classroom.

The publishing professionals at Cengage continue to justify our belief that they are the best team in educational publishing. Peggy Williams, thank you for championing our vision and creativity. Kristina Razmara built a world-class technology package for both students and instructors. Andy Marinkovich and Michelle Cole made sure that production went smoothly. Mandy Hetrick and her associates at Lachina Publishing Services were in the trenches every day for months, implementing the new design and managing the myriad tasks that yield a quality textbook. Many thanks to John Walker, our Art Director, who championed our new design and cover. Thanks also to our Executive Marketing Manager Stacy Best for making sure our book is seen by as many as possible, to Linda Sykes for her creative and resourceful photo research, to Elizabeth Momb for managing our extensive print supplements program, and to Alexis Glubka for her conscientious, good-natured editorial assistance. Together this team created an extraordinary resource for students and the dedicated instructors who strive to provide the best in biology education.

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Learning about Human Biology

1

IMPACTS, ISSUES

What Kind of World Do We Live In?

GLANCE at a newspaper or click on your Web browser and you may wonder what kind of world you're living in. Headlines mingle news about wars or political wrangles with tips for managing your love life or choosing food supplements. On any given day you'll read about how infectious diseases such as "bird flu" and West Nile virus pose global threats, or about the devastation caused by a natural catastrophe such as an earthquake. Often there are stories about how the growing human population is having major impacts on nature. We hear more and more about global warming, glaciers and polar ice caps melting, and various regions experiencing record storms, droughts, and heat waves. But while coping with an environmental disaster or predicting the course of a flu epidemic definitely are challenging, we humans have an ace in the hole.

We learned a long time ago that it is possible to study nature, including ourselves, in a systematic way that may help us understand the natural world and our place in it. We can observe carefully, come up with ideas, and find ways to test them. Gradually we can learn a great deal about factors that affect our health, the environment, and a host of other issues. That's what this book is for—to help give you a fuller understanding of how your body works and where all of us fit in the larger world.

Each chapter in this book will give you a chance to express your opinion on an issue that is challenging us today. When you cast your vote on this book's website, you will be able to see how others feel about a wide variety of concerns related to the environment, health, and ethical issues.

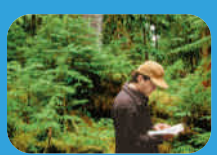
KEY CONCEPTS

The Nature of Life

Living things share basic features, including the genetic material DNA. A cell is the smallest unit that can be alive. Section 1.1

Life's Organization and Diversity

Nature is organized from simple to complex, starting with nonliving atoms. The biosphere is the most encompassing level of life's organization. Sections 1.2, 1.3



Studying Life

Biology is a way of thinking critically about the natural world. Biologists make and test predictions by experiments in nature and in the laboratory. Critical thinking is valuable in many life decisions. Sections 1.4–1.7

LINKS TO EARLIER CONCEPTS

- This book follows nature's levels of organization, from atoms to the biosphere. This first chapter provides a broad view of where we humans fit in the world of life. Later chapters will introduce you to the chemical foundations of life and how our body cells are built and operate. This background paves the way for a survey of how the body's tissues, organs, and organ systems function. You will also learn about genes, how traits pass from parents to their children, and basic concepts of evolution and ecology.
- Each chapter in this book builds upon previous ones. Orange bullets and cross-references will link you to sections in earlier chapters where you can review related topics.

How Would You Vote?

Spraying pesticides where mosquitoes breed offers protection against West Nile virus. However, some people worry that spraying might harm human health. Would you support spraying in your community? See CengageNOW for details, then vote online.

1.1 The Characteristics of Life

- **Several basic characteristics allow us to distinguish between living things and nonliving objects.**

Living and nonliving things are all alike in some ways. For instance, both are made up of atoms, which are the smallest units of nature's fundamental substances. On the other hand, wherever we look in nature we find that all living things share some features that nonliving ones don't have. These basic characteristics of life are:

1. **Living things take in energy and materials.** Like other animals, and many other kinds of organisms, we humans take in energy and materials by consuming food (Figure 1.1). Our bodies use the energy and raw materials to build and operate their parts in ways that keep us alive.
2. **Living things sense and respond to changes in the environment.** For example, a tulip's petals close up when night falls, and you might put on a sweater or turn up the heat on a chilly afternoon.

Figure 1.1 Humans take in energy by eating food. This boy's body will extract energy and raw materials from the food and use them for processes that are required to keep each of his cells, and his body as a whole, alive.

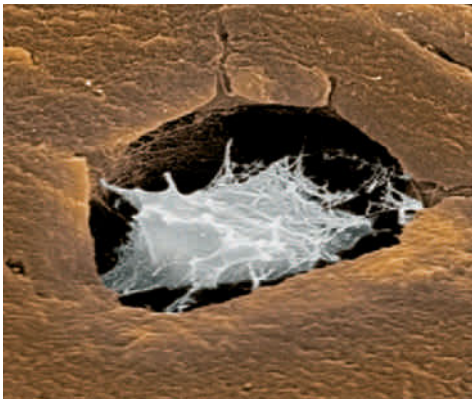


Figure 1.2 Cells are the basic units of life. A bone cell looks white and delicate in this picture. Like other types of body cells, it contains DNA and uses ATP energy.

3. **Living things reproduce and grow.** Organisms can make more of their own kind, based on instructions in DNA, the genetic material. Only living things have DNA. Guided by the instructions in their DNA, most organisms develop through a series of life stages. For us humans, the basic life stages are infancy, childhood, adolescence, and adulthood.
4. **Living things consist of one or more cells.** A **cell** is an organized unit that can live and reproduce by itself, using energy, the required raw materials, and instructions in DNA. Figure 1.2 shows a living bone cell. Cells are the smallest units that can be alive. The energy for all cell activities comes from another special chemical found only in living things, ATP.
5. **Living things maintain homeostasis.** **Homeostasis** (hoe-me-oh-STAY-sis) means "staying the same." Homeostasis is a state of chemical and physical stability inside the body that must be maintained in order for individual cells, and the whole body, to stay alive. For now, simply keep in mind that body cells are part of systems that maintain internal homeostasis. In later chapters you will learn how each of eleven main body systems contribute to this task.

Take-Home Message

What are the basic characteristics of life?

- Living organisms share characteristics that nonliving objects do not have.
- All living things take in and use energy and materials, and they sense and can respond to changes in their environment.
- Living things can reproduce and grow, based on instructions in DNA.
- The cell is the smallest unit that can be alive.
- Organisms maintain homeostasis, meaning that conditions inside the body are kept within life-supporting limits.

1.2 Our Place in the Natural World

- **Human beings arose as a distinct group of animals during an evolutionary journey that began billions of years ago.**

Humans have evolved over time

In biology, **evolution** means change in the body plan and functioning of organisms through the generations. It is a process that began billions of years ago on the Earth and continues today. In the course of evolution, major groups of life forms have emerged.

Figure 1.3 provides a snapshot of how we fit into the natural world. Humans, apes, and some other closely related animals are **primates** (PRY-mates). Primates are mammals, and mammals make up one group of "animals with backbones," the **vertebrates** (VER-tuh-braytes). Of course, we share our planet with millions of other animal species, as well as with plants, fungi, countless bacteria, and other life forms. Biologists classify living things according to their characteristics, which in turn reflect their evolutionary heritage. Notice that Figure 1.3 shows three domains of life. Animals, plants, fungi, and microscopic organisms called protists are assigned to kingdoms in a domain called Eukarya. The other two domains are reserved for bacteria and some other single-celled life forms. Some biologists prefer different schemes. For example, for many years all living things were simply organized into five kingdoms—animals, plants, fungi, protists, and bacteria. The key point is that despite the basic features all life forms share, evolution has produced a living world of incredible diversity.

Figure 1.3 Animated!
Organisms are classified into groups according to their characteristics. Humans are one of more than a million species in the Animal Kingdom, which is part of the domain Eukarya. Plants, fungi, and some other life forms make up other kingdoms in Eukarya. The domains Bacteria and Archaea contain vast numbers of single-celled organisms.

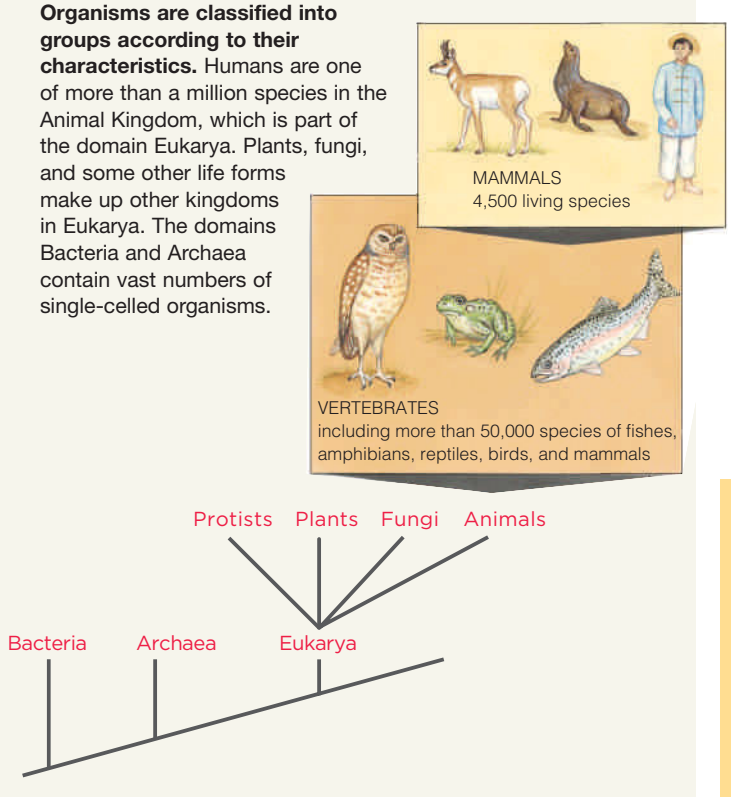


Figure 1.4 Humans are related to Earth's other organisms. Bonobos (left) are our closest primate relatives. Like us, they walk upright and use tools.

Humans are related to all other living things—and they have some distinctive characteristics

Because of evolution, we humans are related to every other life form and share characteristics with many of them. For instance, we and all other mammals have body hair, a feature that no other vertebrate has. We share the most characteristics with apes, our closest primate relatives (Figure 1.4). But humans also have some distinctive features that evolved as traits of our primate ancestors were modified. For example, we have great manual dexterity due to the arrangement of muscles and bones in our hands and the wiring of our nervous system to operate them. Even more astonishing is the human brain. Relative to overall body mass it is the largest brain of any animal, and it gives us the capacity for sophisticated language and analysis, for developing advanced technology, and for a remarkably wide variety of social behaviors.

Take-Home Message

Why is evolution an important concept in human biology?

- Like all life forms, human beings arose through evolution—changes in bodily structures and functions of organisms through the generations.
- Evolution has given rise to the features that set humans apart from other complex animals. These characteristics include sophisticated verbal skills, analytical abilities, and exceptionally complex social behavior.

1.3 Life's Organization

- **Nature is organized on many levels, starting with nonliving materials and eventually including the whole living world.**

Nature is organized on many levels

When you look closely at the living world, it doesn't take long to realize that nature is organized on many different levels (Figure 1.5). At the most basic level are atoms. Next come molecules, which are combinations of atoms. Atoms and molecules are the nonliving materials from which cells are built. In a multicellular organism such as a human, cells are organized into tissues—muscle, the epithelium of your skin, and so forth. Different kinds of tissues make up organs, and coordinated systems of organs make up whole complex organisms.

We can study the living world on any of its levels. Many courses in human biology focus on organ systems, and a good deal of this textbook explores their structure and how they function.

Nature's organization doesn't end with individuals. Each organism is part of a population, such as the Earth's whole human population. When we cast the net a little farther, populations of different organisms interact in communities, the populations of all species occupying the same area. Communities in turn interact in ecosystems. The most inclusive level of organization is the **biosphere**. This term refers to all parts of Earth's waters, crust, and atmosphere in which organisms live.

Organisms are connected through the flow of energy and cycling of materials

Organisms must take in energy and materials to keep their life processes going. Where do these essentials come from? Energy flows into the biosphere from the sun. This solar energy is captured by "self-feeding" life forms such as plants, which use a sunlight-powered process called photosynthesis to make fuel for building tissues, such as a corn kernel. Raw materials such as carbon that are needed to build the corn come from air, soil, and water. Thus self-feeding organisms are the living world's basic food producers. Animals, including humans, are the consumers: When we eat plant parts, or feed on animals that have done so, we take in materials and energy to fuel our body functions. You tap directly into stored energy when you eat corn on the cob, and you tap into it indirectly when you eat the meat of a chicken that fed on corn. Organisms such as bacteria and fungi obtain energy and materials when they decompose tissues, breaking down biological molecules to substances that can be recycled back to producers. By

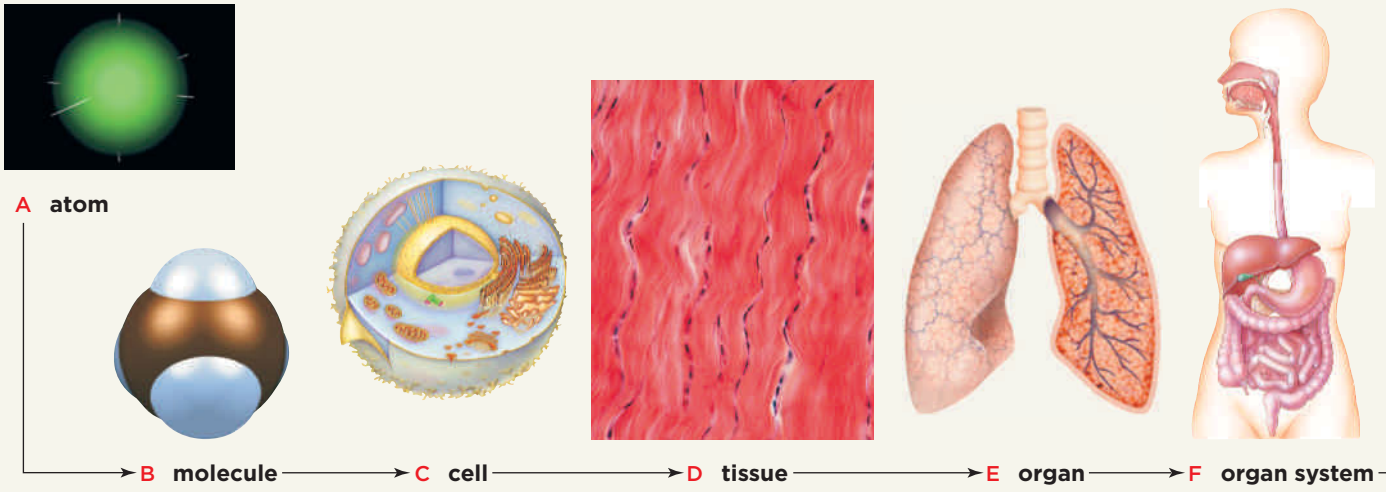


Figure 1.5 Animated! An overview of the levels of organization in nature.

way of this one-way flow of energy through organisms, and the cycling of materials among them, every part of the living world is linked to every other part. Figure 1.6 summarizes these relationships, which we'll return to in Chapter 24.

Because of the interconnections among organisms, it makes sense to think of ecosystems as webs of life. With this perspective, we can see that the effects of events in one part of the web will eventually ripple through the whole and may even affect the entire biosphere. For example, we see evidence of large-scale impacts of human activities in phenomena such as global warming, the loss of biodiversity in many parts of the world, acid rain, and a host of other problems.

Take-Home Message

What are the levels of organization in nature, and what factors sustain these organized states?

- Nature is organized from the simple—atoms—to the complex, culminating with the biosphere.
- Energy from the sun and the cycling of raw materials among organisms sustain the living world's organization.
- Because living things are interconnected, ecosystems are webs of life. What happens in one part of the web ripples through the whole.

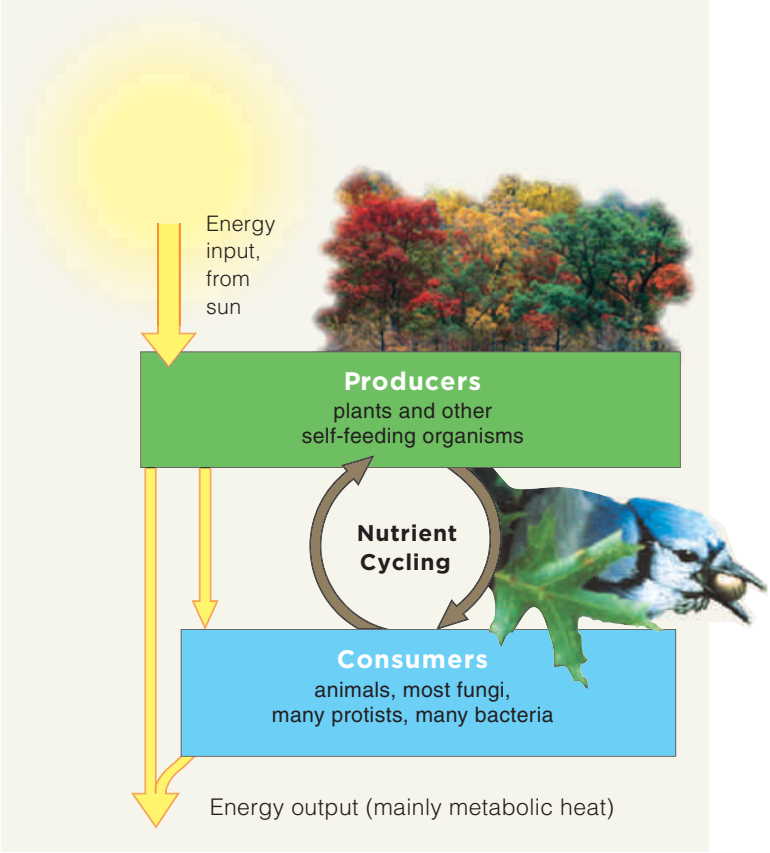
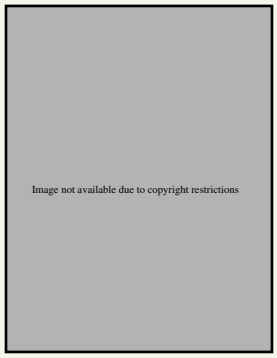


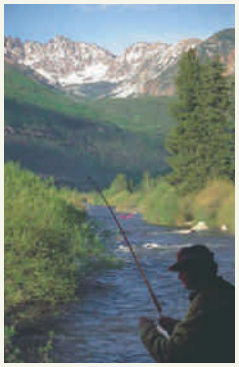
Figure 1.6 Animated! **The flow of energy and the cycling of materials maintain nature's organization.**

G multicellular organism



H population

I community



J ecosystem

K the biosphere

1.4 Using Science to Learn about the Natural World

- **Science basically is a way of thinking about the natural world. Scientists try to explain natural phenomena by making and testing predictions. They search for evidence that may disprove or support a proposed explanation.**

Science is a systematic study of nature

Antibiotics. Insights into genetic disorders, health issues such as cancer and diabetes, and environmental problems such as global warming and water pollution. Advances like these—not to mention technologies such as genetic engineering and the Internet—have changed our lives. In this textbook you will be learning a great deal of science-based information about the human body, health issues, and many related topics. So before continuing, let's look briefly at what "doing science" means.

We can define "science"as a systematic way of obtaining knowledge about the natural world. This system is sometimes called the **scientific method**, but there is no single script for it. Researchers can pursue their work in the laboratory or in the field, using a variety of tools (Figure 1.7). The following steps are common.

1. **Observe some aspect of nature.** For example, in the late 1990s, a fat substitute called Olestra® was approved for use in foods. Made from vegetable oil and sugar, Olestra is indigestible and seemed to be a dieter's dream. When potato chips made with Olestra were marketed, however, some consumers reported intestinal gas, cramps, and diarrhea.
2. **Ask a question about the observation or identify a problem to explore.** Researchers at Johns Hopkins University began to wonder about the intestinal upsets Olestra users were reporting. Was Olestra causing the problems?
3. **Develop a hypothesis.** A **hypothesis** is a proposed explanation for an observation or how some natural process works. With a scientific hypothesis, there must be some objective way of testing it, such as experiments. The Johns Hopkins scientists hypothesized that Olestra can indeed cause cramps and they had an idea for an experiment to test this explanation.
4. **Make a prediction.** As a first step in testing their hypothesis, the scientists made a prediction: People who eat food containing Olestra are more likely to have intestinal side effects than people who do not. As in this example, a prediction states what you should observe about the question or problem if the hypothesis is valid.
5. **Test the prediction.** To see if their prediction was accurate, the researchers invited almost 1,100 people aged 13 to 38 to watch a movie in a Chicago theater. They were divided into two roughly equal groups and given unmarked bags of potato chips. One group got chips made with Olestra while the other group got regular chips. Almost 16 percent of those in the Olestra group later reported intestinal problems—but so did nearly 18 percent in the "regular" group. There was no evidence that eating Olestra-laced potato chips causes intestinal ills, at least after a one-time use. The experiment was not a failure, however. A properly designed test is supposed to reveal flaws. If the findings don't support the initial prediction, then some factor that influenced the test may have been overlooked, or the hypothesis may simply have been wrong.
6. **Repeat the tests or develop new ones**—the more the better. Hypotheses that are supported by the results of repeated testing are more likely to be correct.
7. **Analyze and report the test results and conclusions.** Scientists typically publish their findings in scientific journals, with a detailed description of their methods so that other researchers can try the same test and see if they get the same result.

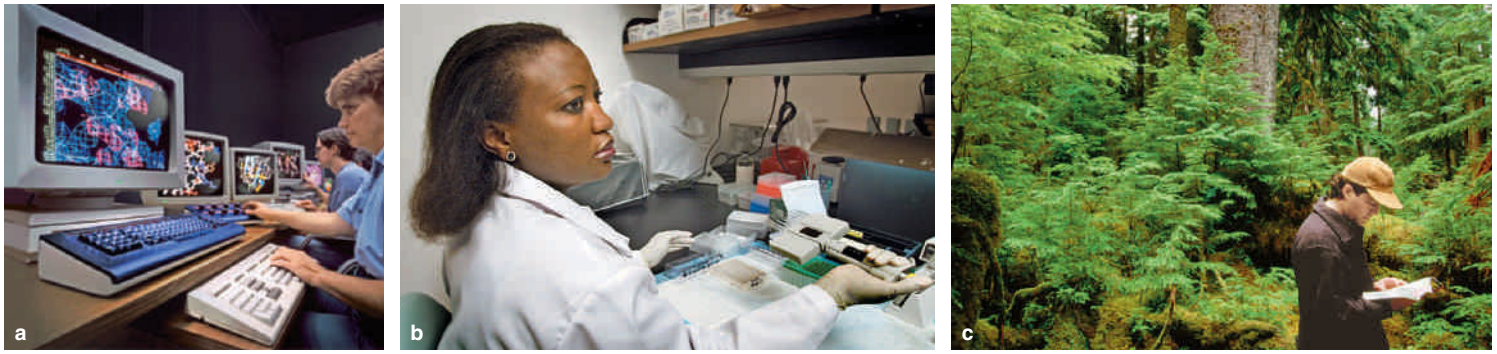


Figure 1.7 **Scientists do research in the laboratory and in the field.** (**a**) Analyzing data with computers. (**b**) At the Centers for Disease Control, Mary Ari testing a sample for the presence of dangerous bacteria. (**c**) Making field observations in an old-growth forest.

Hypothesis
Olestra® causes intestinal cramps.

Prediction
People who eat potato chips made with Olestra will be more likely to get intestinal cramps than those who eat potato chips made without Olestra.

Experiment	Control Group	Experimental Group
	Eats regular potato chips	Eats Olestra potato chips
Results	93 of 529 people get cramps later (17.6%)	89 of 563 people get cramps later (15.8%)

Conclusion
Percentages are about equal. People who eat potato chips made with Olestra are just as likely to get intestinal cramps as those who eat potato chips made without Olestra. These results do not support the hypothesis.

Figure 1.8 The Olestra study followed a sequence of steps used in many scientific experiments.

Many scientists use experiments in their work

Experimenting is a time-honored way to test a scientific prediction. An experiment is a test that is carried out under controlled conditions that the researcher can manipulate. Figure 1.8 shows the typical steps followed, using the Olestra study as an example.

To get meaningful test results, experimenters use safeguards. They begin by reviewing information that may bear on their project. The makers of Olestra had conducted tests on human subjects before their product was approved, and the Johns Hopkins study considered these reports. Then the researchers designed a **controlled experiment**, one that would test only a single prediction of a hypothesis at a time. In this case, it was the prediction that people who consume Olestra have a greater chance of developing intestinal side effects.

Almost any aspect of the natural world is the result of interacting variables. As the term suggests, a **variable** is a factor that can change with time or in different circumstances. Researchers design experiments to test one variable at a time. They also set up a **control group** to which one or more experimental groups can be compared. The control group in the Olestra study was identical to the experimental one except for the variable being studied—chips containing Olestra. Identifying possible variables, and eliminating unwanted ones, is extremely important if an experiment is to produce reliable results. For instance, if some people in the Olestra study had had a prior history of unrelated intestinal difficulties, they could have skewed the study results. Likewise, if any of the participants included people who were already eating foods made with Olestra, it would have been impossible for the experimenters to determine if any reported side effects were due not to the single bag of chips but to long-term use.

Scientists usually can't observe all the individuals in a group they want to study. In studies of a food additive such as Olestra it would be hard to include all possible consumers. If the sample is too small, the findings might be skewed by differences among research subjects. To avoid this problem, researchers use a sample group that is large enough to be representative of the whole. That is why the Olestra study recruited so many participants.

Science never stops

In science, a researcher must draw logical conclusions about any findings. That is, the conclusion cannot be at odds with the evidence used to support it. Based on the results of their Olestra experiment, the Johns Hopkins scientists could not conclude that the promising "fake fat" did cause intestinal problems. On the other hand, their limited, one-time experiment also could not give Olestra a clean bill of health. In fact, in the years since Olestra was first developed, the United States Food and Drug Administration (FDA) has received more than 20,000 consumer complaints alleging problems, and Olestra has been reformulated to reduce certain side effects. Today a variety of processed foods sold in the United States are made with Olestra, but the jury may still be out on its potential effects in some people, and some advocates say that more research is needed.

Take-Home Message

What is a scientific approach to studying nature?

- Scientists begin by observing a natural event or object and then posing a question about it.
- They then propose a possible explanation, make a testable prediction about this hypothesis, devise one or more tests, and then objectively report the results.
- Controlled experiments are one way to test scientific ideas. This kind of experiment explores a single variable and uses a control group as a standard to which experimental results can be compared.

1.5 Critical Thinking in Science and Life

- **To think critically, we must evaluate information before accepting it.**

Have you ever tried a new or "improved" product and been disappointed when it didn't work as expected? Everyone learns, sometimes the hard way, how useful it can be to cast a skeptical eye on advertising claims or get an unbiased evaluation of, say, a used car you are considering buying. This objective evaluation of information is called *evidence-based* or **critical thinking**.

Scientists use critical thinking in their own work and to review findings reported by others. Anyone can make a mistake, and there is always a chance that pride or bias will creep in. Critical thinking is a smart practice in everyday life, too, because so many decisions we face involve scientific information. Will an herbal food supplement really boost your immune system? Is it safe to eat irradiated food? Table 1.1 gives guidelines for evidence-based, critical thinking.

Evaluate the source of information

An easy way to begin evaluating information is to notice where it is coming from and how it is presented. Simple strategies for sifting the factual wheat from the unreliable or biased chaff are the following:

Let credible scientific evidence, not opinions or hearsay, do the convincing For instance, if you are concerned about reports that heavy use of a cell phone might cause brain cancer, information on the website of the American Cancer Society is more likely to be reliable than something cousin Fred heard at work. Informal information may be correct, but you can't know for sure without investigating further.

Question credentials and motives For example, if an advertisement is printed in the format of a news story or a product is touted on TV by someone being paid to sing its praises, your critical thinking antennae should go up. Is the promoter merely trying to sell a product with the help of "scientific" window dressing? Can any facts presented be checked out? Responsible scientists try to be cautious and accurate in discussing their findings and are willing to supply the evidence to back up their statements.

Evaluate the content of information

Even if information seems authoritative and unbiased, it is important to be aware of the difference between the cause of an event or phenomenon and factors that may only be correlated with it. For example, studies show that recirculation of air in an airplane's passenger cabin increases travelers' exposure to germs coughed or sneezed out by others. An "airplane cold," however, is caused directly by infection by a virus.

Also keep in mind the difference between facts and opinions or speculation. A **fact** is verifiable information, such as the price of a loaf of bread. An *opinion*—whether the bread tastes good—can't be verified because it involves a subjective judgment. Likewise, a marketer's prediction that many consumers will favor a new brand of bread is speculation, at least until there are statistics to back up the claim.

A Guide to Critical Thinking

Be able to state clearly your view on a subject.

Be aware of the evidence that led you to hold this view.

Ask yourself if there are alternative ways to interpret the evidence.

Think about the kind of information that might make you reconsider your view.

If you decide that nothing can ever persuade you to alter your view, recognize that you are not being objective about this subject.

A Critical Thinking Checklist

- ✔ ***Do*** gather information or evidence from reliable sources.
- ✗ ***Don't*** rely on hearsay.
- ✔ ***Do*** look for facts that can be checked independently and for signs of obvious bias (such as paid testimonials).
- ✗ ***Don't*** confuse *cause* with *correlation.*
- ✔ ***Do*** separate *facts* from *opinions.*

Take-Home Message

What do we mean by critical thinking?

- Critical thinking means using systematic, objective strategies to judge the quality of information.

1.6 Science in Perspective

- **A scientific theory explains a large number of observations.**

We know that the practice of science can yield powerful ideas, like the theory of evolution, that explain key aspects of life. At the same time, we also know that science is only one part of human experience.

It is important to understand what the word "theory" means in science

You've probably said, "I've got a theory about that!" In everyday usage, this expression means that you have an untested idea about something. In science, a theory is exactly the opposite: It is an explanation of a broad range of related natural events and observations that is based on repeated, careful testing of hypotheses. Table 1.2 lists some major scientific theories.

A hypothesis usually becomes accepted as a theory only after years of testing by many scientists. Then, if the hypothesis has not been disproved, scientists may feel confident about using it to explain more data or observations. The theory of evolution by natural selection—a topic we will look at in Chapter 23—is a prime example of a "theory" that is supported by tens of thousands of scientific observations.

Science demands critical thinking, so a theory can be modified, and even rejected, if results of new scientific tests call it into question. It's the same with other scientific ideas. Today, for instance, sophisticated technologies are giving us a new perspective on subjects such as how our immune system operates to defend the body against disease threats. Some of the "facts" in this textbook one day will likely be revised as we learn more about various processes. This willingness to reconsider ideas as new information comes to light is a major strength of science.

Examples of Scientific Theories

Gravitational theory	Objects attract one another with a force that depends on their mass and how close together they are.
Cell theory	All organisms consist of one or more cells, the cell is the basic unit of life, and all cells arise from existing cells.
Germ theory	Germs cause infectious diseases.
Plate tectonics theory	Earth's crust is like a cracked eggshell, and its huge, fragmented slabs slowly collide and move apart.
Theory of evolution	Change can occur in lines of descent.
Theory of natural selection	Variation in heritable traits influences which individuals of a population reproduce in each generation.

Science has limits

Science requires an objective mind-set, and this means that scientists can only do certain kinds of studies. No experiment can explain the "meaning of life," for example, or why each of us dies at a certain moment. Those kinds of questions have subjective answers, shaped by our experiences and beliefs. Every culture and society has its own standards of morality and esthetics, and there are hundreds or thousands of different sets of religious beliefs. All guide their members in deciding what is important and morally good and what is not. By contrast, the external world, rather than internal conviction, is the only testing ground for scientific views.

Because science does not involve value judgments, it sometimes has been or can be used in controversial pursuits. The discovery of atomic power in the early twentieth century, and its continuing use today, is one example. Some people also are worried about issues such as the use of animals in scientific research and possible negative consequences of genetic modification of food plants. Debate over the causes of global warming, and steps necessary to deal with its effects, grows stronger by the day. Meanwhile, whole ecosystems are being altered by technologies that allow millions of a forest's trees to be cut in a single year and hundreds of millions of fishes to be taken from the sea. These are matters we can't leave to the scientific community alone to resolve. That responsibility also belongs to us.

Take-Home Message

In science, what is a theory? Which subjects are off limits to scientific investigation?

- A scientific theory is a testable explanation about the cause or causes of a broad range of related natural phenomena. It remains open to tests, revision, and even rejection if new evidence comes to light.
- Science only concerns itself with questions and problems that are objectively testable.
- Responsibility for the wise use of scientific information must be shared by all.

1.7 Living in a World of Infectious Disease

You already know that this textbook's main focus is the complex structure and remarkable functioning of the human body. Like other students, however, you probably also are concerned about many related issues, including environmental problems, societal concerns such as cloning and genetic profiling, and diseases and disorders that can harm health. Every chapter contains in-depth information about one or more of these topics. Here we introduce one of the most pressing modern health issues, the threat of infectious disease. Humans have always lived with countless health threats (Figure 1.9), but today we are locked in an escalating global battle with bacteria, viruses, parasites, and other **pathogens**—agents that can cause disease.

Figure 1.9 Medieval attempt to deal with a bubonic plague epidemic—the Black Death—that may have killed half the people in Europe during the Middle Ages.

Infections are a threat because they disrupt homeostasis

"Disease" and "infection" are familiar words, even though you might not be able to explain exactly what they mean in biological terms. An **infection** occurs when a pathogen enters cells or tissues and multiplies. **Disease** develops when the body's defenses cannot be mobilized quickly enough to prevent a pathogen's activities from interfering with normal body functions. And when body cells, tissues, or organs cannot operate properly, they can no longer do their part in maintaining homeostasis. This is why infections are dangerous. Infectious (contagious) pathogens also can move on to another person, often in blood or some other body fluid.

What do pathogens look like?

Most disease-causing microbes and parasites are invisible to the naked eye. The most common ones in humans are bacteria, viruses, certain fungi, and a variety of parasitic protists and worms. Figure 1.10 and other photographs in this section give you an idea of what some of these foes look like.

Emerging diseases present new challenges

Today health officials worry especially about **emerging diseases**. These diseases are caused by pathogens that until recently did not infect humans or were present only in limited areas. Many are caused by viruses. This group includes the encephalitis caused by West Nile virus and the severe respiratory disease caused by the SARS virus (Figure 1.11*a*). Other examples are "hemorrhagic fevers" that cause massive bleeding. In this latter group are dengue fever and the

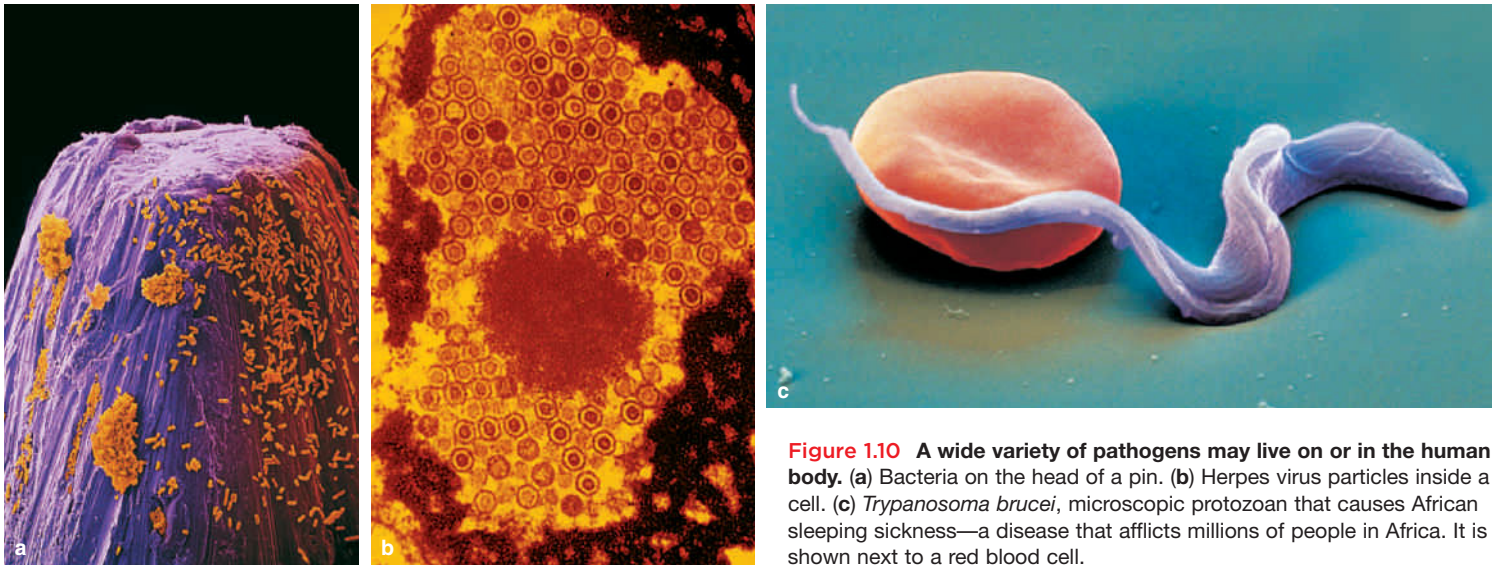
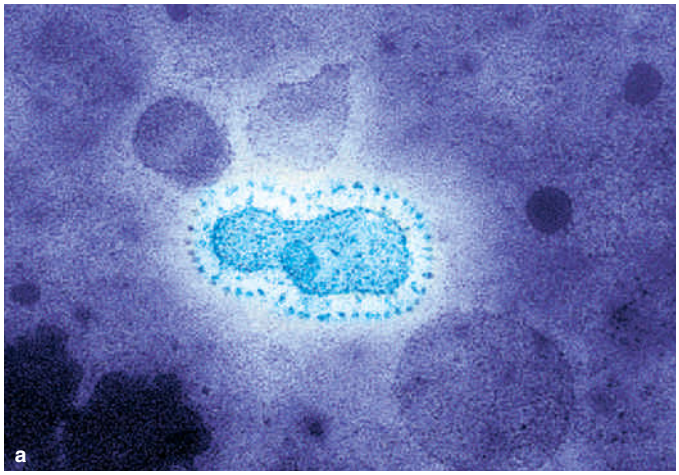


Figure 1.10 A wide variety of pathogens may live on or in the human body. (**a**) Bacteria on the head of a pin. (**b**) Herpes virus particles inside a cell. (**c**) *Trypanosoma brucei*, microscopic protozoan that causes African sleeping sickness—a disease that afflicts millions of people in Africa. It is shown next to a red blood cell.



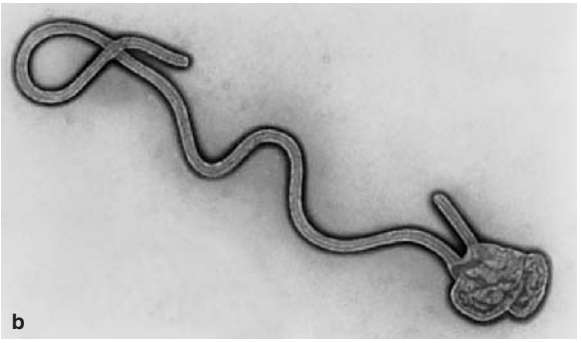


Figure 1.11 The (a) SARS and (b) Ebola viruses cause two currently emerging diseases.

illness caused by the Ebola virus (Figure 1.11*b*). You have probably heard of Lyme disease, which is a major emerging disease in the United States. It is caused by the bacterium *Borrelia burgdorferi*, which is transmitted by ticks when they suck blood.

Why is all this happening? A few factors stand out. For one, there are simply many more of us on the planet, interacting with our surroundings and with each other. Each person is a potential target for pathogens. Also, more people are traveling, carrying diseases along with them. Another important factor is the misuse and overuse of antibiotics.

Antibiotics are a double-edged sword

Antibiotics were discovered in the 1940s, when much of the world was engulfed in World War II, and they were soon harnessed to fight disease (Figure 1.12). An **antibiotic** is a substance that can destroy bacteria and some other microorganisms, or prevent them from growing. Bacteria and fungi produce most antibiotics. The penicillins and some other antibiotics kill microbes by interfering with different cell processes.

You may already know that antibiotics don't work against viruses, which are not cells and so do not have "life processes." Some of the body defenses you will read about in Chapter 9 may prevent certain viruses from multiplying inside cells. Antiviral drugs interfere with the viral "life cyle" in some way.

Antibiotics can have side effects such as triggering an allergic response or reducing the effectiveness of birth control pills. Even more serious, however, are antibiotic-resistant microbes.

Several factors have spurred the development of antibiotic resistance. Over the years, some doctors felt pressured to prescribe antibiotics for patients who had viral illnesses. Also, antibiotics are not prescription drugs in some nations, so people buy and take the drugs whenever they don't feel well. Some patients stop taking an antibiotic when they start to feel better, without finishing the full recommended course of treatment. Antibiotics also have been added to soaps, kitchen wipes, and many other consumer products All these factors have contributed to the emergence of bacteria that are genetically resistant to antibiotics that might otherwise have destroyed them.

Today antibiotic resistance is a major public health problem. The list of drug-resistant bacteria includes strains that cause some cases of tuberculosis, strep throat, STDs such as syphilis and gonorrhea, urinary tract infections, childhood middle-ear infections, and even infections of surgical wounds.

Figure 1.12 Penicillin saved the lives of many soldiers in World War II. This ad is from a 1944 issue of *Life* magazine.

IMPACTS, ISSUES

What Kind of World Do We Live In?

SPRAYING pesticides where mosquitoes breed is a way of protecting against West Nile virus. Even so, some people worry that spraying might harm human health.

How Would You Vote?

If health authorities in your community wanted to spray large areas with anti-mosquito insecticide, would you approve? See CengageNOW for details, then vote online.

SUMMARY

Section 1.1 Humans have the characteristics found in all forms of life, as listed in Table 1.3.

Section 1.2 All life on Earth has come about through a process of evolution. The defining features of humans include a large and well-developed brain, great manual dexterity, sophisticated skills for language and mental analysis, and complex social behaviors.

Section 1.3 The living world is highly organized. Atoms, molecules, cells, tissues, organs, and organ systems make up whole, complex organisms. Each organism is a member of a population, populations live together in communities, and communities form ecosystems. The biosphere is the most inclusive level of biological organization. The organization of life is sustained by a continual flow of energy and cycling of raw materials.

- Use the animation and interaction on CengageNOW to explore levels of biological organization.

Section 1.4 Science is an approach to gathering knowledge. There are many versions of the scientific method. Table 1.4 lists elements important in all of them. A reputable scientist must draw conclusions that are not at odds with the evidence used to support them.

Section 1.5 Critical thinking skills include scrutinizing information sources for bias, seeking reliable opinions, and separating the causes of events from factors that may only be associated with them.

Section 1.6 A scientific theory is a thoroughly tested explanation of a broad range of related phenomena.

Summary of Life's Characteristics

1. Living things take in and use energy and materials.
2. Living things sense and respond to changes in their surroundings.
3. Living things reproduce and grow based on information in DNA.
4. Living things consist of one or more cells.
5. Living things maintain the internal steady state called homeostasis.

Scientific Method Review

Hypothesis	Possible explanation of a natural event or observation
Prediction	Proposal or claim of what testing will show if a hypothesis is correct
Experimental test	Controlled procedure to gather observations that can be compared to prediction
Control group	Standard to compare test group against
Variable	Aspect of an object or event that may differ with time or between subjects
Conclusion	Statement that evaluates a hypothesis based on test results

Science does not address subjective issues, such as religious beliefs and morality.

Review Questions

1. For this and all other chapters, make a list of the boldface terms in the text. Write a definition next to each, and then check it against the one in the text.
2. As a human, you are a living organism. List all the characteristics of life that you exhibit.
3. Why is the concept of homeostasis meaningful in the study of human biology?
4. What is meant by biological evolution?
5. Study Figure 1.5. Then, on your own, summarize what is meant by biological organization.
6. Why does it make sense to think of ecosystems as webs of life?
7. Define and distinguish between:
   a. a hypothesis and a scientific theory
   b. an experimental group and a control group

Self-Quiz *Answers in Appendix V*

1. Instructions in _____ govern how organisms are built and function.
2. A _____ is the smallest unit that can live and reproduce by itself using energy, raw materials, and DNA instructions.

3. _____ is a state in which an organism's internal environment is being maintained within a tolerable range.

4. Humans are _____ (animals with backbones); like other primates, they also are _____.

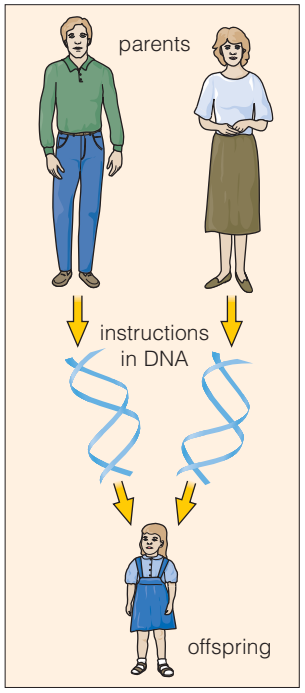
5. Starting with cells, nature is organized on at least _____ levels.

6. A scientific approach to explaining some aspect of the natural world includes all of the following except _____.
   a. a hypothesis
   b. testing
   c. faith-based views
   d. systematic observations

7. A controlled experiment should have all the features listed below except _____.
   a. a control group
   b. a test subject
   c. a variable
   d. several testable predictions

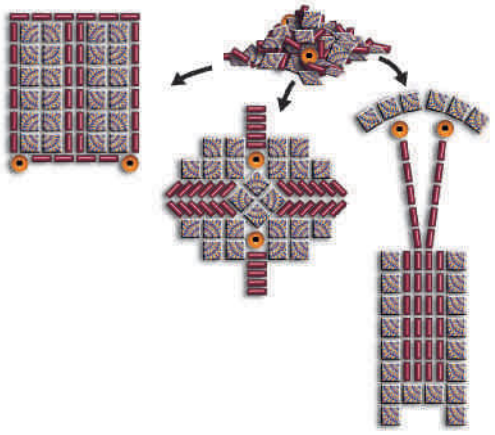
8. A related set of hypotheses that collectively explain some aspect of the natural world makes up a scientific _____.
   a. prediction
   b. test
   c. theory
   d. authority
   e. observation

9. The diagram below depicts the concept of _____.
   a. evolution
   b. reproduction
   c. levels of organization
   d. energy transfers in the living world



Critical Thinking

1. The diagram at the top of the next column shows ways that the same materials—here, a set of tiles—can be put together in different ways. How does this example relate to the role of DNA as the universal genetic material in organisms?



2. Court witnesses are asked "to tell the truth, the whole truth, and nothing but the truth." Research shows, however, that eyewitness accounts of crimes often are unreliable because even the most conscientious witnesses misremember details of what they observed. Can you think of other factors that might affect the "truth" a court witness presents?

3. Design a test (or series of tests) to support or refute this hypothesis: A diet that is high in salt is associated with hypertension (high blood pressure), but hypertension is more common in people with a family history of the condition.

4. In popular magazine articles on health-related topics, the authors often recommend a particular diet or dietary supplement. What kinds of evidence should the articles cite to help you decide whether or not to accept their recommendations?

5. Some years ago Dr. Randolph Byrd and his colleagues started a study of 393 patients admitted to the San Francisco General Hospital Coronary Care Unit. In the experiment, born-again Christian volunteers were asked to pray daily for a patient's rapid recovery and for prevention of complications and death.

   None of the patients knew if he or she was being prayed for. None of the volunteers or patients knew each other. Byrd categorized how each patient fared as "good," "intermediate," or "bad." He concluded that patients who had been prayed for fared a little better than those who had not. His was the first experiment that had documented statistically significant results that seemed to support the prediction that prayer might have beneficial effects for seriously ill patients.

   His published results engendered a storm of criticism, mostly from scientists who cited bias in the experimental design. For instance, Byrd had categorized the patients after the experiment was over, instead of as they were undergoing treatment, so he already knew which ones had improved, stayed about the same, or gotten worse. Think about how experimenters' bias might play a role in how they interpret data. Why do you suppose the experiment generated a heated response from many in the scientific community? Can you think of at least one other variable that might have affected the outcome of each patient's illness?

EXPLORE ON YOUR OWN

As you read in Section 1.4, having a sample of test subjects or observations that is too small can skew the results of experiments. This phenomenon is called *sampling error*. To demonstrate this for yourself, all you need is a partner, a blindfold, and a jar containing beans of different colors—jelly beans will do just fine (Figure 1.13). Have your partner stay outside the room while you combine 120 beans of one color with 280 beans of the other color in a bowl. This will give you a ratio of 30 to 70 percent. With the bowl hidden, blindfold your partner; then ask him or her to pick one bean from the mix. Hide the bowl again and instruct your friend to remove the blindfold and tell you what color beans are in the bowl, based on this limited sample. The logical answer is that all the beans are the color of the one selected.

Next repeat the trial, but this time ask your partner to select 50 beans from the bowl. Does this larger sample more closely approximate the actual ratio of beans in the bowl? You can do several more trials if you have time. Do your results support the idea that a larger sample size more closely reflects the actual color ratio of beans?

a Natalie, blindfolded, randomly plucks a jelly bean from a jar of 120 green and 280 black jelly beans, a ratio of 30 to 70 percent.

b The jar is hidden before she removes her blindfold. She observes a single green jelly bean in her hand and assumes the jar holds only green jelly beans.

c Still blindfolded, Natalie randomly picks 50 jelly beans from the jar and ends up with 10 green and 40 black ones.

d The larger sample leads her to assume one-fifth of the jar's jelly beans are green and four-fifths are black (a ratio of 20 to 80). Her larger sample more closely approximates the jar's green-to-black ratio. The more times Natalie repeats the sampling, the greater the chance she will come close to knowing the actual ratio.

Figure 1.13 **Here's how you can demonstrate sampling error.**

Chemistry of Life

2

IMPACTS, ISSUES

Fearsome Fats

THE human body requires about one tablespoon of fat each day to remain healthy, but most of us eat far more than that. The average American consumes the equivalent of one stick of butter per day, which may be part of the reason so many Americans struggle with excess weight and related diseases.

Researchers have discovered, however, that which type of fat we eat may be more important than how much fat we eat. One type, called trans fats, raises the level of cholestrol in our blood more than any other fat, and trans fats also change the functioning of our blood vessels in unhealthy ways.

You may unknowingly be eating a lot of trans fats. They are the key ingredient in partially hydrogenated vegetable oil, an artificial food product used in many store-bought cookies, cakes, doughnuts, muffins, microwave popcorn, pizzas, french fries, chicken nuggets, and so on. Unfortunately, eating as little as 2 grams per day of hydrogenated vegetable oils increases the risk of atherosclerosis (hardening of the arteries), heart attack, and diabetes. On average, one serving of french fries made with hydrogenated vegetable oil contains 5 grams of trans fats.

Chemical reactions explain the bodily effects of trans fats and all the other raw materials that enter the body. Unlike trans fats, however, many substances have indispensable roles in the chemical events that build cell parts and allow them to function properly.

In this chapter you will learn some simple chemical basics that will help you better understand topics of later chapters, such as why certain nutrients are vital to health. As you'll read often in this book, the body's ability to manage changes that disturb its chemistry is equally essential to maintaining the internal stability we call homeostasis.

KEY CONCEPTS

Atoms and Elements

Atoms are fundamental units of all matter. Elements are pure substances that consist of atoms. Bonds between atoms form molecules, including biological molecules. Sections 2.1–2.4

Water and Body Fluids

Life depends on properties of water. Substances dissolved in the water of body fluids have major effects on body functions. Sections 2.5–2.7

Biological Molecules

Cells use chemical reactions to build complex carbohydrates and lipids, proteins, and nucleic acids. All of these large molecules have a backbone of carbon atoms. Groups of atoms that are bonded to the backbone help determine a molecule's properties. Sections 2.8–2.13

LINKS TO EARLIER CONCEPTS

- Atoms are the nonliving raw materials from which living cells, and whole organisms, are built. The processes that harness atoms and assemble them into the many different parts of cells all are guided by DNA (1.1–1.3).
- Each of our cells is surrounded by watery fluid. That is why this chapter gives you some background about the properties of water, which are essential to the body's ability to maintain homeostasis in body fluids (1.1).

How Would You Vote?

Packaged foods in the United States must list trans fat content, but may be marked "zero grams of trans fat content" even if a serving contains up to half a gram of it. Should hydrogenated oils be banned from all food? See CengageNOW for details, then vote online.

2.1 Atoms and Elements

- **Pure substances called elements are the basic raw material of living things.**
- **Each element consists of one type of atom.**
- **The parts of atoms determine how the molecules of life are put together.**
- **Link to Life's organization 1.3**

Elements are fundamental forms of matter

Like all else on Earth, your body consists of chemicals, some of them solids, others liquid, still others gases. Each of these chemicals consists of one or more elements. An element is a fundamental form of matter. No ordinary process can break it down to other substances. There are ninety-two natural elements on Earth, and researchers have created other, artificial ones.

Organisms consist mostly of four elements: oxygen, carbon, hydrogen, and nitrogen. The human body also contains some calcium, phosphorus, potassium, sulfur, sodium, and chlorine, plus trace elements. A trace element is one that makes up less than 0.01 percent of body weight. Trace elements are vital; for example, your red blood cells can't carry oxygen without the trace element iron. The chart in this chapter's *Science Comes to Life* feature shows how much your body's elements might be worth in the chemical marketplace—a reminder that all of us are worth more than the sum of our parts!

Atoms of elements can combine into molecules—the first step in biological organization. Molecules in turn can combine to form larger structures, as described shortly. The body's chemical makeup is finely tuned. For example, many trace elements found in our tissues—such as arsenic, selenium, and fluorine—are toxic in amounts larger than normal.

Atoms are composed of smaller particles

An **atom** is the smallest unit that has the properties of a given element. A million could fit on the period at the end of this sentence. In spite of their tiny size, however, all atoms are composed of more than one hundred kinds of subatomic particles. The ones we are concerned with in this book are protons, electrons, and neutrons, illustrated in Figure 2.1.

All atoms have one or more protons, which carry a positive charge, marked by a plus sign (p^+). Except for hydrogen, atoms also have one or more neutrons, which have no charge. Neutrons and protons make up the atom's core, the atomic nucleus. Electrons move around the nucleus, occupying most of the atom's volume. They have a negative charge, which we write as e^-. An atom usually has an equal number of electrons and protons.

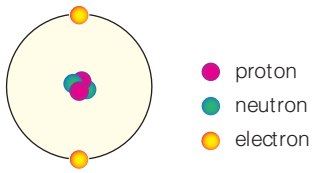


Figure 2.1 Atoms consist of subatomic particles. This model can't show what an atom really looks like. Electrons travel around a nucleus of protons and neutrons, and they occupy spaces about 10,000 times larger than the nucleus.

Each element is assigned its own "atomic number," which is the number of protons in its atoms. Elements also have a "mass number"—the sum of the protons and neutrons in the nucleus of their atoms. Appendix II of this textbook has charts of the elements and of the atomic and mass numbers of the common elements in living things.

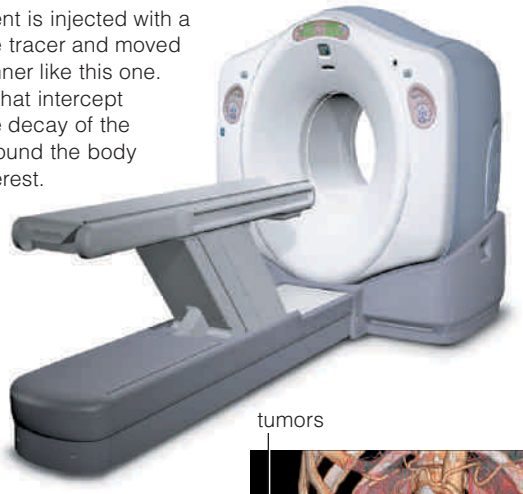
Isotopes are varying forms of atoms

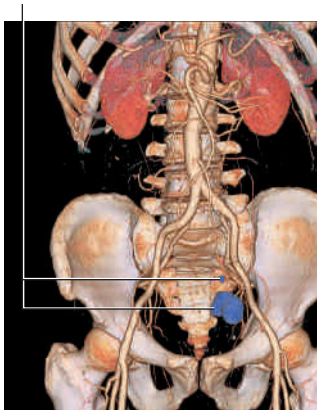
All atoms of a given element have the same number of protons and electrons, but they may *not* have the same number of neutrons. When an atom of an element has more or fewer neutrons than the most common number, it is called an **isotope** (EYE-so-tope). For instance, while a "standard" carbon atom will have six protons and six neutrons, the isotope called carbon 14 has six protons and *eight* neutrons. These two forms of carbon atoms also can be written as ^{12}C and ^{14}C. The prefix *iso-* means same, and all isotopes of an element interact with other atoms in the same way. Most elements have at least two isotopes. Cells can use any isotope of an element for their metabolic activities, because the isotopes behave the same as the standard form of the atom in chemical reactions.

Have you heard of radioactive isotopes? A French scientist discovered them in 1896, after he had set a chunk of rock on top of an unexposed photographic plate in a desk drawer. The rock contained isotopes of uranium, which emit energy. This unexpected chemical behavior is what we today call radioactivity. Soon after the Frenchman's plate was exposed to uranium emissions, he was astonished to see that a faint image of the rock appeared on it.

The nucleus of a **radioisotope** is unstable, but it stabilizes itself by emitting energy and particles (other than protons, electrons, and neutrons). This process, called radioactive decay, takes place spontaneously, and it transforms a radioisotope into an atom of a different element. The decay process happens at a known rate. For instance, over a predictable time span, carbon 14 becomes nitrogen 14. Scientists can use radioactive decay rates to determine the age of very old substances.

A A patient is injected with a radioactive tracer and moved into a scanner like this one. Detectors that intercept radioactive decay of the tracer surround the body part of interest.





B Radioactive decay detected by the scanner is converted into digital images of the body's interior. Two tumors (*blue*) in and near the bowel of a cancer patient are visible in this PET scan.

Figure 2.2 Radioisotopes have important medical uses. (**a**) A PET scanner. (**b**) PET image showing two tumors (*blue*) in and near the bowel of a cancer patient.

2.2 How Much Are You Worth?

Elements in a Human Body

Element	Number of Atoms (x 10^{15})	Retail Cost
Hydrogen	41,808,044,129,611	$ 0.028315
Oxygen	16,179,356,725,877	0.021739
Carbon	8,019,515,931,628	6.400000
Nitrogen	773,627,553,592	9.706929
Phosphorus	151,599,284,310	68.198594
Calcium	150,207,096,162	15.500000
Sulfur	26,283,290,713	0.011623
Sodium	26,185,559,925	2.287748
Potassium	21,555,924,426	4.098737
Chlorine	16,301,156,188	1.409496
Magnesium	4,706,027,566	0.444909
Fluorine	823,858,713	7.917263
Iron	452,753,156	0.054600
Silicon	214,345,481	0.370000
Zinc	211,744,915	0.088090
Rubidium	47,896,401	1.087153
Strontium	21,985,848	0.177237
Bromine	19,588,506	0.012858
Boron	10,023,125	0.002172
Copper	6,820,886	0.012961
Lithium	6,071,171	0.024233
Lead	3,486,486	0.003960
Cadmium	2,677,674	0.010136
Titanium	2,515,303	0.010920
Cerium	1,718,576	0.043120
Chromium	1,620,894	0.003402
Nickel	1,538,503	0.031320
Manganese	1,314,936	0.001526
Selenium	1,143,617	0.037949
Tin	1,014,236	0.005387
Iodine	948,745	0.094184
Arsenic	562,455	0.023576
Germanium	414,543	0.130435
Molybdenum	313,738	0.001260
Cobalt	306,449	0.001509
Cesium	271,772	0.000016
Mercury	180,069	0.004718
Silver	111,618	0.013600
Antimony	98,883	0.000243
Niobium	97,195	0.000624
Barium	96,441	0.028776
Gallium	60,439	0.003367
Yttrium	40,627	0.005232
Lanthanum	34,671	0.000566
Tellurium	33,025	0.000722
Scandium	26,782	0.058160
Beryllium	24,047	0.000218
Indium	20,972	0.000600
Thallium	14,727	0.000894
Bismuth	14,403	0.000119
Vanadium	12,999	0.000322
Tantalum	6,654	0.001631
Zirconium	6,599	0.000830
Gold	6,113	0.001975
Samarium	2,002	0.000118
Tungsten	655	0.000007
Thorium	3	0.004948
Uranium	3	0.000103
Total	67,179,218,505,055 x 10^{15}	**$118.63**

Radioisotopes may help diagnose disease and save lives

Radioisotopes are routinely used in medicine because they permit a physician to diagnose disease without doing exploratory surgery. Radioisotopes also are part of the treatment of certain cancers. For safety's sake, only radioisotopes with extremely short half-lives are used. (*Half-life* is the time it takes for half of a quantity of a radioisotope to decay into a different, more stable one.)

Various devices can detect radioisotope emissions. One of them is the PET scanner (short for Positron Emission Tomography). Figure 2.2 shows a PET scan from a cancer patient. The patient was injected with a **tracer**, a sugar or other molecule in which radioisotopes have been substituted for some atoms. Cells that are more active, such as cancer cells, take up the tracer faster than other cells do. The patient was moved into a scanner, which detected radioactivity concentrated in the tumors. PET also has been useful in studying human brain activity.

Take-Home Message

What are the basic building blocks of all matter?

- Atoms are tiny particles and are the building blocks of all substances.
- Atoms consist of electrons moving around a nucleus of protons and (except for hydrogen) neutrons.
- An element is a pure substance. Each kind consists of atoms having the same number of protons.

2.3 Chemical Bonds: How Atoms Interact

- **Atoms receive, donate, or share electrons.**
- **Whether an atom will interact with other atoms depends on how many electrons it has.**
- **Chemical bonds connect atoms into molecules.**

Atoms interact through their electrons

There are three ways atoms can interact: A given atom may share one or more of its electrons, it can accept extra ones, or it can donate electrons to another atom. *Which* of these events takes place depends on how many electrons an atom has and how they are arranged.

If you have ever played with magnets you know that like charges (++ or −−) repel each other and unlike charges (+−) attract. Electrons carry a negative charge, so they are attracted to the positive charge of protons. On the other hand, electrons repel each other. In an atom, electrons respond to these pushes and pulls by moving around the atomic nucleus in "shells." A shell is not a flat, circular track around the nucleus; it has three dimensions, like the space inside a balloon, and the electron or electrons inside it travel in "orbitals." You can think of an orbital as a room in an apartment building—the atom—that allows exactly two renters per room. This means that in an atom, at most two electrons can occupy an orbital. Recall from Section 2.1 that atoms of different elements differ in how many electrons they have. They also differ in how many of their "rooms" are filled.

Hydrogen is the simplest atom. It has one electron in a single shell (Figure 2.3*a*). In atoms of other elements, the first shell holds two electrons. Any additional electrons are in shells farther from the nucleus.

The shells around an atom's nucleus are equivalent to energy levels. The shell closest to the nucleus is the lowest energy level. Each shell farther out from the nucleus is at a progressively higher energy level. Because the atoms of different elements have different numbers of electrons, they also have different numbers of shells that electrons can occupy. A shell can have up to eight electrons, but not more. This means that larger atoms, which have more electrons than smaller ones do, also have more shells. The known elements, listed in Appendix II, include some that have many shells to hold all their electrons.

Chemical bonds join atoms

A union between the electron structures of atoms is a **chemical bond**. You can think of bonds as the glue that

electron

C Third shell This shell corresponds to the third energy level. It has four orbitals with room for eight electrons. Sodium has one electron in the third shell; chlorine has seven. Both have vacancies, so both form chemical bonds. Argon, with no vacancies, does not.

B Second shell This shell, which corresponds to the second energy level, has four orbitals—room for a total of eight electrons. Carbon has six electrons: two in the first shell and four in the second. It has four vacancies. Oxygen has two vacancies. Both carbon and oxygen form chemical bonds. Neon, with no vacancies, does not.

A First shell A single shell corresponds to the first energy level, which has a single orbital that can hold two electrons. Hydrogen has only one electron in this shell and gives it up easily. A helium atom has two electrons (no vacancies), so it does not form bonds.

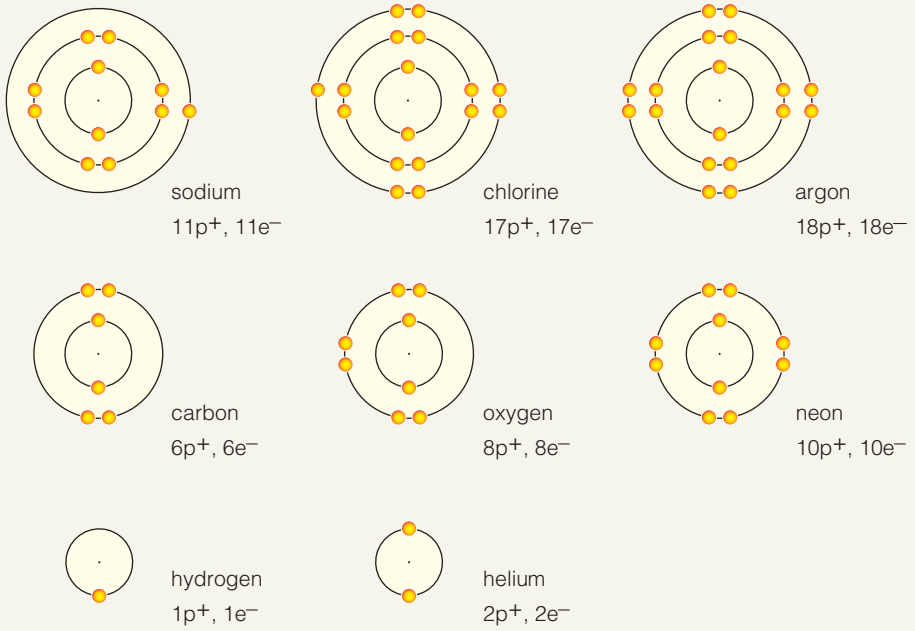
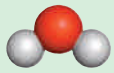
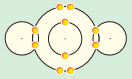


Figure 2.3 Animated! The shell model helps you visualize the vacancies in an atom's outer orbitals. Each circle represents all of the orbitals on one energy level. The larger the circle, the higher the energy level.

joins atoms into molecules. How does this "glue" come about? An atom is most stable when its outer shell is filled. Atoms that have too few electrons to fill their outer shell tend to form chemical bonds with other atoms in order to do so. Atoms of oxygen, carbon, hydrogen, and nitrogen—the four most abundant elements in the human body—are like this. As shown in Figure 2.3, hydrogen and helium atoms have a single shell. It is full when it contains two electrons. Other kinds of atoms that have unfilled outer shells take part in chemical bonds that fill their outer shell with eight electrons. Check for electron vacancies in an atom's outer shell and you have a clue as to whether the atom will bond with others. When its outer shell has one or more vacant "slots," an atom may give up electrons, gain them, or share them.

In Figure 2.3 you can count the electron vacancies in the outer shell of each of the atoms pictured. Atoms like helium, which have no vacancies, are said to be *inert*. They usually don't take part in chemical reactions.

TABLE 2.1 Different Ways to Represent the Same Molecule

Common name	Water	Familiar term.
Chemical name	Hydrogen oxide	Describes the elements making up the molecule.
Chemical formula	H_2O	Indicates proportions of elements. Subscripts show number of atoms of an element per molecule. The absence of a subscript means one atom.
Structural formula	H—O—H H, O, H	Represents a bond as a single line between atoms. The bond angles also may be represented.
Structural model		Shows the positions and relative sizes of atoms.
Shell model		Shows how pairs of electrons are shared.

Atoms can combine into molecules

When chemical bonding joins atoms, the new structure is a **molecule** (Table 2.1). Many molecules contain atoms of only one element. Molecular nitrogen (N_2), with its two nitrogen atoms, is an example. Figure 2.4 explains how to read the notation used in representing chemical reactions that occur between atoms and molecules.

Many other kinds of molecules are **compounds**—they consist of two or more elements in proportions that never vary. For example, water is a compound. Every water molecule has one oxygen atom bonded with two hydrogen atoms. No matter where water molecules are—in rain clouds or in a lake or in your bathtub—they *always* have twice as many hydrogen as oxygen atoms.

In a **mixture**, two or more kinds of molecules simply mingle. The proportions may or may not be the same. For example, the sugar sucrose is a compound of carbon, hydrogen, and oxygen. If you swirl together molecules of sucrose and water, you'll get a mixture—sugar-sweetened water. If you keep the same amount of water but add more sucrose you will still have a mixture—just an extremely sweet one, such as syrup.

We use symbols for elements when writing *formulas*, which identify the composition of compounds. For example, water has the formula H_2O. Symbols and formulas are used in *chemical equations*, which are representations of reactions among atoms and molecules.

In written chemical reactions, an arrow means "yields." Substances entering a reaction (reactants) are to the left of the arrow. Reaction products are to the right. For example, the reaction between hydrogen and oxygen that yields water is summarized this way:

$$2H_2 + O_2 \rightarrow 2H_2O$$

4 hydrogens 2 oxygens 4 hydrogens, 2 oxygens

Note that there are as many atoms of each element to the right of the arrow as there are to the left. Although atoms are combined in different forms, none is consumed or destroyed in the process. The total mass of all products of any chemical reaction equals the total mass of all its reactants. All equations used to represent chemical reactions, including reactions in cells, must be balanced this way.

Figure 2.4 Animated! Symbols are a "shorthand" way to describe chemical reactions.

Take-Home Message

How may atoms interact?

- An atom's electrons determine whether and how it will interact with other atoms.
- Electrons move in orbitals around an atom's nucleus. In the shell model of orbitals, a series of shells correspond to increasing levels of energy. An orbital cannot contain more than two electrons.
- Atoms with unfilled orbitals in their outermost shell tend to interact with other atoms and bond with other atoms. Atoms with no vacancies do not form bonds.
- In molecules of a single element, all atoms are the same kind. In a compound, chemical bonds connect atoms of differing elements, in proportions that stay the same. In a mixture, the proportions can vary.

2.4 Important Bonds in Biological Molecules

- **In biological molecules the main kinds of chemical bonds are ionic, covalent, and hydrogen bonds.**

An ionic bond joins atoms that have opposite electrical charges

Overall, an atom carries no charge because it has just as many electrons as protons. That balance can change if an atom has a vacancy—an unfilled orbital—in its outer shell. For example, a chlorine atom has one vacancy and therefore can gain one electron. A sodium atom, on the other hand, has a single electron in its outer shell, and that electron can be knocked out or pulled away. When an atom gains or loses an electron, the balance between its protons and its electrons shifts, so the atom becomes ionized; it has a positive or negative charge. An atom that has a charge is called an **ion**.

It's common for neighboring atoms to accept or donate electrons among one another. When one atom loses an electron and one gains, both become ionized. Depending on conditions inside the cell, the ions may separate, or they may stay together as a result of the mutual attraction of their opposite charges. An association of two ions that have opposing charges is called an **ionic bond**. Figure 2.5 shows how sodium ions (Na^+) and chloride ions (Cl^-) interact through ionic bonds, forming NaCl, or table salt.

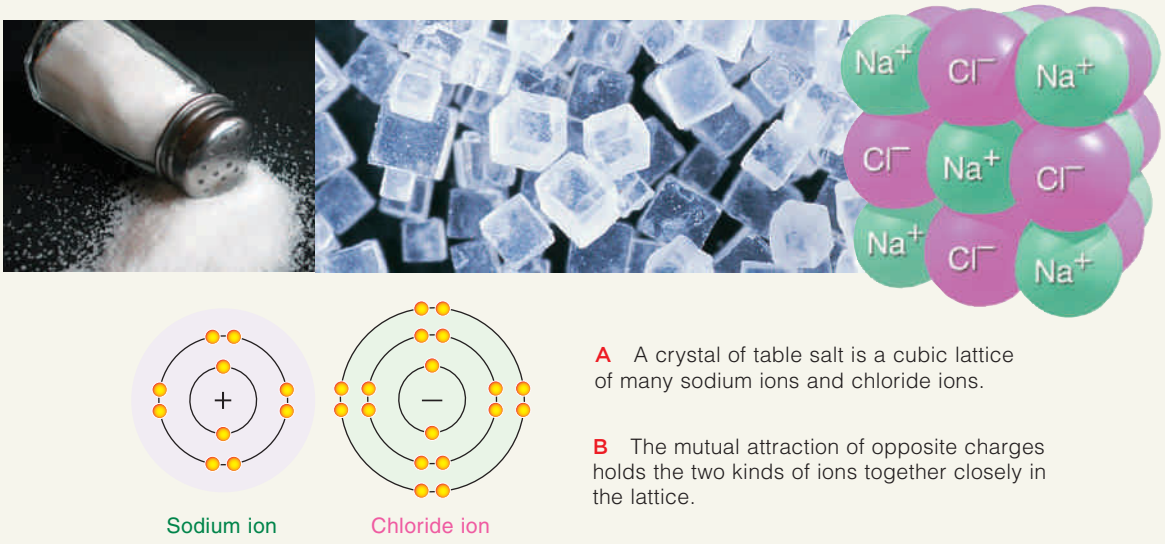
In a covalent bond, atoms share electrons

In a **covalent bond**, atoms *share* two electrons (Figure 2.6). The bond forms when two atoms each have a lone electron in their outer shell and each atom's attractive force "pulls" on the other's unpaired electron. The tug is not strong enough to pull an electron away completely, so the two electrons occupy a shared orbital. Covalent bonds are stable and much stronger than ionic bonds.

As you saw in Table 2.1, in structural formulas a single line between two atoms means they share a single covalent bond. Molecular hydrogen, a molecule that consists of two hydrogen atoms, has this kind of bond and can be written as H—H. In a *double* covalent bond, two atoms share two electron pairs, as in an oxygen molecule (O=O). In a *triple* covalent bond, two atoms share three pairs of electrons. A nitrogen molecule (N≡N) is this way. All three examples are gases. When you breathe, you inhale H_2, O_2, and N_2 molecules.

In a *nonpolar* covalent bond, the two atoms pull equally on electrons and so share them equally. The term "nonpolar" means there is no difference in charge at the two ends ("poles") of the bond. Molecular hydrogen is a simple example. Its two hydrogen atoms, each with one proton, attract the shared electrons equally.

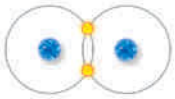
In a *polar* covalent bond, two atoms do not share electrons equally. The atoms are of different elements, and one has more protons than the other. The one with the most protons pulls more, so its end of the bond ends up with a slight negative charge. We say it is "electronegative." The atom at the other end of the bond ends up with a slight positive charge. For instance, a water molecule (H—O—H) has two polar covalent bonds. The oxygen atom carries a slight negative charge, and each of the two hydrogen atoms has a slight positive charge.



A A crystal of table salt is a cubic lattice of many sodium ions and chloride ions.

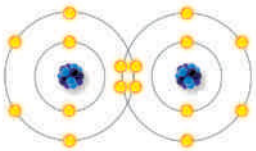
B The mutual attraction of opposite charges holds the two kinds of ions together closely in the lattice.

Figure 2.5 **Animated! Two oppositely charged atoms may stay together in an ionic bond.**



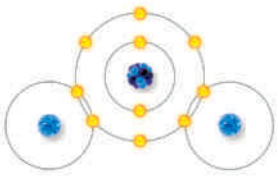
molecular hydrogen (H—H)

Two hydrogen atoms, each with one proton, share two electrons in a single covalent bond that is nonpolar.



molecular oxygen (O═O)

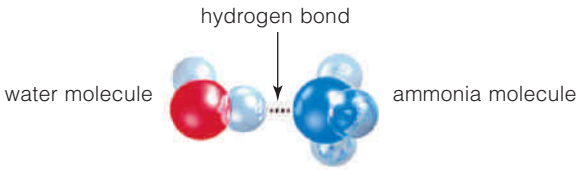
Two oxygen atoms, each with eight protons, share four electrons in a double covalent bond, also nonpolar.



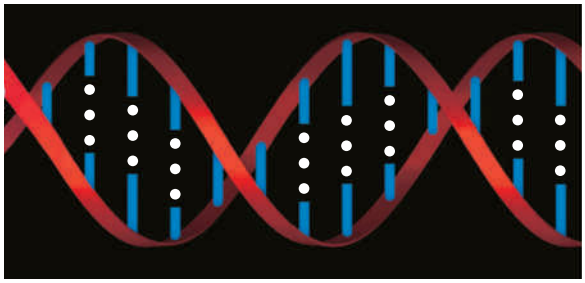
water (H—O—H)

Two hydrogen atoms each share an electron with oxygen. The resulting two covalent bonds form a water molecule. These bonds are polar. The oxygen exerts a greater pull on the shared electrons, so it bears a slight negative charge. Each of the hydrogens has a slight positive charge.

Figure 2.6 Shared electrons make up covalent bonds. Two atoms with unpaired electrons in their outer shell become more stable by sharing electrons. Two electrons are shared in each covalent bond. When the electrons are shared equally, the covalent bond is nonpolar. If one atom exerts more pull on the shared electrons, the covalent bond is polar.



A Two molecules interacting in one hydrogen (H) bond.



B Numerous H bonds (*white* dots) hold the two coiled-up strands of a DNA molecule together. Each H bond is weak, but collectively these bonds stabilize DNA's large structure.

Figure 2.7 Hydrogen bonds can form when a hydrogen atom is already covalently bonded in a molecule. The hydrogen's slight positive charge weakly attracts an atom with a slight negative charge that is already covalently bonded to something else. As shown above, this can happen between one of the hydrogen atoms of a water molecule and the nitrogen atom of an ammonia molecule.

A hydrogen bond is a weak bond between polar molecules

A **hydrogen bond** is a weak attraction that has formed between a covalently bound hydrogen atom and an electronegative atom in a different molecule or in another part of the same molecule. The dotted lines in Figure 2.7 depict this link.

Hydrogen bonds are weak, so they form and break easily. Even so, they are essential in biological molecules. For example, the genetic material DNA is built of two parallel strands of chemical units, and the strands are held together by hydrogen bonds. In Section 2.5 you will learn how hydrogen bonds between water molecules contribute to properties of water that make it one of the essential molecules of life.

Table 2.2 summarizes what you have just read about hydrogen bonds and the other main chemical bonds in biological molecules.

Major Chemical Bonds in Biological Molecules

Bond	Characteristics
Ionic	Joined atoms have opposite charges.
Covalent	Strong; joined atoms share electrons. In a *polar* covalent bond one end is positive, the other negative.
Hydrogen	Weak; joins a hydrogen (H^+) atom in one polar molecule with an electronegative atom in another polar molecule.

Take-Home Message

What kinds of chemical bonds form in biological molecules?

- An ion forms when an atom gains or loses electrons, and so acquires a positive or negative charge. In an ionic bond, ions of opposite charge attract each other and stay together.
- In a covalent bond, atoms share electrons. If the electrons are shared equally, the bond is nonpolar. If the sharing is not equal, the bond is polar—slightly positive at one end, slightly negative at the other.
- In a hydrogen bond, a covalently bound hydrogen atom attracts a small, negatively charged atom in a different molecule or in another part of the same molecule.

2.5 Water: Indispensable for Life

- **Water is required for many life processes.**
- **Other life processes occur only after substances have dissolved in water.**

Life on Earth probably began in water, and for all life forms it is indispensable. Human blood is more than 90 percent water, and water helps maintain the shape and internal structure of our cells. Three unusual properties of water suit it for its key roles in the body, starting with the fact that water is liquid at body temperature.

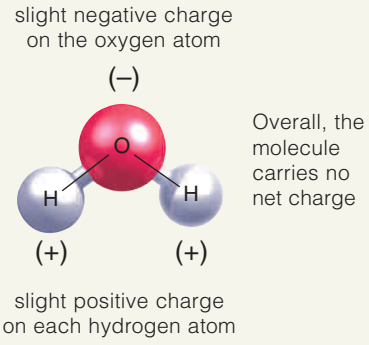
Hydrogen bonding makes water liquid

Any time water is warmer than about 32°F or cooler than about 212°F, it is a liquid. Therefore it is a liquid at body temperature; our watery blood flows and our cells have the fluid they need to maintain their structural integrity and to function properly. What keeps water liquid? You may recall that while a water molecule has no net charge, it does carry charges that are distributed unevenly. The water molecule's oxygen end is slightly negative and its hydrogen end is a bit positive (Figure 2.8*a*). This uneven distribution of charges makes water molecules polar. Because they are polar, the molecules can attract other water molecules and form hydrogen bonds with them. Collectively, the bonds are so strong that they hold the water molecules close together (Figure 2.8*b* and 2.8*c*). This effect of hydrogen bonds is why water is a liquid unless its temperature falls to freezing or rises to the boiling point.

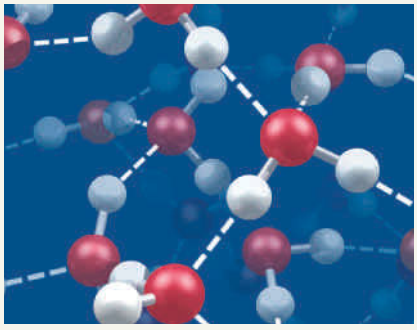
Water attracts and hydrogen-bonds with other polar substances, such as sugars. Because polar molecules are attracted to water, they are said to be **hydrophilic**, or "water-loving." Water repels nonpolar substances, such as oils. Hence nonpolar molecules are **hydrophobic**, or "water-dreading." We will return to these concepts when we look at the structure of cells in Chapter 3.

Water can absorb and hold heat

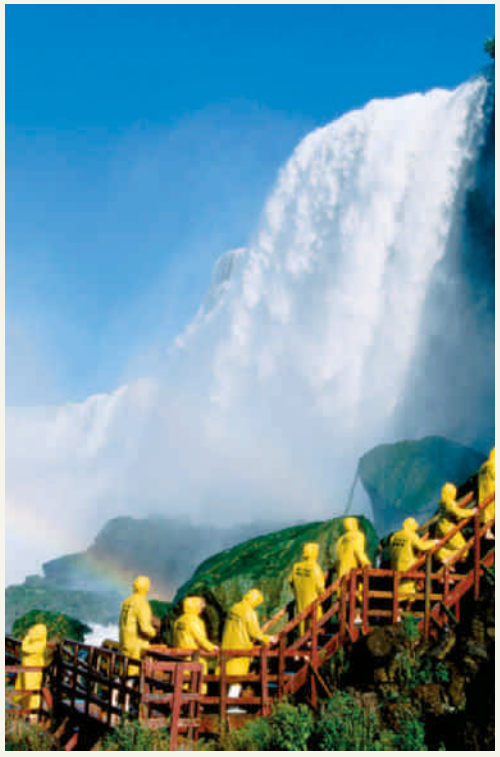
Water's hydrogen bonds give it a high *heat capacity*—they enable water to absorb a great deal of heat energy before it warms significantly or evaporates. This is because it takes a large amount of heat to break the many hydrogen bonds that are present in water. Water's ability to absorb a lot of heat before becoming hot is the reason it was used to cool automobile engines in the days before alcohol-based coolants became available. In a similar way, water helps stabilize the temperature inside cells, which are mostly water. The chemical reactions in cells constantly produce heat, yet cells must stay fairly cool because their proteins can only function properly within narrow temperature limits.



a Polarity of a water molecule.



b Hydrogen bonds between molecules in liquid water (dashed lines).



c Water's cohesion. When water flows over a high ledge, the fall (gravity) pulls molecules away from the surface. The individual water molecules don't scatter every which way, however, because hydrogen bonds pull inward on those at the surface. As a result, the molecules tend to stay together in droplets.

Figure 2.8 Animated!
Water is essential for life.

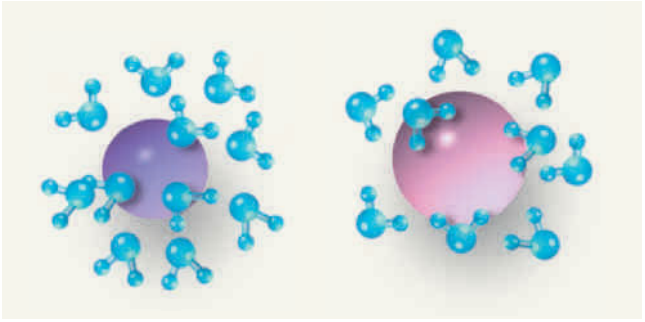


Figure 2.9 Animated! Charged substances dissolve easily in water. This diagram shows clusters of water molecules around ions. The clusters are called "spheres of hydration."

When enough heat energy is present, hydrogen bonds between water molecules break apart and do not re-form. Then liquid water evaporates—molecules at its surface begin to escape into the air. When a large number of water molecules evaporate, heat energy is lost. This is why sweating helps cool you off on a hot, dry day. Your sweat is 99 percent water. When it evaporates from the millions of sweat glands in your skin, heat leaves with it.

Water is a biological solvent

Water also is a superb **solvent**, which means that ions and polar molecules easily dissolve in it. In chemical terms a dissolved substance is called a **solute**. When a substance dissolves, water molecules cluster around its individual molecules or ions and form "spheres of hydration." This is what happens to solutes in blood and other body fluids. Most chemical reactions in the body occur in water-based solutions.

Figure 2.9 shows what happens to table salt (NaCl) when you pour some into a glass of water. After a while, the salt crystals separate into Na^+ and Cl^-. Each Na^+ attracts the negative end of some of the water molecules while each Cl^- attracts the positive end of others.

Take-Home Message

What properties make water indispensable to life?

- A water molecule is polar. One end is slightly positive and the other end is slightly negative.
- Polarity allows water molecules to form hydrogen bonds with one another and with other polar (hydrophilic) substances. Water molecules tend to repel nonpolar (hydrophobic) substances.
- The hydrogen bonds in water help it stabilize temperature in body fluids and allow it to dissolve many substances.

2.6 How Antioxidants Protect Cells

The process in which an atom or molecule loses one or more electrons to another atom or molecule is called *oxidation*. It's what causes a match to burn and an iron nail to rust, and it is part of all kinds of important metabolic events in body cells. Unfortunately, the countless oxidations that go on in our cells also release highly unstable molecules called **free radicals**. Each one is a molecule (such as O_2^-) that includes an oxygen atom lacking a full complement of electrons in its outer shell. To fill the empty slot, a free radical can easily "steal" an electron from another, stable molecule. This theft disrupts both the structure and functioning of the affected molecule.

When free radicals are present in large numbers, they pose a serious threat to various types of molecules, including a cell's DNA. Cigarette smoke and the ultraviolet radiation in sunlight produce additional free radicals in the body.

An **antioxidant** is a substance that can give up an electron to a free radical before the rogue does damage to DNA or some other vital cell component. The body makes some antioxidants, including the hormone melatonin (Chapter 15), that neutralize free radicals by giving up electrons to them. This home-grown chemical army isn't enough to balance the ongoing production of free radicals, however. This is why many nutritionists recommend adding antioxidants to the diet by eating lots of the foods that contain them, using supplements only in moderation.

Ascorbic acid—vitamin C—is an antioxidant, as is vitamin E. So are some carotenoids, such as alpha carotene, which are pigments in orange and leafy green vegetables, among other foods (Figure 2.10). Antioxidant-rich foods typically also are low in fat and high in fiber.

Figure 2.10 Antioxidants help counter free radicals. Good sources are orange and green vegetables and fruits.

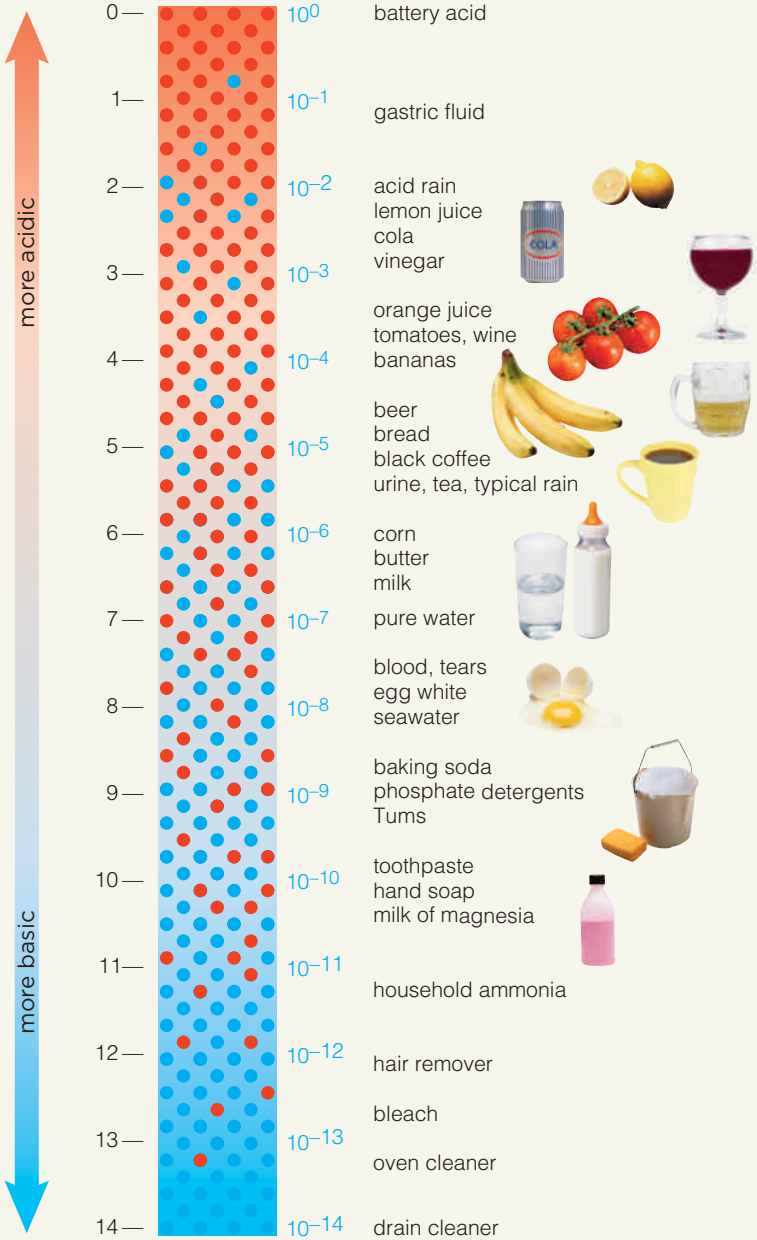
2.7 Acids, Bases, and Buffers: Body Fluids in Flux

- **Ions dissolved in the fluids inside and outside cells influence cell structure and functioning.**
- **Hydrogen ions affect many body functions.**

The pH scale indicates the concentration of hydrogen ions in fluids

The water in the human body contains various ions. Some of the most important are **hydrogen ions**, which have far-reaching effects because they are chemically active and there are so many of them. At any instant, some water molecules are breaking apart into H^+ and **hydroxide ions** (OH^-). These ions are the basis for the **pH scale** (Figure 2.11), which indicates the concentration (relative amount) of H^+ in water, blood, and other fluids. Pure water (not rainwater or tap water) always has just as many H^+ as OH^- ions. This state is neutrality, or pH 7, on the pH scale.

Starting at neutrality, each change by one unit of the pH scale corresponds to a tenfold increase or decrease in the concentration of H^+. One way to get a personal sense of range is to taste a bit of baking soda (pH 9), and then follow it with water (7), and then lemon juice (2.3).



Acids give up H^+ and bases accept H^+

You've probably heard of "acids" and "bases," but what are they, chemically? An **acid** is a substance that donates protons (H^+) to other solutes or to water molecules when it dissolves in water. A **base** accepts H^+ when it dissolves in water. When either an acid or a base dissolves, OH^- then forms in the solution as well. *Acidic* solutions, such as lemon juice and the gastric fluid in your stomach, release more H^+ than OH^-; their pH is below 7. *Basic* solutions, such as seawater, baking soda, and egg white, release more OH^- than H^+. Basic solutions are also called *alkaline* fluids; they have a pH above 7.

The fluid inside most human cells is about 7 on the pH scale. Body cells also are surrounded by fluids, and the pH values of most of those fluids are slightly higher, ranging between 7.3 and 7.5. The pH of the fluid portion of your blood is in the same range.

To a chemist most acids are either weak or strong. Weak ones, such as carbonic acid (H_2CO_3), don't readily donate H^+. Depending on the pH, they just as easily accept H^+ after giving it up, so they alternate between acting as an acid and acting as a base. On the other hand, strong acids totally give up H^+ when they dissociate in water. Hydrochloric acid (HCl), nitric acid (HNO_3), and sulfuric acid (H_2SO_4) are examples.

High concentrations of strong acids or strong bases can be important in the body. For instance, when you eat, cells in your stomach secrete HCl, which separates into H^+ and Cl^- in water. The H^+ ions make stomach fluid more acidic, and the increased acidity switches on enzymes that can digest (chemically break down) food particles. The acid also helps kill harmful bacteria. Eating too much of certain kinds of foods can lead to "acid stomach." Antacids such as milk of magnesia are strong bases. In your stomach,

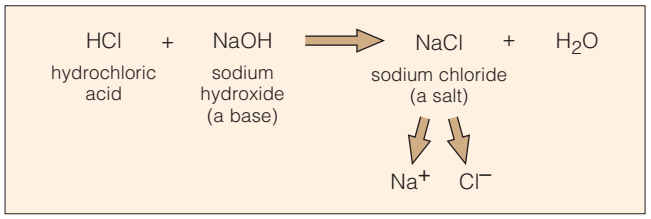
Figure 2.11 Animated! The pH scale indicates the acidity of a solution.

milk of magnesia releases magnesium ions and OH^-, which combines with excess H^+ in your stomach fluid. This chemical reaction raises the fluid's pH, and your acid stomach goes away.

Strong acids or bases also can harm the environment. Read the labels on bottles of ammonia, drain cleaner, and other common household products and you'll learn that many of them can cause severe chemical burns. So can sulfuric acid in car batteries. Smoke from fossil fuels, exhaust from motor vehicles, and nitrogen fertilizers release strong acids, which alter the pH of rain (Figure 2.12). The resulting acid rain is an ongoing environmental problem considered in more detail in Chapter 25.

A salt releases other kinds of ions

Salts are compounds that release ions *other than* H^+ and OH^- in solutions. Salts and water often form when a strong acid and a strong base interact. Depending on a solution's pH value, salts can form and dissolve easily. Consider how sodium chloride forms, then dissolves:



Many salts dissolve into ions that have key functions in cells. For example, the activity of nerve cells depends on ions of sodium, potassium, and calcium, and your muscles contract with the help of calcium ions.

Buffers protect against shifts in pH

Cells must respond quickly to even slight shifts in pH, because protein and many other biological molecules can function properly only within a narrow pH range. Even a slight deviation can completely shut down cell processes.

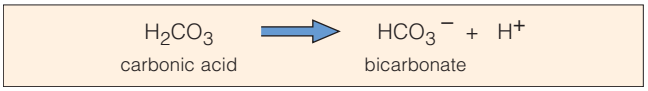
Body fluids stay at a consistent pH because they are buffered. A **buffer system** is set of chemicals, often a weak acid or a base and its salt, that can keep the pH of a solution stable. Buffer systems are extremely important in maintaining homeostasis. They work because the two chemicals can donate and accept ions that affect pH.

For example, when a base is added to a fluid, OH^- is relased. However, if the fluid is buffered, the weak acid partner gives up H^+. The H^+ combines with the OH^-, forming a small amount of water that does not affect pH. So, a buffered fluid's pH stays constant even when a base is added.

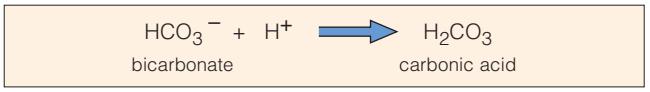
Figure 2.12 Acids produced by human activities affect the environment. This photograph captures sulfur dioxide emissions from a coal-burning power plant. Camera lens filters reveal the otherwise invisible emissions. Sulfur dioxide is a major component of acid rain.

A key point to remember is that the action of a buffer system can't make new hydrogen ions or eliminate those that already are present. It can only bind or release them.

Carbon dioxide forms in many reactions and it takes part in an important buffer system. It combines with water in the blood to form the compounds carbonic acid and bicarbonate. When the pH of blood starts to rise due to other factors, the carbonic acid neutralizes the excess OH^- by releasing H^+. The two kinds of ions combine and form water:



When the blood becomes more acidic, the bicarbonate absorbs excess H^+ and thus shifts the balance of the buffer system toward carbonic acid:



Together these reactions usually keep the blood pH beween 7.3 and 7.5, but a buffer system can neutralize only so many ions. Even slightly more than that limit causes the pH to swing widely.

A buffer system failure in the body can be disastrous. If blood's pH (7.3–7.5) declines to even 7, a person will fall into a *coma*, a severe state of unconsciousness. An increase to 7.8 can lead to *tetany*, a prolonged, possibly fatal contraction of skeletal muscles. In *acidosis*, carbon dioxide builds up in the blood, too much carbonic acid forms, and blood pH plummets. The condition called *alkalosis* is an abnormal increase in blood pH. Left untreated, both acidosis and alkalosis can be deadly.

Take-Home Message

Why are hydrogen ions important in body functions?

- Hydrogen ions contribute to pH. Acids release hydrogen ions and bases accept them. Salts release ions other than H^+ and OH^-.
- Buffer systems keep the pH of body fluids stable. They are an important part of homeostasis.

2.8 Molecules of Life

- **Molecules that make up living things are called biological molecules. They are built on atoms of the element carbon.**
- **The four classes of biological molecules are carbohydrates, lipids, proteins, and nucleic acids.**

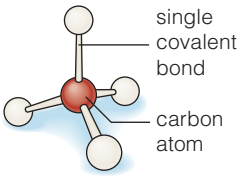
Biological molecules contain carbon

Each of the molecules of life is an **organic compound**: it contains the element carbon and at least one hydrogen atom. Chemists once thought organic substances were those obtained from animals and vegetables, as opposed to "inorganic" ones from minerals.

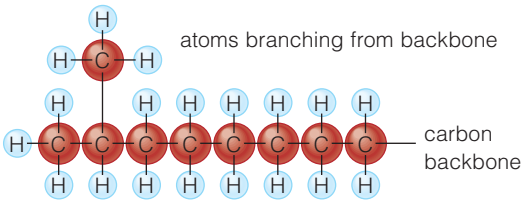
Carbon's key feature is versatile bonding

The human body consists mostly of oxygen, hydrogen, and carbon. The oxygen and hydrogen are mainly in the form of water. Carbon makes up more than half of what is left.

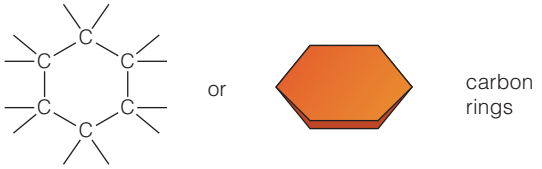
Carbon's importance to life starts with its versatile bonding behavior. As you can see in the sketch below, each carbon atom can share pairs of electrons with as many as four other atoms. The covalent bonds are fairly stable, because the carbon atoms share pairs of electrons equally. This type of bond links carbon atoms together in chains. The chains form a backbone to which atoms of hydrogen, oxygen, and other elements can attach.



The angles of the covalent bonds help produce the three-dimensional shapes of organic compounds. A chain of carbon atoms, bonded covalently one after another, forms a backbone from which other atoms can project:



A carbon backbone with only hydrogen atoms attached to it is a hydrocarbon. The backbone also may form a ring, like this:



Functional groups affect the chemical behavior of organic compounds

Biological molecules also have parts called functional groups. A **functional group** is a particular atom or cluster of atoms that are covalently bonded to carbon. The kind, number, and arrangement of these groups give rise to specific properties, such as polarity or acidity.

Figure 2.13 shows some functional groups. Sugars and other organic compounds classified as alcohols have one or more hydroxyl groups (—OH). Water forms hydrogen bonds with hydroxyl groups, which is why sugars can dissolve in water. The backbone of a protein forms by reactions between amino groups and carboxyl groups. Amino groups also can combine with hydrogen ions and act as buffers against decreases in pH.

Human sex hormones illustrate the importance of exactly where a functional group attaches to a biological molecule. Estrogen and testosterone account for many

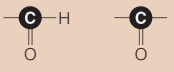
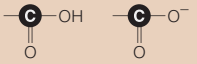
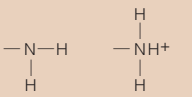
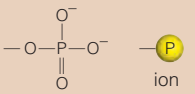
Group	Character	Location	Structure
hydroxyl	polar	amino acids; sugars and other alcohols	—OH
methyl	nonpolar	fatty acids, some amino acids	
carbonyl	polar, reactive	sugars, amino acids, nucleotides	 (aldehyde) (ketone)
carboxyl	acidic	amino acids, fatty acids, carbohydrates	 (ionized)
amine	basic	amino acids, some nucleotide bases	 (ionized)
phosphate	high energy, polar	nucleotides (e.g., ATP); DNA and RNA; many proteins; phospholipids	 ion
sulfhydryl	forms disulfide bridges	cysteine (an amino acid)	—SH —S—S— (disulfide bridge)

Figure 2.13 Animated! Functional groups are important parts of biological molecules.

differences between males and females. The hormones have the same functional groups, but the groups are in different places (Figure 2.14).

Cells have chemical tools to assemble and break apart biological molecules

How do cells make the organic compounds they need for their structure and functioning? To begin with, whatever happens in a cell requires energy, which is provided by a compound called ATP that you will learn more about shortly. Chemical reactions in cells also require a class of proteins called **enzymes**, which make reactions take place faster than they would on their own. Table 2.3 lists the ways cells build, rearrange, or split apart organic compounds. Two important types of reactions are called condensation and hydrolysis.

Condensation Reactions As a cell builds or changes organic compounds, a common step is the **condensation reaction**. Often in this kind of reaction, enzymes remove a hydroxyl group from one molecule and an H atom from another, then speed the formation of a covalent bond between the two molecules (Figure 2.15*a*). The discarded hydrogen and oxygen atoms may combine to form a molecule of water (H_2O). Because this kind of reaction often forms water as a by-product, condensation is sometimes called *dehydration* ("un-watering") *synthesis*. Cells can use condensation reactions to assemble polymers. *Poly-* means many, and a **polymer** is a large molecule built of three to millions of subunits. The subunits, called **monomers**, may be the same or different.

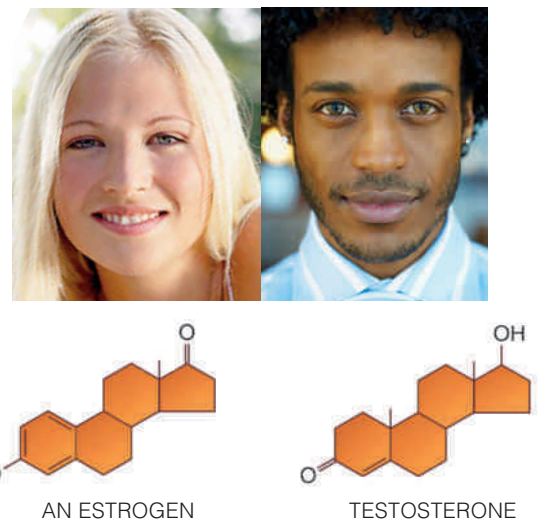


Figure 2.14 The arrangement of functional groups determine the difference between the sex hormones estrogen and testosterone.

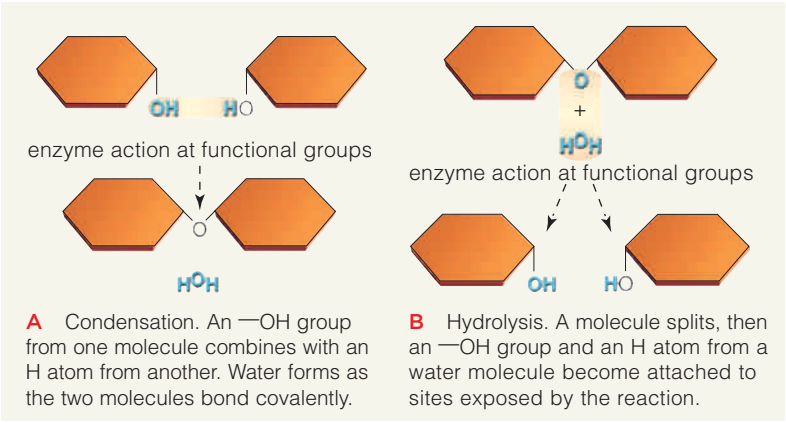


Figure 2.15 Animated! Metabolic reactions build, rearrange, and break apart most biological molecules. (**a**) Condensation, with two molecules being covalently bonded into a larger one. (**b**) Hydrolysis, a cleavage reaction that splits a larger molecule into two smaller ones. Hydrolysis produces water as a by-product.

TABLE 2.3 What Cells Do to Organic Compounds

Class of Reaction	What Happens
Condensation	Two molecules covalently bond into a larger one.
Cleavage	A molecule splits into two smaller ones, as by hydrolysis.
Functional group transfer	One molecule gives up a functional group, and a different molecule immediately accepts it.
Electron transfer	One or more electrons from one molecule are donated to another molecule.
Rearrangement	Moving internal bonds converts one type of organic compound to another.

Hydrolysis Reactions **Hydrolysis** is like condensation in reverse (Figure 2.15*b*). In a first step, enzymes that act on particular functional groups split molecules into two or more parts. Then they attach an —OH group and a hydrogen atom from a molecule of water to the exposed sites. With hydrolysis, cells can break apart large polymers into smaller units when these are required for building blocks or energy.

Take-Home Message

What are biological molecules, and how are they used in chemical reactions?

- Carbohydrates, lipids, proteins, and nucleic acids are the main biological molecules. All are organic compounds.
- Organic compounds have carbon backbones. Different bonding patterns help give organic compounds their three-dimensional shapes.
- Functional groups increase the structural and functional diversity of organic compounds.
- Enzymes speed the chemical reactions cells use to build, rearrange, and break down organic compounds.
- Chemical reactions in cells include the combining or splitting of molecules, as in condensation and hydrolysis.

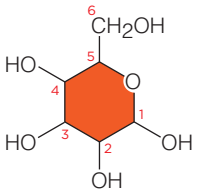
2.9 Carbohydrates: Plentiful and Varied

- **Carbohydrates are the most abundant biological molecules.**
- **Cells use carbohydrates to help build cell parts or package them for energy.**

Most **carbohydrates** consist of carbon, hydrogen, and oxygen atoms in a 1:2:1 ratio. Due to differences in structure, chemists separate carbohydrates into three major classes, **monosaccharides**, **oligosaccharides**, and **polysaccharides**.

Simple sugars are the simplest carbohydrates

"Saccharide" comes from a Greek word meaning sugar. A *mono*saccharide, meaning "one monomer of sugar," is the simplest carbohydrate. It has at least two —OH groups joined to the carbon backbone plus an aldehyde or a ketone group. Monosaccharides usually taste sweet and dissolve easily in water. The most common ones have a backbone of five or six carbons; for example, there are five carbon atoms in deoxyribose, the sugar in DNA. The simple sugar glucose is the main energy source for body cells. Each glucose molecule (at *left*) has six carbons, twelve hydrogens, and six oxygens. (Notice how it meets the 1:2:1 ratio noted above.) Glucose is a building block for larger carbohydrates. It also is the parent molecule (precursor) for many compounds, such as vitamin C, which are derived from sugar monomers.



Oligosaccharides are short chains of sugar units

Unlike the simple sugars, an *oligo*saccharide is a short chain of two or more sugar monomers that are joined by dehydration synthesis. (*Oligo-* means a few.) The type known as *di*saccharides consists of just two sugar units. Lactose, sucrose, and maltose are examples. Lactose (a glucose and a galactose unit) is a milk sugar. Sucrose, the most plentiful sugar in nature, consists of one glucose and one fructose unit (Figure 2.16). You consume sucrose when you eat fruit, among other plant foods. Table sugar is sucrose crystallized from sugar cane and sugar beets.

Proteins and other large molecules often have oligosaccharides attached as side chains to their carbon backbone. Some chains have key roles in activities of cell membranes, as you will read in Chapter 3. Others are important in the body's defenses against disease.

Grapes, a natural source of sucrose in the diet.

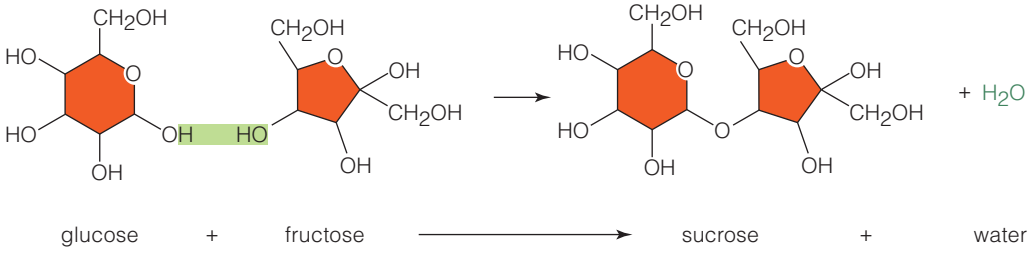
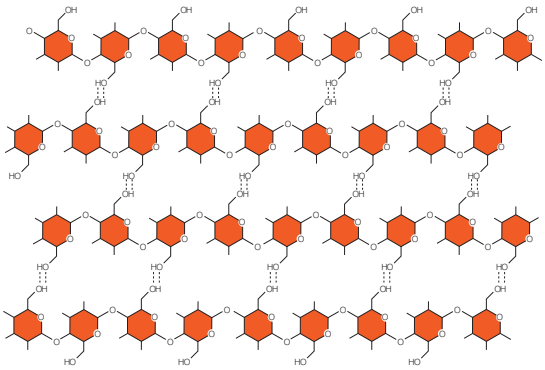
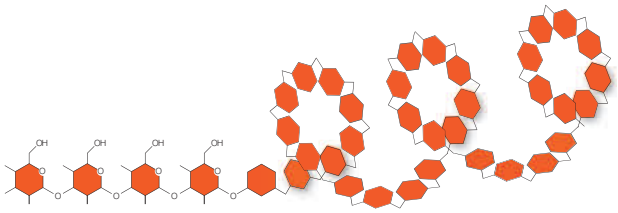


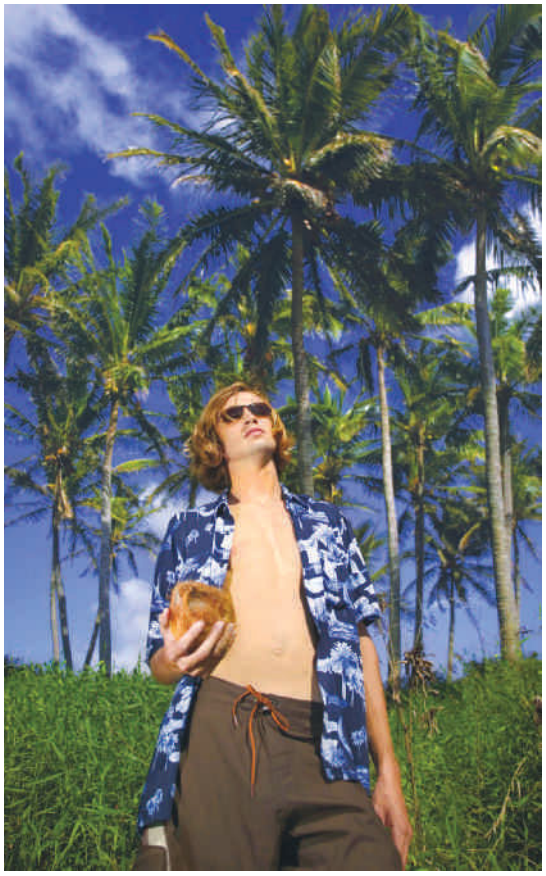
Figure 2.16 Sucrose, or table sugar, is a disaccharide formed from glucose and fructose. As you can see in this diagram, the synthesis of a sucrose molecule is a condensation reaction, which forms water as a by-product.

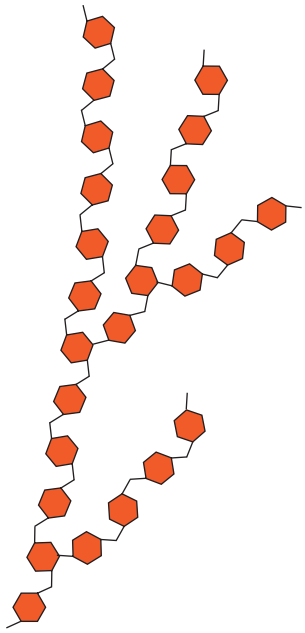


a Cellulose, a structural component of plants. Chains of glucose units stretch side by side and hydrogen-bond at many —OH groups. The hydrogen bonds stabilize the chains in tight bundles that form long fibers.

b In amylose, one type of starch, a series of glucose units form a chain that coils. Starch is the main energy reserve in plants, which store it in their roots, stems, leaves, fruits, and seeds (such as coconuts).







c Glycogen. This polysaccharide functions as an energy reservoir. A great deal of it is stored in the liver and muscles of active animals, including people.

Figure 2.17 Complex carbohydrates are straight or branched chains of many sugar monomers. This diagram shows the structure of (**a**) cellulose, (**b**) starch, and (**c**) glycogen. Glucose is the basic building block of all three of these carbohydrates.

Polysaccharides are sugar chains that store energy

The "complex" carbohydrates, or polysaccharides, are straight or branched chains of sugar monomers. Often thousands have been joined by dehydration synthesis. A great deal of energy is stored in the many chemical bonds in polysaccharides. The energy is released to cells when these sugars are digested. Most of the carbohydrates humans eat are in the form of polysaccharides. The most common ones—glycogen, starch, and cellulose—consist only of glucose.

Plants store a large amount of glucose in the form of cellulose (Figure 2.17*a*). Humans don't have digestive enzymes that can break down the cellulose in whole grains, vegetables, fruits, and other plant tissues. We do benefit from it, however, as undigested "fiber" that adds bulk and so helps move wastes through the lower part of the digestive tract.

Foods such as potatoes, rice, wheat, and corn are all rich in starch, which is a storage form of glucose in plants. In starch the glucose subunits form a string, as with the starch amylose illustrated in Figure 2.17*b*).

The polysaccharide glycogen is one form in which animals store sugar, most notably in their muscles and the liver (Figure 2.17*c*). When a person's blood sugar level falls, liver cells break down glycogen and release glucose to the blood. When you exercise, your muscle cells tap into their glycogen stores as a quick source of energy.

Take-Home Message

What are carbohydrates?

- Carbohydrates range from simple sugars such as glucose to molecules composed of many sugar units.
- From simple to complex, the three major types of carbohydrates are monosaccharides, oligosaccharides, and polysaccharides.
- Cells use carbohydrates for energy or as structural materials.

2.10 Lipids: Fats and Their Chemical Kin

- **Cells use lipids to store energy, as structural materials, and as signaling molecules.**

Oil and water don't mix. Why? Oils are a type of lipid, and a **lipid** is a nonpolar hydrocarbon. A lipid's large nonpolar region makes it hydrophobic, so it tends not to dissolve in water. Lipids easily dissolve in other nonpolar substances. For example, you can dissolve melted butter in olive oil. Here we are interested in fats and phospholipids, both of which have chemical "tails" called fatty acids, and on sterols, which have a backbone of four carbon rings.

Fats are energy-storing lipids

The lipids called **fats** have as many as three fatty acids, all attached to glycerol. Each **fatty acid** has a backbone of up to thirty-six carbons and a carboxyl group (—COOH) at one end. Hydrogen atoms occupy most or all of the remaining bonding sites. A fatty acid typically stretches out like a flexible tail (Figure 2.18).

In *saturated* fats, the fatty acid backbones have only single covalent bonds. Animal fats are saturated. Like uncooked bacon fat or lard, they are solid at room temperature. The fatty acid tails of *unsaturated* fats have one or more double covalent bonds. Such strong bonds make rigid kinks that prevent unsaturated fats from packing tightly. Most vegetable oils such as canola, peanut oil, corn oil, and olive oil are unsaturated. They stay liquid at room temperature.

Butter, lard, plant oils, and other dietary fats consist mostly of **triglycerides**. These "neutral" fats have three fatty acid tails attached to a glycerol backbone (Figure 2.19). Triglycerides are the most common lipids in the body as well as its richest source of energy. Compared to complex carbohydrates, they yield more than twice as much energy, gram for gram, when they are broken down. This is because triglycerides have more removable electrons than do carbohydrates—and energy is released when electrons are removed. In the body, cells of fat-storing tissues stockpile triglycerides as fat droplets.

Some unsaturated fats are unhealthy. A double bond in so-called cis fatty acids keeps them kinked, but in trans fatty acids a double bond keeps them straight (Figure 2.20). Some trans fatty acids occur naturally in beef, but most of those in human food are formed by a manufacturing process (called hydrogenation) that is used to solidify vegetable oils for solid margarines and shortenings that are used in many prepared foods. A diet high in trans fatty acids increases the risk of heart disease.

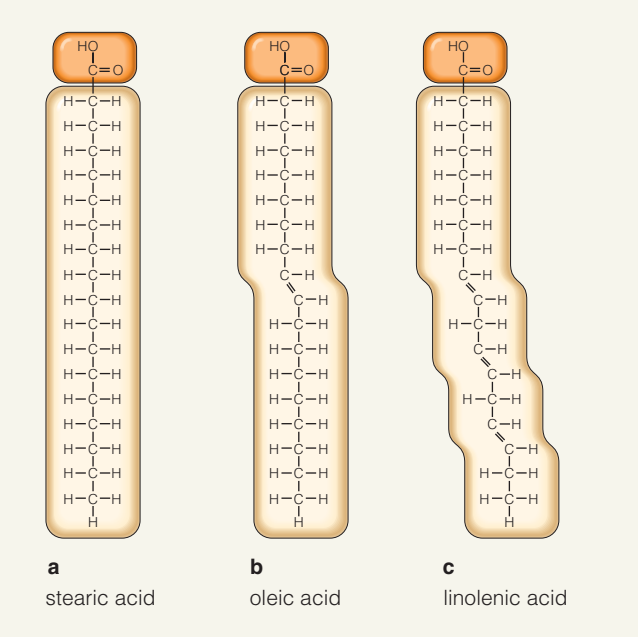


Figure 2.18 Animated! Fatty acids are the building blocks of fats. (**a**) Stearic acid has a carbon backbone fully saturated with hydrogens. (**b**) Oleic acid, with its double bond in the carbon backbone, is unsaturated. (**c**) Linolenic acid, with three double bonds, is a polyunsaturated fatty acid.

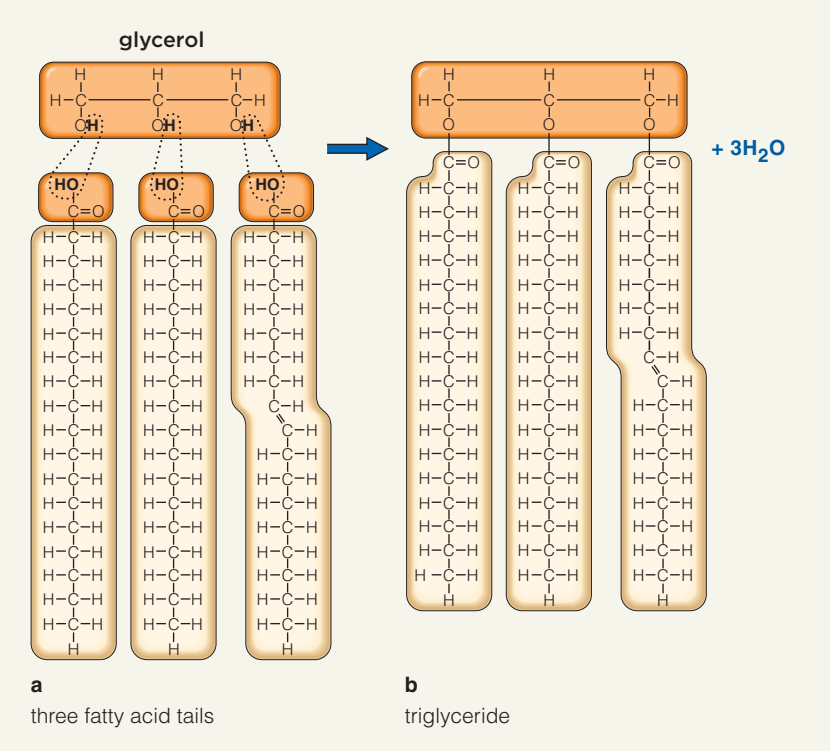


Figure 2.19 Animated! Triglycerides have three fatty acid tails. The diagram shows the condensation of (**a**) three fatty acids and a glycerol molecule into (**b**) a triglyceride.

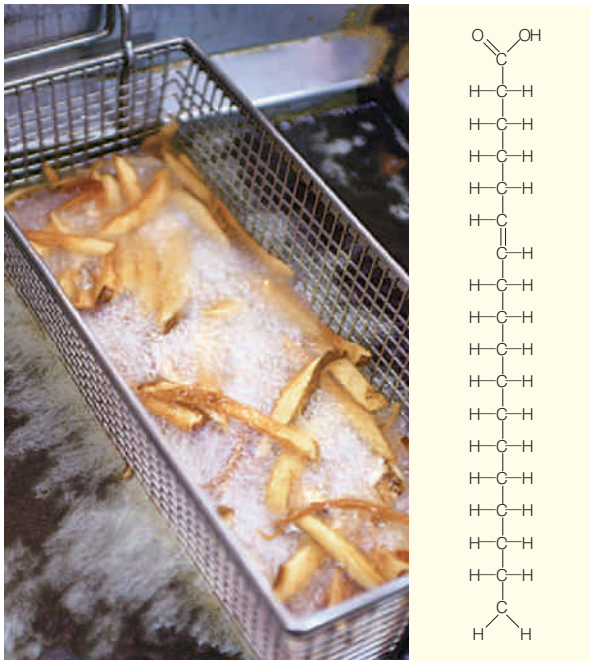


Figure 2.20 **Some foods contain unhealthy trans fats.** French fries cooked in certain types of oil contain a great deal of trans fatty acids. It is the arrangement of carbon atoms around the carbon-carbon double bond in the middle of a trans fatty acid that makes it a very unhealthy food.

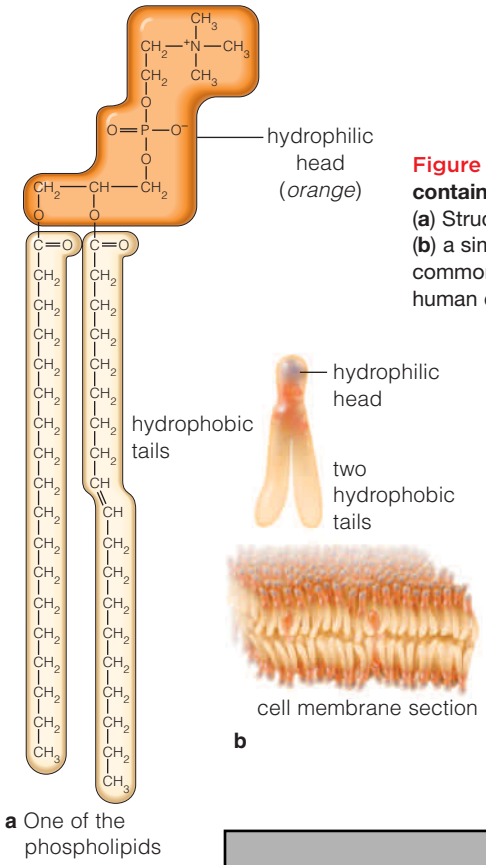


Figure 2.21 **Phospholipids contain a phosphate atom.** (**a**) Structural formula and (**b**) a simple diagram of a common phospholipid in human cell membranes.

Image not available due to copyright restrictions

Phospholipids are key building blocks of cell membranes

A **phospholipid** has a glycerol backbone, two fatty acid tails, and a hydrophilic "head" with a phosphate group—a phosphorus atom bonded to four oxygen atoms—and another polar group (Figure 2.21*a*). Phospholipids are the main materials of cell membranes, which have two layers of lipids. The heads of one layer are dissolved in the cell's fluid interior, while the heads of the other layer are dissolved in the surroundings. Sandwiched between the two are all the fatty acid tails, which are hydrophobic.

Cholesterol and steroids are built from sterols

Sterols are among the lipids that have no fatty acid tails. Sterols differ in the number, position, and type of their functional groups, but they all have a rigid backbone of four fused-together carbon rings:

sterol backbone

Many people associate the sterol cholesterol (Figure 2.22) with heart disease. However, normal amounts of this sterol are essential in the body. For instance, the sterol cholesterol is a vital component of membranes of every cell in your body. Important derivatives of cholesterol include vitamin D (essential for bone and tooth development), bile salts (which help with fat digestion in the small intestine), and steroid hormones such as estrogen and testosterone. Later chapters discuss how steroid hormones influence reproduction, development, growth, and other functions.

Take-Home Message

What are lipids?

- Lipids are hydrophobic greasy or oily compounds.
- Triglycerides (neutral fats) are major reservoirs of energy.
- Phospholipids are the main components of cell membranes.
- Sterols (such as cholesterol) are components of membranes and precursors of steroid hormones and other vital molecules.

2.11 Proteins: Biological Molecules with Many Roles

- **Proteins are the most diverse biological molecules.**

A **protein** is an organic compound composed of one or more chains of amino acids. Those called enzymes speed up chemical reactions. Structural proteins are building blocks of your bones, muscles, and other body elements. Transport proteins help move substances and regulatory proteins, including some hormones, adjust cell activities. They help make possible activities such as waking, sleeping, and engaging in sex, to cite just a few. Other proteins are important parts of body defenses.

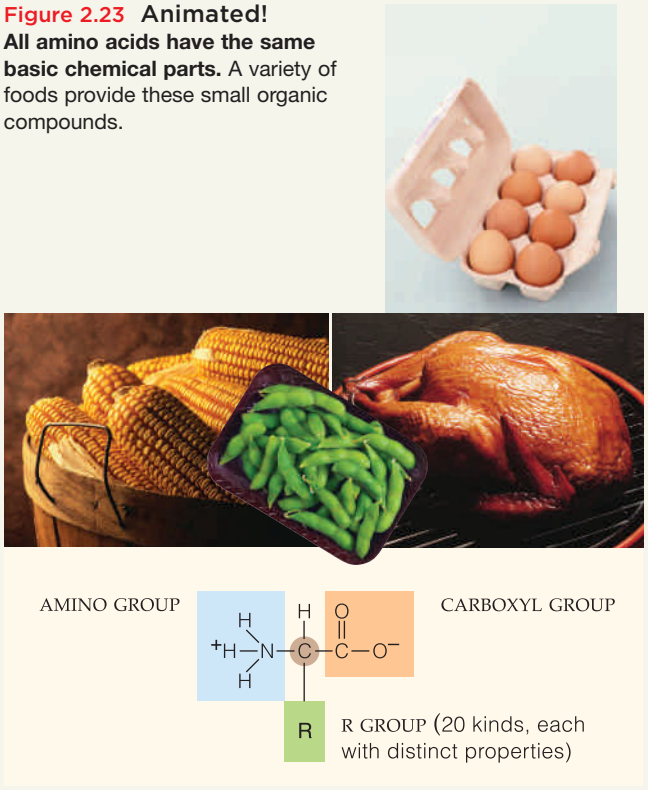
Proteins are built from amino acids

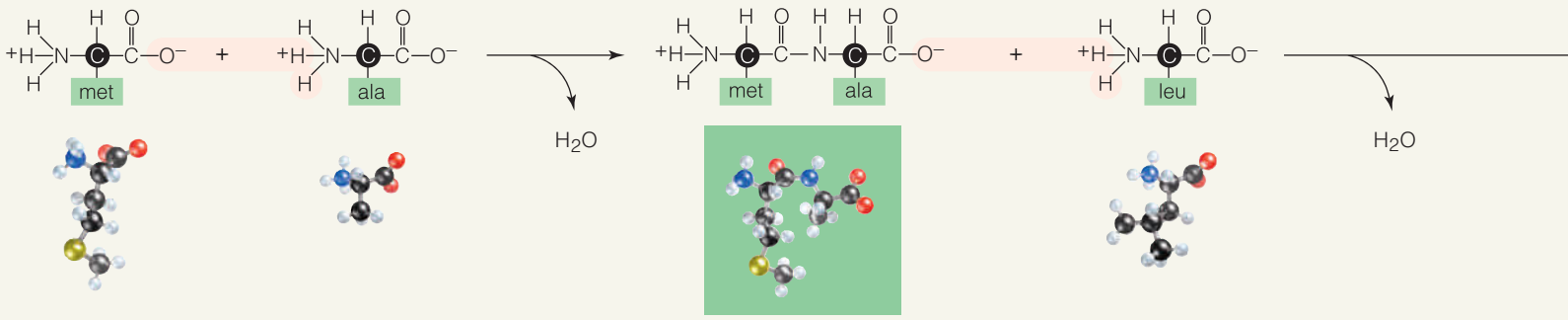
Amazingly, our body cells build thousands of different proteins from only twenty kinds of amino acids. An **amino acid** is a small organic compound that consists of an amino group, a carboxyl group (an acid), an atom of hydrogen, and one or more atoms called its R group. As you can see from the structural formula in Figure 2.23, these parts generally are covalently bonded to the same carbon atom. R groups include functional groups, which help determine an amino acid's chemical properties.

The sequence of amino acids is a protein's primary structure

When a cell makes a protein, amino acids become linked, one after the other, by *peptide* bonds. As Figure 2.24

Figure 2.23 Animated!
All amino acids have the same basic chemical parts. A variety of foods provide these small organic compounds.





A DNA determines the order of amino acids in a polypeptide chain. Methionine (met) normally is the first amino acid.

B In a condensation reaction, a peptide bond forms between the methionine and the next amino acid, alanine (ala). Leucine (leu) will be next.

Figure 2.24 Animated! A protein is built as peptide bonds form between amino acids.

shows, this is the type of covalent bond that forms between one amino acid's amino group (NH_3^+) and the carboxyl group (—COO^-) of the next amino acid.

When peptide bonds join two amino acids together, we have a dipeptide. When they join three or more amino acids, we have a **polypeptide chain**. The backbone of each chain incorporates nitrogen atoms in this regular pattern: —N—C—C—N—C—C—.

Each type of protein has a unique sequence of amino acids. The sequence forms as different amino acids are added in a specific order, one at a time, from the twenty kinds available to body cells. Figure 2.25 gives you an idea of how different amino acids can vary in their chemical structure.

As a later chapter describes, DNA determines the order in which amino acids are "chosen" to be added to the growing chain. Every other kind of protein in the body will have its own sequence of amino acids, linked one to the next like the links of a chain. This sequence is called the *primary* structure of a protein. A large number of amino acids can be linked up this way. The primary structure of the largest known protein, which is a building block of human muscle, is a string of some 27,000 amino acids!

As you will see next, a protein's primary structure is just the starting point for the final shape it will have, and that shape will dictate how the protein functions.

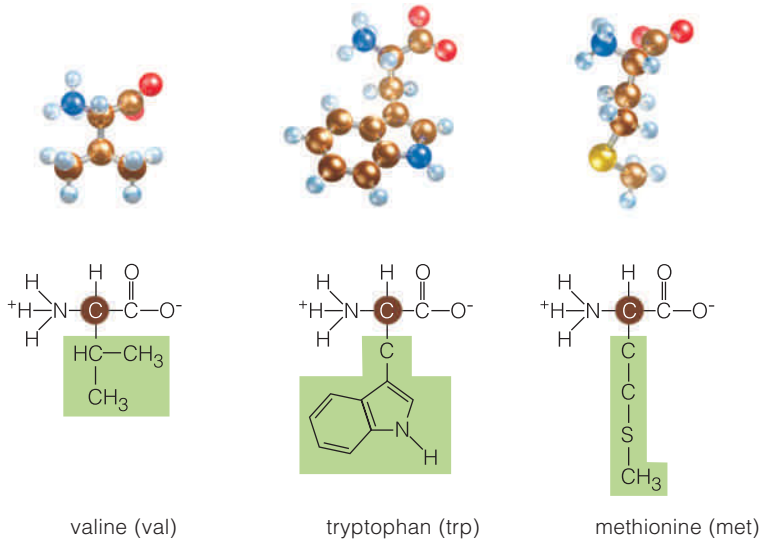
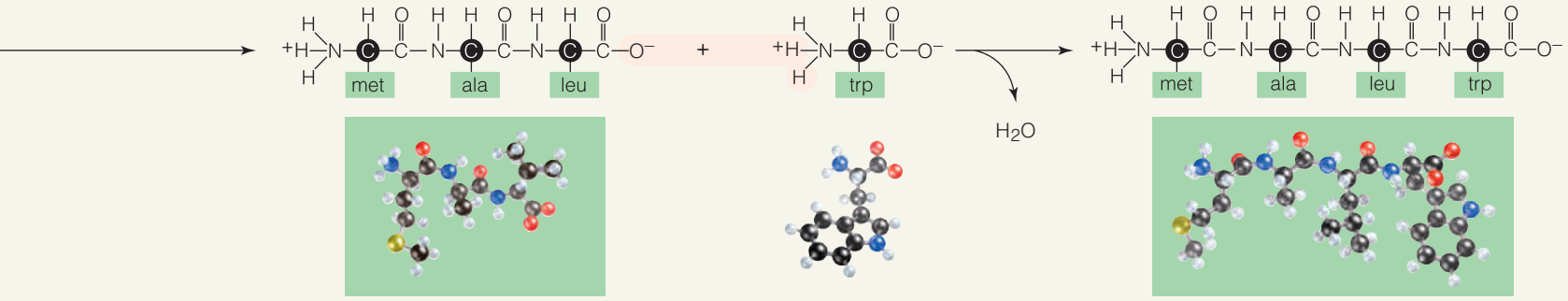


Figure 2.25 A protein contains many different amino acids. Three common amino acids used in human cells are shown here.

Take-Home Message

What is a protein?

- A protein consists of one or more chains of amino acids.
- Each type of protein has a unique sequence of amino acids.
- The sequence of amino acids that makes up a protein is the protein's primary structure.



C A peptide bond forms between the alanine and leucine. Tryptophan (trp) will be next. The chain also is starting to twist and fold as atoms swivel around some bonds and weakly attract or repel their neighbors.

D The sequence of amino acid subunits in this newly forming peptide chain is now met–ala–leu–trp. The process may continue until there are hundreds or thousands of amino acids in the chain.

2.12 A Protein's Shape and Function

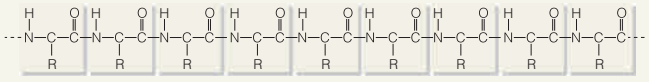
- **Once amino acids have been assembled into a protein, the protein folds into its final shape.**
- **A protein's final shape determines its function.**

Proteins fold into complex shapes that determine their function

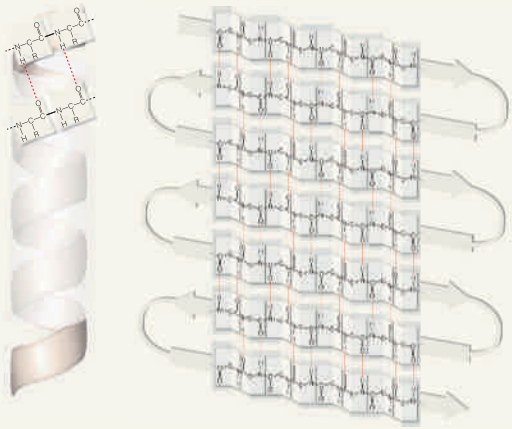
As you have just read, a protein's primary structure is the first step in the formation of a functioning protein (Figure 2.26*a*). Secondary structure emerges as the chain twists, bend, loops and folds. These shape changes occur as hydrogen bonds form between different amino acids in different parts of the chain (Figure 2.26*b*). Even though the primary structure of each protein is unique, similar patterns of coils, sheets, and loops occur in most proteins.

The coils, sheets, and loops of a protein fold up even more, much like an overly twisted rubber band. This is the third level of organization, or *tertiary* structure, of a protein (Figure 2.26*c*). Tertiary structure is what makes a protein a molecule that can perform a particular function. For instance, some proteins fold into a hollow "barrel" that provides a channel through cell membranes.

a Protein primary structure: Amino acids bonded in a polypeptide chain.

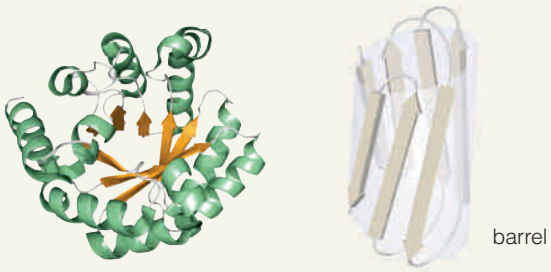


b Protein secondary structure: A coiled (helical) or sheetlike array, held in place by hydrogen bonds (*dotted lines*) between different parts of the polypeptide chain.



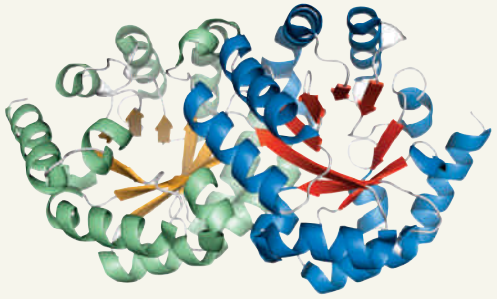
helical coil sheet

c Protein tertiary structure: A chain's coiled parts, sheetlike arrays, or both have folded and twisted into stable, functional domains, including clusters, pockets, and barrels.



barrel

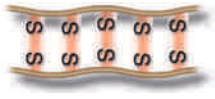
d Protein quaternary structure: Many weak interactions hold two or more polypeptide chains together as a single molecule.



A protein may have more than one polypeptide chain

Imagine that bonds form between *four* molecules of globin and that an iron-containing functional group, a heme group, nestles near the center of each (Figure 2.27). The result is hemoglobin, protein that transports oxygen. At this moment, each of the millions of red blood cells in your body is transporting a billion molecules of oxygen, bound to 250 million molecules of hemoglobin.

With its four globin molecules, hemoglobin is a good example of a protein that is built of more than one polypeptide chain. The hormone insulin, which consists of two chains, is another. Proteins that are constructed this way are said to have *quaternary* structure (Figures 2.26*d* and 2.27). Their polypeptide chains are joined by weak interactions (such as hydrogen bonds) and sometimes by covalent bonds between sulfur atoms of R groups. These bonds between two sulfur atoms are called disulfide bridges (di = two).



Disulfide bridges

Figure 2.26 Animated! Proteins can have up to four levels of organization.

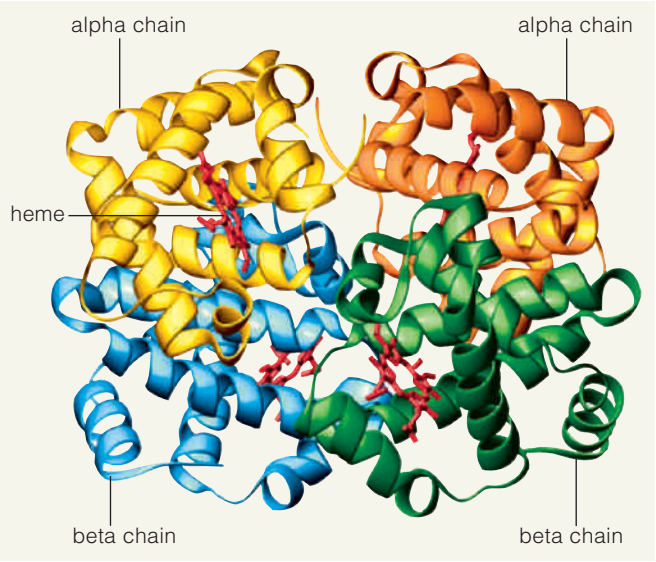


Figure 2.27 Animated! Hemoglobin is a protein with quaternary structure. Hemoglobin is a pigment protein that carries oxygen in red blood cells. It has four globin chains and four heme groups.

Hemoglobin and insulin are globular proteins; so are most enzymes. Many other proteins with quaternary structure are fibrous. Collagen, the most common protein in the body, is an example of this. (Your skin, bones, corneas, and other body parts depend on collagen's strength.) Keratin, a structural protein of hair, is another example. The chemicals used in a permanent wave break hydrogen bonds in disulfide bridges in the keratin chains in hair. After the hair is wrapped around curlers that hold polypeptide chains in new positions, a second chemical causes disulfide bridges to form between *different* sulfur-bearing amino acids. The rearranged bonding locks the hair in curls (Figure 2.28).

Glycoproteins have sugars attached and lipoproteins have lipids

Some proteins have other organic compounds attached to their polypeptide chains. For example, **lipoproteins** form when certain proteins circulating in blood combine with cholesterol, triglycerides, and phospholipids that were consumed in food. Most **glycoproteins** (from *glukus*, the Greek word for sweet) have oligosaccharides bonded to them. Most of the proteins found at the surface of cells are glycoproteins, as are many proteins in blood and those that cells secrete (such as protein hormones).

Disrupting a protein's shape denatures it

When a protein or any other large molecule loses its normal three-dimensional shape, it is *denatured*. For example, hydrogen bonds are sensitive to increases or decreases in temperature and pH. If the temperature or pH exceeds a protein's tolerance, its hydrogen bonds break, polypeptide chains unwind or change shape, and the protein no longer functions. Cooking an egg destroys weak bonds that contribute to the three-dimensional shape of the egg white protein albumin. Some denatured proteins can resume their shapes when normal conditions are restored—but not albumin. There is no way to uncook a cooked egg white.

Take-Home Message

How do proteins get their final shape?

- Proteins fold into their secondary structure, a coil or an extended sheet.
- More folding produces the third level of protein structure, which dictates how the protein will function.
- Proteins that consist of more than one polypeptide chain have a fourth level of organization called quaternary structure.

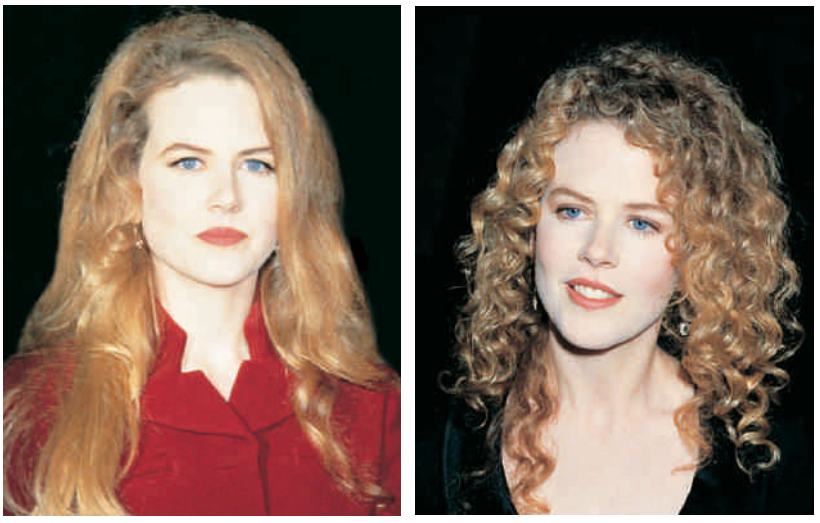


Figure 2.28 Changes in the chemical structure of a protein may show up in changes in the structure or functioning of body parts. Actress Nicole Kidman's hair changed shape after a structural protein, keratin, was exposed to the chemicals that create a permanent wave.

2.13 Nucleotides and Nucleic Acids

- The fourth and final class of biological molecules consists of nucleotides and nucleic acids.
- Link to Life's characteristics 1.1

Nucleotides are energy carriers and have other roles

A **nucleotide** (NOO-klee-oh-tide) is composed of one sugar, at least one phosphate group, and one nitrogen-containing base. The sugar—ribose or deoxyribose—has a five-carbon ring structure. Ribose has two oxygen atoms attached to the ring and deoxyribose has one. The bases have a single or double carbon ring structure.

The nucleotide **ATP** (for adenosine triphosphate), has a row of three phosphate groups attached to its sugar (Figure 2.29). In cells, ATP links chemical reactions that *release* energy with other reactions that *require* energy. This connection is possible because ATP can transfer a phosphate group to many other molecules in the cell, providing the acceptor molecules with the energy they need to enter into a reaction.

Some nucleotides are part of **coenzymes**, or "enzyme helpers." They move hydrogen atoms and electrons from one reaction site to another. Some other nucleotides act as chemical messengers inside and between cells. One of these is a nucleotide called cAMP (for cyclic adenosine monophosphate). It is extremely important in the action of some hormones.

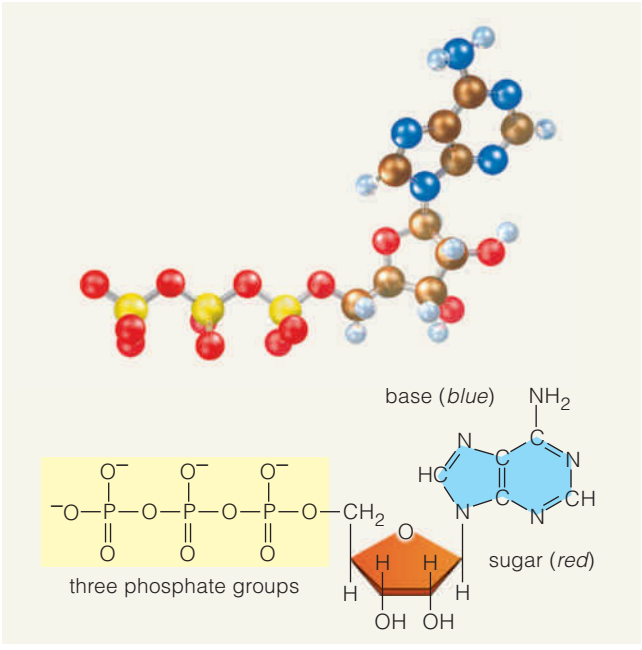


Figure 2.29 Animated! **ATP is the energy-carrying nucleotide in cells.**

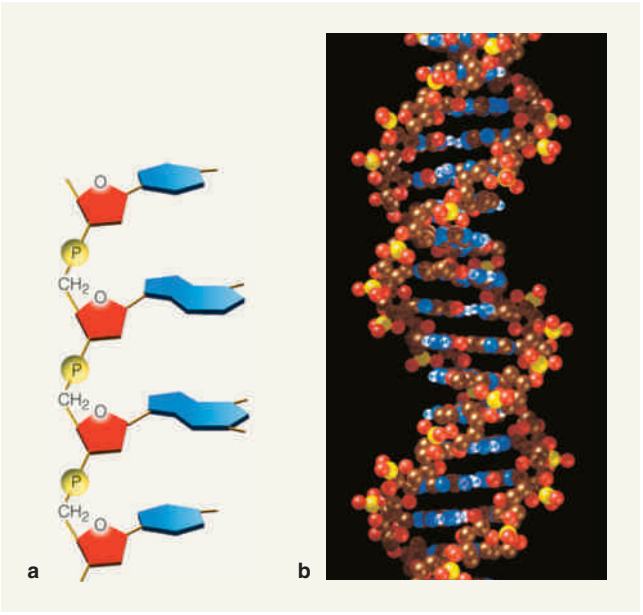


Figure 2.30 Animated! **Chains of nucleotides form nucleic acids such as DNA.** (**a**) Bonds between the bases in nucleotides. (**b**) Model of DNA, which has two strands of nucleotides joined by hydrogen bonds and twisted into a double helix. Here the nucleotide bases are blue.

Nucleic acids include DNA and the RNAs

Nucleotides are building blocks for **nucleic acids**, which are single- or double-stranded molecules. In the backbones of the strands, covalent bonds join each nucleotide's sugar to a phosphate group of the neighboring nucleotide (Figure 2.30*a*). In this book you will read often about the nucleic acid **DNA** (deoxyribonucleic acid), which contains the sugar deoxyribose. DNA consists of two strands of nucleotides, twisted together in a double helix (Figure 2.30*b*). Hydrogen bonds between the nucleotide bases hold the strands together, and the sequence of bases encodes genetic information. Unlike DNA, the **RNAs** (short for ribonucleic acid) are usually single strands of nucleotides. There are several kinds of RNA, but all have the sugar ribose. RNAs have crucial roles in processes that use genetic information to build proteins in cells.

Take-Home Message

What is a nucleic acid?

- A nucleotide is an organic compound with a sugar, one or more phosphate groups, and a base. Nucleotides are building blocks for DNA and RNA. Some, including ATP, have key roles in energy transfers.
- DNA is a double-stranded nucleic acid. Its sequence of nucleotide bases carries genetic information. RNAs are single-stranded nucleic acids with roles in the processes by which DNA's genetic information is used to build proteins.

2.14 Food Production and a Chemical Arms Race

The next time you shop for groceries, consider what it takes to provide you with your daily supply of organic compounds. For example, the lettuce for your salad most likely grew in fertilized cropland, and the grower may well have been concerned about invading weeds and attacks by insects. Each year, these food pirates and others ruin or eat nearly half of the food that people all over the world try to grow.

People—and plants—marshal various chemical defenses against the attackers (Figure 2.31). For instance, the tissues of many plants contain toxins that repel or kill harmful organisms. Humans encounter natural plant toxins in a wide range of foods—chili peppers, potatoes, figs, celery, and alfalfa sprouts, for instance. By and large, our bodies seem to be able to cope with those chemicals just fine—perhaps because we have evolved our own biochemical ways of neutralizing them.

In 1945, the human race took a cue from the plant world as chemists began developing synthetic toxins that could improve our ability to protect crop yields, stored grains, ornamental plants, and even our pets. Since then researchers have developed a wide array of herbicides to kill weeds, insecticides to eradicate unwanted insects, and fungicides against harmful molds and other fungi.

Although extremely useful in some applications, pesticides are powerful chemicals and have become more so with the passing years. Some of them kill natural enemies of the targeted pest and others harm wildlife such as birds. Some, such as DDT, stay active for years. (DDT is banned in the United States, although not in many other countries.) When people are exposed to unsafe doses, either by accident or misuse, some pesticides can trigger rashes, hives, headaches, asthma, and joint pain. According to some authorities, young children who are exposed to pesticides applied to keep a lawn thick and green may be at risk of developing behavior problems, learning disabilities, and other problems. Although manufacturers dispute these claims, it is worth noting that according to the U.S. Environmental Protection Agency, homeowners in the United States use 10 times more pesticides on their lawns than farmers do in agricultural fields.

On the other hand, many studies show that, used properly, modern pesticides increase food supplies and profits for farmers. They also save lives by killing disease-causing insects and other pathogens. And despite the natural worries of consumers, for now there is little evidence that the usual amounts of pesticides in or on food pose a significant health risk.

Figure 2.31 A low-flying crop duster rains pesticides on agricultural fields. Such chemicals may leave residues in food.

IMPACTS, ISSUES

Fearsome Fats

IN the United States ingredient labels must list whether the food contains trans fat, but the law allows a producer to claim "zero grams of trans fat content" even if a serving contains up to half a gram of it.

How Would You Vote?

Should trans fats be banned from all prepared foods?

See CengageNOW for details, then vote online.

SUMMARY

Sections 2.1, 2.2 An element is a fundamental substance that cannot be broken down to other substances by ordinary chemical means. The four main elements in the body are oxygen, carbon, hydrogen, and nitrogen.

An atom is the smallest unit that has the properties of an element. Atoms are composed of protons, neutrons, and electrons. An element's atoms may vary in how many neutrons they contain. These variant forms are isotopes. The number and arrangement of an atom's electrons determines its interactions with other atoms.

- Use the animation and interaction on CengageNOW to learn how radioisotopes are used in a PET scan.

Section 2.3 Electrons move in orbitals within in a series of shells around an atom's nucleus. An atom with one or more unfilled orbitals in its outer shell is likely to take part in chemical bonds.

A chemical bond is a union of the electron structures of atoms. Bonds join atoms into molecules. A chemical compound consists of atoms of two or more elements in unchanging proportions. In a mixture, two or more kinds of molecules mingle in varible proportions.

- Use the animation and interaction on CengageNOW to investigate electrons and the shell model.

Sections 2.4, 2.5 Atoms generally have no net charge. An atom that gains or loses one or more electrons becomes an ion with a positive or negative charge.

In an ionic bond, positive and negative ions stay together by the mutual attraction of their opposite charges. In a covalent bond, atoms share one or more electrons. A hydrogen bond is a weak bond between polar molecules.

- Use the animation and interaction on CengageNOW to compare the types of chemical bonds found in biological molecules.

Section 2.6 Water is vital for the physical structure and chemical activities of cells. Hydrogen bonds between its molecules give water special properties, such as the ability to resist temperature changes and to dissolve other polar substances. A dissolved substance is a solute. Polar molecules are hydrophilic (attracted to water). Nonpolar substances, such as oils, are hydrophobic (repelled by water).

- Use the animation and interaction on CengageNOW to explore the structure and properties of water.

Section 2.7 The pH scale measures the concentration of hydrogen ions in a fluid. Acids release hydrogen ions (H^+), and bases release hydroxide ions (OH^-) that can combine with H^+.

At pH 7, the H^+ and OH^- concentrations in a solution are equal; this is a neutral pH. A buffer system maintains pH values of blood, tissue fluids, and the fluid inside cells. A salt is a compound that releases ions other than H^+ and OH^-.

- Use the animation and interaction on CengageNOW to investigate the pH of common solutions.

Section 2.8 Carbon atoms bonded together in linear or ring structures are the backbone of organic compounds. Functional groups help determine the chemical and physical properties of many compounds.

Cells assemble and break apart most organic compounds by way of five kinds of reactions: transfers of functional groups, electron transfers, internal rearrangements, condensation reactions (dehydration synthesis), and cleavage reactions such as hydrolysis. Enzymes speed all these reactions. A polymer is a molecule built of three or more subunits; each subunit is called a monomer.

Cells have pools of dissolved sugars, fatty acids, amino acids, and nucleotides. These are small organic compounds with no more than about twenty carbon atoms. They are building blocks for the larger biological molecules—the carbohydrates, lipids, proteins, and nucleic acids (Table 2.4).

- Use the animations and interactions on CengageNOW to learn more about functional groups and watch animations that explain condensation, hydrolysis, and how a triglyceride forms.

Section 2.9 Cells use carbohydrates for energy or to build cell parts. Monosaccharides, or single sugar units, are the simplest ones. Chains of sugars linked by covalent bonds are oligosaccharides; common ones, such as glucose, are disaccharides built of two sugar units. Polysaccharides are longer chains that store energy in the bonds between the sugar units (Table 2.4).

Section 2.10 The body uses lipids for energy, to build cell parts, and as signaling molecules. The most important dietary fats are triglycerides. Phospholipids are building blocks of cell membranes; sterols also are constituents of membranes and various key molecules.

Sections 2.11, 2.12 Proteins are built of amino acids and each one's function depends on its structure. Linked amino acids form a polypeptide chain. The linear sequence

TABLE 2.4 Summary of the Main Organic Molecules in Living Things

Category	Main Subcategories	Some Examples and Their Functions	
CARBOHYDRATES . . . contain an aldehyde or a ketone group, and one or more hydroxyl groups.	**Monosaccharides** (simple sugars)	Glucose	Energy source
	Oligosaccharides (short-chain carbohydrates)	Sucrose (a disaccharide)	Most common form of sugar; the form transported through plants
	Polysaccharides (complex carbohydrates)	Starch, glycogen	Energy storage
		Cellulose	Structural roles
LIPIDS . . . are mainly hydrocarbon; generally do not dissolve in water but do dissolve in nonpolar substances, such as alcohols and other lipids.	**Glycerides** Glycerol backbone with one, two, or three fatty acid tails (e.g., triglycerides)	Fats (e.g., butter), oils (e.g., corn oil)	Energy storage
	Phospholipids Glycerol backbone, phosphate group, another polar group, and often two fatty acids	Lecithin	Key component of cell membranes
	Waxes Alcohol with long-chain fatty acid tails	Waxes in cutin	Conservation of water in plants
	Sterols Four carbon rings; the number, position, and type of functional groups differ among sterols	Cholesterol	Component of animal cell membranes; precursor of many steroids and vitamin D
PROTEINS . . . are one or more polypeptide chains, each with as many as several thousand covalently linked amino acids.	**Mostly fibrous proteins** Long strands or sheets of polypeptide chains; often strong, water-insoluble	Keratin	Structural component of hair, nails
		Collagen	Structural component of bone
		Myosin, actin	Functional components of muscles
	Mostly globular proteins One or more polypeptide chains folded into globular shapes; many roles in cell activities	Enzymes	Great increase in rates of reactions
		Hemoglobin	Oxygen transport
		Insulin	Control of glucose metabolism
		Antibodies	Immune defense
NUCLEIC ACIDS . . . are chains of units (or individual units) that each consist of a five-carbon sugar, phosphate, and a nitrogen-containing base.	**Adenosine phosphates**	ATP	Energy carrier
		cAMP	Messenger in hormone regulation
	Nucleotide coenzymes	NAD^+, $NADP^+$, FAD	Transfer of electrons, protons (H^+) from one reaction site to another
	Nucleic acids Chains of nucleotides	DNA, RNAs	Storage, transmission, translation of genetic information

of the amino acids is a protein's primary structure. A protein's final shape comes about as the polypeptide chain bends, folds, and coils. Many proteins consist of more than one polypeptide chain. Some have other organic compounds bonded to them; examples are glycoproteins, which have oligosaccharides attached, and lipoproteins, which have lipids attached.

A protein becomes denatured when some factor changes its normal three-dimensional shape.

- Use the animation and interaction on CengageNOW to learn more about amino acids and how peptide bonds form a polypeptide chain.

Section 2.13 Nucleic acids such as DNA and RNA consist of nucleotides. A nucleotide is composed of one sugar (such as deoxyribose, the sugar in DNA), one or more phosphate groups, and a nitrogen-containing base. The nucleotide ATP transfers energy that powers chemical reactions in cells.

- Use the animation and interaction on CengageNOW to explore the structure of DNA.

Review Questions

1. Distinguish between an element, an atom, and a molecule.
2. Explain the difference between an ionic bond and a covalent bond.
3. Ionic and covalent bonds join atoms into molecules. What do hydrogen bonds do?
4. Name three vital properties of water in living cells.
5. Which small organic molecules make up carbohydrates, lipids, proteins, and nucleic acids?
6. Which of the following is the carbohydrate, the fatty acid, the amino acid, and the polypeptide?
   a. $^{+}NH_3—CHR—COO^{-}$
   b. $C_6H_{12}O_6$
   c. $(glycine)_{20}$
   d. $CH_3(CH_2)_{16}COOH$
7. Describe the four levels of protein structure. How do a protein's side groups influence its interactions with other substances? What is denaturation?
8. Distinguish among the following:
   a. monosaccharide, polysaccharide, disaccharide
   b. peptide bond, polypeptide
   c. glycerol, fatty acid
   d. nucleotide, nucleic acid

Self-Quiz *Answers in Appendix V*

1. The backbone of organic compounds forms when _____ atoms are covalently bonded.
2. Each carbon atom can form up to _____ bonds with other atoms.
   a. four
   b. six
   c. eight
   d. sixteen
3. All of the following except _____ are small organic molecules that serve as the main building blocks or energy sources in cells.
   a. fatty acids
   b. simple sugars
   c. lipids
   d. amino acids
   e. nucleotides
4. Which of the following is not a carbohydrate?
   a. glucose molecule
   b. simple sugar
   c. margarine molecule
   d. polysaccharide
5. _____, a class of proteins, make metabolic reactions proceed much faster than they would on their own.
   a. Nucleic acids
   b. Amino acids
   c. Fatty acids
   d. Enzymes
6. Examples of nucleic acids are _____.
   a. polysaccharides
   b. DNA and RNA
   c. proteins
   d. simple sugars
7. Which phrase best describes what a functional group does?
   a. assembles large organic compounds
   b. influences the behavior of organic compounds
   c. splits molecules into two or more parts
   d. speeds up metabolic reactions
8. In _____ reactions, small molecules are linked by covalent bonds, and water can also form.
   a. hydrophilic
   b. hydrolysis
   c. condensation
   d. ionic
9. Match each type of molecule with its description.
   ___ chain of amino acids
   ___ energy carrier
   ___ glycerol, fatty acids, phosphate
   ___ chain of nucleotides
   ___ one or more sugar units
   a. carbohydrate
   b. phospholipid
   c. protein
   d. DNA
   e. ATP
10. What kinds of bonds often control the shape (or tertiary form) of large molecules such as proteins?
    a. hydrogen
    b. ionic
    c. covalent
    d. inert
    e. single

Critical Thinking

1. Black coffee has a pH of 5, and milk of magnesia has a pH of 10. Is coffee twice as acidic as milk of magnesia?
2. Your cotton shirt has stains from whipped cream and strawberry syrup, and your dry cleaner says that two separate cleaning agents will be needed to remove the stains. Explain why two agents are needed and what different chemical characteristic each would have.
3. A store clerk tells you that vitamin C extracted from rose hips is better for you than synthetic vitamin C. Based on what you know of the structure of organic compounds, does this claim seem credible? Why or why not?
4. Use the Internet to find three examples of acid rain damage and efforts to combat the problem. You might start with the United States Environmental Protection Agency's acid rain home page.
5. Carbonated drinks get that way when pressurized carbon dioxide gas is forced into flavored water. A chemical reaction between water molecules and some of the CO_2 molecules creates hydrogen ions (H^+) and bicarbonate, which is a buffer. In your opinion, is this reaction likely to raise the pH of a soda above 7, or lower it? Give your reasoning.

EXPLORE ON YOUR OWN

It's easy to demonstrate the practical consequences of differences between hydrophilic and hydrophobic molecules. Just try this little kitchen experiment. Take two identical clean plates. Smear one with grease (such as margarine) and pour syrup over the other.

Next run moderately warm water over both plates for thirty seconds and observe the results. Which plate got cleaner, and why? The companies that make dishwashing detergents manipulate them chemically so that their molecules have both hydrophobic and hydrophilic regions. Given what you know about the ability of water by itself to dissolve hydrophilic and hydrophobic substances, why might this be?

Cells and How They Work

3

IMPACTS, ISSUES

Alcohol and Liver Cells

EACH of your cells leads a double life. Its various internal parts carry out tasks that keep the cell alive, and they also help maintain homeostasis in the body by performing one or more specialized functions. For example, cells in the liver, one of your largest organs, are specialized to help rid the body of harmful toxins such as the ethanol in alcoholic beverages. They perform this service by making enzymes that convert ethanol to a much less harmful compound called acetic acid.

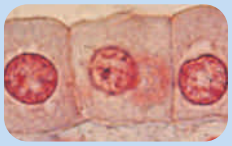
These chemical reactions occur in a series of steps, and it takes about 2 hours for them to detoxify the alcohol in one drink. When people consume alcohol more rapidly than this, they may become intoxicated. A hangover is one way the body registers the ill effects of excess alcohol consumption.

Detoxifying alcohol takes a toll on liver cells, especially when a person drinks heavily. Other, unrelated cell activities slow down or are disturbed, in part because detoxification uses oxygen that is needed for other chemical reactions. With time the lack of oxygen may kill liver cells.

Heavy drinkers risk several alcohol-induced liver diseases, such as a serious inflammation called alcoholic hepatitis and the permanent scarring of alcoholic cirrhosis. Binge drinking—having five or more alcoholic beverages in a brief period—is a common phenomenon on many college campuses. Taken to an extreme, the flood of alcohol can not only damage the liver but may also stop heart muscle cells from contracting. Each year some binge drinkers die this way.

In this chapter we look at how cells are built and operate—bringing in certain substances, releasing or keeping out others, and conducting their activities with the proverbial "Swiss watch" precision that keeps them, and the whole body, alive.

KEY CONCEPTS

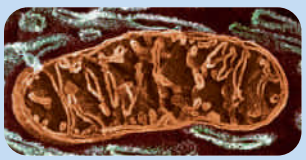


Basic Cell Features

Cells have an outer plasma membrane. The interior consists of cytoplasm and an inner region of DNA. Most cells are too small to be visible without the aid of a microscope. Sections 3.1–3.4

Cells and Their Parts

In all cells except bacteria the cytoplasm contains organelles, including a nucleus. These internal compartments have specialized functions. The DNA is in the nucleus. Sections 3.6–3.13



How Cells Gain Energy

Cells use organic compounds to make a chemical called ATP, which fuels life processes. Organelles called mitochondria make most of the body's ATP. Sections 3.14–3.16

LINKS TO EARLIER CONCEPTS

- The living cell is one of the first levels of organization in nature (1.3).
- In this chapter, you will learn how lipids are organized to form cell membranes (2.10). You will also see where DNA and RNA are found in cells (2.13) and which cell structures use amino acids and carbohydrates as building blocks for other molecules, such as proteins (2.9, 2.11, 2.12).
- The chapter explains principles that govern the movement of water and solutes into and out of cells (2.6). It also considers how cells make and use the nucleotide ATP to fuel their activities (2.13).

How Would You Vote?

A liver transplant can save the life of someone with liver disease, regardless of the cause. Some people object to scarce donor organs being used in cases where liver failure is related to alcohol abuse. Should lifestyle be a factor in deciding who gets a transplant? See CengageNOW for details, then vote online.

3.1 What Is a Cell?

- **From its size and shape to the structure of its parts, a cell is built to carry out life functions efficiently.**
- **Links to Life's characteristics 1.1, 1.3, Phospholipids 2.10**

There are trillions of cells in your body, and each one is a highly organized bit of life. A desire to understand cells led early biologists to develop the **cell theory**:

1. **Every organism is composed of one or more cells.**
2. **The cell is the smallest unit having the properties of life.**
3. **All cells come from pre-existing cells.**

These basic ideas still hold true, and they provide the foundation for everything that modern researchers have learned about cells.

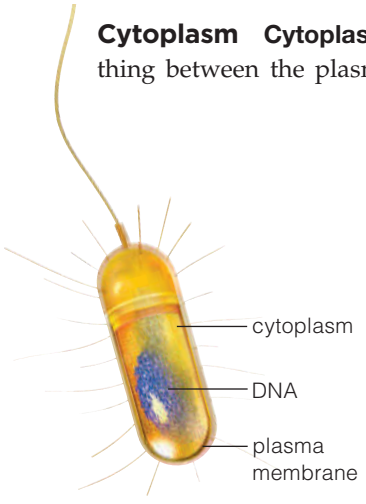
All cells are alike in three ways

All living cells have three things in common. They have an outer **plasma membrane**, they contain DNA, and they contain cytoplasm.

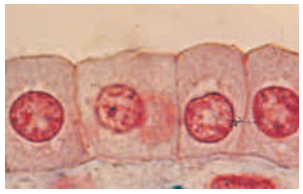
The Plasma Membrane This outer covering encloses the cell's internal parts, so that cell activities can go on apart from events that may be taking place outside the cell. The plasma membrane does not completely isolate the cell's interior. Substances still can move across the membrane, as you will read later in this chapter.

DNA A cell has DNA somewhere inside it, along with molecules that can copy or read the inherited genetic instructions DNA carries.

Cytoplasm **Cytoplasm** (SIGH-toe-plaz-um) is everything between the plasma membrane and the region of DNA. It consists of a thick, jellylike fluid, the **cytosol**, and various other components.



a Bacterial cell (prokaryotic)



b Animal cell (eukaryotic)

Figure 3.1 There are two basic types of cells. (**a**) A prokaryotic cell. (**b**) Eukaryotic cells. These kidney cells are shown in cross section. A dye makes the nucleus look reddish.

Eukaryotic and Prokaryotic Cells Compared

	Eukaryotic	Prokaryotic
Plasma membrane	yes	yes
DNA-containing region	yes	yes
Cytoplasm	yes	yes
Nucleus inside a membrane	yes	no

There are two basic kinds of cells

Cells are classified into two basic kinds, depending on how they are organized internally (Table 3.1). In a **prokaryotic cell** (prokaryotic means "before the nucleus") nothing separates the cell's DNA from other internal cell parts. Bacteria, like the one diagrammed in Figure 3.1*a*, are the only prokaryotic cells.

By contrast, all other cells are **eukaryotic cells** ("true nucleus"). In their cytoplasm are tiny compartments and sacs called **organelles** ("little organs"). One organelle, the nucleus, contains the DNA of a eukaryotic cell. Nuclei are clearly visible in the cells pictured in Figure 3.1*b*.

Most cells have a large surface area compared to their volume

A few cells—including the yolks of chicken eggs—can be seen with the unaided eye, but most cells are so small that they can only be seen with a microscope. For instance, a human red blood cell is so tiny that you could line up 2,000 of them across your thumbnail.

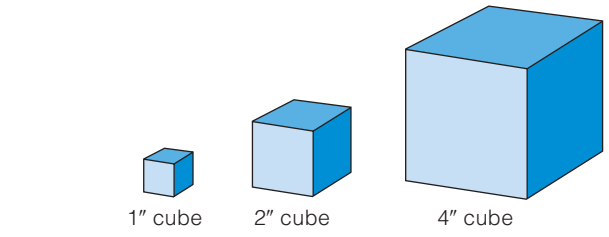
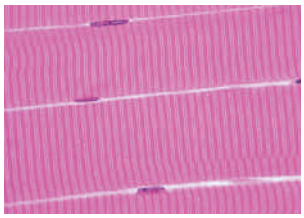
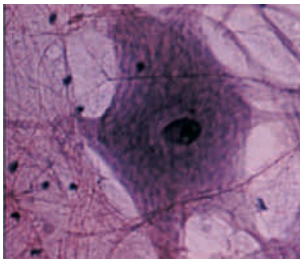


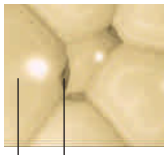
Figure 3.2 The relationship of surface to volume influences the size of cells. Here boxes represent cells. If the linear dimensions of a box double, the volume increases 8 times but the surface area increases only 4 times. As in the text example, if the linear dimensions increase by 4 times, the volume is 64 times greater but the surface area is only 16 times larger.

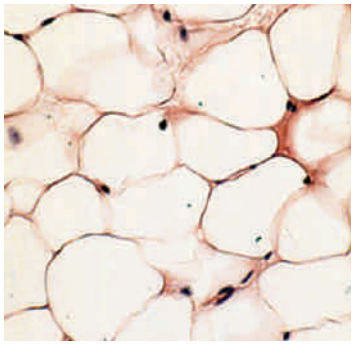


a Skeletal muscle cells

b Motor neuron







c Fat cells

Figure 3.3 Human cells come in many shapes and sizes. (**a**) The cells of skeletal muscles are long and slender. (**b**) A motor neuron, a type of nerve cell, has threadlike extensions. (**c**) The cells that make up body fat are rounded.

The **surface-to-volume ratio** is responsible for the small size of cells. This ratio is a physical relationship. It dictates that as the linear dimensions of a three-dimensional object increase, the volume of the object increases faster than its surface area does (Figure 3.2). For instance, if a round cell grew like an inflating balloon so that its diameter increased to 4 times the starting girth, the volume inside the cell would be 64 times more than before, but the cell's surface would be just 16 times larger. The cell would not have enough surface area to allow nutrients to flow inward rapidly, or for wastes or cell products to move rapidly outward. In short order the cell would die.

A large, round cell also would have trouble moving materials through its cytoplasm. In small cells, though, random, tiny motions of molecules easily distribute materials. If a cell isn't small, it probably is long and thin or has folds that increase its surface area relative to its volume. The smaller or narrower or more frilly the cell, the more efficiently materials can cross its surface and disperse inside it. Figure 3.3 shows three of the many shapes of cells in your own body. Part *a* depicts

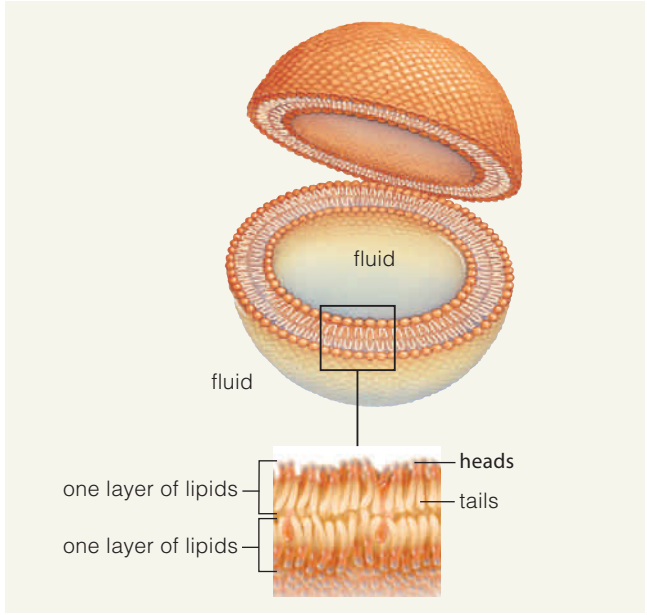


Figure 3.4 Animated! In cell membranes, phospholipids are arranged in a bilayer.

long, slender cells in a type of muscle called skeletal muscle. In the biceps of your upper arm they are many inches long—as long as the muscle itself.

Membranes enclose cells and organelles

A eukaryotic cell and its organelles are enclosed by membranes. Most of the molecules in cell membranes are phospholipids, which were introduced in Section 2.10. You may remember that a phospholipid has a hydrophilic (water-loving) head and two fatty acid tails, which are hydrophobic (water-dreading). When a large number of phospholipids are immersed in water, they interact with the water molecules and with one another. They may spontaneously organize into two layers with all the hydrophobic tails sandwiched between all the heads (Figure 3.4). This heads-out, tails-in arrangement is called a **lipid bilayer**. All cell membranes have the lipid bilayer structure. The hydrophilic heads of the phospholipids are dissolved in the watery fluids inside and outside cells.

Take-Home Message

What are the basic features of cells?

- A cell has an outer plasma membrane, which encloses its jellylike cytoplasm and DNA. Complex organisms such as humans consist of eukaryotic cells. The cell's DNA is contained in an organelle, the nucleus.
- In prokaryotic cells DNA is not contained inside a nucleus. Bacteria are the only cells of this type.
- The surface-to-volume ratio limits cell size.
- A cell's membranes consist mainly of phospholipids arranged in a bilayer.

3.2 The Parts of a Eukaryotic Cell

- **The interior of a cell is divided into organelles, each with one or more special functions.**

In every eukaryotic cell, at any given moment, a vast number of chemical reactions are going on. Many of the reactions would conflict if they occurred in the same cell compartment. For example, a molecule of fat can be built by some reactions and taken apart by others, but a cell gains nothing if both sets of reactions proceed at the same time on the same fat molecule.

In eukaryotic cells, including those of the human body, organelles (Table 3.2) solve this problem. Most of them have an outer membrane that separates the inside of the organelle from the rest of the cytoplasm. It also controls the types and amounts of substances that enter or leave the organelle. For example, organelles called lysosomes contain enzymes that break down various unwanted substances. If the enzymes escaped from the organelle, they could destroy the entire cell. Only the organelles called ribosomes do not have a membrane.

Organelles also may serve as "way stations" for operations that occur in steps. Proteins are assembled and modified in steps involving several organelles.

Figure 3.5 shows where organelles and some other structures might be located in a body cell. This is only a general picture of cells. There are major differences in the structures and functions of cells in different tissues.

Organelles of Eukaryotic Cells

Name	Function
Organelles with membranes	
Nucleus	Protecting, controlling access to DNA
Endoplasmic reticulum (ER)	Routing, modifying new polypeptide chains; synthesizing lipids; other tasks
Golgi body	Modifying new polypeptide chains; sorting, shipping proteins and lipids
Vesicles	Transporting, storing, or digesting substances in a cell; other functions
Mitochondrion	Making ATP by sugar breakdown
Chloroplast	Making sugars in plants, some protists
Lysosome	Intracellular digestion
Peroxisome	Inactivating toxins
Vacuole	Storage
Organelles without membranes	
Ribosomes	Assembling polypeptide chains
Centriole	Anchor for cytoskeleton

Take-Home Message

What is the overall role of cell organelles?

- Organelles isolate chemical reactions inside cells. They also provide separate locations for activities that occur in a sequence of steps.

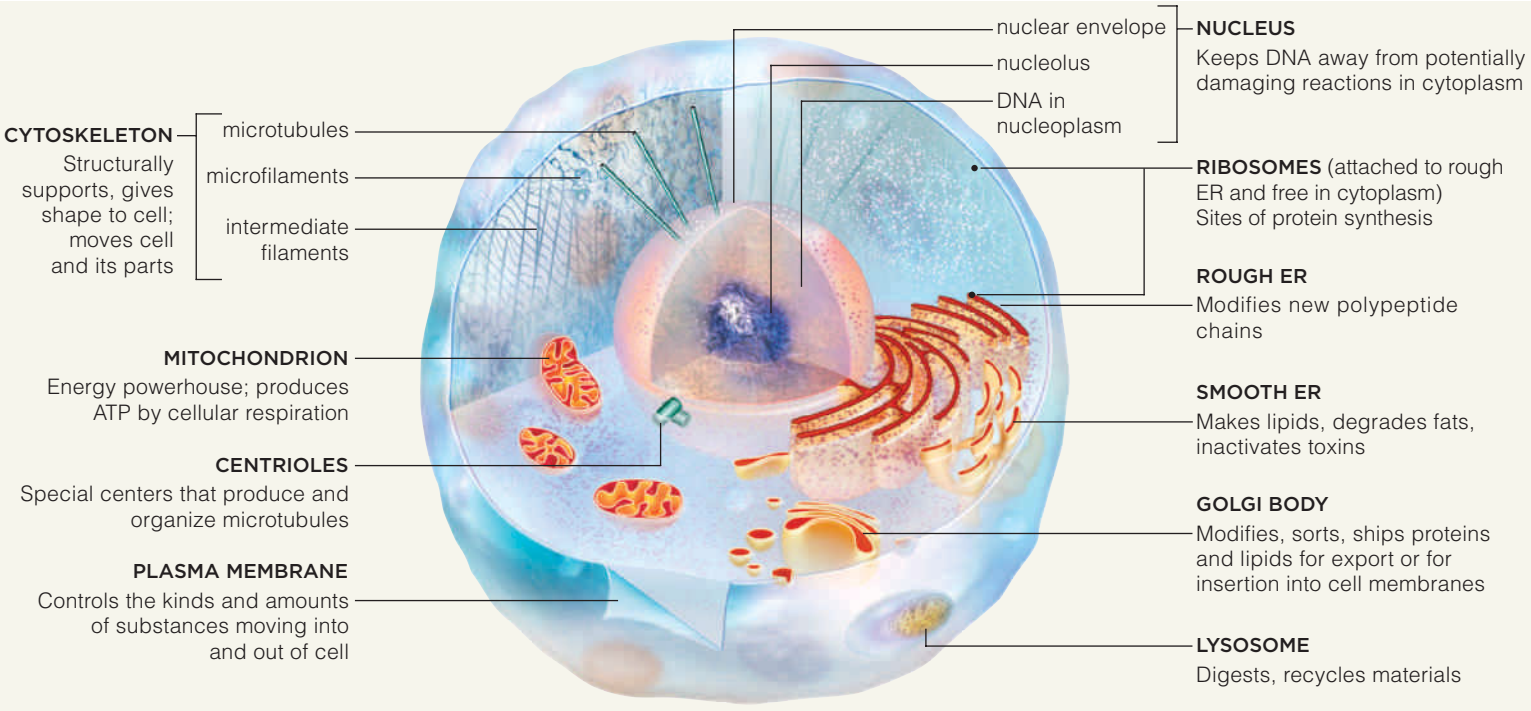


Figure 3.5 Animated! **An animal cell has a variety of internal parts.**

3.3 How Do We See Cells?

Microscopy has allowed us to learn a great deal about cells. A photograph formed using a microscope is called a micrograph.

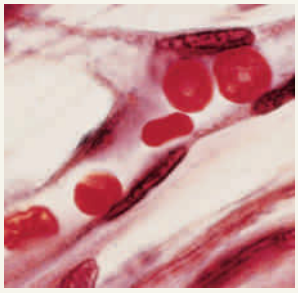
The micrographs in Figure 3.6 compare the sorts of detail different types of microscopes can reveal. For example, the red blood cells in Figure 3.6*a* were viewed using a compound light microscope, in which two or more glass lenses bend (refract) incoming light rays to form an enlarged image of a specimen. With this method, the cell must be small or thin enough for light to pass through, and its parts must differ in color or optical density from their surroundings. Unfortunately, most cell parts are nearly colorless and they have about the same density. For this reason, before viewing cells through a light microscope, researchers expose the cells to dyes that react with some cell parts but not with others. Even with the best glass lens system, however, light microscopes only provide sharp images when the diameter of the object being viewed is magnified by 2,000 times or less.

Electron microscopes use magnetic lenses to bend beams of electrons. They reveal smaller details than even the best light microscopes can. There are several types, with new innovations occurring often.

A transmission electron microscope uses a magnetic field as the "lens" that bends a stream of electrons and focuses it into an image, which then is magnified. With a scanning electron microscope, a beam of electrons is directed back and forth across a specimen thinly coated with metal. The metal emits some of its own electrons, and then the electron energy is converted into an image of the specimen's surface on a television screen. Most of the images have fantastic depth (Figure 3.6*b*, right).

A scanning tunneling microscope magnifies objects up to 100 million times (Figure 3.6*c*). The scope's needlelike probe has a single atom at its tip. As an electric current passes between the tip and specimen's surface, electrons "tunnel" from the probe to the specimen. A computer analyzes the tunneling motion and makes a 3-D view of the surface.

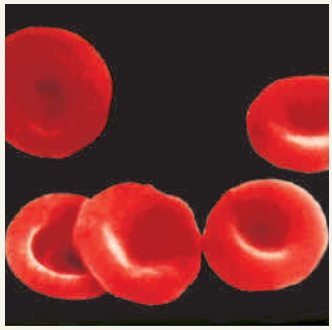
Compound light microscope



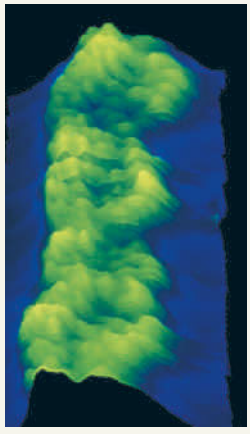
a

Transmission electron microscope

Figure 3.6 Animated! Different types of microscopes reveal different kinds of details. (**a**) Red blood cells inside a small blood vessel, as revealed by a light microscope. (**b**) Electron micrographs. *Top:* A transmission electron micrograph (TEM) shows the hemoglobin packed inside of mature red blood cells. *Bottom:* A scanning electron micrograph (SEM) with color added shows the "doughnut without a hole" shape of red blood cells. (**c**) The green-colored image is a micrograph of DNA obtained with a scanning tunneling microscope.



b



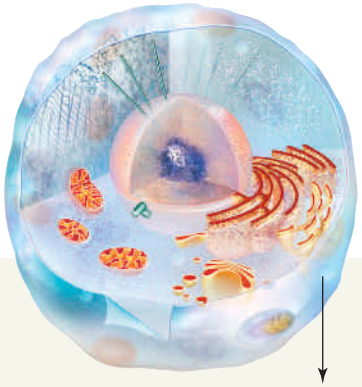
c

3.4 The Plasma Membrane: A Double Layer of Lipids

- **The plasma membrane controls the movement of substances into and out of cells.**
- **Links to Polar molecules 2.4, Enzymes 2.8, Phospholipids 2.10**

The plasma membrane is a mix of lipids and proteins

The plasma membrane isn't a solid, rigid wall between a cell's cytoplasm and the fluid outside. If it were, needed substances couldn't enter the cell and wastes couldn't leave it. Instead, the plasma membrane has a fluid quality, something like cooking oil. The membrane also is extremely thin. A thousand stacked like pancakes would be about as thick as this page.



In Figure 3.4 you've already seen a simple picture of a plasma membrane lipid bilayer with its "sandwich" of phospholipids. This structure often is described as a "mosaic" of proteins and different kinds of lipids. These include phospholipids, glycolipids, and, in the cells of humans and other animals, the lipid we call cholesterol. Plasma membrane proteins are embedded in the bilayer or attach to its outer or inner surface.

What makes the membrane fluid? A key factor is the movement of the molecules in it. Most phospholipids can spin on their long axis like a chicken on a rotisserie. They also move sideways and flex their tails. These movements help keep neighboring molecules from packing into a solid layer.

Proteins carry out most of the functions of cell membranes

The proteins that are embedded in or attached to a lipid bilayer carry out most of a cell membrane's functions (Figure 3.7). Many of these proteins are enzymes; you may recall from Chapter 2 that enzymes speed chemical reactions in cells. Other membrane proteins serve a

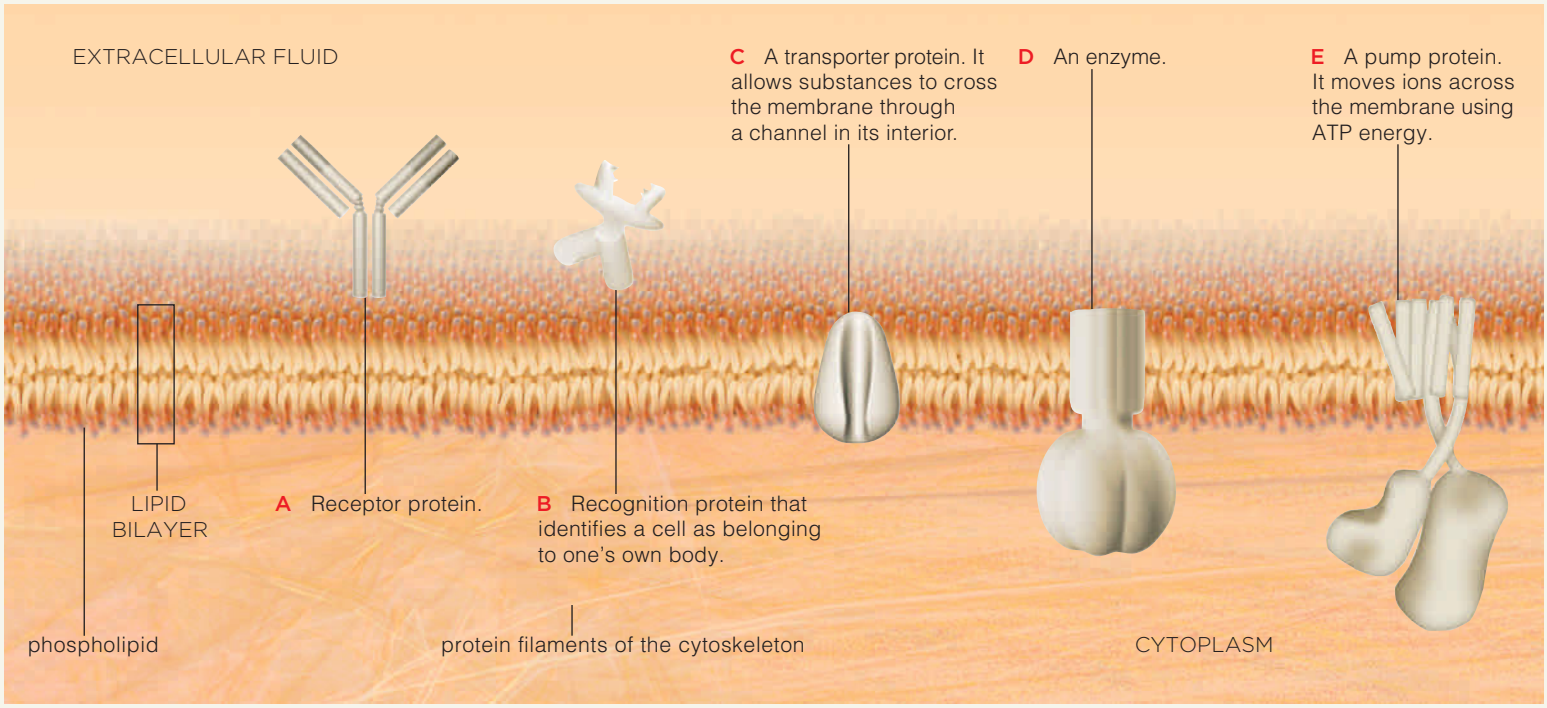


Figure 3.7 Animated! A cell's plasma membrane consists of lipids and proteins. Most of the lipids are phospholipids. This diagram also shows examples of membrane proteins. Biologists refer to the membrane's mix of lipids and proteins as a "mosaic."

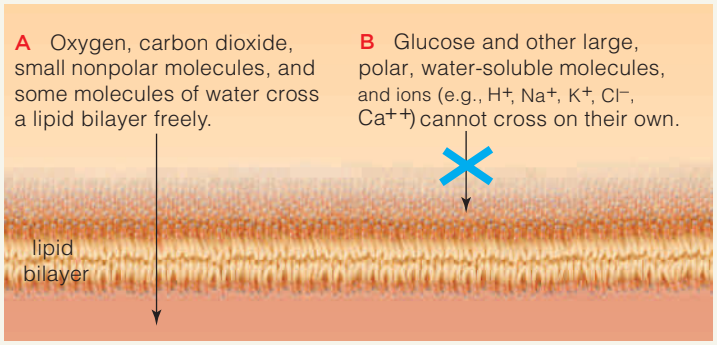


Figure 3.8 Animated! Cell membranes are selectively permeable.

range of functions. Some are channels through the membrane, while others are transporters that move substances across it. Still others are receptors; they are like docks for signaling molecules, such as hormones, that trigger changes in cell activities. Recognition proteins that wave like flags on the surface of a cell are "fingerprints" that identify the cell as being of a specific type. You will read more about membrane proteins in upcoming chapters.

The plasma membrane is "selective"

You have just read that a cell's plasma membrane is a bilayer containing lipids and proteins. These molecules give the membrane **selective permeability**. They allow some substances but not others to enter and leave a cell (Figure 3.8). They also control *when* a substance can cross and how much crosses at a given time. Lipids in the bilayer are mostly nonpolar, so they let small, nonpolar molecules such as carbon dioxide and oxygen slip across. Water molecules are polar, but some can move through gaps that briefly open up in the bilayer. Ions and large polar molecules (such as the blood sugar glucose) cross the bilayer through the interior of its transport proteins. You will read more about this topic in Section 3.10.

Take-Home Message

What is the connection between the structure and functions of the plasma membrane?

- The plasma membrane is a lipid bilayer. It is a mix of various lipids and proteins and has a fluid quality.
- Proteins of the bilayer carry out most of the membrane's functions.
- The structure of the plasma membrane makes it selectively permeable. Some substances can cross it but others cannot.

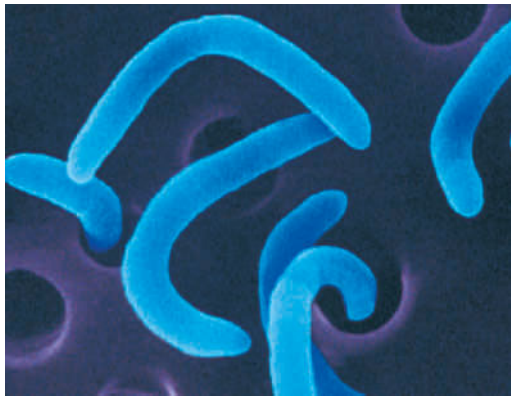
3.5 Deadly Water Pollution

In places where public sanitation is poor, people run the risk of getting the dangerous disease called cholera. Drinking water and some foods may be contaminated by human sewage, which in turn may contain the bacterium *Vibrio cholerae*. This microbe produces cholera exotoxin, or CXT, a poison that affects certain pump proteins in the plasma membranes of cells in the small intestine. CXT causes cells to pump out chloride and sodium ions, and other dissolved substances follow. As these substances leave, cells lose their water by osmosis, a process that is described in Section 3.10.

Cholera's main symptom is sudden, massive diarrhea that can literally drain a person's body of water in less than 24 hours. It is a common, deadly threat in parts of Africa, Asia, and South America. After Hurricane Katrina in 2005, officials feared it would strike the U.S. Gulf Coast as well. Luckily it did not.

Experts estimate that a person must ingest at least 1 million cholera bacteria in order to fall ill, but that many of the microbes may be present in just a single glass of contaminated water or on a few bites of tainted food. Fortunately, the immune system often can destroy the bacteria before they do serious damage. Only about one in ten people who are exposed ever become seriously ill. But infected people who don't show symptoms still can pass living bacteria in their feces for as long as 10 days—adding to the pool of infectious microbes in unsanitary water supplies.

In well-off nations cholera is treated with antibiotics. Elsewhere patients may recover if they receive prompt rehydration therapy, which replenishes lost fluid and needed ions.



Vibrio cholerae bacteria, the cause of cholera

3.6 The Nucleus

- **The nucleus is often described as a cell's master control center. It also is a protective "isolation chamber" for DNA, the genetic material.**

The **nucleus** encloses the DNA of a eukaryotic cell. DNA contains instructions for building a cell's proteins. Those proteins in turn determine a cell's structure and function. In a human cell there are forty-six DNA molecules that together would be more than 6 feet long if they were stretched out end to end.

Figure 3.9 shows the basic structure of the nucleus, and Table 3.3 lists its five main parts. The nucleus has several key functions. First, it prevents DNA from getting entangled with structures in the cytoplasm. When a cell divides, its DNA molecules must be copied so that each new cell receives a full set. Keeping the DNA separate makes it easier to copy and organize these hereditary instructions. In addition, outer membranes of the nucleus are a boundary where cells control the movement of substances to and from the cytoplasm.

Components of the Nucleus

Nuclear envelope	Double membrane with many pores; it separates the interior of the nucleus from the cytoplasm
Nucleolus	A cluster of the RNA and proteins used to assemble ribosome subunits
Nucleoplasm	Fluid interior portion of the nucleus
Chromatin	All the DNA molecules and their attached proteins
Chromosomes	The individual DNA molecules and their attached proteins

A nuclear envelope encloses the nucleus

Unlike the cell itself, the nucleus has two outer lipid bilayers, one pressed against the other. This double-membrane system is called a **nuclear envelope** (Figure 3.10). The envelope surrounds the fluid part of the nucleus (the nucleoplasm), and many proteins are embedded in its layers. The outer portion of the nuclear envelope merges with the membrane of ER, an organelle in the cytoplasm, which you will read more about in Section 3.7.

Threadlike bits of protein attach to the inner surface of the nuclear envelope. They anchor DNA molecules to the envelope and help keep them organized.

Proteins that span both bilayers have a wide variety of functions. Some are receptors or transporters. Others form pores, as you can see in Figure 3.10*b*. The pores are passageways. They allow small ions and molecules dissolved in the watery fluid inside and outside the nucleus to cross the nuclear membrane.

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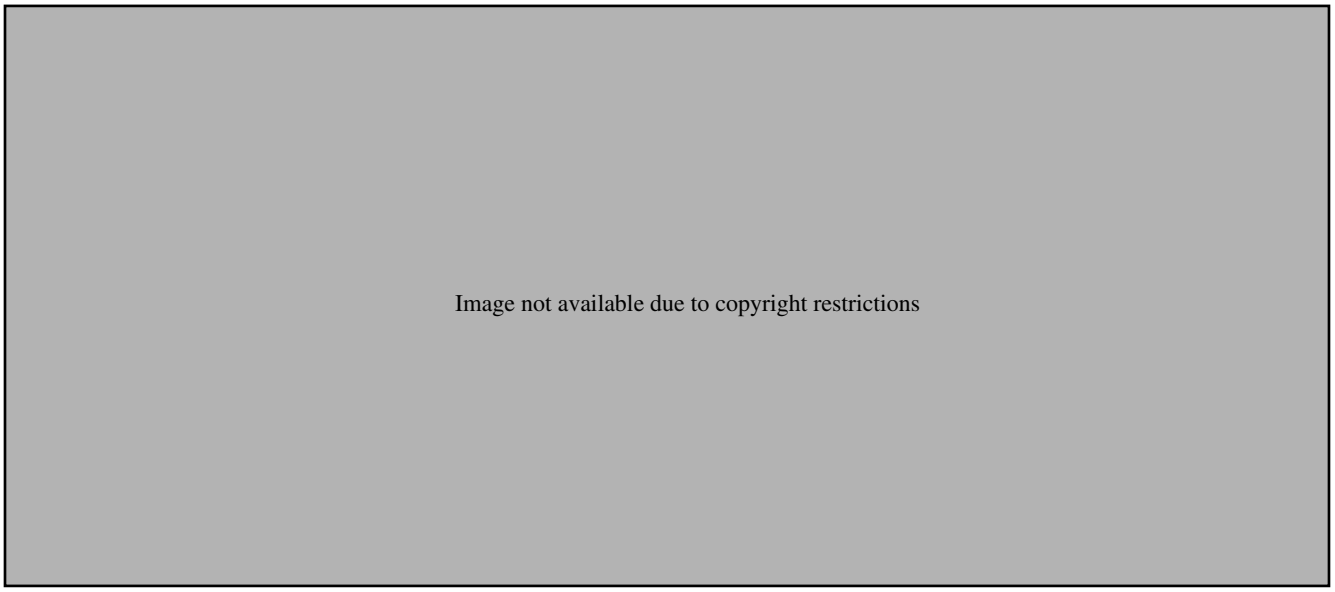
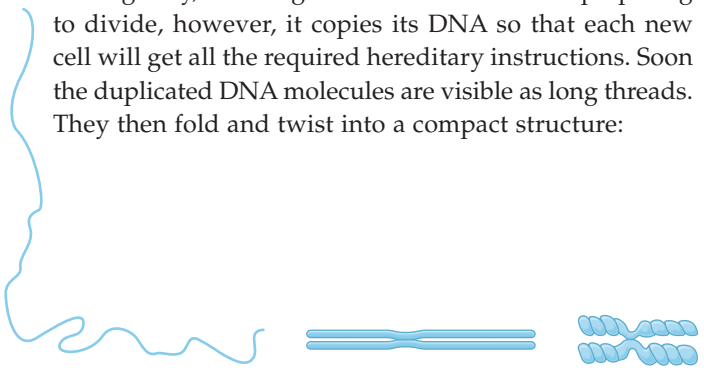


The nucleolus is where cells make the parts of ribosomes

As a cell grows, one or more dense masses appear inside its nucleus. Each mass is a **nucleolus** (noo-KLEE-oh-luhs), a construction site where some proteins and RNAs are combined to make the parts of ribosomes. These subunits eventually will cross through nuclear pores to the cytoplasm. There, they briefly join up to form ribosomes. These organelles are "workbenches" where amino acids are assembled into proteins.

DNA is organized in chromosomes

When a eukaryotic cell is not dividing, you cannot see individual DNA molecules, nor can you see that each consists of two strands twisted together. The nucleus just looks grainy, as in Figure 3.10. When a cell is preparing to divide, however, it copies its DNA so that each new cell will get all the required hereditary instructions. Soon the duplicated DNA molecules are visible as long threads. They then fold and twist into a compact structure:



one chromosome (one dispersed DNA molecule + proteins; not duplicated)

one chromosome (threadlike and now duplicated; two DNA molecules + proteins)

one chromosome (duplicated and also condensed tightly)

Early microscopists named the seemingly grainy substance in the nucleus *chromatin*, and they called the compact structures *chromosomes* ("colored bodies"). Today we define **chromatin** as the cell's DNA along with the proteins associated with it. We also understand that sections of chromatin make up each **chromosome**—a double-stranded DNA molecule that carries genetic information. A chromosome looks different at different times, being grainy or compact depending on whether the cell is dividing or is in another part of its life cycle.

Events that begin in the nucleus continue to unfold in the cell cytoplasm

Outside the nucleus, new polypeptide chains for proteins are assembled on ribosomes. Many of them are used at once or stockpiled in the cytoplasm. Others enter the endomembrane system. As you'll read in the next section, this system includes various structures. It is where many proteins get their final form and where lipids are assembled and packaged.

Take-Home Message

What is the function of the cell nucleus?

- The nucleus protects the DNA in a cell's chromosomes and keeps the chromosomes separated from the cell's cytoplasm.
- The separation makes it easier to organize the DNA and to copy it before a cell divides.
- The nuclear envelope encloses the fluid part of the nucleus. Proteins embedded in the envelope's two bilayers control the passage of molecules between the nucleus and the cytoplasm.

3.7 The Endomembrane System

- **Organelles of a cell's endomembrane system assemble lipids and produce the final forms of proteins, and then sort and ship these molecules to various destinations.**

ER is a protein and lipid assembly line

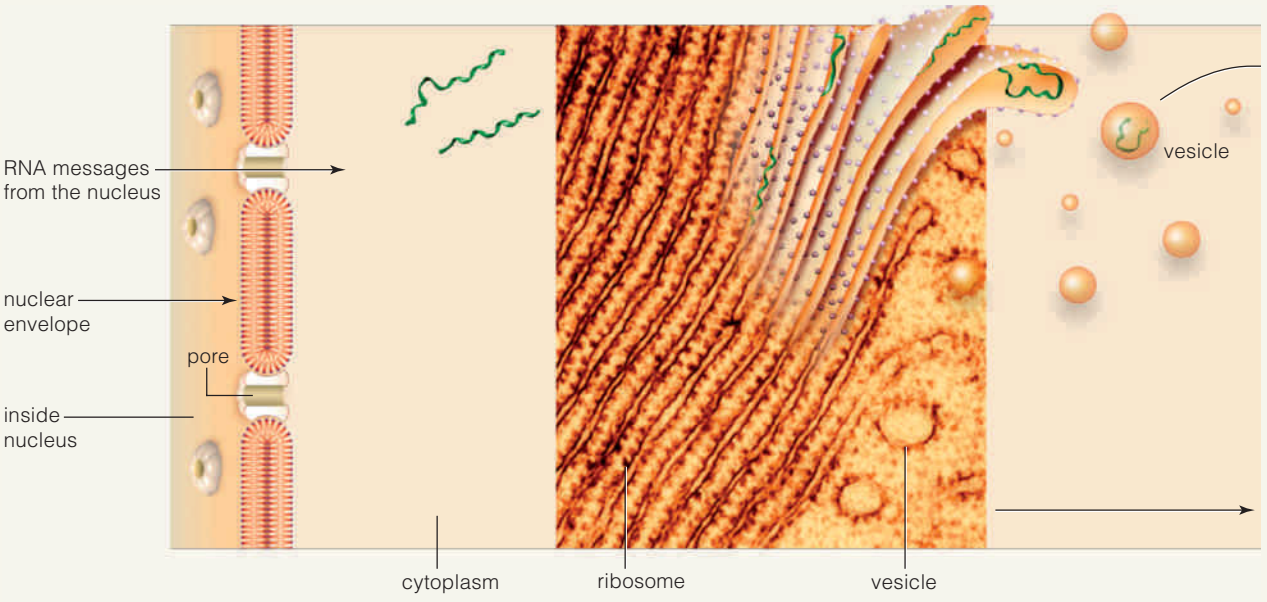
The functions of the **endomembrane system** begin with **endoplasmic reticulum**, or **ER**. The ER is a flattened channel that starts at the nuclear envelope and snakes through the cytoplasm (Figure 3.11). At various points inside the channel, lipids are assembled and "raw" polypeptide chains are modified into final proteins. In different places the ER looks rough or smooth, depending mainly on whether the organelles called **ribosomes** are attached to the side of the membrane that faces the cytoplasm. Like a workbench, a ribosome is a platform for building a cell's proteins.

Rough ER is studded with ribosomes (Figure 3.11*b*). Newly forming polypeptide chains that have a built-in signal (a string of amino acids) can enter the space inside rough ER or be incorporated into ER membranes. Once the chains are in rough ER, enzymes in the channel may attach side chains to them. Body cells that secrete finished proteins have extensive rough ER. For example, in your pancreas, ER-rich gland cells make and secrete enzymes that end up in your small intestine and help you digest your meals.

Smooth ER has no ribosomes and curves through the cytoplasm like flat connecting pipes (Figure 3.11*c*). Many cells assemble most lipids inside these pipes. In liver cells, smooth ER inactivates certain drugs and harmful by-products of metabolism. In skeletal muscle cells a type of smooth ER called sarcoplasmic reticulum stores and releases calcium ions essential for muscles to contract.

Golgi bodies "finish, pack, and ship"

A **Golgi body** is a series of flattened sacs that often resemble a stack of pancakes (Figure 3.11*d*). Enzymes in the sacs put the finishing touches on proteins and lipids, then sort and package the completed molecules in vesicles for shipment to specific locations. A **vesicle** is a tiny sac that moves through the cytoplasm or takes up positions



the cell nucleus **rough ER**

A RNA messages are translated into polypeptide chains on ribosomes. Many chains are stockpiled in the cytoplasm or used at once. Others enter the rough ER.

B Flattened sacs of rough ER form one continuous channel between the nucleus and smooth ER. Polypeptide chains that enter the channel are modified. They will be inserted into organelle membranes or will be secreted from the cell.

Figure 3.11 Animated! The endomembrane system builds lipids and modifies many cell proteins. These products are sorted and shipped to other cell parts or to the plasma membrane to be exported out of the cell.

in it. For example, an enzyme in one Golgi region might attach a phosphate group to a new protein and then "pack" the protein into a vesicle, thereby giving it a "mailing tag" to its proper destination. The top pancake of a Golgi body is the organelle's "shipping gate" for molecules to be exported. Here, vesicles form as patches of the membrane bulge out and then break away into the cell's cytoplasm.

A variety of vesicles move substances into and through cells

Many kinds of vesicles shuttle substances around cells. A common type, the lysosome, buds from the membranes of Golgi bodies. A **lysosome** is specialized for digestion: It contains a potent stew of enzymes that speed the breakdown of proteins, complex sugars, nucleic acids, and some lipids. Lysosomes may even digest whole cells or cell parts. Often, lysosomes fuse with vesicles that have formed at a cell's plasma membrane. The vesicles usually contain molecules, bacteria, or other items that attach to the plasma membrane. White blood cells of the immune system take in foreign material in vesicles and dispose of it.

Peroxisomes, another type of vesicle, are tiny sacs of enzymes that break down fatty acids and amino acids. The reactions produce hydrogen peroxide, a potentially harmful substance. But before hydrogen peroxide can injure the cell, another enzyme in peroxisomes converts it to water and oxygen or uses it to break down alcohol. After someone drinks alcohol, nearly half of it is broken down in peroxisomes of liver and kidney cells.

Take-Home Message

What are the functions of the endomembrane system?

- In the ER and Golgi bodies of the cytomembrane system, many proteins take on final form, and lipids are assembled.
- Vesicles move substances around cells or transport them to the outside.
- The vesicles called lysosomes and peroxisomes break down unwanted material.

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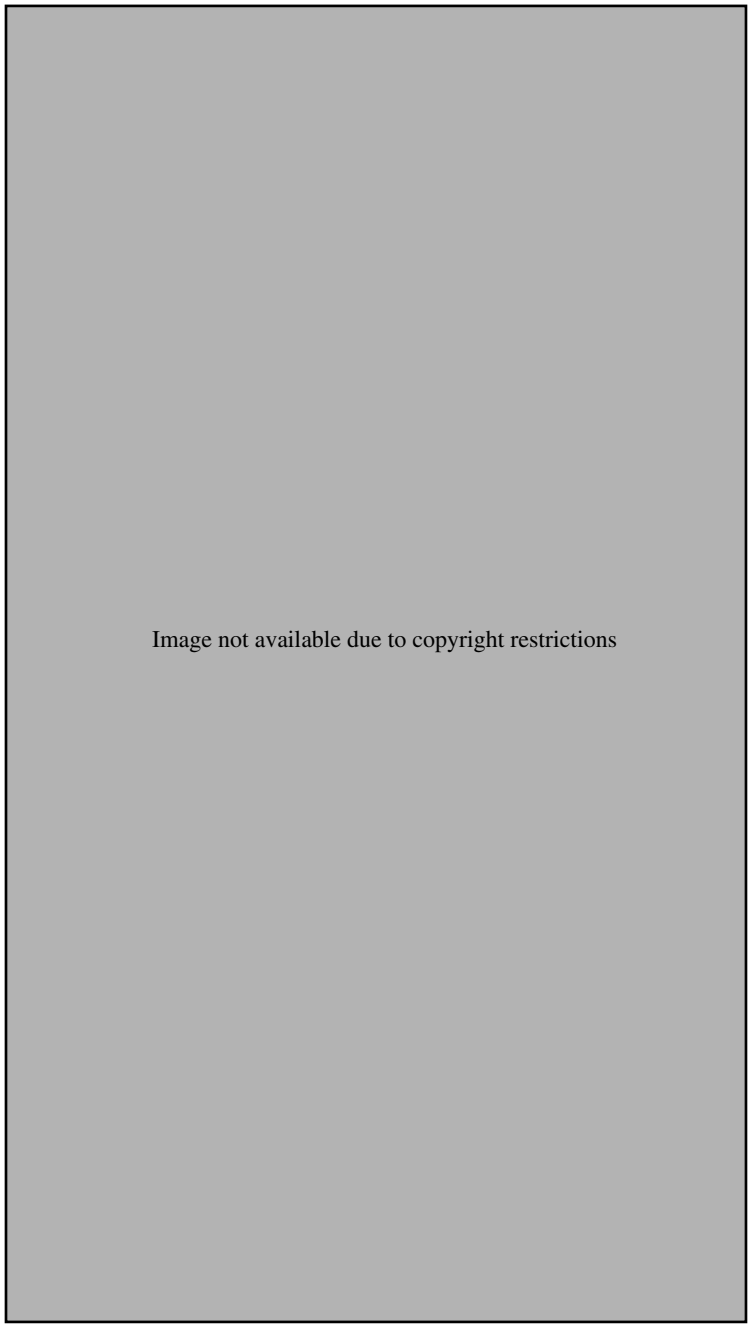
3.8 Mitochondria: The Cell's Energy Factories

- **The energy for cell activities comes from ATP made in the cell's sausage-shaped mitochondria.**
- **Link to ATP 2.13**



Mitochondria make ATP

Section 2.13 introduced the main energy carrier in cells, ATP. Because ATP can deliver energy to nearly all the reaction sites in a cell, ATP drives nearly all of a cell's activities. ATP forms during reactions that break down organic compounds to carbon dioxide and water in a **mitochondrion** (plural: mitochondria).

Only eukaryotic cells contain mitochondria. The one shown in Figure 3.12 gives you an idea of their structure. The kind of ATP-forming reactions that occur in mitochondria extract far more energy from organic compounds than can be obtained by any other means. The reactions cannot be completed without an ample supply of oxygen. Every time you inhale, you are taking in oxygen mainly for mitochondria in your cells.

ATP forms in an inner compartment of the mitochondrion

A mitochondrion has a double-membrane system. As shown in the sketch at the upper right, the outer membrane faces the cell's cytoplasm. The inner one generally folds back on itself, accordion-fashion. Each fold is a crista (KRIS-tuh; plural: cristae). This membrane system is the key to the mitochondrion's function because it forms two separate compartments inside the organelle. In the outer one, enzymes and other proteins stockpile hydrogen ions. This process is fueled by energy from electrons. As electrons are depleted of energy, oxygen binds and removes them. When the stockpiled hydrogen ions later flow out of the compartment, energy inherent in the flow (as in a flowing river) powers the reactions that form ATP.

Mitochondria have intrigued biologists because they are about the same size as bacteria and function like them in many ways as well. Mitochondria even have their own DNA and some ribosomes, and they divide independently of the cell they are in. Many biologists believe mitochondria evolved from ancient bacteria that were consumed by another ancient cell, yet did not die. Perhaps they were able to reproduce inside the predatory cell and its descendants. If they became permanent, protected residents, they might have lost structures and functions required for independent life while they were becoming mitochondria, the ATP-producing organelles without which we humans could not survive.

Take-Home Message

What is the function of mitochondria?

- Mitochondria are the ATP-producing powerhouses of eukaryotic cells.
- ATP is produced by reactions that take place in the inner compartment formed by a mitochondrion's double-membrane system. These reactions require oxygen.

3.9 The Cell's Skeleton

- **A cell's internal framework is called the cytoskeleton. It is not permanently rigid, however. Its elements assemble and disassemble as needed for various cell activities.**

The **cytoskeleton** is a system of interconnected fibers, threads, and lattices in the cytosol (Figure 3.13). It gives cells their shape and internal organization, as well as their ability to move. **Microtubules** are the largest cytoskeleton elements. Their main function is to spatially organize the interior of the cell, although microtubules also help move cell parts.

Microfilaments often reinforce some part of a cell, such as the plasma membrane. Some membrane proteins are anchored in place by microfilaments.

Some kinds of cells also have **intermediate filaments** that add strength much as steel rods strengthen concrete pillars. Intermediate filaments also anchor the filaments of two other proteins, called actin and myosin, which interact in muscle cells and enable the muscle to contract. Chapter 6 looks at this process.

Some types of cells move about by **flagella** (singular: flagellum) or **cilia** (singular: cilium). In both structures nine pairs of microtubules ring a central pair; a system of spokes and links holds this "9 + 2 array" together (Figure 3.14). The flagellum or cilium bends when microtubules in the ring slide over each other. Whiplike flagella propel human sperm (Figure 3.13*b*).

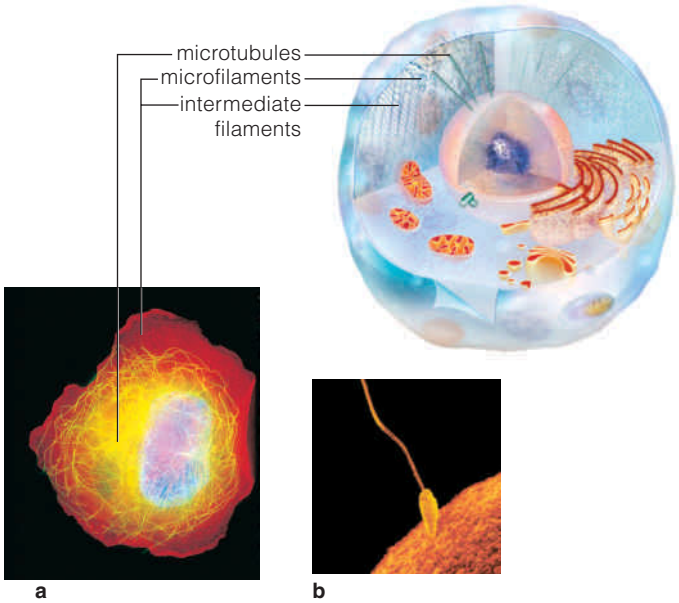


Figure 3.13 The cytoskeleton consists of microtubules and two types of filaments. (**a**) The cytoskeleton of a human pancreas cell. The blue area is DNA. (**b**) The "tail" of a sperm cell is a whiplike flagellum.

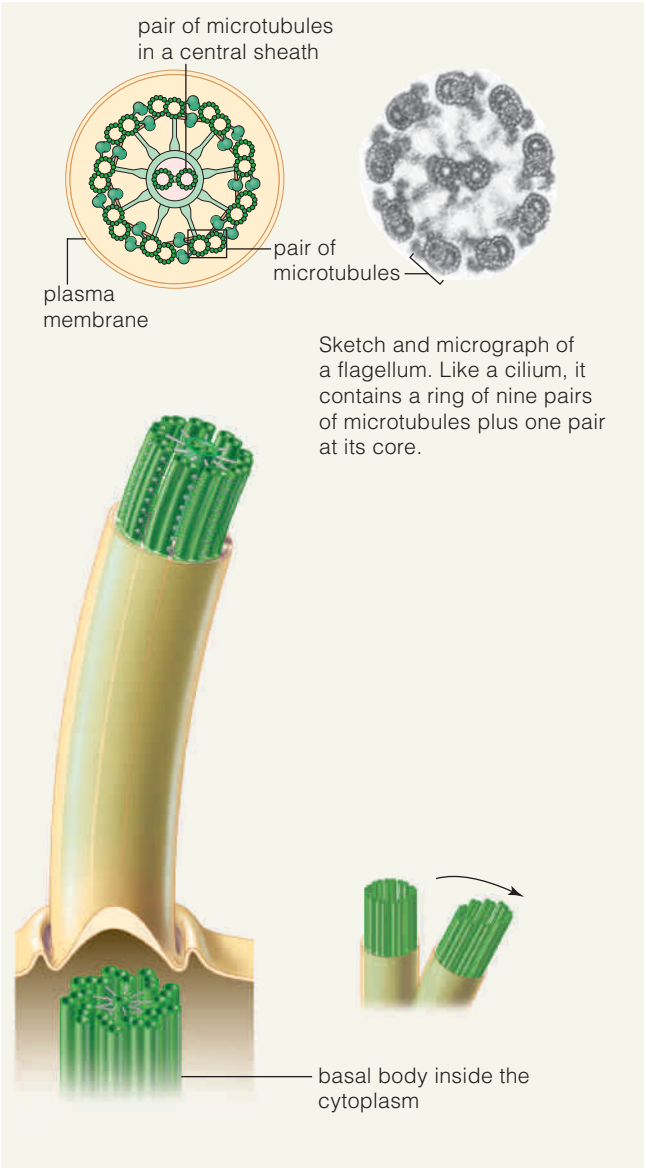


Figure 3.14 Animated! Microtubules allow cilia and flagella to move.

Cilia are shorter than flagella, and there may be more of them per cell. In your respiratory tract, thousands of ciliated cells whisk out mucus laden with dust or other undesirable material. The microtubules of cilia and flagella arise from **centrioles**, which remain at the base of the completed structure as a "basal body." As you will read in Chapter 18, centrioles have an important role when a cell divides.

Take-Home Message

What is the function of the cytoskeleton?

- The cytoskeleton gives each cell its shape, internal structure, and capacity for movement. Its main elements are microtubules, microfilaments, and intermediate filaments.
- Certain types of cells move their bodies or parts by way of flagella or cilia.

3.10 How Diffusion and Osmosis Move Substances across Membranes

- **A cell takes in and expels substances across its plasma membrane. Diffusion and osmosis are the major means for accomplishing these tasks.**
- **Links to Phospholipids 2.10, Protein function 2.12**

As you already know, a cell's plasma membrane has the property of selective permeability. Only certain kinds of substances can enter and leave the cell. Why does a solute move one way or another at any given time? The answer starts with concentration gradients.

In diffusion, a dissolved molecule or ion moves down a concentration gradient

There is fluid on both sides of a cell's plasma membrane, but the kinds and amounts of dissolved substances in the fluid are not the same on the two sides. "Concentration" refers to the number of molecules of a substance in a certain volume of fluid. "Gradient" means that the number of molecules in one region is not the same as in another. Therefore, a **concentration gradient** is a difference in the number of molecules or ions of a given substance in two neighboring regions. Molecules are always moving between the two regions, but on balance, unless other forces come into play, they tend to move into the region where they are less concentrated.

The net movement of like molecules or ions down a concentration gradient is called **diffusion**. In living organisms, the diffusion of a substance across a cell membrane is called **passive transport**. It is "passive" because a cell does not have to draw energy from ATP, the cell's chemical fuel, to make diffusion happen. Diffusion moves substances to and from cells, and into and out of the fluids bathing them. Diffusion also moves substances through a cell's cytoplasm.

Each type of solute follows its own gradient

If a solution contains more than one kind of solute, each kind diffuses down its own concentration gradient. For example, if you put a drop of dye in one side of a bowl of water, the dye molecules diffuse to the region where they are less concentrated. Likewise, the water molecules move in the opposite direction, to the region where *they* are less concentrated (Figure 3.15).

Molecules diffuse faster when the gradient is steep. Where molecules are most concentrated, more of them move outward, compared to the number that are moving in. As the gradient smooths out, there is less difference in the number of molecules moving either way. Even when the gradient disappears, molecules are still moving, but the total number going one way or the other during a given interval is about the same. For charged molecules, transport is influenced by both the concentration gradient and the *electric gradient*—a difference in electric charge across the cell membrane. As you will read in Chapter 13, nerve impulses depend on electric gradients.

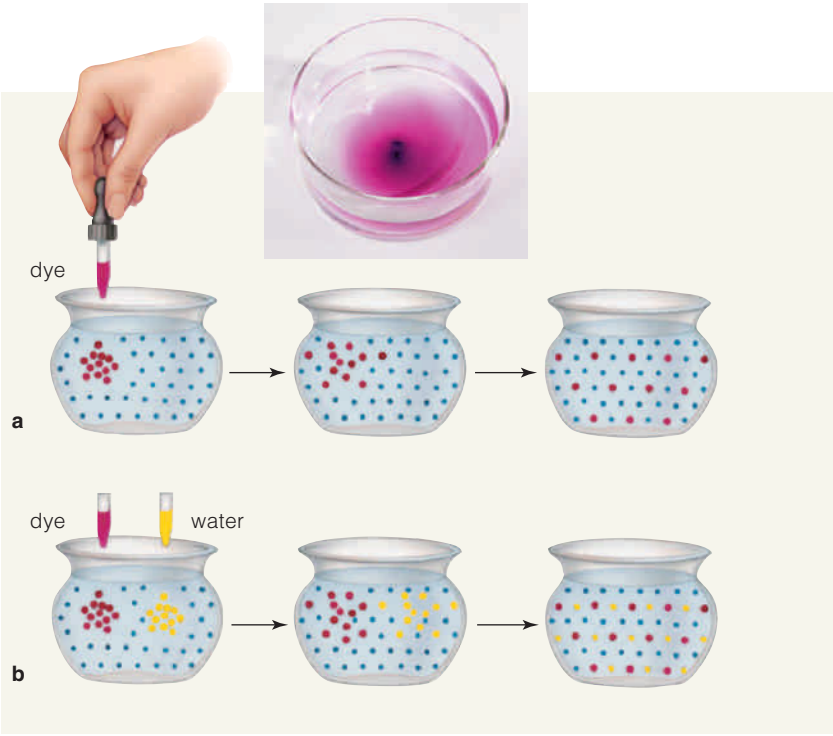


Figure 3.15 Animated! Substances diffuse down a concentration gradient. (**a**) A drop of dye enters a bowl of water. Gradually the dye molecules become evenly dispersed through the molecules of water. (**b**) The same thing happens with the water molecules. Here, red dye and yellow dye are added to the same bowl. Each substance will move (diffuse) down its own concentration gradient.

Water crosses membranes by osmosis

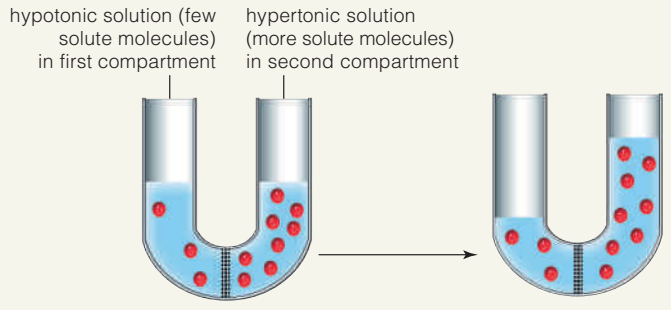
Because the plasma membrane is selectively permeable, the concentration of a solute can increase on one side of the membrane but not on the other. For example, the cytoplasm of most cells usually contains solutes (such as proteins) that cannot diffuse across the plasma membrane. When solutes become more concentrated on one side of the plasma membrane, the resulting solute concentration gradients affect how water diffuses across the membrane. **Osmosis** (oss-MOE-sis) is the name for the diffusion of water across a selectively permeable membrane in

response to solute concentration gradients. Figure 3.16 provides a simple diagram of this process.

Tonicity is the ability of a solution to draw water into or out of a cell. When solute concentrations in the fluids on either side of a cell membrane are the same, the fluids are **isotonic** (*iso-* means same) and there is no net flow of water in either direction across the membrane. When the solute concentrations are not equal, one fluid is **hypotonic**—it has fewer solutes. The other has more solutes and it is **hypertonic**. Figure 3.17 shows how the tonicity of a fluid affects red blood cells. A key point to remember is that water always tends to move from a hypotonic solution to a hypertonic one because it always moves down its concentration gradient.

If too much water enters a cell by osmosis, in theory the cell will swell up until it bursts. This is not a danger for most body cells because they can selectively move solutes out—and as solutes leave, so does water. Also, the cytoplasm exerts pressure against the plasma membrane. When this pressure counterbalances the tendency of water to follow its concentration gradient, osmosis stops.

Moment to moment, cell activities and other events change the factors that affect the solute concentrations of body fluids and water movements between them. Cells that are not equipped to adjust to such differences shrivel or burst, as Figure 3.17 illustrates. In Chapter 12 you will see how osmotic water movements help maintain the body's proper water balance.



A Initially, the volumes of the two compartments are equal, but the solute concentration across the membrane differs.

B The fluid volume rises in the second compartment as water follows its concentration gradient and diffuses into it.

Figure 3.16 Animated! The concentration of a solute affects the movement of water by osmosis.

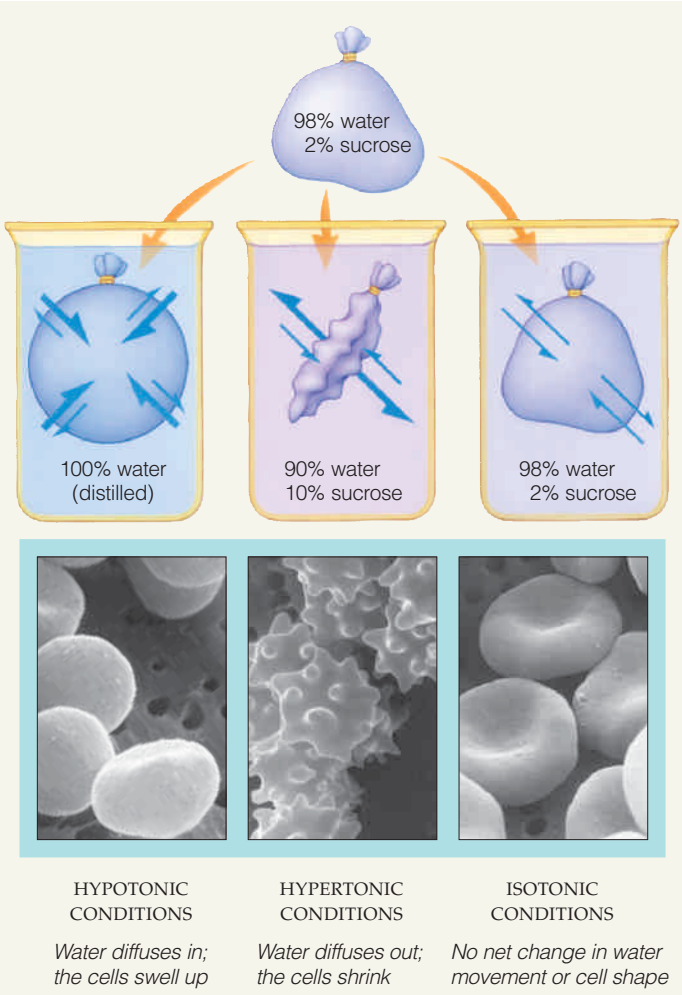


Figure 3.17 Animated! The tonicity of body fluids can have a major effect on cells. In the sketches, membrane-like bags through which water but not sucrose can move are placed in hypotonic, hypertonic, and isotonic solutions. In each container, arrow width represents the relative amount of water movement. The sketches show what happens when red blood cells—which cannot actively take in or expel water—are placed in similar solutions.

Take-Home Message

What are diffusion and osmosis?

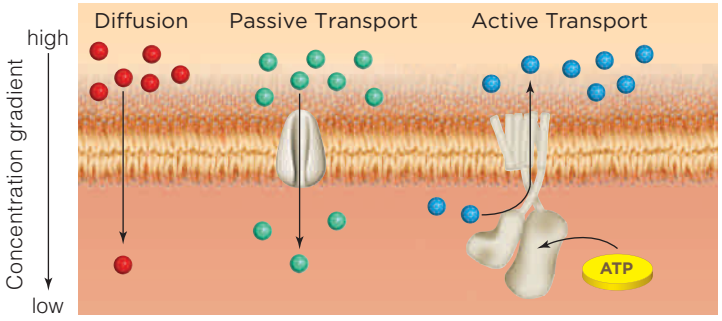
- The movement of like molecules (or ions) from a region of higher concentration to a region of lower concentration is called diffusion.
- Osmosis is the diffusion of water across a selectively permeable membrane. Most body cells have mechanisms for adjusting the movement of water and solutes into and out of the cell.

3.11 Other Ways Substances Cross Cell Membranes

- **Substances also cross cell membranes by mechanisms called facilitated diffusion, active transport, exocytosis, and endocytosis.**

Many solutes cross membranes through the inside of transport proteins

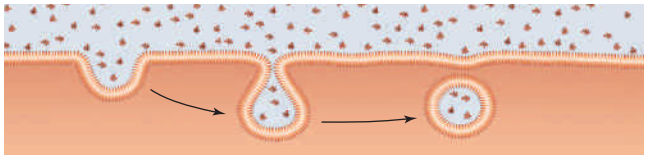
Diffusion directly through a plasma membrane is just one of three ways by which substances can move into and out of a cell (Figure 3.18). You may remember that Section 3.4 mentioned transport proteins, which span the lipid bilayer. Many of them provide a channel for ions and other solutes to diffuse across the membrane down their concentration gradients. The process does not require ATP energy, so it is a form of passive transport (Figure 3.18*b*). It is called **facilitated diffusion** because the transport proteins provide a route for the solute that is crossing the cell membrane.



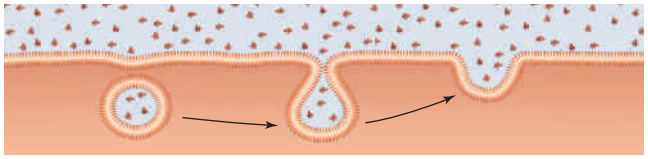
A Some substances can diffuse across lipid bilayer.

B Many water-soluble substances follow their concentration gradient through interior of passive transporters in bilayer; no energy input required.

C Active transporters bilayer pump a given solute through their interior, against its concentration gradient; energy input required.



D Endocytosis



E Exocytosis

Figure 3.18 Substances cross cell membranes in a variety of ways. Notice that diffusion and passive transport do not require the cell to invest energy.

Two features allow a transport protein to fulfill its role. First, its interior can open to both sides of a cell membrane. Second, when the protein interacts with a solute, its shape changes, then changes back again. The changes move the solute through the protein, from one side of the lipid bilayer to the other. Transport proteins are "choosy" about which solutes pass through them. For example, the protein that transports amino acids will not carry glucose.

As cells use and produce substances, the concentrations of solutes on either side of their membranes are constantly changing. A cell also must actively move certain solutes in, out, and through its cytoplasm. Action requires energy, and so cells have mechanisms called "membrane pumps" that move substances across membranes *against* concentration gradients. This pumping is called **active transport** (Figure 3.18*c*). ATP provides most of the energy for active transport, and membrane pumps can continue working until the solute is *more* concentrated on the side of the membrane where it is being pumped. This difference lays the chemical foundation for vital processes such as the contraction of your muscles.

Vesicles transport large solutes

Transport proteins can only move small molecules and ions into or out of cells. To bring in or expel larger molecules or particles, cells use vesicles that form through endocytosis and exocytosis.

In **endocytosis** ("coming inside a cell"), a cell takes in substances next to its surface. A small indentation forms at the plasma membrane, balloons inward, and pinches off. The resulting vesicle transports its contents or stores them in the cytoplasm (Figure 3.18*d*). When endocytosis brings organic matter into the cell, the process is called **phagocytosis**, or "cell eating."

In **exocytosis** ("moving out of a cell"), a vesicle moves to the cell surface and the protein-studded lipid bilayer of its membrane fuses with the plasma membrane (Figure 3.18*e*). Its contents are then released to the outside.

Take-Home Message

What are the ways substances can move across cell membranes?

- Some substances diffuse across the plasma membrane, either directly or through transport proteins (passive transport.)
- In active transport, membrane pumps move solutes against their gradient. ATP provides much of the needed energy.
- Exocytosis and endocytosis move large molecules or particles across the membrane.

3.12 When Mitochondria Fail

In the early 1960s, Swedish physician Rolf Luft was treating a young patient who felt weak and too hot all the time. Even on the coldest winter days, she couldn't stop sweating, and her skin was flushed. She was thin, yet had a huge appetite.

Luft inferred that his patient's symptoms pointed to a metabolic disorder. Her cells seemed to be spinning their wheels—they were active, but much of their activity was being lost as metabolic heat. Luft checked his patient's basal metabolic rate, the amount of energy her body was expending at rest. The tests showed that her cells were consuming oxygen at the highest rate ever recorded!

Next Luft examined a sample of the patient's muscle tissue. Cells in the sample contained too many mitochondria, the organelles that make each cell's ATP fuel. Their shape also was abnormal and too little ATP was forming inside them, even though they were working at top speed.

The disorder, now known as *Luft's syndrome*, was the first human disease to be linked directly to a defective cell organelle. A person with this disorder is like a city with half of its power plants shut down. Skeletal and heart muscles, the brain, and other hardworking body parts with the greatest energy needs are hurt the most.

Dozens of mitochondrial disorders are now known, and some run in families. One inherited mitochondrial disease, Friedrich's ataxia, causes a loss of muscle coordination (ataxia), weak muscles, and serious heart problems. Many affected people die in young adulthood.

Figure 3.19 shows a sister and brother, Leah and Joshua, who are affected by the disorder. Leah started to lose her sense of balance and coordination at age five. At the time this photograph was taken, she was in a wheelchair, partially deaf, and suffering from diabetes. Joshua lost the ability to walk when he was eleven and eventually lost his sight as well. Both he and his sister have heart problems. Special equipment allows them to attend school and work part-time, Leah as a model.

Mitochondrial diseases generally affect only a small number of people. While this is good news from one standpoint, it also means that there is little incentive for pharmaceutical companies to develop drugs that might save the lives of affected persons.

Figure 3.19 Leah and Joshua have Friedrich's ataxia. The genetic disorder prevents their mitochondria from making enough ATP for proper body functioning.

3.13 Metabolism: Doing Cellular Work

- **Cells need energy for their activities. Cell mitochondria convert the raw energy in organic compounds from food to ATP—a chemical form the cell can use.**
- **Links to Organic compounds 2.8, Energy carriers 2.13**

ATP is the cell's energy currency

The chemical reactions in cells are called **metabolism**. Some reactions release energy and others require it. ATP links the two kinds of reactions, carrying energy from one reaction to another. You may remember that ATP is short for adenosine triphosphate, one of the nucleotides. A molecule of ATP consists of the five-carbon sugar ribose to which adenine (a nucleotide base) and three phosphate groups are attached (Figure 3.20*a*). ATP's stored energy is contained in the bond between the second and third phosphate groups.

Enzymes can break the bond between the second and third phosphate groups of the ATP molecule. The enzymes then can attach the released phosphate group to another molecule. When a phosphate group is moved from one molecule to another, stored energy goes with it.

Cells use ATP constantly, so they must renew their ATP supply. In many metabolic processes, phosphate (symbolized by P_i) or a phosphate group that has been split off from some substance, is attached to ADP, adenosine diphosphate (the prefix *di-* indicates that *two* phosphate groups are present). Now the molecule, with three phosphates, is ATP. And when ATP transfers a phosphate group elsewhere, it reverts to ADP. In this way it completes the **ATP/ADP cycle** (Figure 3.20*b*).

Like money earned at a job and then spent to pay your expenses, ATP is earned in reactions that produce energy and spent in reactions that require it. That is why textbooks often use a cartoon coin to symbolize ATP.

There are two main types of metabolic pathways

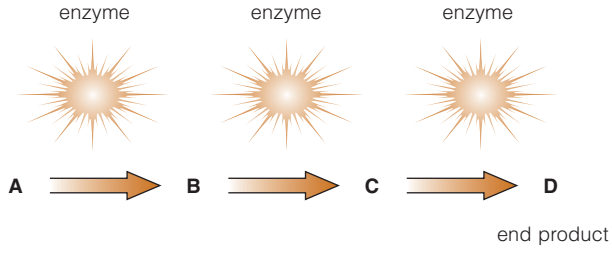
At this moment thousands of reactions are transforming thousands of substances inside each of your cells. Most of these reactions are part of **metabolic pathways**, steps in which reactions take place one after another. There are two main types of metabolic pathways, called anabolism and catabolism.

In **anabolism**, small molecules are put together into larger ones. In these larger molecules, the chemical bonds hold more energy. Anabolic pathways assemble complex carbohydrates, proteins, and other large molecules. The energy stored in their bonds is a major reason why we can use these substances as food.

In **catabolism**, large molecules are broken down to simpler ones. Catabolic reactions disassemble complex carbohydrates, proteins, and similar molecules, releasing their components for use by cells. For example, when a complex carbohydrate is catabolized, the reactions release the simple sugar glucose, the main fuel for cells.

Any substance that is part of a metabolic reaction is called a *reactant*. A substance that forms between the beginning and the end of a metabolic pathway is an *intermediate*. Substances present at the end of a reaction or a pathway are the *end products*.

Many metabolic pathways advance step-by-step from reactants to end products:



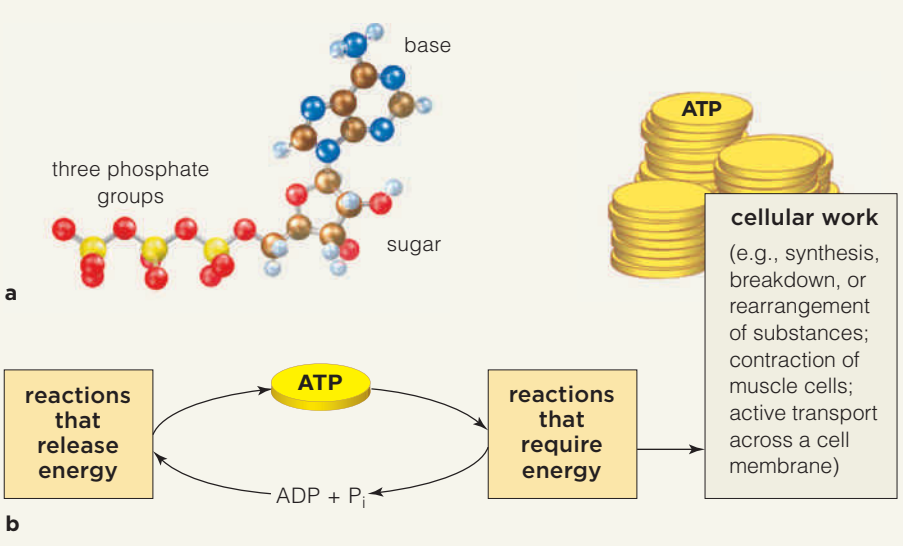
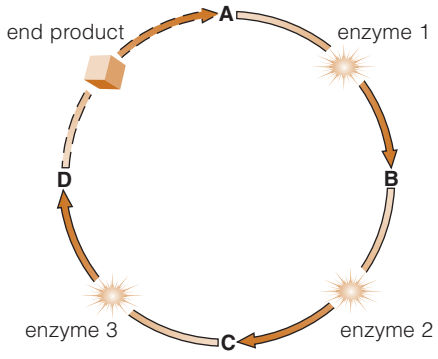


Figure 3.20 Animated! ATP provides energy for cell activities. (**a**) Structure of ATP. (**b**) ATP connects energy-releasing reactions with energy-requiring ones. In the ATP/ADP cycle, the transfer of a phosphate group turns ATP into ADP, then back again to ATP.

In other pathways the steps occur in a cycle, with the end products serving as reactants to start things over.



Enzymes play a vital role in metabolism

The metabolic reactions that keep all of us alive require **enzymes**, which you first read about in Section 2.8. Most enzymes are proteins, and they have several key features. Most importantly enzymes are catalysts: They speed up chemical reactions. In fact, enzymes usually make reactions occur hundreds to millions of times faster than would be possible otherwise. Enzymes are not used up in reactions, so a given enzyme molecule can be used over and over.

Each kind of enzyme can only interact with specific kinds of molecules, which are called its **substrates**. The enzyme can chemically recognize a substrate, bind it, and change it in some way. An example is thrombin, one of the enzymes required to clot blood. It only recognizes a side-by-side alignment of two particular amino acids in a protein. When thrombin "sees" this arrangement, it breaks the peptide bond between the amino acids.

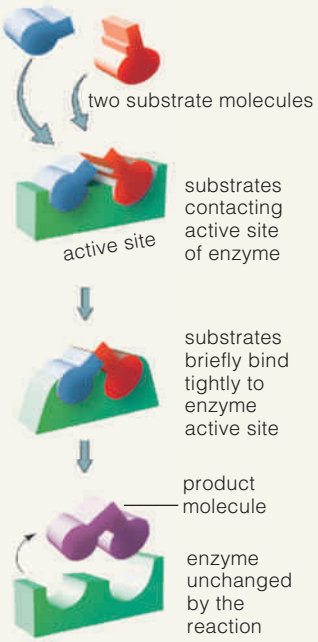


Figure 3.21 Animated! Enzymes and substrates fit together physically. When substrate molecules contact an enzyme's active site, they bind to the site for a brief time and a product molecule forms. When the product molecule is released, the enzyme goes back to its previous shape. It is not changed by the reaction it catalyzed.

All body actvities require enzymes.

An enzyme and its substrate interact at a surface crevice on the enzyme. This area is called an **active site**. Figure 3.21 shows how enzyme action can combine two substrate molecules into a new, larger product molecule.

Powerful as they are, enzymes only work well within a certain temperature range. For example, if a person's body temperature rises too high, the increased heat energy breaks bonds holding an enzyme in its three-dimensional shape. The shape changes, substrates can't bind to the active site as usual, and chemical reactions are disrupted. People usually die if their internal temperature reaches 44°C (112°F).

Enzymes also function best within a certain pH range—in the body, from pH 7.35 to 7.4. Above or below this range most enzymes cannot operate normally.

Organic molecules called **coenzymes** assist with many reactions. Lots of coenzymes, including **NAD^+** (nicotinamide adenine dinucleotide) and **FAD** (flavin adenine dinucleotide), are derived from vitamins, which is one reason why vitamins are important in the diet.

To maintain homeostasis, the body controls the activity of enzymes

Different types of controls boost or slow the action of enzymes. Others adjust how fast new enzyme molecules are made, and thus how many are available for a given metabolic pathway. For example, when you eat, food arriving in your stomach causes gland cells there to secrete the hormone gastrin into your bloodstream. Stomach cells with receptors for gastrin respond in a variety of ways, such as secreting the ingredients of "gastric juice"—including enzymes that break down food proteins.

Take-Home Message

How do chemical reactions take place in cells?

- Most chemical reactions in cells are organized in the orderly steps of metabolic pathways.
- Enzymes speed the rate of chemical reactions.
- Each enzyme acts only on specific substrates. Enzymes function best within certain ranges of temperature and pH.

3.14 How Cells Make ATP

- **The chemical reactions that sustain the body depend on energy that cells capture when they produce ATP.**
- **Link to Carbohydrates 2.9**

Cellular respiration makes ATP

To make ATP, cells break apart carbohydrates, especially glucose, as well as lipids and proteins. The reactions remove electrons from intermediate compounds, then energy associated with the electrons powers the formation of ATP. Human cells typically form ATP by **cellular respiration**. In large, complex organisms like ourselves, this process usually is aerobic, which means that it uses oxygen. Glucose is the most common raw material for cellular respiration, so it will be our example here.

Step 1: Glycolysis breaks glucose down to pyruvate

Cellular respiration starts in the cell's cytoplasm, in a set of reactions called **glycolysis**—literally, "splitting sugar." You may recall that glucose is a simple sugar. Each glucose molecule consists of six carbon atoms, twelve hydrogens, and six oxygens, all joined by covalent bonds. During glycolysis, a glucose molecule is broken into two **pyruvate** molecules, each with three carbons (Figure 3.22).

When glycolysis begins, two ATPs each transfer a phosphate group to glucose, donating energy to it. This kind of transfer is called **phosphorylation**. It adds enough energy to glucose to begin the energy-releasing steps of glycolysis.

The first energy-releasing step breaks the glucose into two molecules of **PGAL** (for phosphoglyceraldehyde), which are converted to intermediates. These molecules then each donate a phosphate group to ADP, forming ATP. The same thing happens with the next intermediate in the sequence, and the end result is two molecules of pyruvate and four ATP. However, because two ATP were invested to start the reactions, the *net* energy yield is only two ATP.

Notice that glycolysis does not use oxygen. If oxygen is not available for the following aerobic steps of cellular respiration, for a short time a cell can still form a small amount of ATP by a process of fermentation, which also does not use oxygen. You will read more about this "back-up" process for forming ATP later in the chapter.

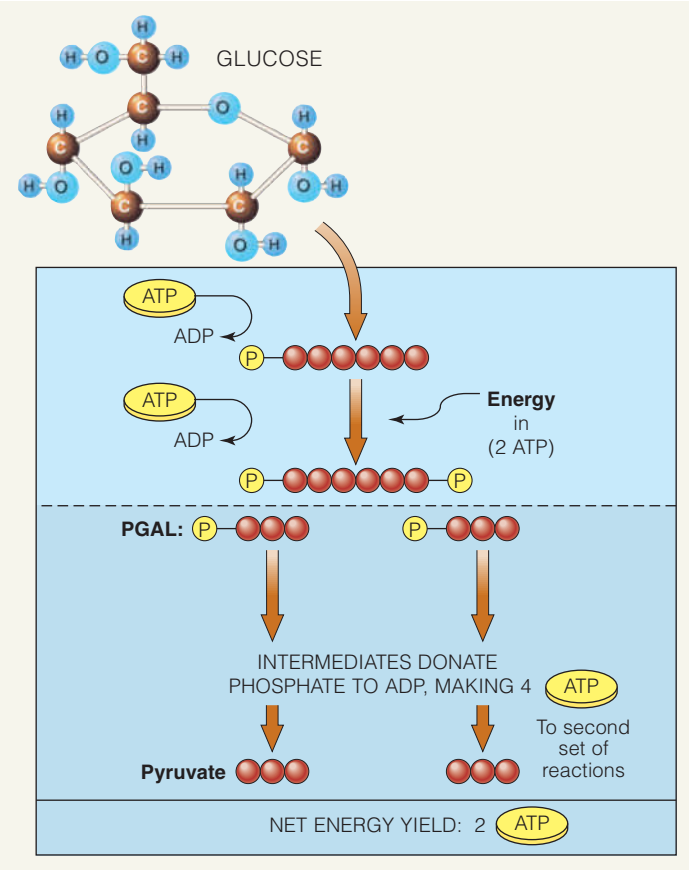


Figure 3.22 Animated! Glycolysis splits glucose molecules and forms a small amount of ATP.

Step 2: The Krebs cycle produces energy-rich transport molecules

The pyruvate molecules formed by glycolysis move into a mitochondrion. There the oxygen-requiring phase of cellular respiration will be completed. Enzymes catalyze each reaction, and the intermediate molecules formed at one step become substrates for the next.

In preparatory steps, an enzyme removes a carbon atom from each pyruvate molecule. A coenzyme called coenzyme A combines with the remaining two-carbon fragment and becomes a compound called **acetyl-CoA**. This substance enters the **Krebs cycle**. For each turn of the cycle, six carbons, three from each pyruvate, enter and six also leave, in the form of carbon dioxide. The bloodstream then transports this CO_2 to the lungs where it is exhaled.

Reactions in mitochondria before and during the Krebs cycle have three important functions. First, they produce two molecules of ATP. Second, they regenerate intermediate compounds required to keep the Krebs cycle going. And in a third, crucial step, a large number of the coenzymes called NAD^+ and FAD pick up H^+ and electrons, in the process becoming NADH and $FADH_2$. Loaded with energy, NADH and $FADH_2$ will now move to the site of the third and final stage of reactions that make ATP.

Step 3: Electron transport produces many ATP molecules

ATP production goes into high gear during the final stage of cellular respiration. In the production "assembly line," chains of reactions capture and use energy released by electrons. Each chain is called an **electron transport system**. It includes enzymes inside the membrane that divide the mitochondrion into two compartments (Figure 3.23). As electrons flow through the system, each step transfers a bit of energy to a molecule that briefly stores it. This gradual releasing of energy reduces the amount of energy that is lost (as heat) while a cell is generating ATP.

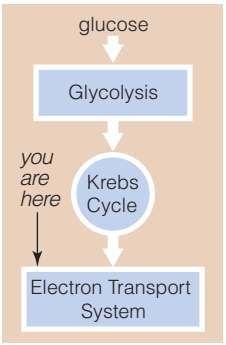
As you can see at the bottom left of Figure 3.23, an electron transport system uses electrons and hydrogen ions delivered by NADH and $FADH_2$. The electrons are transferred from one molecule of the transport system to the next in line. The yellow "bouncing" line in Figure 3.23 represents this process. When molecules in the chain accept and then donate electrons, they also pick up hydrogen ions in the inner compartment, then release them to the outer compartment. At the end of an electron transport system, oxygen accepts electrons in a reaction that forms water (H_2O).

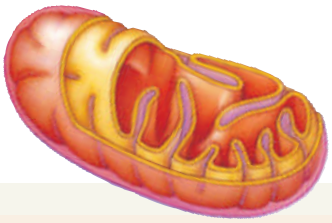
As the system moves hydrogen ions into the outer compartment, an H^+ concentration gradient develops. As the ions become more concentrated in the outer compartment, they follow the gradient back into the inner compartment, crossing the inner membrane through the interior of enzymes that can catalyze the formation of ATP from ADP and phosphate (P_i). This step is shown at the far right of Figure 3.23.

Take-Home Message

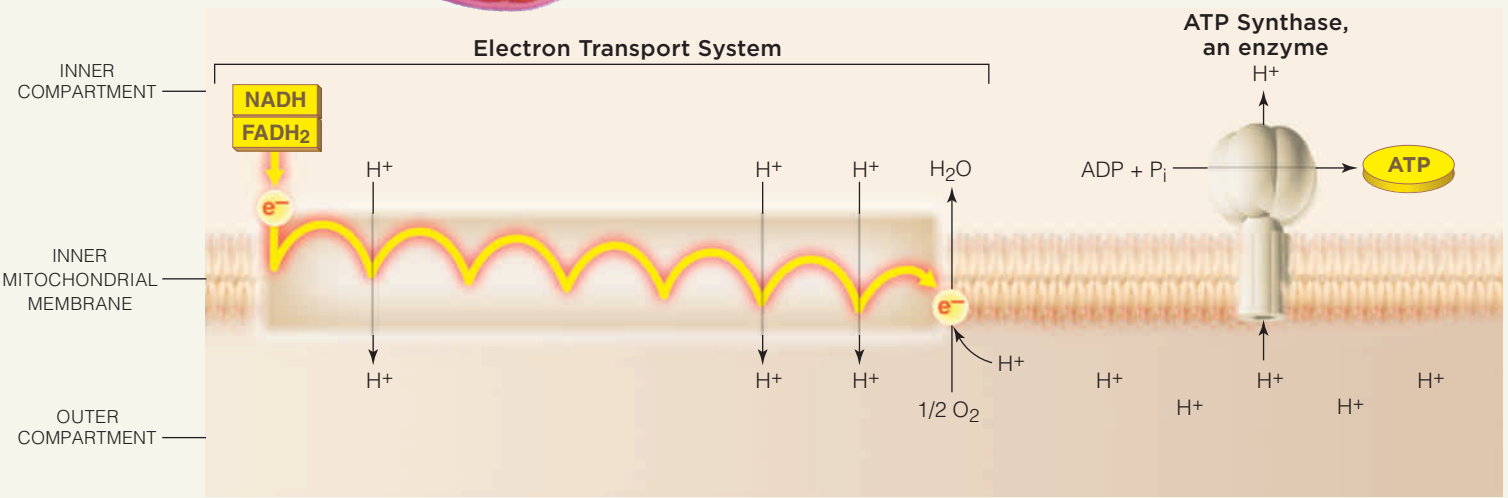
How do cells form large amounts of ATP?

- First, in glycolysis, a carbohydrate such as glucose is broken down to two molecules of pyruvate. Overall, glycolysis yields two ATPs.
- Next, the two pyruvates from glycolysis enter a mitochondrion. Each gives up a carbon atom and the rest of the molecule enters the Krebs cycle. The carbon atoms end up in carbon dioxide. The Krebs cycle and its preparatory steps yield two more ATP molecules.
- Last, electrons and H^+ move through transport systems inside mitochondria. ATP forms when hydrogen ions flow through membrane enzymes that add a phosphate group to ADP.





e^- = electron
H^+ = hydrogen ion
P_i = phosphate



A Electrons from NADH and $FADH_2$ pass through electron transport chains in the inner mitochondrial membrane. An H^+ gradient forms as the electron flow drives the transfer of H^+ from the inner to the outer compartment.

B Oxygen is the final acceptor of electrons at the end of the transport chains.

C H^+ follows its gradient and flows back to the inner compartment through enzymes. The flow drives formation of ATP from ADP and phosphate (P_i).

Figure 3.23 **Animated!** **Electron transport forms ATP.**

3.15 Summary of Cellular Respiration

Figure 3.24 reviews the steps and ATP yield from cellular respiration. Only this aerobic pathway delivers enough energy to build and maintain a large, active, multicellular organism such as a human. In many types of cells, the third stage of reactions forms thirty-two ATP. When we add these to the final yield from the preceding stages, the total harvest is thirty-six ATP from one glucose molecule. This is a very efficient use of our cellular resources!

While aerobic cellular respiration typically yields thirty-six ATP, the actual amount may vary, depending on conditions in a cell at a given moment—for instance, if a cell requires a particular intermediate elsewhere and pulls it out of the reaction sequence. To learn more about this topic, see Appendix I at the back of this book.

Take-Home Message

What are the overall steps of aerobic cellular respiration?

- Cellular respiration begins with glycolysis in the cytoplasm and ends with electron transport systems in mitochondria. From start to finish this aerobic process typically nets thirty-six ATP for every glucose molecule.

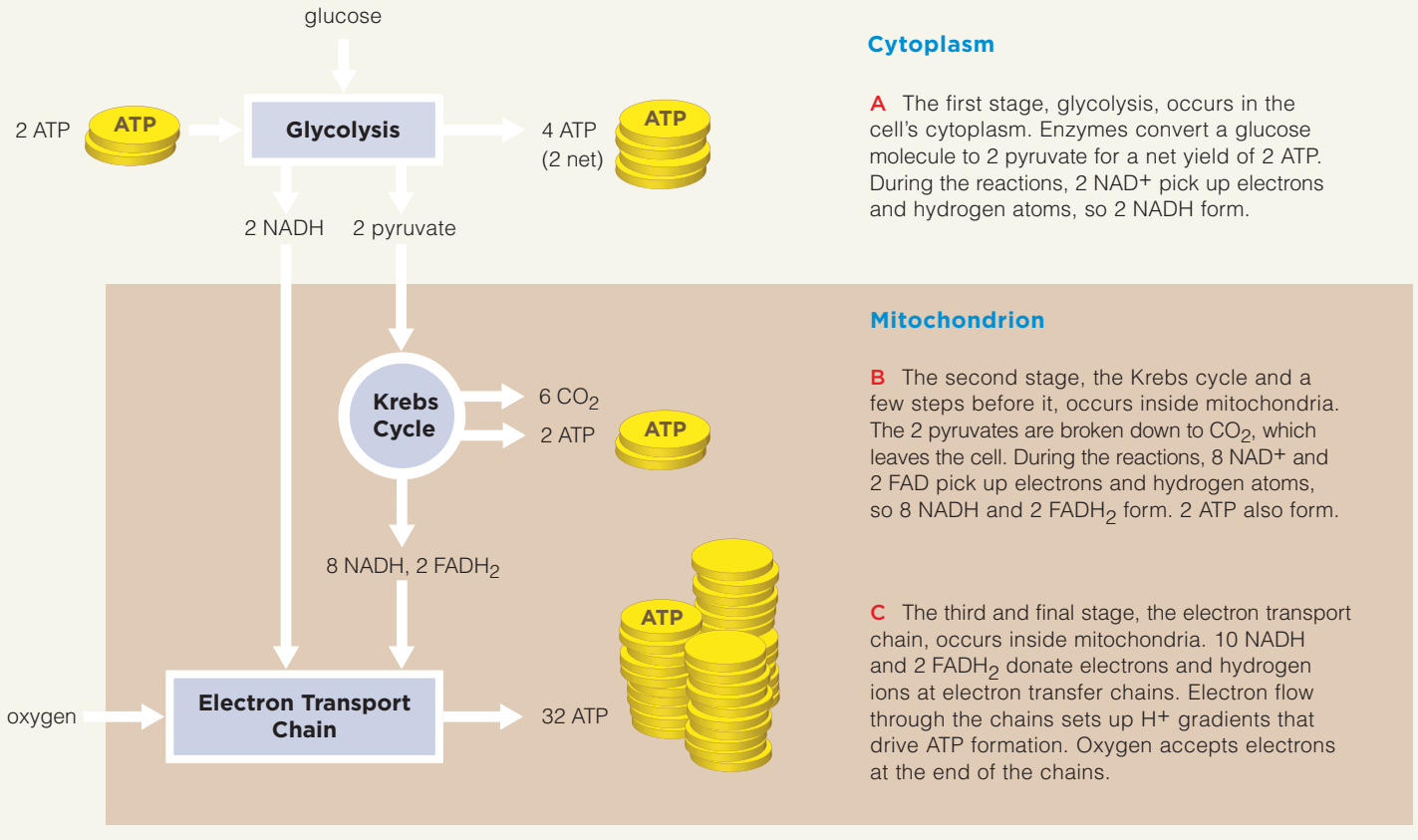


Figure 3.24 Animated! **This diagram summarizes aerobic cellular respiration.**

3.16 Alternative Energy Sources in the Body

- **Carbohydrates, fats, and proteins all can supply needed fuel for making ATP.**

Glucose from carbohydrates is the body's main energy source

When glucose from food moves into your bloodstream, a rise in the glucose level in blood prompts an organ, the pancreas, to release insulin. This hormone makes cells take up glucose faster.

If you consume more glucose than your cells need for the moment, one of the intermediates of glycolysis is diverted into an anabolic pathway that makes a storage sugar called glycogen. The detour halts glycolysis, so for the time being no more ATP forms. This switch occurs quite often in muscle and liver cells, which store most of the body's glycogen. Other kinds of cells tend to store excess glucose as fat.

Sudden, intense exercise, such as weightlifting or a sprint, may call on cells in skeletal muscles (which attach to our bones) that use a different kind of ATP-forming mechanism, a process called *lactate fermentation* (Figure 3.25). The process converts pyruvate from glycolysis to lactic acid. It does not use oxygen and produces ATP quickly but not for very long. Muscles feel sore when lactic acid builds up in them.

Between meals, glucose is not moving into your bloodstream and its level in the blood falls. The decline must be offset because nerve cells in the brain use glucose as their preferred energy source. Accordingly, the pancreas responds to falling blood glucose by secreting a hormone that makes liver cells convert glycogen back to glucose and release it to the blood. Thus, hormones control whether the body's cells use glucose as an energy source or store it for future use.

Only about 1 percent of the body's total energy reserves consists of glycogen, however. Of the total energy stores in a typical adult American, 78 percent is in body fat and 21 percent in proteins.

Figure 3.25 **Sprinters rely on muscle cells that make ATP by lactate fermentation.**

Fats and proteins also provide energy

Most of the body's stored fat consists of triglycerides, which accumulate inside the fat cells in certain tissues (called *adipose* tissues) of the buttocks and other locations beneath the skin.

Between meals or during exercise, the body may tap triglycerides as energy alternatives to glucose. Enzymes in fat cells break apart triglycerides into glycerol and fatty acids, which enter the bloodstream. When glycerol reaches the liver, enzymes convert it to PGAL, the intermediate of glycolysis mentioned in Section 3.14. Most body cells take up the circulating fatty acids. Enzymes convert them to acetyl-CoA, which can enter the Krebs cycle. Each fatty acid tail has many more carbon-bound hydrogen atoms than glucose does, so breaking down a fatty acid yields much more ATP. In fact, this pathway can supply about half the ATP required by your muscle, liver, and kidney cells.

The body stores excess fats but not proteins. Enzymes dismantle unneeded proteins into amino acids. Then they remove the molecule's amino group ($—NH_3^+$) and ammonia (NH_3) forms. The cell's metabolic machinery may use leftover carbons to make fats or carbohydrates. Or the carbons may enter the Krebs cycle, where coenzymes can pick up hydrogen as well as electrons removed from the carbon atoms. These can be used to make ATP in electron transport systems in mitochondria. The ammonia is converted to urea, a waste that is excreted in urine.

Take-Home Message

What types of substances can provide energy for body cells?

- Complex carbohydrates, fats, and proteins all can serve as energy sources in the human body.
- Certain muscle cells can make a small amount of ATP by the process of lactate fermentation.

IMPACTS, ISSUES

Alcohol and Liver Cells

TOO few donor livers are available to meet the needs of all the patients awaiting a liver transplant. This group includes people who have damaged their livers by excess alcohol use.

How Would You Vote?

Should the lifestyle of someone with severe liver disease be a factor in determining whether that individual is eligible to receive a liver transplant? See CengageNOW for details, then vote online.

Summary

Sections 3.1, 3.2 A living cell has a plasma membrane surrounding an inner region of cytoplasm. In a eukaryotic cell, including human cells, membranes divide the cell into functional compartments called organelles. Organelle membranes separate metabolic reactions in the cytoplasm.

- Use the animation and interaction on CengageNOW to investigate the physical limits on cell size and learn how different types of microscopes function.

Section 3.4 Cell membranes consist mostly of phospholipids and proteins. The phospholipids form a lipid bilayer. Various kinds of proteins in or attached to the membrane perform most of its functions.

Some membrane proteins are transport proteins. Others are receptors. Still others have carbohydrate chains that serve as a cell's identity tags. Adhesion proteins help cells stay together in tissues.

- Use the animation and interaction on CengageNOW to learn more about the functions of receptor proteins.

Section 3.6 The largest organelle is the nucleus, where the genetic material DNA is located. The nucleus is surrounded by a double membrane, the nuclear envelope. Pores in the envelope help control the movement of substances into and out of the nucleus.

A cell's DNA and proteins associated with it are called chromatin. Each chromosome in the nucleus is one DNA molecule with its associated proteins.

- Use the animation and interaction on CengageNOW to introduce yourself to the major types of organelles and take a close-up look at the nuclear membrane.

Section 3.7 The endomembrane system includes the endoplasmic reticulum (ER), Golgi bodies, and various vesicles. In this system new proteins are modified into final form and lipids are assembled. Unwanted materials may be broken down in lysosomes and peroxisomes.

- Use the animation and interaction on CengageNOW to follow a path through the endomembrane system.

Section 3.8 Mitochondria carry out the oxygen-requiring reactions that make ATP, the cell's energy currency. These reactions occur in the inner compartment of a mitochondrion.

Section 3.9 The cytoskeleton gives a cell its shape and internal structure. It consists mainly of microtubules and microfilaments; some types of cells also have intermediate filaments. Microtubules are the framework for cilia or flagella, which develop from centrioles and are used in movement.

- Use the animation and interaction on CengageNOW to learn more about elements of the cytoskeleton and what they do.

Section 3.10 A cell's plasma membrane is selectively permeable—only certain substances may cross it, by way of several transport mechanisms. In diffusion, substances move down their concentration gradient. Osmosis is the diffusion of water across a selectively permeable membrane in response to a concentration gradient, a pressure gradient, or both.

- Use the animation and interaction on CengageNOW to investigate how substances diffuse across membranes and how water crosses by osmosis.

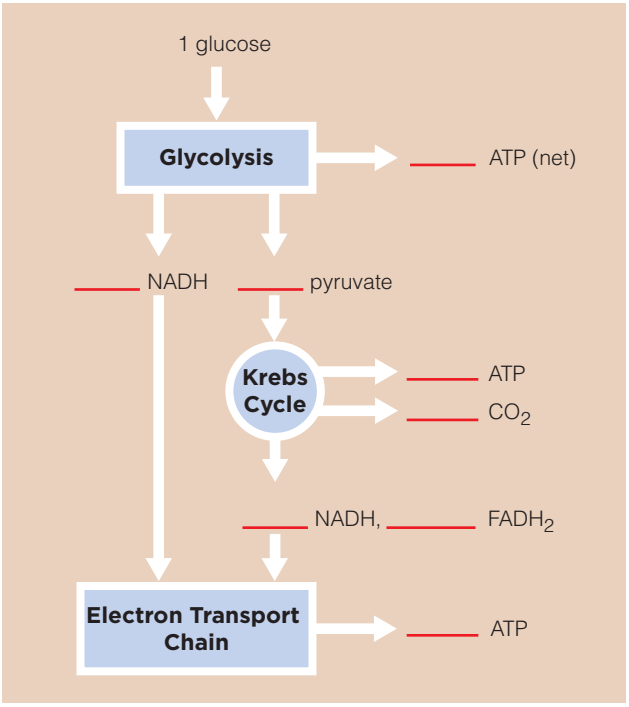
Section 3.11 In passive transport, a solute moves down its concentration gradient through a membrane transport protein. In active transport, a solute is pumped through a membrane protein *against* its concentration gradient. Active transport requires an energy boost, as from ATP.

Cells use vesicles to take in or expel large molecules or particles. In exocytosis, a vesicle moves to the cell surface and fuses with the plasma membrane. In endocytosis, a vesicle forms at the surface and moves inward. In phagocytosis, an endocytic vesicle brings organic matter into a cell.

- Use the animation and interaction on CengageNOW to compare passive and active transport, and see how vesicles move substances into and out of cells.

Section 3.13 The chemical reactions in a cell are collectively called its metabolism. A metabolic pathway is a stepwise sequence of chemical reactions catalyzed by enzymes—catalytic molecules that speed up the rate of metabolic reactions. Each enzyme interacts only with a specific substrate, linking with it at one or more active sites.

Anabolism builds large, energy-rich organic compounds from smaller molecules. Catabolism breaks down molecules to smaller ones. Cofactors such as the coenzymes



Summary of Energy Sources in the Human Body

Starting Molecule	Subunit	Entry Point into the Aerobic Pathway
Complex carbohydrate	Simple sugars (e.g., glucose)	Glycolysis
Fat	Fatty acids	Preparatory reactions for Krebs cycle
	Glycerol	Raw material for key intermediate in glycolysis (PGAL)
Protein	Amino acids	Carbon backbones enter Krebs cycle or preparatory reactions

NAD^+ and FAD assist enzymes or carry electrons, hydrogen, or functional groups from a substrate to other sites.

- Use the animation and interaction on CengageNOW to investigate how enzymes facilitate chemical reactions.

Section 3.14 Most anabolic reactions run on energy from ATP. In human cells, aerobic respiration produces most ATP molecules. This pathway releases chemical energy from glucose and other organic compounds. ATP is replenished by way of the ATP/ADP cycle.

Section 3.15 In aerobic cellular respiration, oxygen is the final acceptor of electrons removed from glucose. The pathway has three stages: glycolysis (in the cytoplasm), the Krebs cycle, and electron transport, which generates a large amount of ATP in mitochondria. The typical net energy yield of cellular respiration is thirty-six ATP.

- Use the animation and interaction on CengageNOW to take a step-by-step journey through glycolysis and cellular respiration.

Section 3.16 The body can extract energy from carbohydrates, fats, and proteins. Complex carbohydrates are broken down to the simple sugar glucose, the body's main metabolic fuel. Alternatives to glucose include fatty acids and glycerol from triglycerides and, in certain circumstances, amino acids from proteins (Table 3.4).

- Use the animation and interaction on CengageNOW to learn more about how cells can use different kinds of organic molecules as energy sources.

Review Questions

1. Describe the general functions of the following in a eukaryotic cell: the plasma membrane, cytoplasm, DNA, ribosomes, organelles, and cytoskeleton.
2. Which organelles are part of the cytomembrane system?
3. Distinguish between the following pairs of terms:
   a. diffusion; osmosis
   b. passive transport; active transport
   c. endocytosis; exocytosis
4. What is an enzyme? Describe the role of enzymes in metabolic reactions.
5. In aerobic cellular respiration, which reactions occur only in the cytoplasm? Which ones occur only in a cell's mitochondria?
6. For the diagram of the aerobic pathway shown above, fill in the number of molecules of pyruvate and the net ATP formed at each stage.

Self-Quiz *Answers in Appendix V*

1. The plasma membrane _____.
   a. surrounds the cytoplasm
   b. separates the nucleus from the cytoplasm
   c. separates the cell interior from the environment
   d. both a and c are correct
2. The _____ is responsible for a eukaryotic cell's shape, internal organization, and cell movement.
3. Cell membranes consist mainly of a _____.
   a. carbohydrate bilayer and proteins
   b. protein bilayer and phospholipids
   c. phospholipid bilayer and proteins
4. _____ carry out most membrane functions.
   a. Proteins
   b. Phospholipids
   c. Nucleic acids
   d. Hormones

5. The passive movement of a solute through a membrane protein down its concentration gradient is an example of _____.
   a. osmosis
   b. active transport
   c. endocytosis
   d. diffusion

6. Match each organelle with its correct function.
   ____ protein synthesis — a. mitochondrion
   ____ movement — b. ribosome
   ____ intracellular digestion — c. smooth ER
   ____ modification of proteins — d. rough ER
   ____ lipid synthesis — e. nucleolus
   ____ ATP formation — f. lysosome
   ____ ribosome assembly — g. flagellum

7. Which of the following statements is *not* true? Metabolic pathways _____.
   a. occur in stepwise series of chemical reactions
   b. are speeded up by enzymes
   c. may break down or assemble molecules
   d. always produce energy (such as ATP)

8. Enzymes _____.
   a. enhance reaction rates
   b. are affected by pH
   c. act on specific substrates
   d. all of the above are correct

9. Match each substance with its correct description.
   ____ a coenzyme or metal ion — a. reactant
   ____ formed at end of a metabolic pathway — b. enzyme
   ____ mainly ATP — c. cofactor
   ____ enters a reaction — d. energy carrier
   ____ catalytic protein — e. end product

10. Cellular respiration is completed in the _____.
    a. nucleus
    b. mitochondrion
    c. plasma membrane
    d. cytoplasm

11. Match each type of metabolic reaction with its function:
    ____ glycolysis — a. many ATP, NADH, $FADH_2$, and CO_2 form
    ____ Krebs cycle — b. glucose to two pyruvate molecules and some ATP
    ____ electron transport — c. H^+ flows through channel proteins, ATP forms

12. In a mitochondrion, where are the electron transport systems and enzymes required for ATP formation located?

Critical Thinking

1. Using Section 3.2 as a reference, suppose you want to observe the surface of a microscopic section of bone. Would you benefit most from using a compound light microscope, a transmission electron microscope, or a scanning electron microscope?
2. Jogging is considered aerobic exercise because the cardiovascular system (heart and blood vessels) can adjust to supply the oxygen needs of working cells. In contrast, sprinting the 100-meter dash might be called "anaerobic" (lacking oxygen) exercise, and golf "nonaerobic" exercise. Explain these last two observations.
3. The cells of your body never use nucleic acids as an energy source. Can you suggest a reason why?

EXPLORE ON YOUR OWN

In this chapter you learned that an enzyme can only act on certain substrates. Because your saliva contains enzymes that can use some substances as substrates but not others, you can easily gain some insight into practical impacts of this concept (Figure 3.26). Start by holding a bite of plain cracker in your mouth for thirty seconds, without chewing it. What happens to the cracker, which is mostly starch (carbohydrate)? Repeat the test with a dab of butter or margarine (lipid), then with a piece of meat, fish, or even scrambled egg (protein). Based on your results, what type of biological molecules do your salivary enzymes act upon?

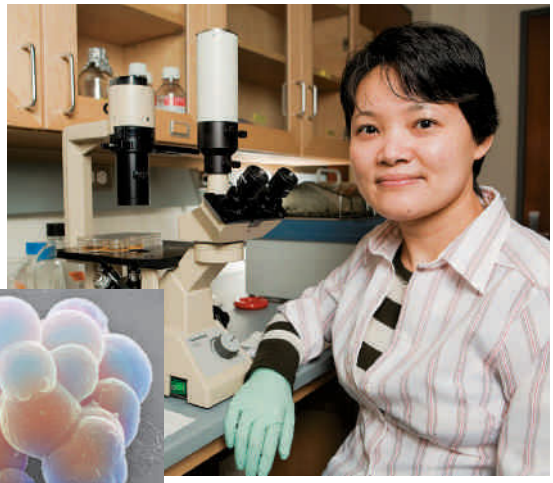
Figure 3.26 **Enzymes digest the different kinds of biological molecules in foods.**

Tissues, Organs, and Organ Systems 4

IMPACTS, ISSUES

A Stem Cell Future?

EACH year tens of thousands of people develop a disease or suffer an injury that severely damages an organ or tissues. If only it were possible to grow new body parts! Actually, that is the dream of those who study stem cells, like Junying Yu, the cell researcher pictured below.



Above: Researcher Junying Yu
Left: Embryonic stem cells

All cells in your body "stem" from **stem cells**, which are the first to form when a fertilized egg starts dividing. Accordingly, embryonic stem cells can give rise to a range of different cell types, including blood cells, cartilage, muscle, and nerve cells. Adult stem cells in your body are more limited, although certain ones regularly produce new skin and blood cells.

You have probably heard about the controversy surrounding embryonic stem cells. Because in theory, they can produce every kind of cell in the body, many scientists feel they may be well-suited for therapies that can replace damaged tissues and organs. Other people believe it is unethical to use embryonic cells for any reason, because doing so destroys or may seriously harm the embryo.

Stem cells from adults are less controversial. They have shown quite a bit of promise for regenerating some kinds of tissues, such as missing cartilage and heart muscle damaged by a heart attack. In 2007 researchers in the United States and Japan reported major progress in "reprogramming" adult stem cells to be as versatile as embryonic ones. We will look more fully at some stem cell successes later in this chapter.

The topic of stem cells is a fitting introduction to anatomy—the body's parts and how they are put together. A **tissue** is a group of similar cells that perform a certain function. Combinations of tissues form **organs**, such as the heart. Two or more organs that work together in a common task form an **organ system**. This chapter begins our study of both human anatomy and physiology—how tissues, organs, and organ systems function.

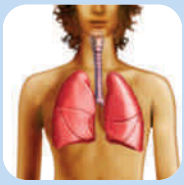
KEY CONCEPTS

Types of Body Tissues

Four types of tissues occur in the body. These are epithelial tissues, connective tissue, muscle tissue, and nervous tissue. Sections 4.1–4.7

Organs and Organ Systems

Combinations of tissues form organs, the components of the body's organ systems. The skin is an example of an organ system. Sections 4.8, 4.9



Homeostasis

Mechanisms of negative and positive feedback work to maintain homeostasis—stable operating conditions—in the body. Sections 4.10, 4.11

LINKS TO EARLIER CONCEPTS

- This chapter is an introduction to the tissue, organ, and organ system levels of biological organization (1.3).
- As you learn about different types of body tissues, you will also get a look at some of the many variations on basic cell structure (3.1–3.9) that occur in your body. The variations are a reminder that cells that perform different functions must be built to carry out those specialized tasks.

How Would You Vote?

Human embryonic stem cells have potential medical benefits, but some people object to their use. Should scientists be allowed to destroy embryos created in fertility clinics and donated by their parents as a source of cells for research? See CengageNOW for details, then vote online.

4.1 Epithelium: The Body's Covering and Linings

- **Epithelial tissues cover the body surface or line its cavities and tubes.**
- **Link to the Cell cytoskeleton 3.9**

The first type of tissue we consider, **epithelium** (plural: epithelia), is a sheetlike tissue with one surface that faces the outside environment or an internal body fluid (Figure 4.1*a*). The other surface rests on a **basement membrane** that is sandwiched between it and the tissue below (Figure 4.1*a*). A basement membrane has no cells but is packed with proteins and polysaccharides.

Various types of junctions hold the cells in epithelium close together. In some epithelia, cells are specialized to absorb or secrete substances.

There are two basic types of epithelia

Epithelium may be "simple," with just one layer of cells, or it may be "stratified" and have several layers. Simple epithelium lines the body's cavities, ducts, and tubes—for example, the chest cavity, tear ducts, and the tubes in the kidneys where urine is formed (Figure 4.1*b*–*d*). In general, the cells in a simple epithelium function in the diffusion, secretion, absorption, or filtering of substances across the layer.

Some single-layer epithelia look stratified in a side view because the nuclei of neighboring cells don't line up. Most of the cells also have cilia. This type of simple epithelium is termed *pseudostratified* (*pseudo-* means false). It lines the throat, nasal passages, reproductive tract, and other sites in the body where cilia sweep mucus or some other fluid across the surface of the tissue.

Stratified epithelium has two or more layers of cells, and its typical function is protection. For example, this is the tissue at the surface of your skin, which is exposed to nicks, bumps, scrapes, and so forth.

The two basic types of epithelium are subdivided into categories depending on the shape of cells at the tissue's free surface (Table 4.1). A *squamous epithelium* has flattened cells, a *cuboidal epithelium* has cube-shaped cells, and a *columnar epithelium* has tall, elongated cells. Each shape correlates with a given function. For instance, oxygen and carbon dioxide easily diffuse across the thin simple squamous epithelium that makes up the walls of fine blood vessels, as in Figure 4.1*b*. The plumper cells of cuboidal and columnar epithelia secrete substances.

Major Types of Epithelium

Type	Shape	Typical Locations
Simple (one layer)	Squamous	Linings of blood vessels, lung alveoli (air sacs)
	Cuboidal	Glands and their ducts, surface of ovaries, pigmented epithelium of eye
	Columnar	Stomach, intestines, uterus
Pseudostratified	Columnar	Throat, nasal passages, sinuses, trachea, male genital ducts
Stratified (two or more layers)	Squamous	Skin, mouth, throat, esophagus, vagina
	Cuboidal	Ducts of sweat glands
	Columnar	Male urethra, ducts of salivary glands

Glands develop from epithelium

A **gland** makes and releases specific products, such as saliva or mucus. Some glands consist of a single cell, while others are more complex. All glands develop from epithelial tissue and often stay connected to it. Mucus-secreting goblet cells, for instance, are embedded in epithelium that lines the trachea (your windpipe) and other tubes leading to the lungs. The stomach's epithelial lining contains gland cells that release protective mucus and digestive juices.

Glands may be classified by how their products reach the place where they are used. **Exocrine glands** release substances through ducts or tubes. Mucus, saliva, earwax, oil, milk, and digestive enzymes are all in this group. Many exocrine glands simply release the substance they make; salivary glands and most sweat glands are like this. In other cases, a gland's secretions include bits of the gland cells. For instance, milk from a nursing mother's mammary glands contains bits of the glandular epithelial tissue. In still other cases, such as sebaceous (oil) glands in your skin, whole cells full of material are shed into the duct, where they burst and their contents spill out.

Endocrine glands do not release substances through tubes or ducts. They make hormones that directly enter the extracellular fluid bathing the glands.

Take-Home Message

What is epithelium?

- Epithelia are sheetlike tissues with one free surface. Simple epithelium lines body cavities, ducts, and tubes. Stratified epithelium typically protects the underlying tissues.
- Glands develop from epithelium. They make and secrete various types of substances.

Figure 4.1 Animated! All types of epithelium share basic characteristics. All epithelia have a free surface that faces either the outside environment or an internal body fluid.

(**a**) Squamous epithelium of skin, showing the tissue's free surface. It consists of several layers of cells that flatten as they near the free surface.

(**b**) The basement membrane is sandwiched between the lower epithelial surface and underlying connective tissue. The diagram shows simple epithelium, a single layer of cells.

(**c**) Examples of simple epithelium, showing the three basic cell shapes in this type of tissue.

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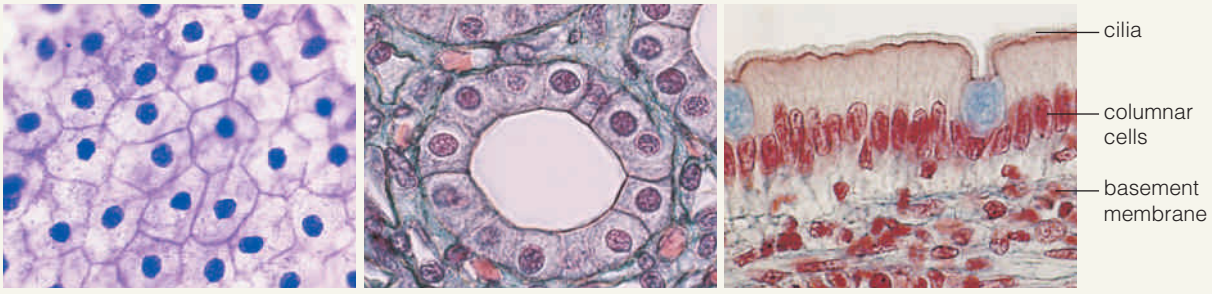
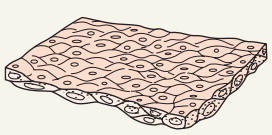
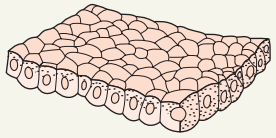




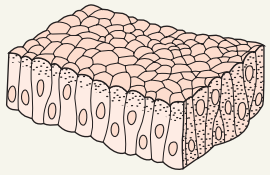
b

Type Simple squamous
Description Friction-reducing slick, single layer of flattened cells
Common Locations Lining of blood and lymph vessels, heart; air sacs of lungs; peritoneum
Function Diffusion; filtration; secretion of lubricants



c

Type Simple cuboidal
Description Single layer of squarish cells
Common Locations Ducts, secretory part of small glands; retina; kidney tubules; ovaries, testes; bronchioles
Function Secretion; absorption



d

Type Simple columnar
Description Single layer of tall cells; free surface may have cilia, mucus-secreting glandular cells, microvilli
Common Locations Glands, ducts; gut; parts of uterus; small bronchi
Function Secretion; absorption; ciliated types move substances

4.2 Connective Tissue: Binding, Support, and Other Roles

- **Connective tissue connects, supports, and anchors the body's parts.**
- **Links to Lipids 2.10, Structural proteins 2.11**

Connective tissue makes up more of your body than any other tissue. It is grouped into fibrous connective tissues and specialized types, which include cartilage, bone, blood, and adipose (fat) tissue (Table 4.2). In most kinds of connective tissues, the cells secrete fiberlike structural proteins and a "ground substance" of polysaccharides. Together these ingredients form a **matrix** around the cell. The matrix can range from hard to liquid, and it gives each kind of connective tissue its specialized properties.

Fibrous connective tissues are strong and stretchy

Fibrous connective tissue is subdivided into several categories. All the different kinds have cells, fibers, and a matrix, but in different proportions that make each one well-suited to perform its special function.

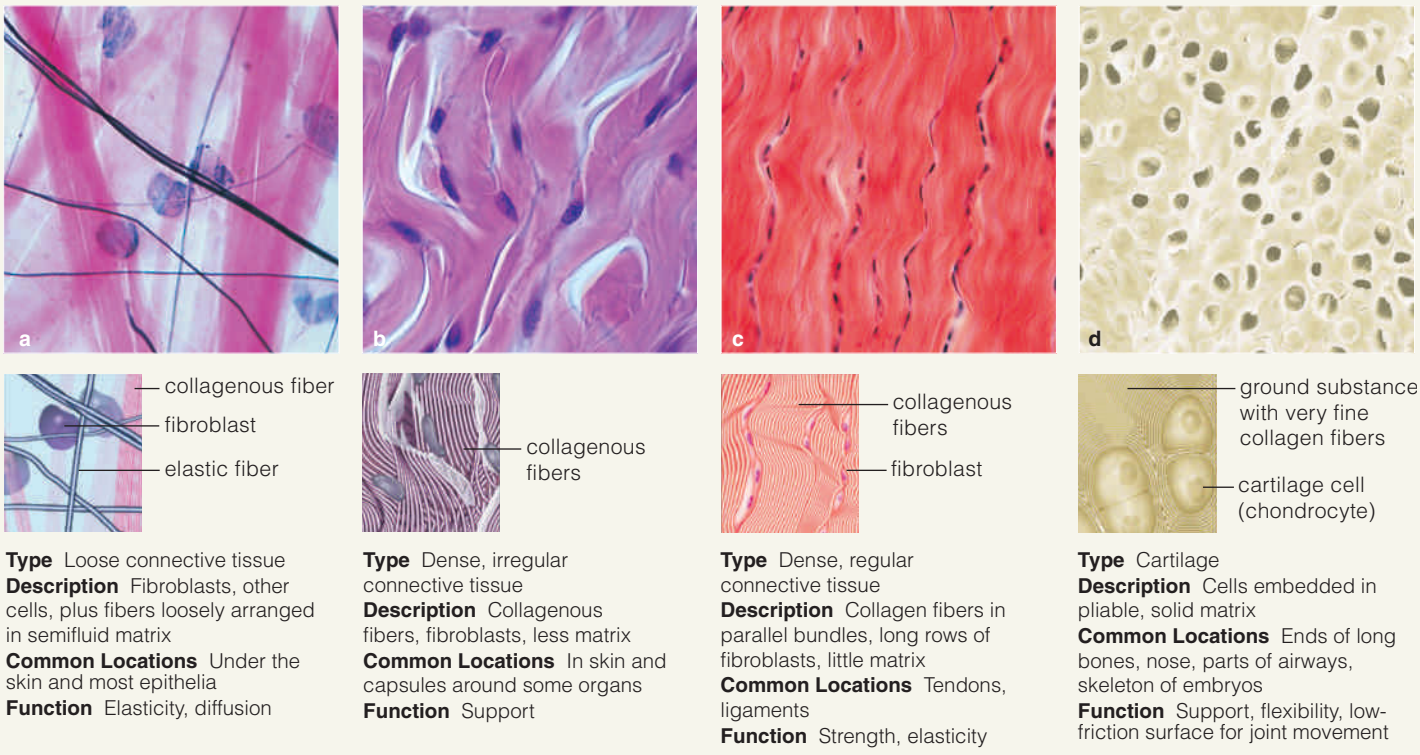
For example, the various forms of **loose connective tissue** have few fibers and cells, and they are loosely arranged in a jellylike ground substance, as pictured in Figure 4.2*a*. This structure makes loose connective tissue flexible. The example in Figure 4.2*a* wraps many organs and helps support the skin. A "reticular" (netlike) form of loose connective tissue is the framework for soft organs such as the liver, spleen, and lymph nodes.

Dense connective tissues have more collagen than do loose connective tissue, so they are less flexible but much stronger. The form pictured in Figure 4.2*b* helps support the skin's lower layer, the dermis. It also wraps around muscles and organs that do not need to stretch much, such as kidneys. Another version of this tissue has large bundles of collagen fibers aligned in the same plane (Figure 4.2*c*). It is found in tendons, which attach skeletal muscles to bones, and in ligaments, which attach bones to one another. The tissue's structure allows a tendon to resist being torn, and in ligaments the tissue's elastic fibers allow the ligament to stretch so bones can move at joints such as the knee.

Elastic connective tissue is a form of dense connective tissue in which most of the fibers are the protein elastin. As a result, this tissue is elastic and is found in organs that must stretch, such as the lungs, which expand and recoil as air moves in and out.

Cartilage, bone, adipose tissue, and blood are specialized connective tissues

Like rubber, **cartilage** is both solid and pliable and is not easily compressed. Its matrix is a blend of collagen and elastin fibers in a rubbery ground substance. The end



Type Loose connective tissue
Description Fibroblasts, other cells, plus fibers loosely arranged in semifluid matrix
Common Locations Under the skin and most epithelia
Function Elasticity, diffusion

Type Dense, irregular connective tissue
Description Collagenous fibers, fibroblasts, less matrix
Common Locations In skin and capsules around some organs
Function Support

Type Dense, regular connective tissue
Description Collagen fibers in parallel bundles, long rows of fibroblasts, little matrix
Common Locations Tendons, ligaments
Function Strength, elasticity

Type Cartilage
Description Cells embedded in pliable, solid matrix
Common Locations Ends of long bones, nose, parts of airways, skeleton of embryos
Function Support, flexibility, low-friction surface for joint movement

Figure 4.2 Animated! **Connective tissues connect, support, and anchor.**

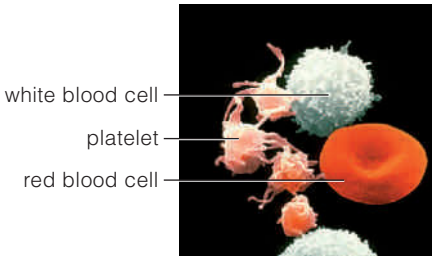


Figure 4.3 Blood is an unusual connective tissue that transports substances. The image shows some components of human blood. This tissue's straw-colored, liquid matrix (plasma) is mostly water in which numerous substances are dissolved.

result is a tissue that can withstand considerable physical stress. The collagen-producing cells become trapped inside small cavities in the matrix (Figure 4.2*d*). If you have ever accidentally torn a cartilage, you know that injured cartilage heals slowly. This is because cartilage lacks blood vessels.

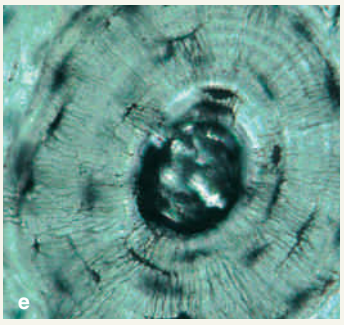
Most cartilage in the body is whitish, glistening *hyaline cartilage* (hyalin = "glassy"). Hyaline cartilage at the ends of bones reduces friction in movable joints. It also makes up parts of your nose, windpipe (trachea), and ribs. An early embryo's skeleton consists of hyaline cartilage.

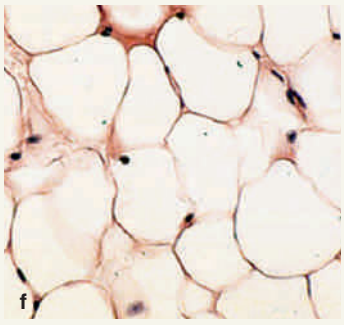
Elastic cartilage has both collagen and elastin fibers. It occurs where a flexible yet rigid structure is required, such as in the flaps of your ears. Sturdy *fibrocartilage* is packed with thick bundles of collagen fibers. It can withstand a lot of pressure, and it forms the cartilage "cushions" in joints such as the knee and in the disks between the vertebrae in the spinal column.

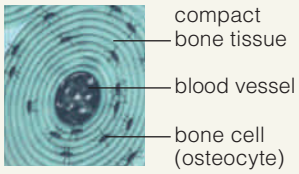
Bone tissue is the main tissue in bones. It is hard because its matrix includes not only collagen fibers and ground substance but also calcium salts (Figure 4.2*e*). As part of the skeleton our bones serve the body in many ways that you will learn about in Chapter 5.

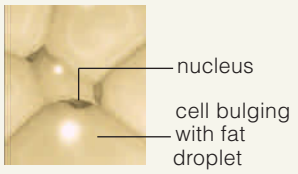
Adipose tissue stores fat—the way the body deals with carbohydrates and proteins that are not immediately used for metabolism. It is mostly cells packed with fat droplets, with just a little matrix between them (Figure 4.2*f*). Most of our adipose tissue is located just beneath the skin, where it provides insulation and cushioning.

Blood is classified as connective tissue even though it does not "connect" or bind other body parts. Instead blood's role is transport. Its matrix is the fluid plasma, which contains proteins (blood's "fibers") as well as a variety of blood cells and cell fragments called platelets (Figure 4.3). Chapter 8 discusses this complex tissue.









Type Bone tissue
Description Collagen fibers, matrix hardened with calcium
Common Locations Bones of skeleton
Function Movement, support, protection

Type Adipose tissue
Description Large, tightly packed fat cells occupying most of matrix
Common Locations Under skin, around heart, kidneys
Function Energy reserves, insulation, padding

Connective Tissues at a Glance

Fibrous Connective Tissues	
Loose	Collagen and elastin loosely arranged in ground substance; quite flexible and fairly strong
Dense	Mainly collagen; somewhat flexible and quite strong. Collagen fibers are aligned in parallel in the dense connective tissue of tendons and ligaments
Elastic	Mainly elastin; easily stretches and recoils
Special Connective Tissues	
Cartilage	Mainly collagen in a watery matrix; resists compression
Bone	Mineral-hardened matrix; very strong
Adipose tissue	Mainly cells filled with fat; soft matrix
Blood	Matrix is the fluid blood plasma, which contains blood cells and other substances

Take-Home Message

What are connective tissues?

- Overall, connective tissue binds together and supports other body tissues and organs. All connective tissues consist of cells in a matrix.
- The differing types of fibrous connective tissues have different amounts and arrangements of collagen and elastin fibers.
- Cartilage, bone, blood, and adipose tissue are specialized connective tissues. Cartilage and bone are structural materials. Blood transports substances. Adipose tissue stores energy.

4.3 Muscle Tissue: Movement

- **Cells in muscle tissue can contract, allowing muscle to move body parts.**

The cells in **muscle tissue** contract, or shorten, when they are stimulated by an outside signal; then they relax and lengthen. Muscle tissue has long, cylindrical cells lined up in parallel. This shape is why muscle cells are often called "muscle fibers." Muscle layers—and muscular organs—contract and relax in a coordinated way. This is how the action of muscles maintains and changes the positions of body parts, movements that range from walking to blinking your eyes. The three types of muscle tissue are skeletal, smooth, and cardiac muscle tissues.

Skeletal muscle is the main tissue of muscles that attach to your bones (Figure 4.4*a*). In a typical muscle, skeletal muscle cells line up in parallel bundles. This arrangement makes them look striped, or *striated*. The bundles, called fascicles, are enclosed by a sheath of dense connective tissue. This arrangement of muscle and connective tissue makes up the organs we call "muscles." The structure and functioning of skeletal muscle tissue are topics we consider in Chapter 6.

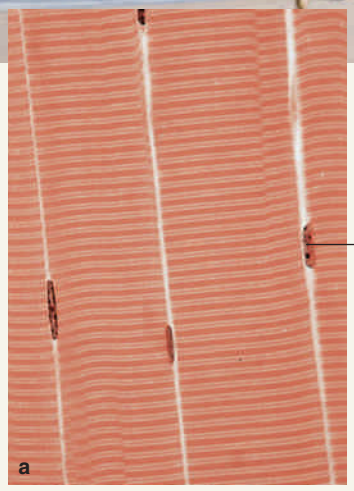
Smooth muscle cells taper at both ends (Figure 4.4*b*). Junctions hold the cells together (Section 4.6), and they are bundled inside a connective tissue sheath. This type of muscle tissue is specialized for steady contraction. It is found in the walls of internal organs—including blood vessels, the stomach, and the intestines. The contraction of smooth muscle is "involuntary" because we usually cannot make it contract just by thinking about it (as we can with skeletal muscle).

Cardiac muscle (Figure 4.4*c*) is found only in the wall of the heart and its sole function is to pump blood. As you will read in Chapter 7, special junctions fuse the plasma membranes of cardiac muscle cells. In places, communication junctions allow the cells to contract as a unit. When one cardiac muscle cell is signaled to contract, the cells around it contract, too.

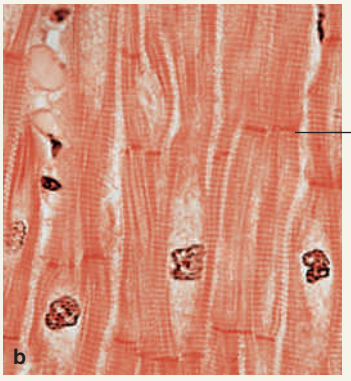
Take-Home Message

What is the function of muscle tissue?

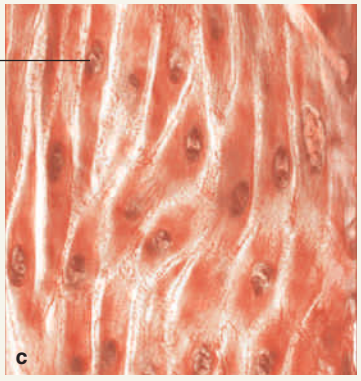
- Muscle tissue can contract (shorten) when it is stimulated by an outside signal. It helps move the body and its parts.
- Skeletal muscle attaches to bones. Smooth muscle is found in internal organs. Cardiac muscle makes up the walls of the heart.



Type Skeletal muscle; bundles of long, cylindrical, striated muscle fibers, many mitochondria
Location Partner of bones, against which it exerts great force
Functions Locomotion; posture; head and limb movements



Type Cardiac muscle; cylindrical muscle fibers that abut at their ends; contract rapidly as a unit
Location Heart wall
Function Forcefully pump blood through circulatory system



Type Smooth muscle; contractile cells tapered at both contractile ends
Locations Wall of arteries, veins, sphincters, stomach, urinary bladder, many other internal organs
Functions Controlled constriction, motility (as in gut), blood flow in arteries

Figure 4.4 Animated! **All types of muscle tissue consist of cells that can contract.**

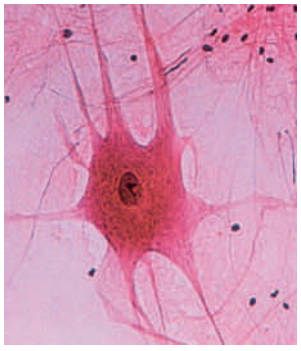
4.4 Nervous Tissue: Communication

- **Nervous tissue makes up the nervous system.**

The body's **nervous tissue** consists mostly of cells. They include **neurons**, the "nerve cells," and support cells. There are tens of thousands of neurons in the brain and spinal cord, and millions more are present throughout the body. Neurons carry signals called nerve impulses. They make up the body's communication lines.

Neurons carry messages

Like other kinds of cells, a neuron has a cell body that contains the nucleus and cytoplasm. It also has two types of extensions, or cell "processes." Branched processes called **dendrites** receive incoming messages. Processes called **axons** conduct outgoing messages. Depending on the type of neuron, its axon may be very short, or it may be as long as three or four feet. The image at left shows the cell processes of a motor neuron, which carries signals to muscles and glands.



A motor neuron

Neuroglia are support cells

About 90 percent of the cells in the nervous system are **glial cells** (also called **neuroglia**). The word *glia* means glue, and glial cells were once thought to simply be the "mortar" that physically supported neurons. Today we know that they also have other functions. In the central nervous system, glia help bring nutrients to neurons, provide physical support, and remove debris or other foreign matter. Outside the brain and spinal cord glia called Schwann cells provide insulation—a vital function that helps speed nerve impulses through the body, as described in Chapter 13.

Take-Home Message

What types of cells make up nervous tissue?

- Neurons are the communication cells of nervous tissue.
- Support cells called neuroglia make up most of nervous tissue.

4.5 Replacing Tissues

Stem cell research may lead to therapies that can help patients with numerous serious health problems, including Parkinson's disease, type 2 diabetes, muscular dystrophy, and paralysis due to spinal cord injury. Some other technologies are focused on growing replacement tissues in the laboratory.

Given the controversy surrounding embryonic stem cells, there is strong interest in alternative means for obtaining or creating stem cells. Some researchers, like Junying Yu, who is pictured in the chapter introduction, want to perfect methods for "reverse engineering" mature cells to convert them back into stem cells.

Scientists at the Sloan-Kettering Cancer Center are taking a different tack to find a cure for sickle cell anemia, a genetic disease in which faulty stem cells in a patient's bone marrow produce defective red blood cells. They are using biotechnology to put healthy genes into such flawed bone marrow cells. The "cured" stem cells can later be re-infused into the patient and in theory produce normal red blood cells.

Scientists at the University of Minnesota Medical School have reported exciting progress in using stem cells from both bone marrow and umbilical cord blood to treat people with a rare genetic disorder called EB (epidermolysis bullosa). Patients lack normal structural proteins of epithelium, such as collagen. Among other symptoms, their skin develops open sores and tears so easily that their bodies often must be bandaged head to toe. Several children with EB have shown marked improvement after receiving experimental injections of stem cells that produce the normal proteins.

Using a cultured skin substitute (Figure 4.5) is another option for EB patients, burn victims, and people with chronic wounds. The tissue is grown in a laboratory from skin and connective tissue cells extracted from foreskins removed when infant boys are circumcised.

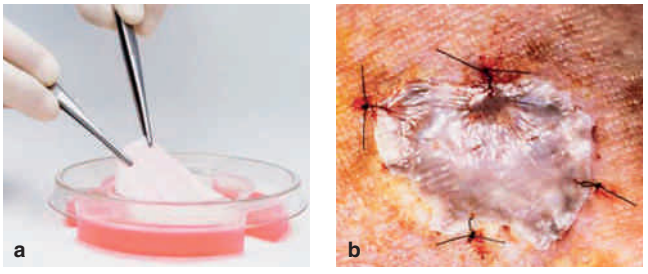


Figure 4.5 Skin substitutes are grown in the laboratory. (**a**) A cultured skin substitute called Apligraf. (**b**) Placed over a wound, the cultured skin can help prevent infection and also speeds up the healing process.

4.6 Cell Junctions: Holding Tissues Together

- **Junctions between the cells in a tissue knit the cells firmly together, stop leaks, and serve as communication channels.**
- **Links to Plasma membrane 3.4, Cytoskeleton 3.8**

Our tissues and organs would fall into disarray if there were not some way for individual cells to "stick together" and to communicate. In all tissues, cell junctions meet these needs. These junctions are most common where substances must not leak from one body compartment to another.

Figure 4.6 shows some examples of cell junctions. **Tight junctions** (Figure 4.6*a*) are strands of protein that help stop substances from leaking across a tissue. The strands form gasketlike seals that prevent molecules from moving easily across the junction. In epithelium, for example, tight junctions allow the epithelial cells to control what enters the body. For instance, while food is being digested, various types of nutrient molecules can diffuse into epithelial cells or enter them selectively by active transport, but tight junctions keep those needed molecules from slipping *between* cells. Tight junctions also prevent the highly acidic gastric fluid in your stomach from leaking out and digesting proteins of your own body instead of those you consume in food.

Adhering junctions (Figure 4.6*b*) cement cells together. One type, sometimes called desmosomes, are like spot welds at the plasma membranes of two adjacent cells. They are anchored to the cytoskeleton in each cell and help hold cells together in tissues that often stretch, such as epithelium of the skin, the lungs, and the stomach. Another type of adhering junction forms a tight collar around epithelial cells.

Gap junctions (Figure 4.6*c*) are channels that connect the cytoplasm of neighboring cells. They help cells communicate by promoting the rapid transfer of ions and small molecules between them. Gap junctions are most plentiful in smooth muscle and cardiac muscle. As you will read in Chapter 6, ions moving through them from muscle cell to muscle cell play a key role in contraction of whole muscles. In other kinds of tissues gap junctions are passages for many kinds of signaling molecules.

Take-Home Message

What are cell junctions?

- Tight junctions between cells help stop leaks in a tissue.
- Adhering junctions cement cells in a tissue together.
- Gap junctions are channels that allow ions and small molecules to cross between cells.

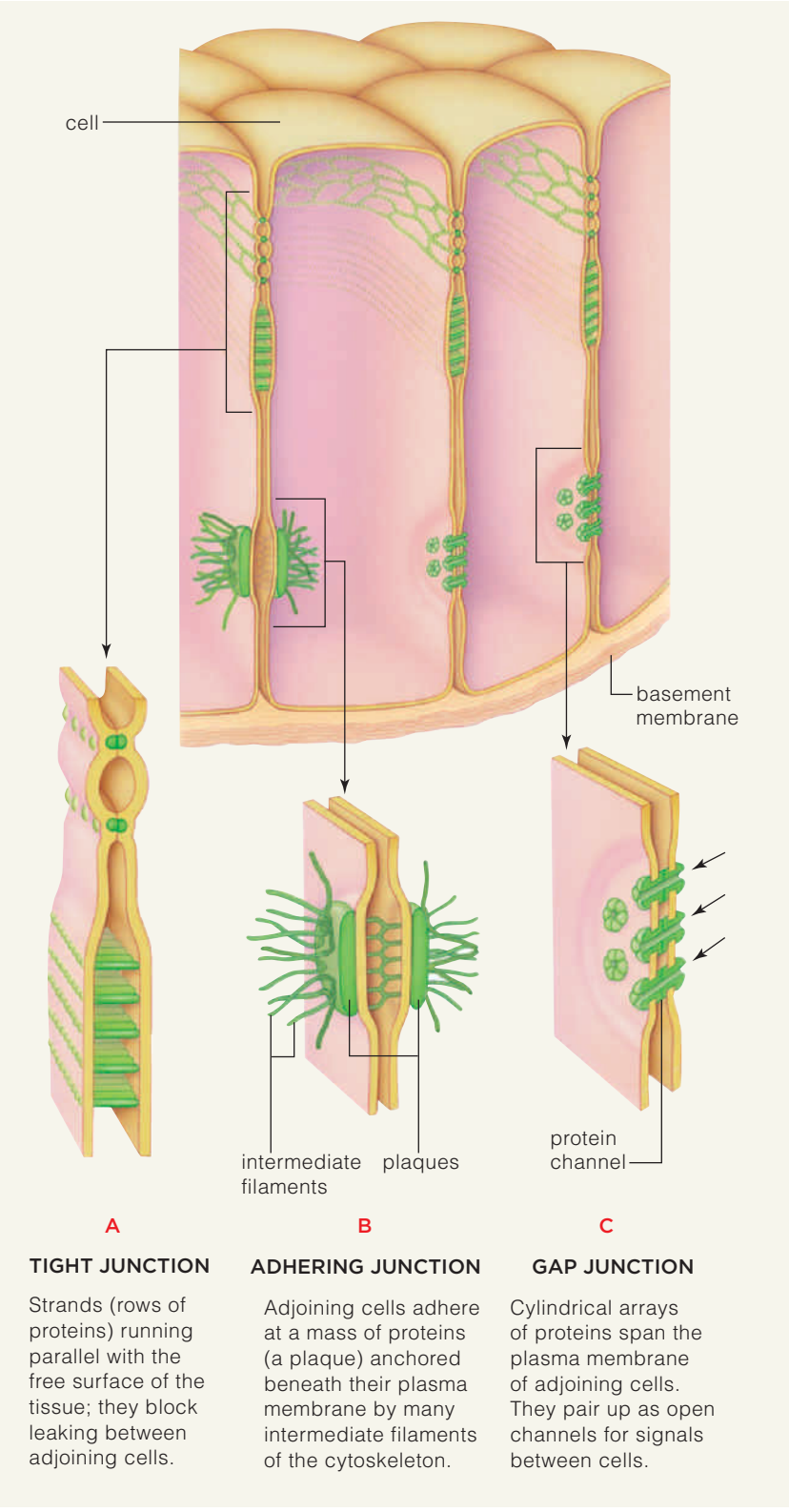


Figure 4.6 Animated! Junctions knit cells together in tissues.

4.7 Tissue Membranes: Thin, Sheetlike Covers

- **Thin, sheetlike membranes cover many body surfaces and cavities. Some provide protection. Others both protect and lubricate organs.**

A membrane is assigned to one of two categories, depending on its structure. In one group are *epithelial membranes*, while in the second group are *connective tissue membranes*. Here we consider some examples of each.

Epithelial membranes pair with connective tissue

Epithelial membranes consist of a sheet of epithelium atop connective tissue. For instance, consider the body's **mucous membranes**, also called mucosae (singular: mucosa). These are the pink, moist membranes lining the tubes and cavities of your digestive, respiratory, urinary, and reproductive systems (Figure 4.7*a*). Most mucous membranes are specialized to absorb substances, secrete them, or both. And as you might guess, most mucous membranes, like the lining of the stomach, contain glands, including mucous glands that secrete mucus. Not all do, though. For instance, the mucous membrane lining the urinary tract (including the tubes that carry urine out) has no glands. Later chapters will provide many examples of how mucous membranes protect other tissues and secrete or absorb substances.

Serous membranes are epithelial membranes that occur in paired sheets. Imagine one paper sack inside another, with a narrow space between them, and you'll get the idea. Serous membranes don't have glands, but the layers do secrete a fluid that fills the space between them. Examples include the membranes that line the chest (thoracic) cavity and enclose the heart and lungs. Among other functions, serous membranes help anchor internal organs in place and provide lubricated smooth surfaces that prevent chafing between adjacent organs or between organs and the body wall.

A third type of epithelial membrane is the **cutaneous membrane** (Figure 4.7*c*). You know this hardy, dry membrane as your skin. Its tissues also are part of one of the body's major organ systems, the integumentary system, which we examine in Section 4.9.

Membranes in joints consist of connective tissue

A few membranes in the body are composed only of connective tissue. These **synovial membranes** (Figure 4.7*d*) line cavities of the body's movable joints. They contain cells that secrete fluid that lubricates the ends of moving bones or prevents friction between a bone and a moving tendon.

Take-Home Message

What are body membranes?

- Epithelial membranes consist of epithelium overlying connective tissue. Different types include mucous and serous membranes and the cutaneous membrane of skin.
- Most epithelial membranes contain glands.
- Connective tissue membranes consist only of connective tissue. They line joint cavities.

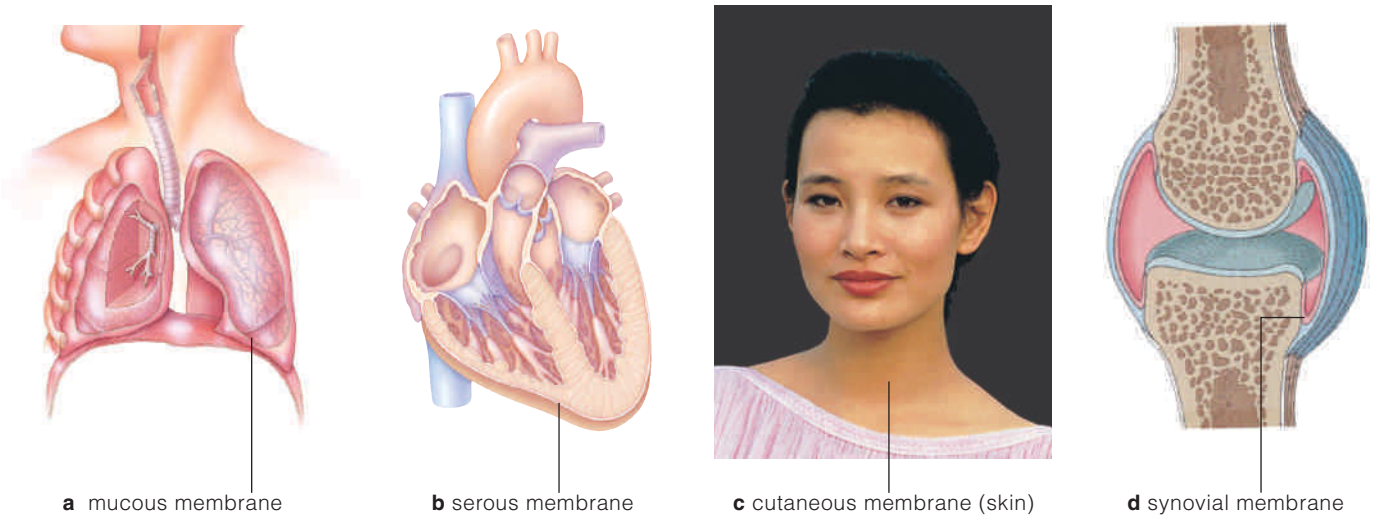


Figure 4.7 **Membranes cover many body surfaces and line body cavities.**

4.8 Organs and Organ Systems

- **Body organs are organized into eleven organ systems.**
- **Link to Levels of biological organization 1.3**

An **organ** is a combination of two or more kinds of tissue that together perform one or more functions. As an example, the stomach contains all four of the tissue types you have read about in previous sections (Figure 4.8a). Its wall is mainly muscle, and nerves help regulate muscle contractions that mix and move food. Connective tissue provides support, while the stomach lining is epithelium.

The heart and many other major organs are located inside body cavities shown in Figure 4.8*b*. The **cranial cavity** and **spinal cavity** house your brain and spinal cord—the central nervous system. Your heart and lungs reside in the **thoracic cavity**—essentially, inside your chest. The diaphragm muscle separates the thoracic cavity from the **abdominal cavity**, which holds your stomach, liver, most of the intestine, and other organs. Reproductive organs, the bladder, and the rectum are located in the **pelvic cavity**.

Two or more organs combine to make up each of the body's eleven **organ systems**. Each organ system in turn contributes to the survival of all living cells in the body (Figure 4.9). Does this statement seem like a stretch? After all, how could, say, bones and muscles help each microscopically small cell to stay alive? Yet, interactions between your skeletal and muscular systems allow you to move about—toward sources of nutrients and water, for example. Parts of those systems help keep your blood circulating to cells, as when contractions of leg muscles help move blood in veins back to your heart. Blood inside the circulatory system rapidly carries nutrients and other substances to cells and transports products and wastes away from them. Your respiratory system swiftly delivers oxygen from air to your circulatory system and takes up carbon dioxide wastes from it, skeletal muscles assist the respiratory system—and so it goes, throughout the entire body.

Take-Home Message

What are organs and organ systems?

- The body's organ systems each serve a specialized function that contributes to the survival of all living body cells.

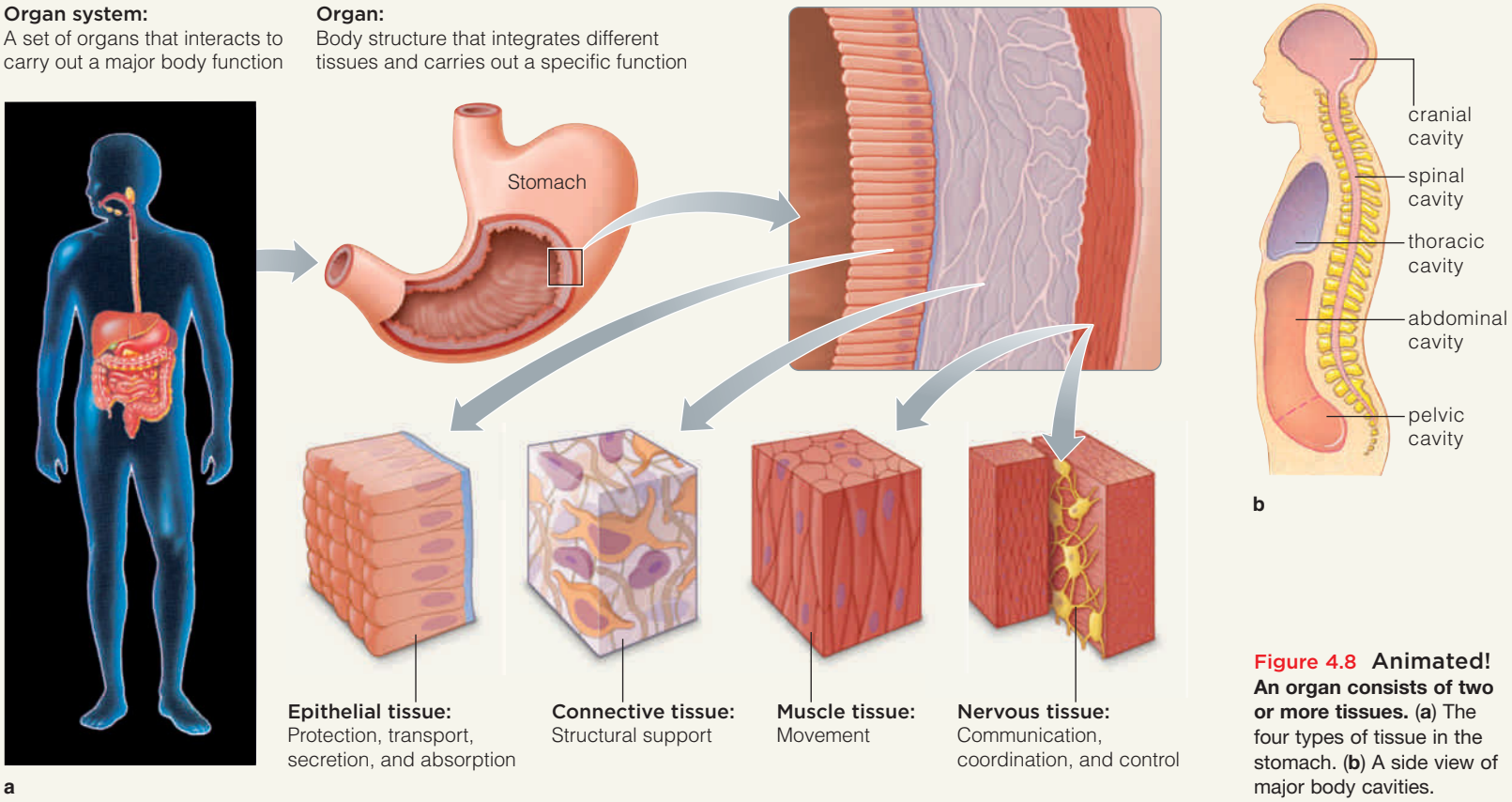
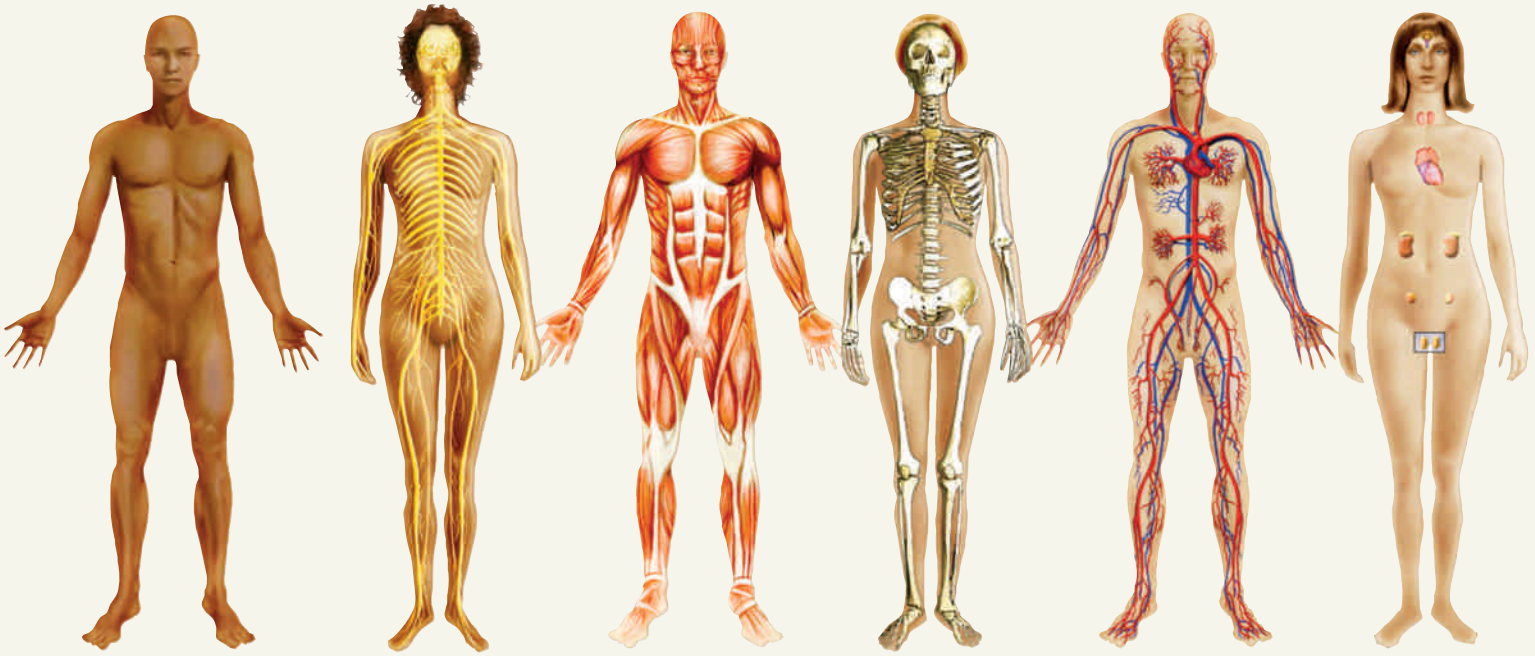


Figure 4.8 Animated! **An organ consists of two or more tissues.** (**a**) The four types of tissue in the stomach. (**b**) A side view of major body cavities.



Integumentary System
Protects body from injury, dehydration, and some microbes; controls body temperature; excretes some wastes; receives some sensory information.

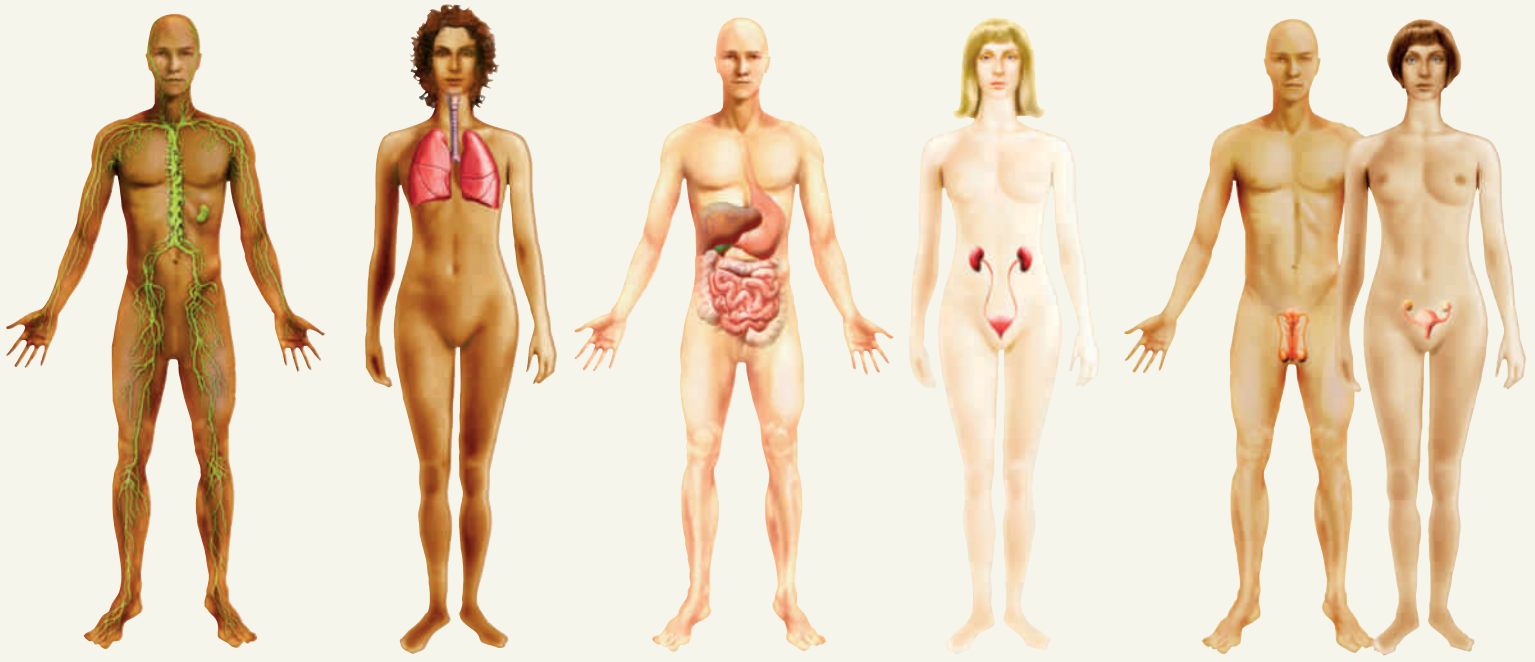
Nervous System
Detects external and internal stimuli; controls and coordinates the responses to stimuli; integrates all organ system activities.

Muscular System
Moves body and its parts; maintains posture; generates heat by increasing metabolic activity.

Skeletal System
Supports and protects body parts; provides muscle attachment sites; produces red blood cells; stores calcium, phosphorus.

Circulatory System
Rapidly transports many materials to and from cells; helps stabilize internal pH and temperature.

Endocrine System
Hormonally controls body functioning; works with nervous system to integrate short-term and long-term activities.



Lymphatic System
Collects and returns tissue fluid to the blood; defends the body against infection and tissue damage.

Respiratory System
Delivers oxygen to all living cells; removes carbon dioxide wastes of cells; helps regulate pH.

Digestive System
Ingests food and water; mechanically, chemically breaks down food and absorbs small molecules into internal environment; eliminates food residues.

Urinary System
Maintains the volume and composition of blood and tissue fluid; excretes excess fluid and blood-borne wastes.

Reproductive System
Female: Produces eggs; after fertilization, affords a protected, nutritive environment for the development of a fetus. *Male:* Produces and transfers sperm to the female. Hormones of both systems also influence other organ systems.

Figure 4.9 Animated! **The body has eleven organ systems.**

4.9 The Skin: An Example of an Organ System

- **Skin and structures that develop from it make up the integument—the body's covering.**

Of all your organ systems, you know your integument the best. The **integument** (from Latin *integere*, "to cover") consists of your skin, oil and sweat glands, hair, and nails. The skin has the largest surface area of any organ. It weighs about 9 pounds in an average-sized adult, and as coverings go, it is pretty amazing. It holds its shape through years of washing and being stretched, blocks harmful solar radiation, bars many microbes, holds in moisture, and fixes small cuts and burns. The skin also helps regulate body temperature, and signals from its sensory receptors help the brain assess what's going on in the outside world. Yet except for places subjected to regular abrasion (such as your palms and the soles of your feet), your skin is generally not much thicker than a sheet of construction paper. It is even thinner in some places, such as the eyelids.

Human skin also makes cholecalciferol, a precursor of vitamin D—a catchall name for compounds that help the body absorb calcium from food. When skin is exposed to sunlight, some cells release vitamin D into the bloodstream, just as hormones are. In this way your skin acts like an endocrine gland.

Epidermis and dermis are the skin's two layers

Skin has an outer **epidermis** and an underlying **dermis** (Figure 4.10). Sweat glands, oil glands, hair follicles, and nails develop from the epidermal tissue. The dermis is mainly dense connective tissue, so it contains elastin fibers that make skin resilient and collagen fibers that make it strong. Together, the epidermis and dermis form the cutaneous membrane you read about in Section 4.7. Below the dermis is a subcutaneous ("under the skin") layer, the hypodermis. This is loose connective tissue that anchors the skin while allowing it to move a bit. Fat in the hypodermis helps insulate the body and cushions some of its parts.

The epidermis is stratified squamous epithelium. Its cells arise in deeper layers and are pushed toward the surface as new cells arise beneath them. (This efficient replacement is one reason why the skin can mend minor damage so quickly.) As cells move upward, they become flattened, lose their nucleus, and die. Eventually they rub off or flake away.

Most cells of the epidermis are **keratinocytes**. These cells make keratin, a tough, water-insoluble protein. By the time they reach the skin surface and have died, all that remain are the keratin fibers inside plasma membranes.

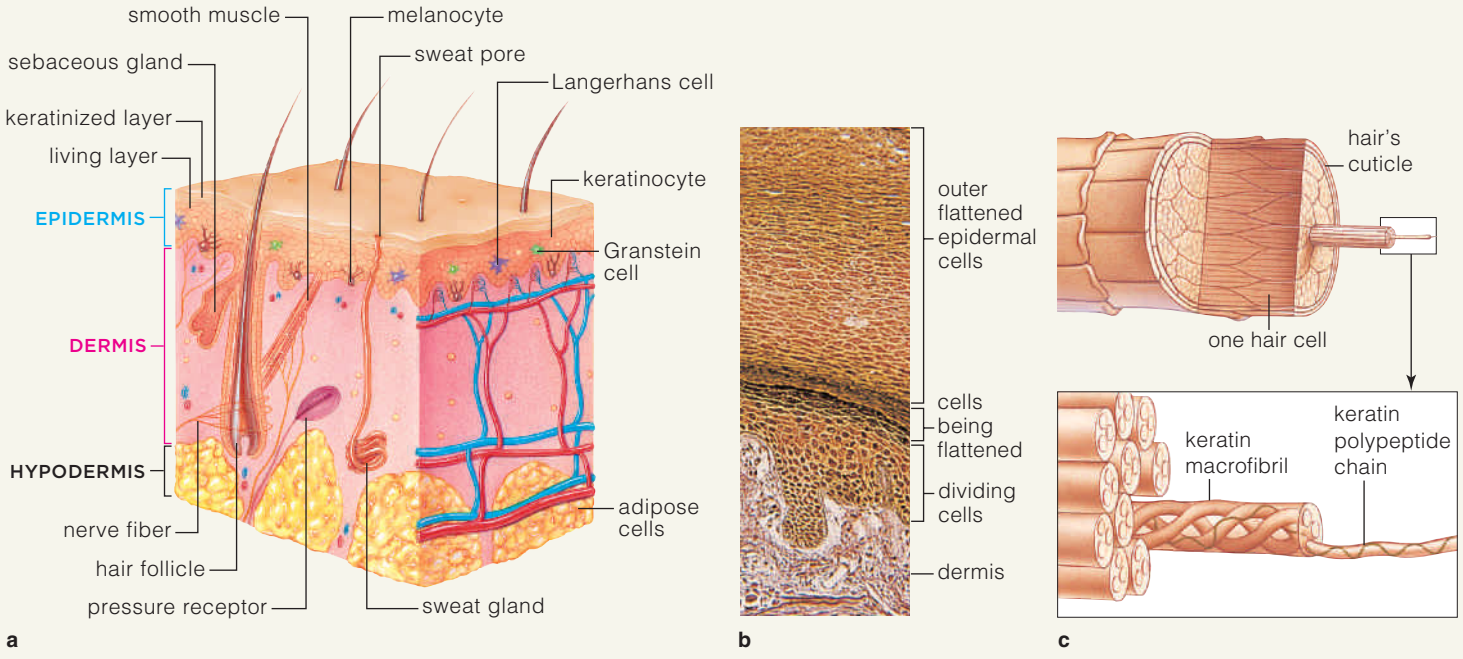


Figure 4.10 **Animated!** **Skin is the main component of the integumentary system.** (**a**) The structure of human skin. The dark spots in the epidermis are cells that contain pigment. (**b**) A section through human skin. (**c**) Close-up of a hair. Dead, flattened hair cells form a tubelike cuticle around the hair shaft.

This helps make the skin's outermost layer—the stratum corneum—tough and waterproof.

In the deepest layer of epidermis, cells called **melanocytes** produce a brown-black pigment called melanin. The pigment is transferred to keratinocytes and helps give skin its color. A yellow-orange pigment in the dermis, called carotene, also contributes some color. Skin color varies due to differences in the distribution and activity of those cells. Pale Caucasian skin has only a little melanin, so the pigment hemoglobin inside red blood cells shows through thin-walled blood vessels and the epidermis itself, both of which are transparent. There is more melanin in naturally brown or black skin.

The epidermis also contains some defensive cells. *Langerhans cells* are phagocytes ("cell eaters"). They consume bacteria or viruses, mobilizing the immune system in the process. *Granstein cells* may help control immune responses in the skin.

Small blood vessels and sensitive nerve endings lace through the dermis, and hair follicles, sweat glands, and oil glands are embedded in it. On the palms and soles of the feet it also has ridges that push up corresponding ridges on the epidermis. These ridges loop and curve in the intricate patterns we call fingerprints. The pattern is genetically determined and is different for each of us, even identical twins.

Sweat glands and other structures develop from epidermis

The body has about 2.5 million sweat glands. Sweat is 99 percent water; it also contains dissolved salts, traces of ammonia and other wastes, vitamin C, and other substances. A subset of sweat glands that are in the palms, soles of the feet, forehead, and armpits is important for cooling the body when it becomes overheated. Another type of sweat glands is abundant in the skin around the genitals. Stress, pain, and sexual foreplay all can increase the amount of sweat they secrete.

Oil glands (or *sebaceous glands*) are everywhere except on the palms and the soles of the feet. The oily substance they release, called sebum, softens and lubricates the hair and skin. Other secretions kill harmful bacteria.

A **hair** consists mainly of keratinized cells, rooted in skin with a shaft above its surface. As cells divide near the root's base, older cells are pushed upward, then flatten and die. The outermost layer of the shaft consists of flattened cells that overlap like roof shingles (Figure 4.10*c*). These dead cells are what frizz out as "split ends." On average the scalp has about 100,000 hairs. However, genes, nutrition, hormones, and stress influence the growth and the density of a person's hair.

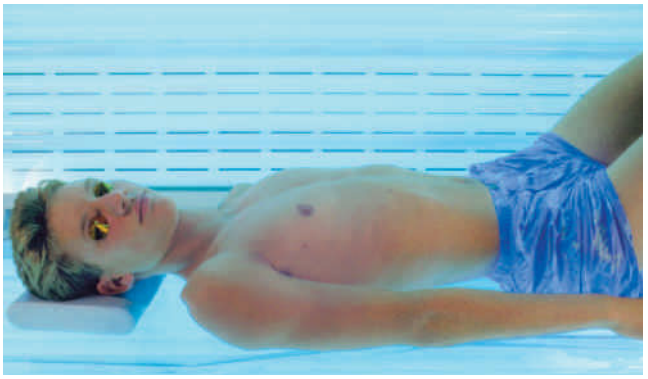


Figure 4.11 **Tanning damages the skin.**

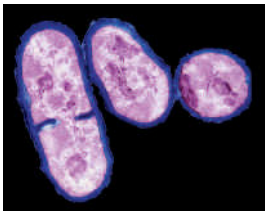
Skin disorders are common

The dense connective tissue of the dermis makes it quite tough, but this protection has limits. For example, steady abrasion—as might happen if you wear a too-tight shoe—separates the epidermis from the dermis, the gap fills with a watery fluid, and you get a *blister.*

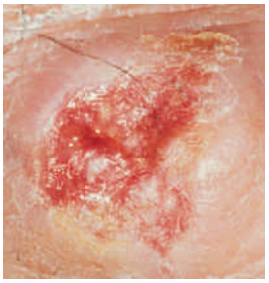
Acne is a skin inflammation that develops when bacteria infect the ducts of oil glands. *Cold sores* (fever blisters) are caused by a type of herpes virus.

Ultraviolet (UV) radiation stimulates the melanin-producing cells of the epidermis. Prolonged sun exposure increases melanin levels and light-skinned people become tanned. Tanning gives some protection against UV radiation, but over the years, it causes elastin fibers in the dermis to clump together. The skin loses its resiliency and begins to look leathery and wrinkled (Figure 4.11).

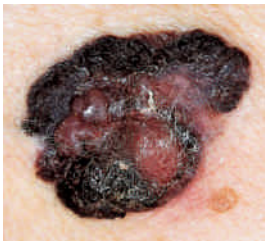
Ultraviolet radiation from sunlight or from the lamps of tanning salons also can trigger cancer. The *squamous cell carcinoma* shown at right is a common and easily treatable form of skin cancer. Much more serious is *malignant melanoma*, which forms a dark, uneven, raised lesion on the skin (*right*). It is a grave threat because in its later stages it spreads quickly to other parts of the body.



Bacterium that causes acne



Squamous cell carcinoma



Malignant melanoma

Take-Home Message

What are the main features of skin?

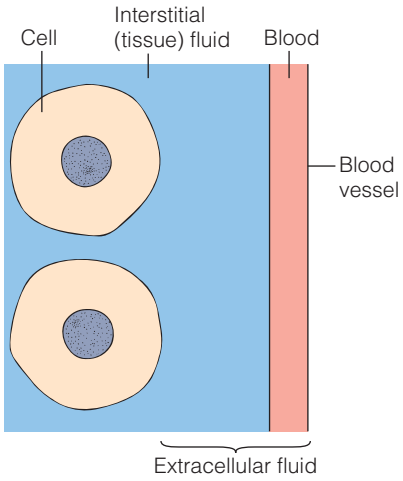
- With its layers of keratinized and melanin-shielded epidermal cells, skin helps the body conserve water, limit damage from ultraviolet radiation, and resist mechanical stress.
- Hairs, oil glands, sweat glands, and nails are derived from the skin's epidermis.

4.10 Homeostasis: The Body in Balance

- **Cells and more complex body parts function properly only when conditions inside the body are stable.**
- **Links to Life's characteristics 1.1, Acid–base balance 2.7**

The internal environment is a pool of extracellular fluid

The trillions of cells in your body all are bathed in fluid—about 15 liters, or a little less than four gallons. This fluid, called **extracellular** ("outside the cell") **fluid**, is what we mean by the "internal environment." Much of the extracellular fluid is *interstitial*, meaning that it fills spaces between cells and tissues. The rest is blood plasma, the fluid portion of blood. Substances constantly enter and leave interstitial fluid as cells draw nutrients from it and expel metabolic waste products into it. Those substances can include ions, compounds such as water, and other materials.



All this chemical traffic means that the chemical makeup and volume of extracellular fluid change from moment to moment. If the changes are drastic, they can have drastic effects on cell activities. The number and type of ions in extracellular fluid (such as H^+) are especially crucial, because they must be kept at levels that allow metabolism to continue normally. As you read in Chapter 1, **homeostasis** means "staying the same." The mechanisms of homeostasis operate to maintain stability in the volume and chemical makeup of extracellular fluid.

In maintaining homeostasis, all components of the body work together in the following general way:

- Each cell engages in metabolic activities that ensure its own survival.
- Tissues, which consist of cells, perform one or more activities that contribute to the survival of the whole body.
- Together, the operations of individual cells, tissues, organs, and organ systems help keep the extracellular fluid in a stable state—a state of homeostasis that allows cells to survive.

Homeostasis requires the interaction of sensors, integrators, and effectors

Three "partners" must interact to maintain homeostasis. They are sensory receptors, integrators, and effectors. **Sensory receptors** are cells or cell parts that can detect a **stimulus**—a specific change in the environment. For a simple example, if someone taps you on the shoulder, there is a change in pressure on your skin. Receptors in the skin translate the stimulus into a signal, which can be sent to the brain. Your brain is an **integrator**, a control point where different bits of information are pulled together in the selection of a response. It can send signals to muscles, glands, or both. Your muscles and glands are **effectors**—they carry out the response, which in this case might include turning your head to see if someone is there. Of course, you cannot keep your head turned indefinitely, because eventually you must eat, use the bathroom, and perform other tasks that maintain body operating conditions.

So how does the brain deal with physiological change? Receptors inform it about how things *are* operating, but the brain also maintains information about how things *should be* operating—that is, information from "set points." When conditions shift sharply from a set point, the brain brings them back within proper range. It does this by sending signals that cause specific muscles and glands to step up or reduce their activity. Set points are important in a great many physiological mechanisms, including those that influence eating, breathing, thirst, and urination, to name a few.

Negative feedback is the most common control mechanism in homeostasis

Mechanisms for feedback help keep physical and chemical aspects of the body within tolerable ranges. In

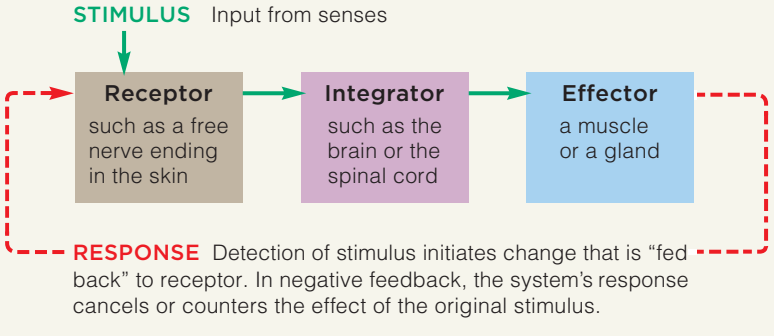
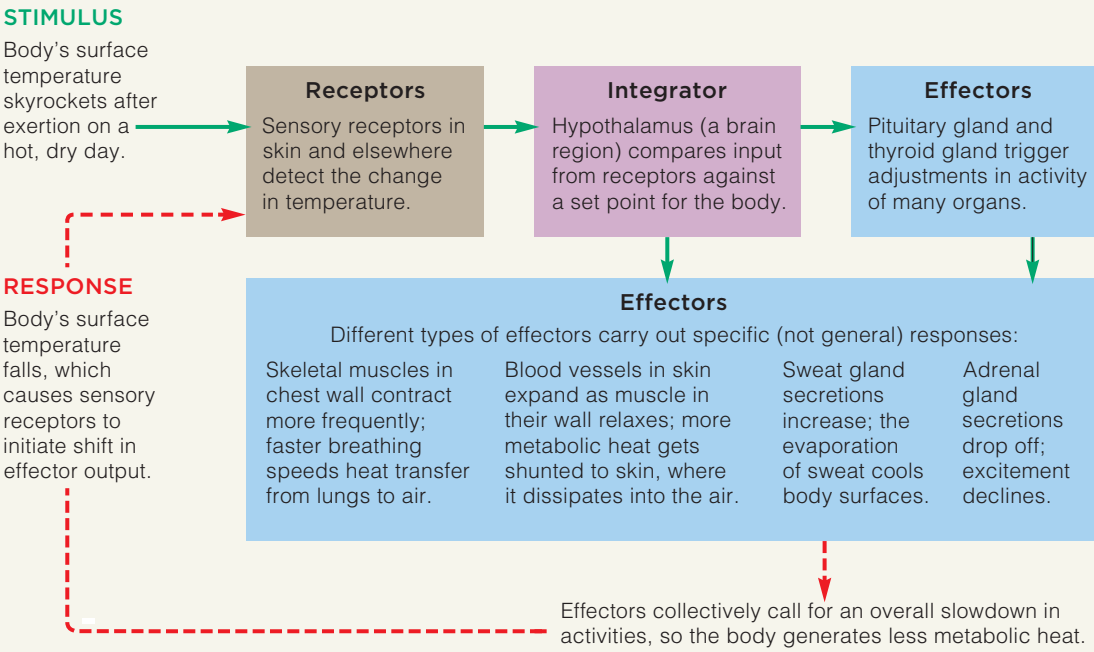
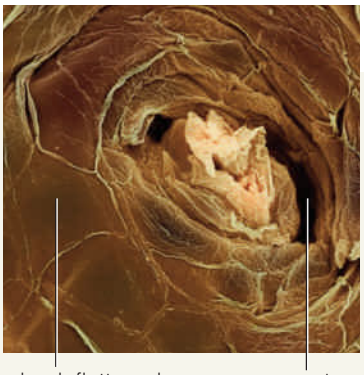


Figure 4.12 Animated! Three basic components are part of negative feedback at the organ level.





Scanning electron micrographs of a sweat gland pore at the skin surface. Such glands are among the effectors for this control pathway.

Figure 4.13 Animated!
A negative feedback loop regulates body temperature. The dashed line shows how the feedback loop is completed. The solid arrows indicate the main control pathways.

negative feedback, an activity alters a condition in the internal environment, and this triggers a response that reverses the altered condition (Figure 4.12). By analogy, think of a furnace with a thermostat. The thermostat senses the air temperature and mechanically compares it to a preset point on a thermometer built into the furnace control system. When the temperature falls below the preset point, the thermostat signals a switch that turns on the heating unit. When the air warms enough to match the preset level, the thermostat signals the switch to shut off the heating unit.

In a similar way, negative feedback helps keep body temperature within a normal range (Figure 4.13). For example, when sensors indicate that the skin is getting too hot while you work outside in the sun, mechanisms kick in that slow both the metabolic activity of cells *and* overall activity levels. You may move less and look for shade. At the same time, blood flow to the skin increases and your sweat glands secrete more sweat. As water in sweat evaporates, your body loses more heat. These and other changes curb the body's heat-producing activities and release excess heat to the surroundings.

In a few situations **positive feedback** operates. In this type of mechanism, a chain of events *intensify* a change from an original condition—and after a limited time, the intensifying feedback reverses the change. There are not many instances of positive feedback in body functions, but one familiar example is childbirth. During labor a fetus exerts pressure on the walls of its mother's uterus. The pressure stimulates the production and secretion of a hormone (oxytocin) that causes the mother's uterine muscles to contract and exert pressure on the fetus, which exerts more pressure on the uterine wall, and so on until the fetus is expelled.

As the body monitors and responds to information about the external world and the internal environment, its organ systems must operate in a coordinated way. In upcoming chapters we will be asking four important questions about how organ systems function:

1. What physical or chemical aspect of the internal environment is each organ system working to maintain as conditions change?
2. How is each organ system kept informed of changes?
3. How does each system process incoming information?
4. What are the responses?

As you will see, all organ systems operate under precise controls of the nervous system and the endocrine system.

Take-Home Message

How does the body maintain homeostasis?

- Homeostatic control mechanisms maintain the characteristics of the internal environment within ranges that allow cells to function properly.

4.11 How Homeostatic Feedback Maintains the Body's Core Temperature

- **Controls over the body's core temperature provide good examples of negative feedback loops.**

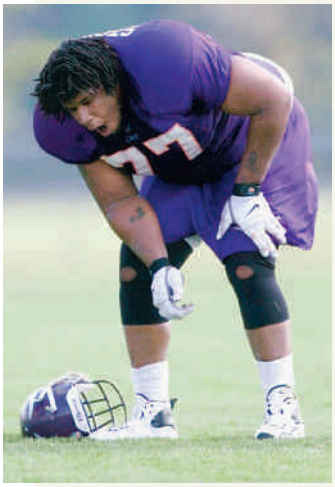
We humans are **endotherms**, which means "heat from within." The body's **core temperature**—the temperature of the head and torso—is about 37°C, or 98.6°F. It is controlled mainly by metabolic activity, which produces heat, and by negative feedback loops. These homeostatic controls adjust physiological responses for conserving or getting rid of heat (Figure 4.14). We can assist the physiological controls by altering our behavior—for example, by changing clothes or switching on a furnace or an air-conditioner.

Metabolism produces heat. If that heat were to build up internally, your core temperature would steadily rise. Above 41°C (105.8°F), some enzymes become denatured and virtually shut down. By the same token, the rate of enzyme activity generally *decreases* by at least half when body temperature drops by 10°F. If it drops below 35°C (95°F), you are courting danger. As enzymes lose their ability to function, your heart will not beat as often or as effectively, and heat-generating mechanisms such as shivering stop. At this low core temperature breathing slows, so you may lose consciousness. Below 80°F the human heart may stop beating entirely. Given these stark physiological facts, humans require mechanisms that help maintain the core body temperature within narrow limits.

Excess heat must be dissipated

Table 4.3 summarizes the main responses to heat stress. They are governed by the **hypothalamus**, a structure in the brain that includes both neurons and endocrine cells. When core temperature rises above a set point, the hypothalamus orders key adjustments. In **peripheral vasodilation**, its signals cause blood vessels in the skin to dilate. More blood flows to the skin, where the excess heat that the blood carries is dissipated.

The hypothalamus also can activate sweat glands and increase the amount of body heat lost via evaporation. With roughly 2.5 million sweat glands in skin, lots of heat is dissipated when the water in sweat evaporates. With prolonged heavy sweating the body also loses key salts, especially sodium chloride. Losing too many of these electrolytes can make you feel woozy. So-called "sports drinks" replenish electrolytes.



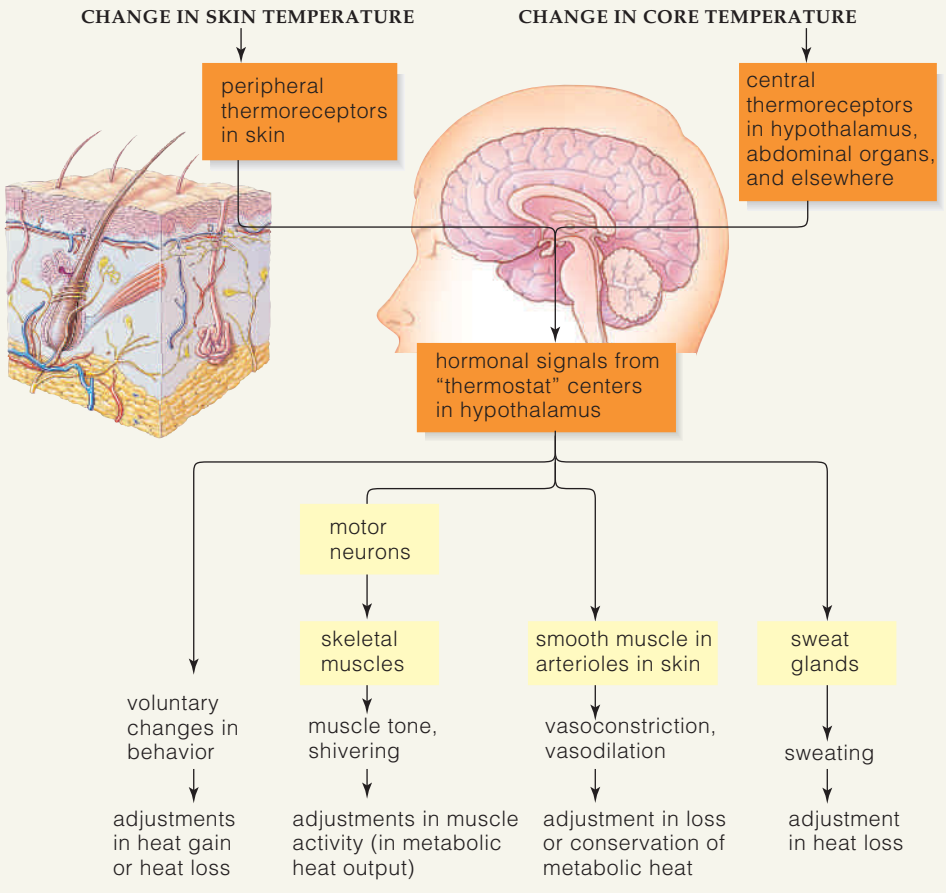


Figure 4.14 Animated!
Homeostatic controls regulate internal body temperature.
The photograph shows Korey Stringer, a professional football player who became seriously overheated during a workout conducted in extremely hot weather. No one realized the danger in time. Korey Stringer collapsed and died.

Summary of Human Responses to Cold Stress and to Heat Stress

Environmental Stimulus	Main Responses	Outcome
Drop in temperature	Vasoconstriction of blood vessels in skin; pilomotor response; behavior changes (e.g., putting on a sweater)	Heat is conserved
	Increased muscle activity; shivering; nonshivering heat production	More heat is produced
Rise in temperature	Vasodilation of blood vessels in skin; sweating; changes in behavior; heavy breathing	Heat is dissipated from body
	Reduced muscle activity	Less heat is produced

Sometimes peripheral blood flow and evaporative heat loss can't adequately counter heat stress. The result is *hyperthermia*, in which the core temperature rises above normal. If the increase isn't too great, a person can suffer *heat exhaustion*, in which blood pressure drops due to vasodilation and water losses from heavy sweating. The skin feels cold and clammy, and the person may collapse.

When heat stress is severe enough to completely break down the body's temperature controls, *heat stroke* occurs. Sweating stops, the skin becomes dry, and the core body temperature rapidly rises to a level that can be lethal.

When someone has a fever, the hypothalamus has reset the "thermostat" that dictates what the body's core temperature will be. The normal response mechanisms are brought into play, but they are carried out to maintain a higher temperature.

When a fever starts, heat production increases, heat loss drops, and the person feels chilled. When a fever "breaks," peripheral vasodilation and sweating increase as the body tries to restore the normal core temperature; then the person feels warm. The controlled increase in core temperature during a fever seems to enhance the body's immune response, so using fever-reducing drugs such as aspirin or ibuprofen may actually interfere with fever's beneficial effects. A severe fever, however, requires medical supervision because of the dangers it poses.

Several responses counteract cold

Table 4.3 also summarizes the major responses to cold stress, which the hypothalamus also regulates. When the outside temperature drops, thermoreceptors (*thermo-* means heat) at the body surface detect the decrease. When their signals reach the hypothalamus, neurons signal smooth muscle in the walls of certain skin blood vessels to contract. This **peripheral vasoconstriction** reduces blood flow to capillaries near the body surface, so your body retains heat. When your hands or feet get cold, as much as 99 percent of the blood that would otherwise flow to your skin is diverted.

In the **pilomotor response** to a drop in outside temperature, your body hair can "stand on end." This happens because smooth muscle controlling the erection of body hair is stimulated to contract. This creates a layer of still air close to the skin that reduces heat losses. (This response is most effective in mammals with more body hair than humans!) Heat loss can be restricted even more by behaviors that reduce the amount of body surface exposed for heat exchange, as when you put on a sweater or hold your arms tightly against your body.

When other responses can't counteract cold stress, signals from the hypothalamus step up skeletal muscle contractions, similar to the low-level contractions that produce muscle tone. The result? You start shivering. Your skeletal muscles contract ten to twenty times per second, boosting heat production throughout the body.

Prolonged or severe exposure to cold can lead to a hormonal response that elevates the rate of metabolism in cells. This *nonshivering heat production* is especially notable in a specialized type of adipose tissue called "brown fat." Heat is generated as the lipid molecules are broken down. Babies (who can't shiver) have this tissue in the neck and armpits and near their kidneys; adults have little brown fat unless they are cold-adapted.

In *hypothermia*, body core temperature falls below the normal range. A drop of only a few degrees leads to mental confusion; further cooling can cause coma and death. Some victims of extreme hypothermia, mainly children, have survived prolonged immersion in ice-cold water. One reason is that mammals, including humans, have a dive reflex. When the body is submerged, the heart rate slows and blood is shunted to the brain and other vital organs.

Freezing often destroys tissues, a condition we call *frostbite*. Frozen cells may be saved if thawing is precisely controlled. This sometimes can be done in a hospital.

Take-Home Message

How does the body maintain a stable core temperature?

- The hypothalamus regulates physiological changes that adjust the body's core temperature.
- Responses to heat stress include dilation of blood vessels near the body surface and evaporative heat loss.
- Responses to cold stress include constriction of blood vessels near the body surface, the pilomotor response, shivering, and nonshivering heat production.

IMPACTS, ISSUES

A Stem Cell Future?

HUMAN embryonic stem cells have potential medical benefits, but some people object to their use. An estimated 500,000 embryos have been created in fertility clinics, then frozen and stored. It's likely that many of these frozen embryos will never be used to produce a pregnancy.

How Would You Vote?

Should scientists be allowed to destroy embryos created in fertility clinics and donated by their parents as a source of cells for research? See CengageNOW for details, then vote online.

Summary

Introduction A tissue is a group of similar cells that perform the same function (Table 4.4). Different tissues combine to form an organ. In an organ system, two or more organs interact in ways that contribute to the body's survival.

Section 4.1 Epithelial tissue covers body surfaces and lines internal cavities. Each kind of epithelium has one surface exposed to body fluids or the outside environment; the opposite surface rests on a basement membrane between it and underlying tissue.

Glands are derived from epithelium. Exocrine glands release substances (such as saliva and tears) onto the surface of an epithelium through ducts or tubes. Endocrine glands secrete hormones directly into extracellular fluid.

Section 4.2 Connective tissues bind, support, strengthen, and protect other tissues. Most have fibers of structural proteins (especially collagen), fibroblasts, and other cells within a matrix. They include fibrous connective tissue and specialized connective tissues such as cartilage, bone, adipose tissue, and blood.

Section 4.3 Muscle tissue contracts. It helps move the body or its parts. The three types of muscle tissue are skeletal muscle, smooth muscle, and cardiac muscle.

Section 4.4 Nervous tissue receives and integrates information from inside and outside the body and sends signals for responses. Neurons and the support cells called neuroglia are the main cells in nervous tissue.

Section 4.6 Tight junctions help prevent substances from leaking across a tissue. Adhering junctions bind cells together in tissues. Gap junctions link the cytoplasm of neighboring cells.

- Use the animation and interaction on CengageNOW to compare the structure and functions of the main types of cell junctions.

Section 4.7 Membranes cover all body surfaces and cavities. Those made of epithelium include mucous and serous membranes. Connective tissue membranes include the synovial membranes of certain joints. The skin is a cutaneous membrane.

Section 4.8 Body organs are located in five major cavities: the cranial cavity (brain); spinal cavity (spinal cord); thoracic cavity (heart and lungs); abdominal cavity (stomach, liver, most of the intestine, other organs); and pelvic cavity (reproductive organs, bladder, rectum). The various organs in the body are arranged into eleven organ systems. Each system performs a specific function, such as transporting blood (cardiovascular system) or reproduction.

- Use the animation and interaction on CengageNOW to investigate the function of organ systems.

Section 4.9 An example of an organ system is the integument, or skin. Skin has an outer epidermis and an underlying dermis. Most epidermal cells are keratinocytes, which make the protein keratin. Keratin makes the skin's outer layer tough and waterproof. Melanocytes in the epidermis produce pigment that gives skin its color. Hair, nails, sweat glands, and oil glands are derived from the epidermis.

Skin protects the rest of the body from abrasion, invading bacteria, ultraviolet radiation, and dehydration. It helps control internal temperature, contains cells that synthesize vitamin D, and serves as a blood reservoir for the rest of the body. Receptors in skin are essential for detecting environmental stimuli.

- Use the animation and interaction on CengageNOW to explore the structure of skin and hair.

Section 4.10 Extracellular fluid (blood and tissue fluid) is the body's internal environment. Tissues, organs, and organ systems work together to maintain the stable state of homeostasis in this environment. Maintaining homeostasis requires sensory receptors, which can detect a stimulus, integrators, and effectors.

In negative feedback, a change in a condition triggers a response that reverses the change. In positive feedback, a response reverses a change by intensifying it for a limited time.

Section 4.11 Physiological responses that govern temperature rely on negative feedback controls that respond to heat stress and cold stress.

- Use the animation and interaction on CengageNOW to see how negative feedback helps regulate body temperature.

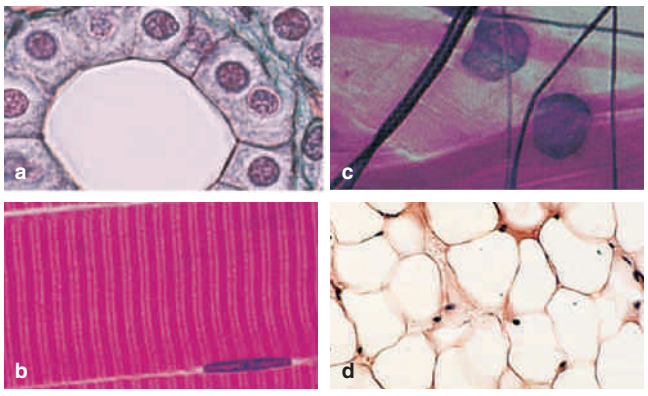
Review Questions

1. List the general characteristics of epithelium, and then describe the basic types of epithelial tissues in terms of specific characteristics and functions.

Summary of Basic Tissue Types in the Human Body

Tissue	Function	Characteristics
Epithelium	Covers body surface; lines internal cavities and tubes	One free surface; opposite surface rests on basement membrane supported by connective tissue
Connective tissue	Binds, supports, adds strength; some provide protection or insulation	Cells surrounded by a matrix (ground substance) containing structural proteins except in blood
FIBROUS CONNECTIVE TISSUES		
Loose	Elasticity, diffusion	Cells and fibers loosely arranged
Dense	Support. elasticity	Several forms. One has collagen fibers in various orientations in the matrix; it occurs in skin and as capsules around some organs. Another form has collagen fibers in parallel bundles; it occurs in ligaments, tendons
Elastic	Elasticity	Mainly elastin fibers; occurs in organs that must stretch
SPECIALIZED CONNECTIVE TISSUES		
Cartilage	Support, flexibility, low-friction surface	Matrix solid but pliable; no blood supply
Bone	Support, protection, movement	Matrix hardened by minerals
Adipose tissue	Insulation, padding, energy storage	Soft matrix around large, fat-filled cells
Blood	Transport	Liquid matrix (plasma) containing blood cells, many other substances
Muscle tissue	Movement of the body and its parts	Made up of arrays of contractile cells
Nervous tissue	Communication between body parts; coordination, regulation of cell activity	Made up of neurons and support cells (neuroglia)

2. List the major types of connective tissues; add the names and characteristics of their specific types.
3. Identify and describe the tissues shown below.



4. List the types of cell junctions and their functions.
5. List the basic types of membranes in the body.
6. Define the terms tissue, organ, and organ system. List the body's eleven major organ systems.
7. What are some functions of skin?
8. Define homeostasis.
9. What is extracellular fluid, and how does the concept of homeostasis pertain to it?
10. What is the difference between negative feedback and positive feedback? Which one is most common for maintaining homeostasis?

Self-Quiz *Answers in Appendix V*

1. _____ tissues have closely linked cells and one free surface.
   a. Muscle
   b. Nerve
   c. Connective
   d. Epithelial
2. Most _____ has collagen and elastin fibers.
   a. muscle tissue
   b. nervous tissue
   c. connective tissue
   d. epithelial tissue
3. _____, a specialized connective tissue, is mostly plasma with cellular components and various dissolved substances.
   a. Irregular connective tissue
   b. Blood
   c. Cartilage
   d. Bone

4. _____ tissue detects and integrates information about changes and controls responses to changes.
   a. Muscle
   b. Nervous
   c. Connective
   d. Epithelial

5. _____ can shorten (contract).
   a. Muscle tissue
   b. Nervous tissue
   c. Connective tissue
   d. Epithelial tissue

6. After you eat too many carbohydrates and proteins, your body converts the excess to storage fats, which accumulate in _____.
   a. loose connective tissue
   b. dense connective tissue
   c. adipose tissue
   d. both b and c

7. In _____, physical and chemical aspects of the body are being kept within tolerable ranges by controlling mechanisms.
   a. positive feedback
   b. negative feedback
   c. homeostasis
   d. metastasis

8. Fill in the blanks: _____ detect specific environmental changes, an _____ pulls different bits of information together in the selection of a response, and _____ carry out the response.

9. Match the concepts:

____ muscles and glands
____ positive feedback
____ sites of body receptors
____ negative feedback
____ brain

a. integrating center
b. reverses an altered condition
c. eyes and ears
d. effectors
e. intensifies the original condition

Critical Thinking

1. In people who have the genetic disorder anhidrotic ectodermal dysplasia, patches of tissue have no sweat glands. What kind of tissue are we talking about?

2. The disease called scurvy results from a deficiency of vitamin C, which the body uses to synthesize collagen. Explain why scurvy sufferers tend to lose teeth, and why any wounds heal much more slowly than normal, if at all.

3. The man pictured in Figure 4.15 wears several dozen ornaments in his skin, nearly all of them applied by piercing. Among the skin's many functions, it serves as a barrier to potentially dangerous bacteria, and some people object to extensive body piercing on the grounds that it opens the door to infections. Explain why you do or don't agree with this objection.

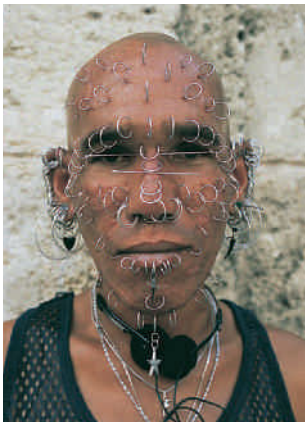
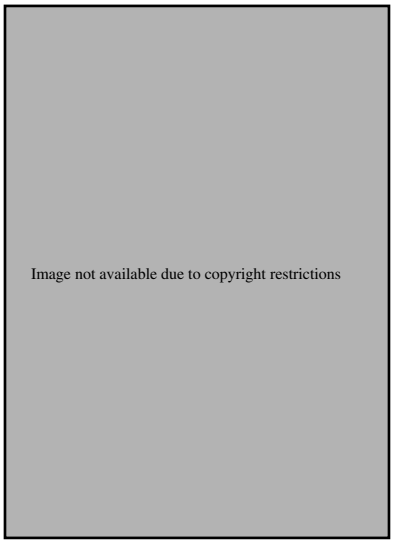


Figure 4.15 **This man has chosen to undergo heavy body piercing.**

4. Porphyria, a genetic disorder, occurs in about 1 in 25,000 humans. Affected people lack enzymes of a metabolic pathway that forms heme, the iron-containing group in hemoglobin. Intermediate chemicals called porphyrins accumulate and cause awful symptoms, especially if the person is exposed to sunlight. Lesions and scars form on the skin (Figure 4.16). Thick hair grows on the face and hands. The gums retreat and the canine teeth can begin to look like fangs. Symptoms get worse if the person consumes alcohol or garlic. Individuals with porphyria can avoid sunlight and aggravating substances. They also can get injections of heme from normal red blood cells. If you are familiar with vampire stories, which date from centuries ago, can you think of a reason why they may have arisen among people who knew nothing about the cause of porphyria?



EXPLORE ON YOUR OWN

As epithelium, your skin contains fibers of collagen and elastin. These structural proteins have different properties that you can see in action when you pull on a patch of skin. Notice that even if you pull firmly, the skin doesn't tear. Which type of protein fiber gives the skin that tensile strength? Which type returns the skin to its original shape when you let go?

The Skeletal System

5

IMPACTS, ISSUES

Creaky Joints

WHETHER you're 18 or 80, you probably have or will develop some degree of osteoarthritis—a disorder in which joints become painfully stiff because their cartilage lining is breaking down or bone spurs have formed there. Disease, sports injuries, obesity, and simple aging cause creaky joints, and common remedies range from nonprescription pain relievers and cartilage-building supplements to injections of steroid drugs. Severely damaged joints often are replaced with high-tech artificial ones.

Some arthritis sufferers try less conventional treatments. Uninformed ones eat ground-up cartilage from sharks or baby chicks. Botanicals—herbs and exotic plant extracts—also are finding customers eager to find relief for their symptoms.

There is a long menu of nontraditional, plant-based arthritis remedies, including ginger, devil's claw, and an exotic herb called ashwaghanda. Do such substances work? Well, in 1998 researchers at a meeting of the American College of Rheumatology reported the results of a carefully designed study of 90 people with osteoarthritis. Of patients who used botanicals suggested by Ayurveda, the traditional medicine of India, half improved, compared to only one-fifth of patients who received a placebo.

Critics pointed out that this research was sponsored by a company that sells the herbs. In general, few herbal remedies have been studied using rigorous scientific methods. Consumers often lack reliable information about purported health effects of many herbal remedies.

Arthritis research introduces our topic in this chapter, the **skeletal system**. This organ system consists of the skeleton along with cartilages, joints, and straplike ligaments that hold our bones together. As you will learn, your bones are not just a sturdy framework for your soft flesh. They partner with skeletal muscles to bring about movement and have an essential role in maintaining the body's calcium balance.

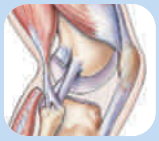
KEY CONCEPTS

The Structure and Functions of Bones

Bones are built of bone tissue. They store minerals, protect and support soft organs, and function in body movement. Some bones contain marrow where blood cells develop. Section 5.1

The Skeleton

The skeleton's key function is to serve as the body's internal framework. Its 206 bones are organized into two parts, the axial skeleton and the appendicular skeleton. Sections 5.2–5.4



Joints

At joints, bones touch or are in close contact with one another. Some of these connections permit adjoining bones to move in ways that in turn move body parts, such as the limbs. Section 5.5

The Skeleton under Siege

Disorders that affect our bones usually prevent them from functioning as usual. In addition to breaks and arthritis, the skeleton may be impaired by cancer, infections, and other conditions. Section 5.6

Disorders of the Skeletal System and Homeostasis

Section 5.7

LINKS TO EARLIER CONCEPTS

- This chapter begins our survey of the body's eleven organ systems. As you study the skeletal system, you will learn more about the structure and functions of bone tissue, cartilage, and some other connective tissues (4.2) that are major components of the system.
- Chapter 1 introduced the concept of homeostasis, and Section 4.11 gave you an overview of mechanisms that help maintain this internal stability. Although courses in human biology usually consider each organ system in turn, it is important to keep in mind that at every moment all of your organ systems are contributing to the survival of your whole body.

How Would You Vote?

Should claims about "medicinal" plant extracts have to be backed up by independent scientific tests? See CengageNOW for details, then vote online.

5.1 Bone: Mineralized Connective Tissue

- **Bones are composed of connective tissue hardened by the mineral calcium.**
- **Link to Connective tissues 4.2**

Bone is a connective tissue, so it is a blend of living cells and a matrix that contains fibers. Bones are covered by a sturdy two-layer membrane called the periosteum (meaning "around the bone"). The membrane's outer layer is dense connective tissue and the inner layer contains bone cells called **osteoblasts** ("bone formers"). As bone develops, the osteoblasts secrete collagen and some elastin, as well as carbohydrates and other proteins. With time, this matrix around osteoblasts hardens when salts of the mineral calcium are deposited in it. The osteoblasts are trapped in spaces, or lacunae, in the matrix (*lacuna* = hole). At this point their bone-forming function ends and they are called **osteocytes** (*osteo* = bone; *cyte* = cell).

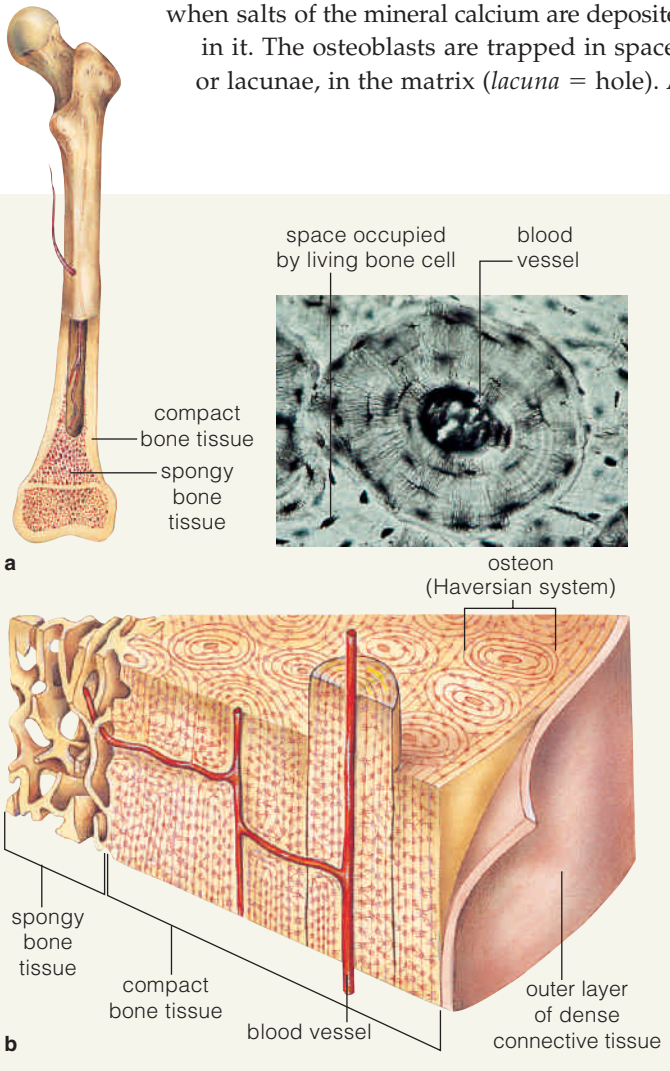


Figure 5.1 Animated! Bones contain both compact bone tissue and spongy bone tissue. (**a**) Spongy and compact bone tissue in a femur. (**b**) The canal in the center of each osteon contains blood vessels and nerves. The blood vessel carries substances to and from osteocytes, living bone cells in small spaces (lacunae) in the bone tissue. Narrow tunnels called canaliculi connect neighboring spaces.

The minerals in bone tissue make it hard, but it is the collagen that gives our bones the strength to withstand the mechanical stresses associated with activities such as standing, lifting, and tugging.

There are two kinds of bone tissue

Bones contain two kinds of tissue, compact bone and spongy bone. Figure 5.1 shows where these tissues are in a long bone such as the femur (thighbone). As its name suggests, **compact bone** is a dense tissue that looks solid and smooth. In a long bone, it forms the bone's shaft and the outer part of its two ends. A cavity inside the shaft contains bone marrow.

Compact bone tissue forms in thin, circular layers around small central canals. Each set of layers is called an **osteon** (or sometimes a *Haversian system*). The canals connect with each other and serve as channels for blood vessels and nerves that transport substances to and from osteocytes. Osteocytes also extend slender cell processes into narrow channels called canaliculi that run between lacunae. These "little canals" allow nutrients to move through the hard matrix from osteocyte to osteocyte. Wastes can be removed the same way.

The bone tissue *inside* a long bone's shaft and at its ends looks like a sponge. Tiny, flattened struts are fused together to make up this **spongy bone** tissue, which looks lacy and delicate but actually is quite firm and strong.

A bone develops on a cartilage model

An early embryo has a rubbery skeleton that consists of cartilage and membranes. Yet, after only about two months of life in the womb, this flexible framework is transformed into a bony skeleton. Once again, we can look at the development of a long bone as an example.

As you can see at the top of Figure 5.2, a cartilage "model" provides the pattern for each long bone. Once the outer membrane is in place on the model, the bone-forming osteoblasts become active and a bony "collar" forms around the cartilage shaft. Then the cartilage inside the shaft calcifies, and blood vessels, nerves, and elements including osteoblasts begin to infiltrate the forming bone. Soon, the marrow cavity forms and osteoblasts produce the matrix that will become mineralized with calcium.

Each end of a long bone is called an **epiphysis** (e-PIF-uh-sis). As long as a person is growing, each epiphysis is separated from the bone shaft by an *epiphyseal plate* of cartilage. Human growth hormone (GH) prevents the plates from calcifying, so the bone can lengthen. When

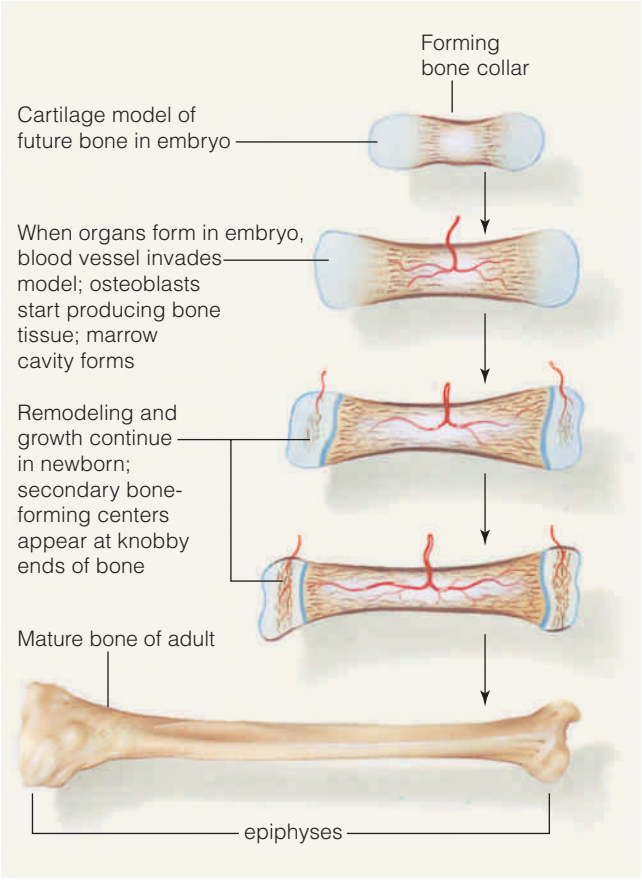


Figure 5.2 **Animated! A long bone forms on a cartilage model.** First, osteoblasts begin to function in a cartilage model in the embryo. The bone-forming cells are active first in the shaft, then at the knobby ends. In time, cartilage is left only in the epiphyses at the ends of the shaft.

growth stops, usually in the late teens or early twenties, bone replaces the cartilage plates.

Bone tissue is constantly "remodeled"

Calcium is constantly entering and leaving a person's bones. Calcium is deposited when osteoblasts form bone, and it is withdrawn when "bone breaker" cells called **osteoclasts** break down the matrix of bone tissue. This ongoing calcium recycling is called **bone remodeling**, and it has several important functions.

Regularly breaking down "old" bone and replacing it with fresh tissue helps keep bone resilient, so it is less likely to become brittle and break. When a bone is subjected to mechanical stress, such as load-bearing exercise, the remodeling process is adjusted so that more bone is deposited than removed. That is why the bones of regular exercisers are denser and stronger than the bones of couch potatoes. On the other hand, when the body must heal a broken bone, osteoclasts release more calcium than usual from bone matrix. Osteoblasts then use the calcium to repair the injured bone tissue.

A child's body requires lots of calcium to meet the combined demands of bone growth and other needs for

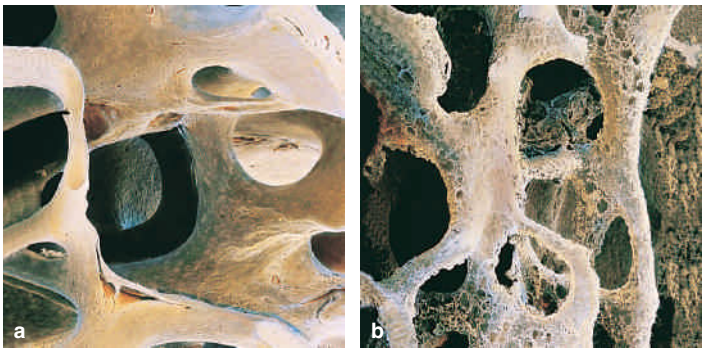


Figure 5.3 **In osteoporosis, bone tissue breaks down faster than it is rebuilt.** (**a**) Normal bone tissue. (**b**) After osteoporosis gets underway, the replacement of mineral ions lags behind their withdrawal during remodeling. In time the tissue erodes, and the bone becomes hollow and brittle.

the calcium stored in bones. Along with dietary calcium, remodeling helps meet the demand. For example, the diameter of a growing child's thighbones increases as osteoblasts form bone at the surface of each shaft. At the same time, however, osteoclasts break down a small amount of bone tissue *inside* the shaft. Thus the child's thighbones become thicker and stronger to support the increasing body weight, but they don't get too heavy.

Bone remodeling also plays a key role in maintaining homeostasis of the blood level of calcium. Neither our nervous system nor our muscles can function properly unless the blood level of calcium stays within a narrow range. When the level falls below this range, a hormone called PTH stimulates osteoclasts to break down bone and release calcium to the blood. If the level rises too high, another hormone, calcitonin, stimulates osteoblasts to *deposit* calcium in bone tissue. Notice that this control mechanism is an example of negative feedback. You will read more about it in Chapter 15, when we take a closer look at hormones.

As we age, bone tissue may break down faster than it is renewed. This steady deterioration is called *osteoporosis* (Figure 5.3). When it occurs, the backbone, pelvis (hip bones), and other bones lose mass. Osteoporosis is most common in women past menopause, although men can be affected, too. Deficiencies of calcium and sex hormones, smoking, and a sedentary lifestyle all may contribute to osteoporosis. Exercise (to stimulate bone deposits) and taking in plenty of calcium can help minimize bone loss. Medications can slow or even help reverse the bone loss.

Take-Home Message

What is bone tissue, and how do bones grow?

- Bone tissue, including both compact bone and spongy bone, consists of living cells and a nonliving mineralized matrix.
- Bones grow, become strong, and are repaired through the process of bone remodeling.

5.2 The Skeleton: The Body's Bony Framework

- **Bones provide a hard surface against which muscles can exert force to move body parts.**
- **Link to Muscle tissue 4.3**

From ear bones the size of a watch battery to massive thighbones, bones vary in size and shape. Some bones, like the thighbone in Figure 5.4, are long and slender. Other bones, like the ankle bones, are short. Still other bones, including the sternum (breastbone), are flat, and still others, such as spinal vertebrae, are "irregular." All bones are alike in some ways, however. They all contain bone tissue and other connective tissue that lines their surfaces and internal cavities. At joints there is cartilage where one bone meets or "articulates" with another. Other tissues associated with bones include nervous tissue and epithelium, which occurs in the walls of blood vessels that carry substances to and from bones.

Bones are complex organs. Some, such as long bones, have cavities that contain **bone marrow**, a connective tissue where blood cells are formed. With time, the red marrow in most long bones is replaced by fatty yellow marrow. For this reason, most of an adult's blood cells form in red bone marrow in irregular bones, such as the hip bone, and in flat bones, such as the sternum. If you lose a great deal of blood, yellow marrow in your long bones can convert to red marrow, which makes red blood cells.

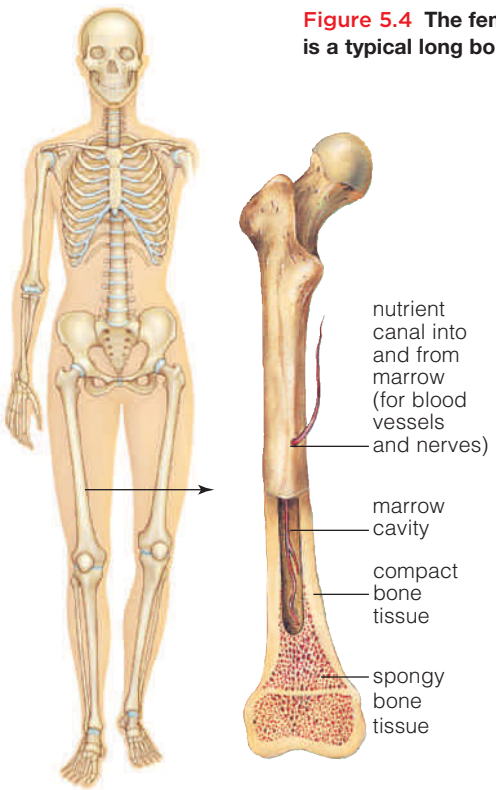


Figure 5.4 The femur (thighbone) is a typical long bone.

Functions of Bone

1. **Movement.** Bones interact with skeletal muscles to maintain or change the position of body parts.
2. **Support.** Bones support and anchor muscles.
3. **Protection.** Many bones form hard compartments that enclose and protect soft internal organs.
4. **Mineral storage.** Bones are a reservoir for calcium and phosphorus. Deposits and withdrawals of these mineral ions help to maintain their proper concentrations in body fluids.
5. **Blood cell formation.** Some bones contain marrow where blood cells are produced.

Bones, ligaments, and tendons are the basic components of the skeleton

A fully formed human skeleton has 206 bones, which grow by way of remodeling until a person is about twenty. The bones are organized into an **axial skeleton** and an **appendicular skeleton** (Figure 5.5). The bones of the axial skeleton form the body's vertical, head-to-toe axis. The appendicular ("hanging") skeleton includes bones of the limbs, shoulders, and hips. **Ligaments** connect bones at joints. Ligaments are composed of elastic connective tissue, so they are stretchy and resilient like thick rubber bands. **Tendons** are cords or straps that attach muscles to bones or to other muscles. They are built of connective tissue packed with collagen fibers, which make tendons strong.

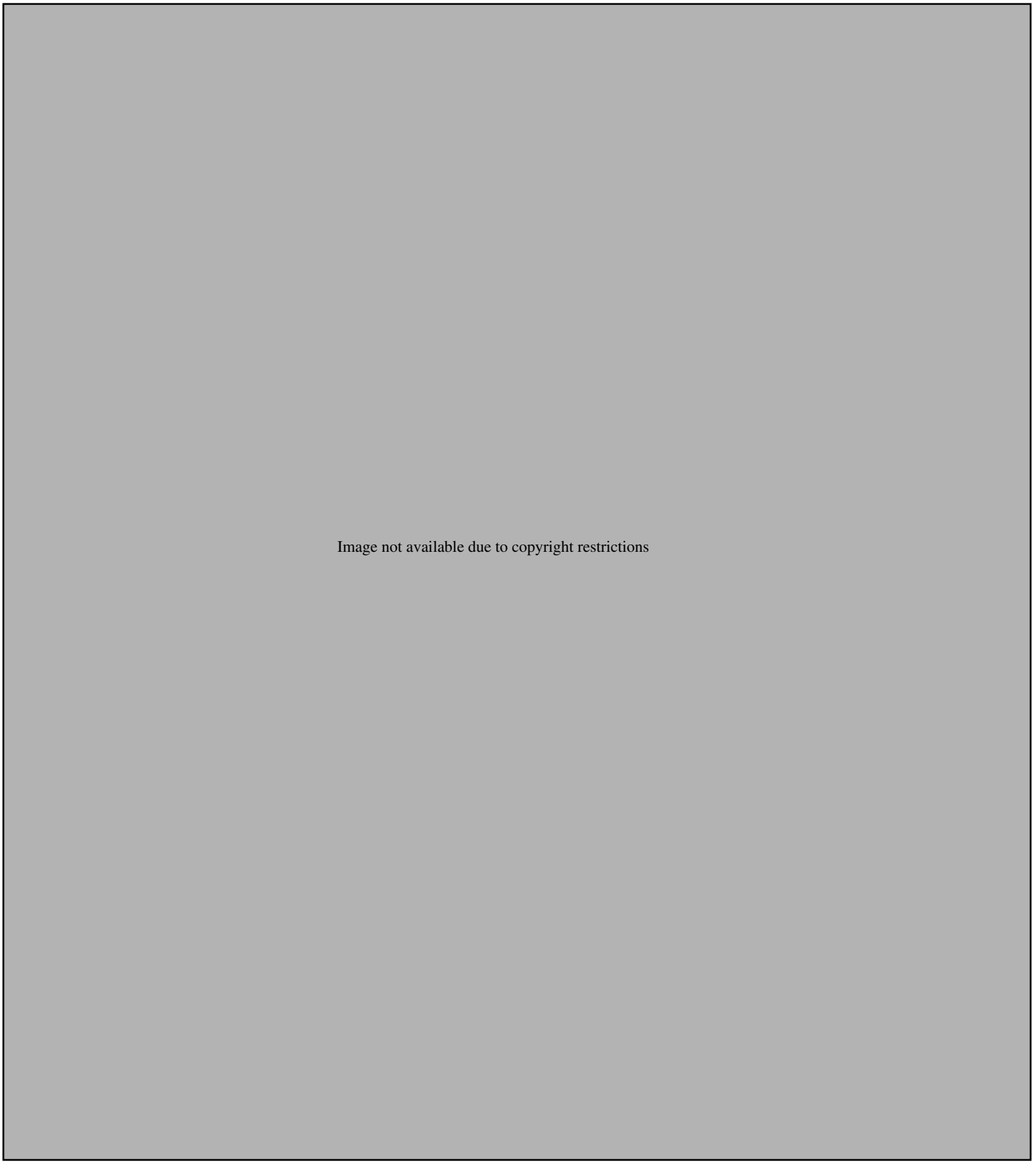
Bones have several important functions

Bones contribute to homeostasis in many ways (Table 5.1). For instance, bones that support and anchor skeletal muscles help maintain or change the positions of our body parts. Some form hard compartments that enclose and protect other organs; for example, the skull encloses and protects the brain, and the rib cage protects the lungs. As noted in Section 5.1, bones also serve as a "pantry" where the body can store calcium. Because the calcium in bone is in the form of the compound calcium phosphate, bone also is a storage depot for phosphorus.

Take-Home Message

What are the main components of the skeleton?

- The fully formed human skeleton consists of 206 bones, in axial and appendicular divisions.
- Bones contribute to homeostasis by providing body support, enabling movement, and storing minerals. Some bones also contain marrow where blood cells are produced.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5.3 The Axial Skeleton

- **The axial skeleton supports much of our body weight and protects many internal organs.**
- **Link to Mucous membranes 4.7**

We begin our tour of the skeleton with bones of the axial skeleton—the skull, vertebral column (backbone), ribs, and sternum (the breastbone).

The skull protects the brain

Did you know that your skull consists of more than two dozen bones? These bones are divided into several groups. By tradition many of them have names derived from Latin, but their roles are easy to grasp. For example, the "cranial vault," or **brain case**, includes eight bones that together surround and protect your brain. As Figure 5.6*a* shows, the *frontal bone* makes up the forehead and upper ridges of the eye sockets. It contains **sinuses**, which are air spaces lined with mucous membrane. Sinuses make the skull lighter, which translates into less weight for the spine and neck muscles to support. But channels connect them to the nasal passages, and their ability to produce mucus can mean misery for anyone who has a cold or pollen allergies. A bacterial infection in the nasal passages can spread to the sinuses, causing *sinusitis*. Figure 5.6*c* shows sinuses in the cranial and facial bones.

Temporal bones form the lower sides of the cranium and surround the ear canals, which are tunnels that lead to the middle and inner ear. Inside the middle ear are tiny bones that function in hearing. On either side of your head, in front of each temporal bone, a *sphenoid bone* extends inward to form part of the inner eye socket. The *ethmoid bone* also contributes to the inner socket and helps support the nose. Two *parietal bones* above and behind the temporal bones form much of the skull; they sweep upward and meet at the top of the head. An *occipital bone* forms the back and base of the skull and also encloses a large opening, the *foramen magnum* ("large hole"). Here, the spinal cord emerges from the base of the brain and enters the spinal column (Figure 5.6*b*). Several passageways provide channels for nerves and blood vessels. For instance, the jugular veins, which carry blood leaving the brain, pass through openings between the occipital bone and each temporal bone.

Facial bones support and shape the face

Figure 5.6 also shows facial bones, many of which you can easily feel with your fingers. The largest is your lower jaw, or **mandible**. The upper jaw consists of two *maxillary bones*. Two *zygomatic bones* form the middle of the hard bumps we call "cheekbones" and the outer parts of the eye sockets. A small, flattened *lacrimal bone* fills out the inner eye socket. Tear ducts pass between this bone and the maxillary bones and drain into the nasal cavity—one reason why your nose runs when you cry. Tooth sockets in the upper and lower jaws also contain the teeth.

Palatine bones make up part of the floor and side wall of the nasal cavity. (Extensions of these bones, together with the maxillary bones, form the back of the hard palate, the "roof" of your mouth.) A *vomer bone* forms part of the

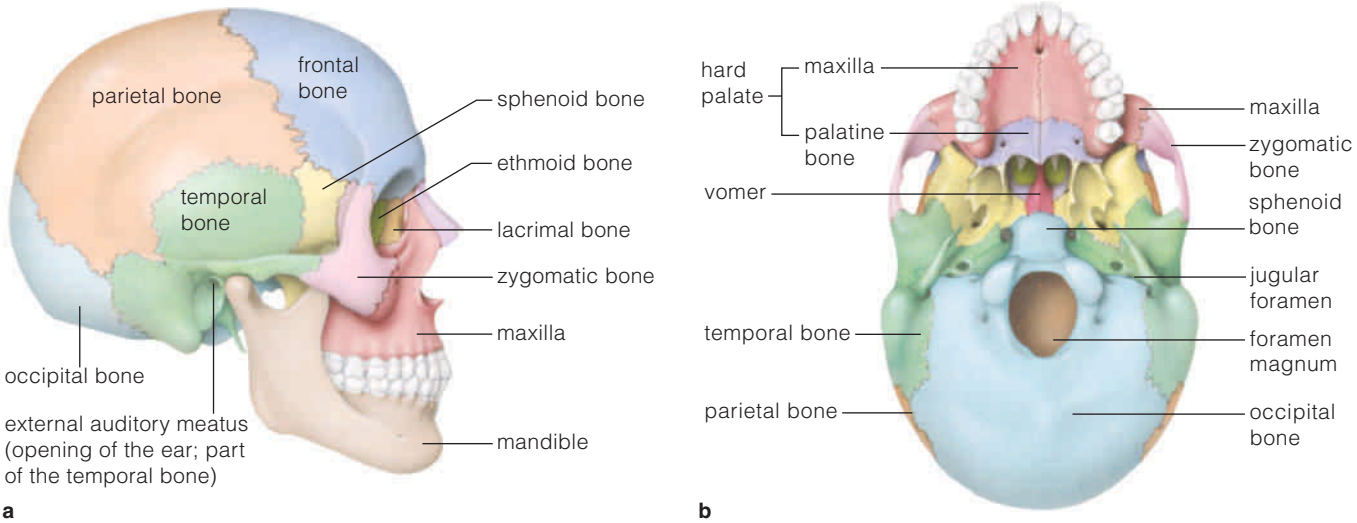


Figure 5.6 Skull bones surround the brain and support the forehead. (**a**) The jagged junctions between skull bones are called sutures. (**b**) A bottom-up view of the skull. The large foramen magnum is situated atop the uppermost cervical vertebra. (**c**) Sinuses in bones in the skull and face.

nasal septum, a thin "wall" that divides the nasal cavity into two sections.

The vertebral column is the backbone

The flexible, curved human vertebral column—your backbone or spine—extends from the base of the skull to the hip bones (pelvic girdle). This arrangement transmits the weight of a person's torso to the lower limbs. As a result, people who gain a large amount of excess weight may develop problems with their knees and ankles because those joints are not designed to bear such a heavy load. The **vertebrae** are stacked one on top of the other. They have bony projections that form a protected channel for the delicate spinal cord. As sketched in Figure 5.7, humans have seven *cervical* vertebrae in the neck, twelve thoracic vertebrae in the chest area, and five *lumbar* vertebrae in the lower back. During the course of human evolution, five other vertebrae have become fused to form the sacrum, and another four have become fused to form the coccyx, or "tailbone." Counting these, there are thirty-three vertebrae in all.

Roughly a quarter of your spine's length consists of **intervertebral disks**—compressible pads of fibrocartilage sandwiched between vertebrae. The disks serve as shock absorbers and flex points. They are thickest between cervical vertebrae and between lumbar vertebrae. Severe or rapid shocks, as well as changes due to aging, can cause a disk to *herniate* or *"slip."* If the slipped disk ruptures, its jellylike core may squeeze out, making matters worse. And if the changes compress neighboring nerves or the spinal cord, the result can be excruciating pain and the loss of mobility that often comes with pain. Depending on the situation, treatment can range from bed rest and use of painkilling drugs to surgery.

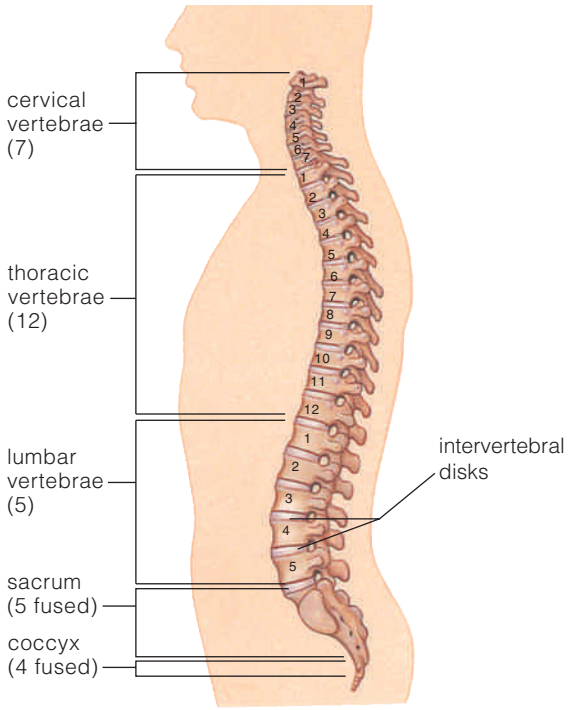
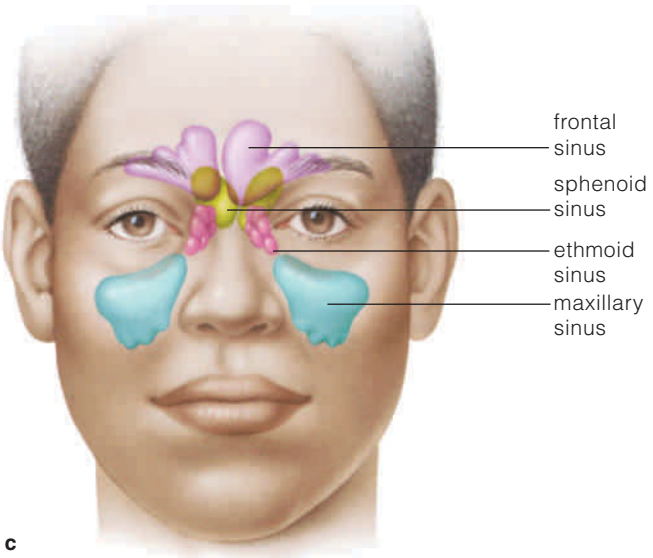


Figure 5.7 Vertebrae and interverterbral disks make up the vertebral column (backbone). The cranium balances on the column's top vertebra.



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The ribs and sternum support and help protect internal organs

In addition to protecting the spinal cord, absorbing shocks, and providing flexibility, the vertebral column also serves as an attachment point for twelve pairs of **ribs**, which in turn function as a scaffolding for the body cavity of the upper torso. The upper ribs also attach to the paddle-shaped **sternum** (see Figure 5.5). As you will read in later chapters, this rib cage helps protect the lungs, heart, and other internal organs and is vitally important in breathing.

Take-Home Message

What are the parts of the axial skeleton?

- Bones of the axial skeleton make up the body's vertical axis. They include the skull and facial bones, the vertebral column, and the ribs and sternum.
- Intervertebral disks absorb shocks and serve as flex points.

5.4 The Appendicular Skeleton

- **The appendicular skeleton includes the bones that support the limbs, upper chest, shoulders, and pelvis.**

"Append" means to hang, and the appendicular skeleton includes the bones of "hanging" body parts such as your arms, hands, legs, and feet. It also includes a pectoral girdle at each shoulder and the pelvic girdle at the hips.

The pectoral girdle and upper limbs provide flexibility

Each **pectoral girdle** (Figure 5.8) has a large, flat shoulder blade—a **scapula**—and a long, slender collarbone, or **clavicle**, that connects to the breastbone (sternum). The rounded shoulder end of the **humerus**, the long bone of the upper arm, fits into an open socket in the scapula. Your arms can move in a great many ways; they can swing in wide circles and back and forth, lift objects, or tug on a rope. Such freedom of movement is possible because muscles only loosely attach the pectoral girdles and upper limbs to the rest of the body. Although the arrangement is sturdy enough under normal conditions, it is vulnerable to strong blows. Fall on an outstretched arm and you might fracture your clavicle or dislocate your shoulder. The collarbone is the bone most frequently broken.

Each of your upper limbs includes thirty separate bones. The humerus connects with two bones of the forearm—the **radius** (on the thumb side) and the **ulna** (on the "pinky finger" side). The upper end of the ulna joins the lower end of the humerus to form the elbow joint. The bony bump sometimes (mistakenly) called the "wrist bone" is the lower end of the ulna.

The radius and ulna join the hand at the wrist joint, where they meet eight small, curved *carpal* bones. Ligaments attach these bones to the long bones. Blood vessels, nerves, and tendons pass in sheaths over the wrist; when a blow, constant pressure, or repetitive movement (such as typing) damages these tendons, the result can be a painful disorder called *carpal tunnel syndrome* (Section 5.6). The bones of the hand, the five *metacarpals*, end at the knuckles. *Phalanges* are the bones of the fingers.

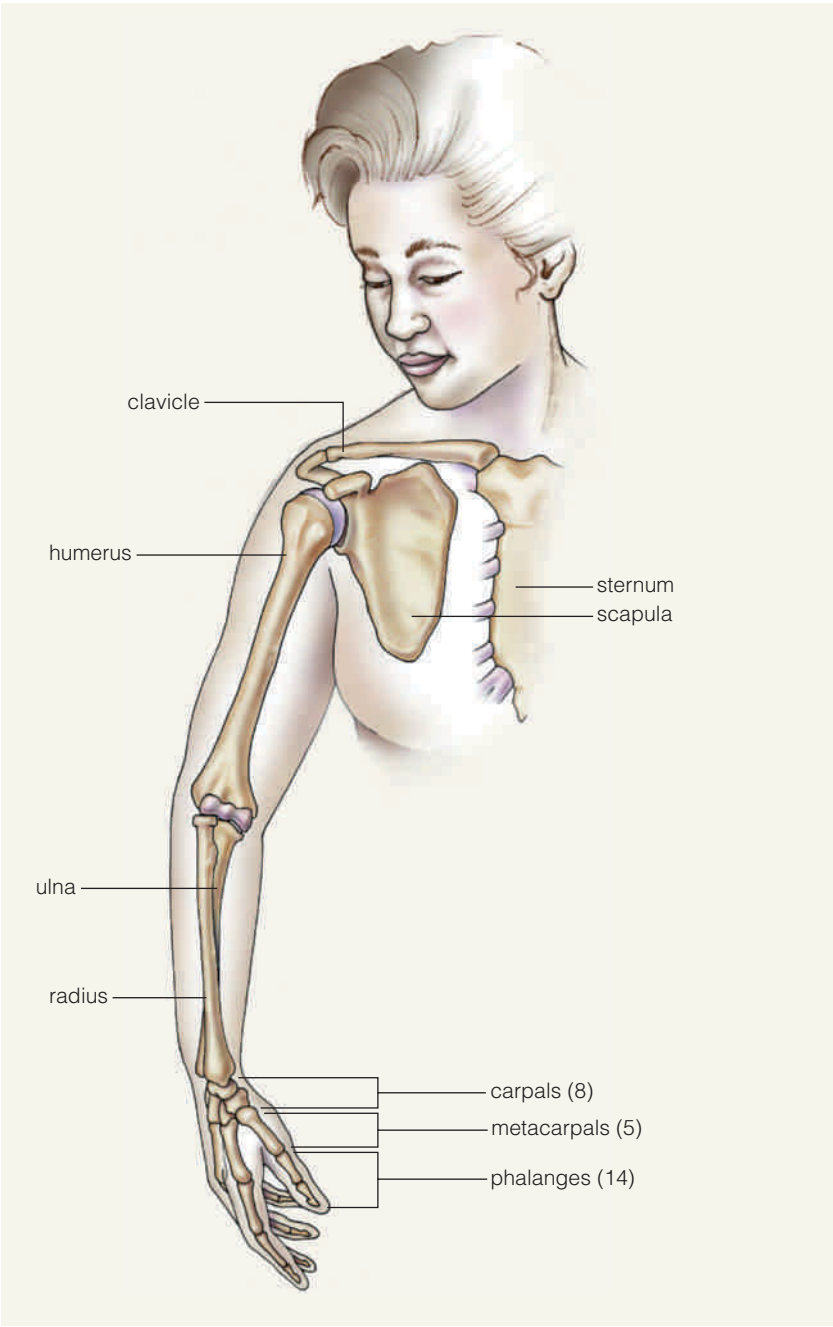


Figure 5.8 Animated! **Bones of the pectoral girdle, the arm, and the hand form the upper part of the appendicular skeleton.**

The pelvic girdle and lower limbs support body weight

For most of us, our shoulders and arms are much more flexible than our hips and legs. Why? Although there are similarities in the basic "design" of both girdles, this lower part of the appendicular skeleton is adapted to bear the body's entire weight when we are standing. The **pelvic girdle** (Figure 5.9) is much more massive than the combined pectoral girdles, and it is attached to the axial skeleton by extremely strong ligaments. It forms an open basin: A pair of *coxal bones* attach to the lower spine (sacrum) in back, then curve forward and meet at the *pubic arch*. ("Hipbones" are actually the upper *iliac* regions of the coxal bones.) This combined structure is the *pelvis*. In females the pelvis is broader than in males, and it shows other structural differences that are evolutionary adaptations for childbearing. A forensic scientist or paleontologist examining skeletal remains can easily establish the sex of the deceased if a pelvis is present.

The legs contain the body's largest bones. In terms of length, the thighbone, or **femur**, ranks number one. It is also extremely strong. When you run or jump, your femurs routinely withstand stresses of several tons per square inch (aided by contracting leg muscles). The femur's ball-like upper end fits snugly into a deep socket in the coxal (hip) bone. The other end connects with one of the bones of the lower leg, the thick, load-bearing tibia on the inner (big toe) side. A slender fibula parallels the tibia on the outer (little toe) side. The tibia is your shinbone. A triangular kneecap, the patella, helps protect the knee joint. In spite of this protection, knees are among the joints most often damaged by athletes, both amateur and professional.

The ankle and foot bones correspond closely to those of the wrist and hand. *Tarsal* bones make up the ankle and heel, and the foot contains five long bones, the *metatarsals*. The largest metatarsal, leading to the big toe, is thicker and stronger than the others to support a great deal of body weight. Like fingers, the toes contain phalanges.

Take-Home Message

- The appendicular skeleton includes bones of the limbs, a pectoral girdle at the shoulders, and a pelvic girdle at the hips.
- The thighbone (femur) is the largest bone in the body and one of the strongest. The wrists and hands and ankles and feet have corresponding sets of bones known respectively as carpals and metacarpals and tarsals and metatarsals.

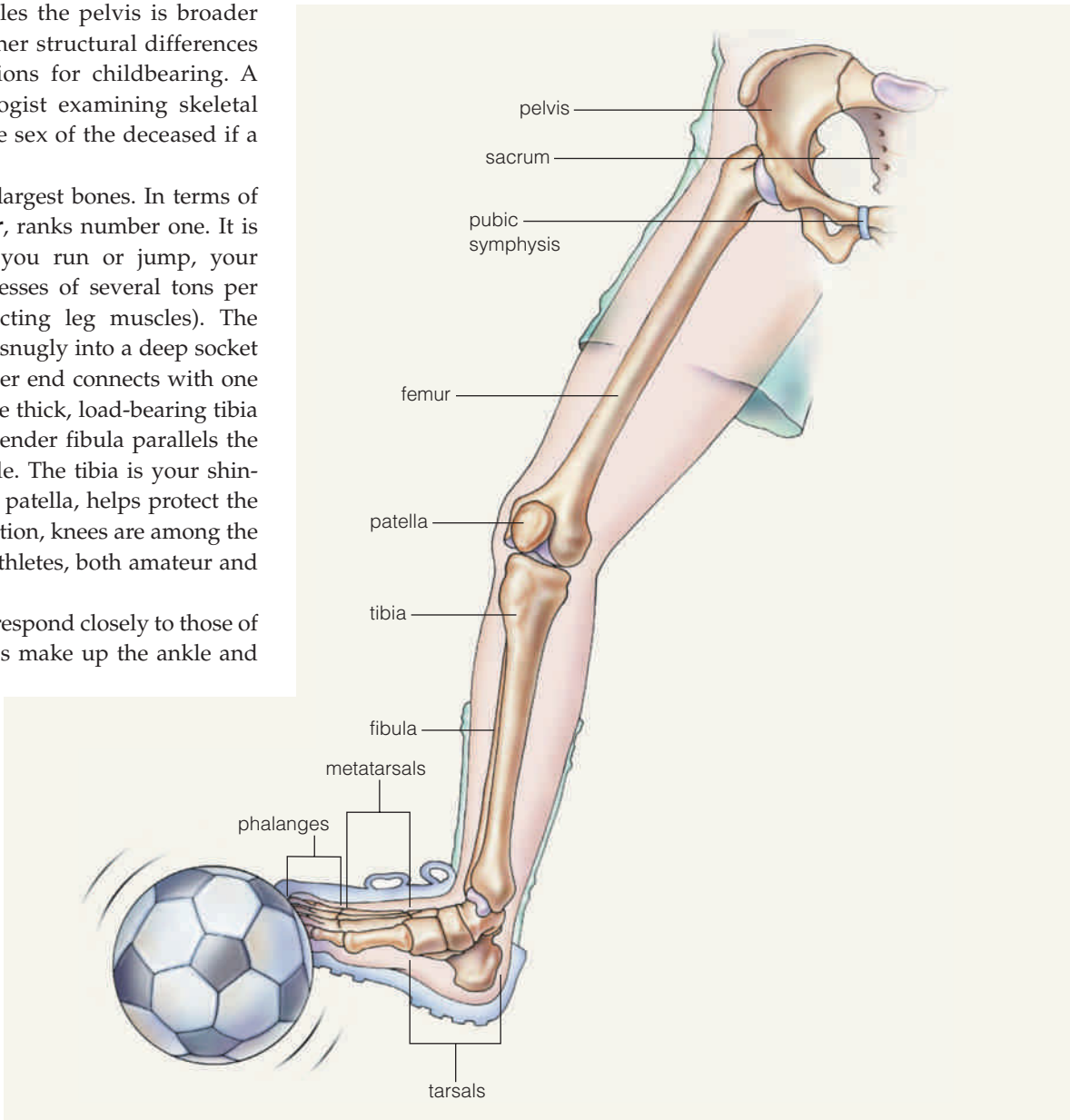


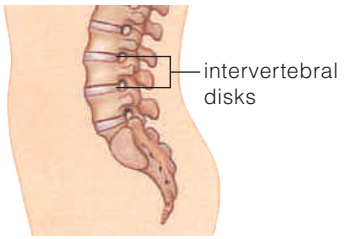
Figure 5.9
Animated! The pelvic girdle, the leg, and the foot form the lower part of the appendicular skeleton.

5.5 Joints: Connections between Bones

- **Joints are areas of contact or near contact between bones. All joints have some form of connective tissue that bridges the gap between bones.**
- **Link to Synovial membranes 4.7**

In the most common type of joint, called a **synovial joint**, adjoining bones are separated by a cavity (Figure 5.10). The articulating ends of the bones are covered with a cushioning layer of cartilage, and they are stabilized by ligaments. A capsule of dense connective tissue surrounds the bones of a synovial joint. The synovial membrane that lines the inner surface of the capsule contains cells that secrete a lubricating *synovial fluid* into the joint cavity.

Synovial joints are built to allow movement. In hinge-like synovial joints such as the knee and elbow, the motion is limited to simple flexing and extending (straightening). The ball-and-socket joints at the hips are capable of a wider range of movements: They can rotate and move in different planes—for instance, up-down or side-to-side. Figure 5.11 shows these and some other ways body parts can move at joints.



In a **cartilaginous joint**, cartilage fills the space between bones, so only slight movement is possible. Such joints occur between vertebrae and between the breastbone and some of the ribs.

There is no cavity in a **fibrous joint**, and fibrous connective tissue unites the bones. An adult's fibrous joints generally don't allow movement. Examples are the fibrous joints that hold your teeth in their sockets. In a fetus, fibrous joints loosely connect the flat skull bones. During childbirth, these loose connections allow the bones to slide over each other, preventing skull fractures. A newborn baby's skull still has fibrous joints and soft areas called fontanels. With time the joints harden into *sutures*. Much later in life the skull bones may fuse completely.

Take-Home Message

What are joints?

- A joint connects one bone to another. In all joints, connective tissue bridges the gap between bones.
- Freely movable (synovial) joints include the hinge-like knee joint and the ball-and-socket joints at the hips.
- Cartilaginous joints have cartilage in the space between bones. They allow only slight movement. In fibrous joints fibrous connective tissue joins the bones.

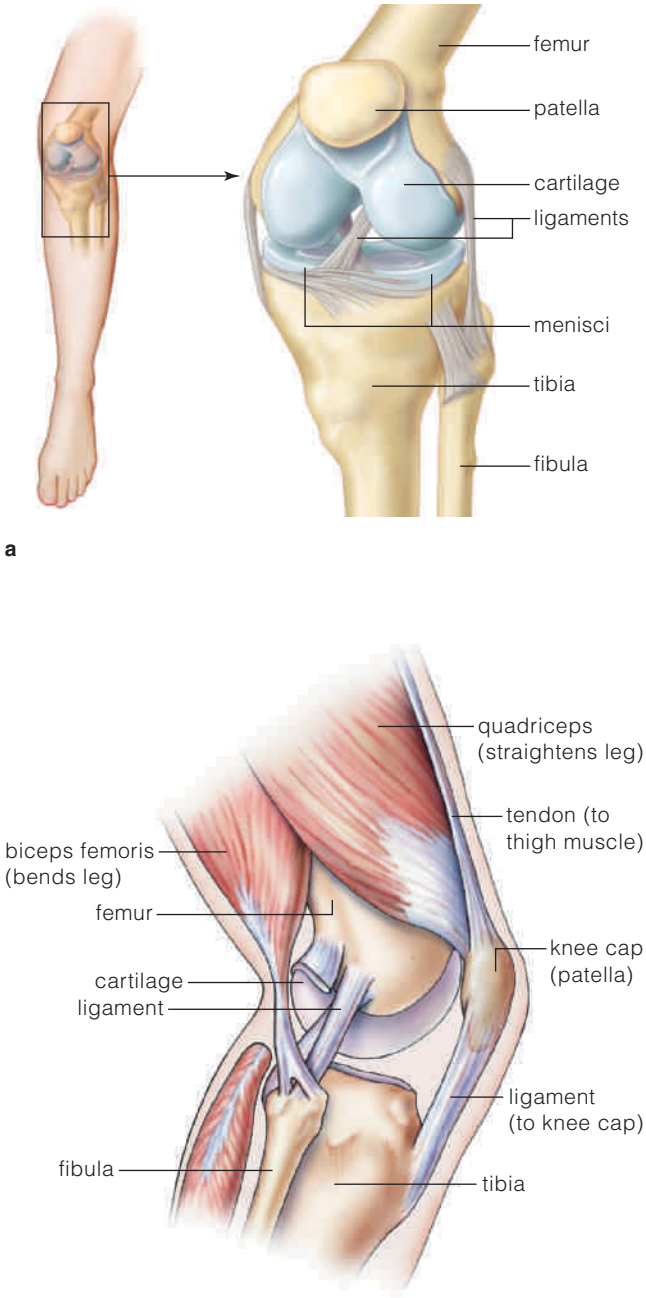
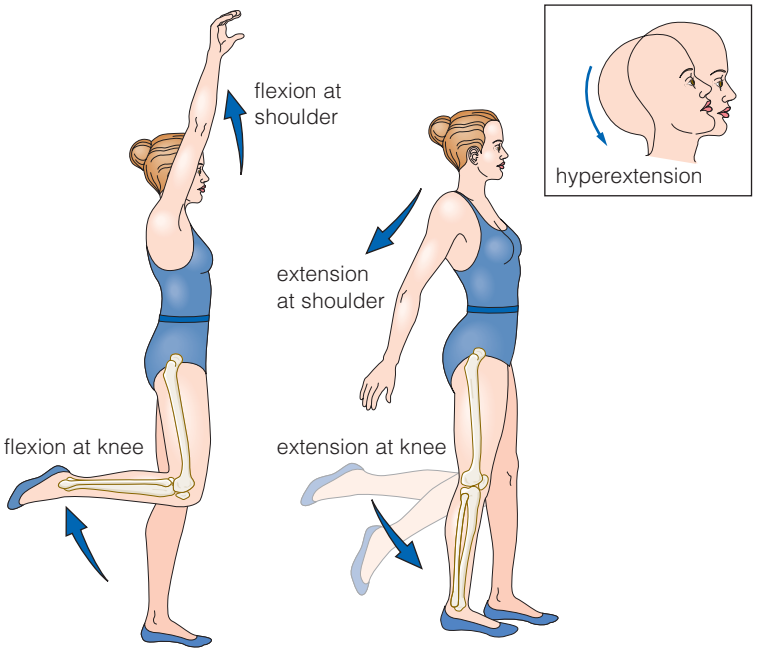
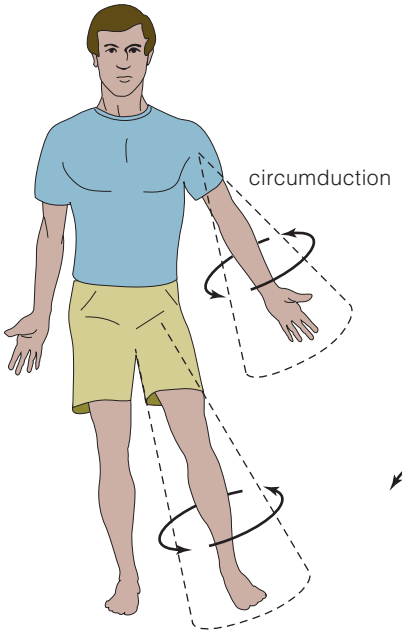
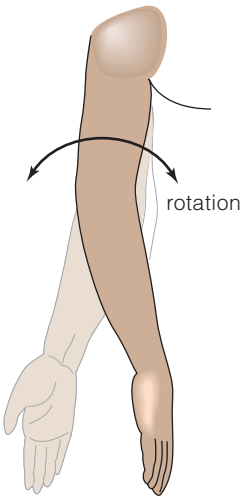


Figure 5.10 The knee joint is an example of a synovial joint. The knee is the largest and most complex joint in the body. Part (**a**) shows the joint with muscles stripped away. In (**b**) you can see where muscles such as the quadriceps attach.

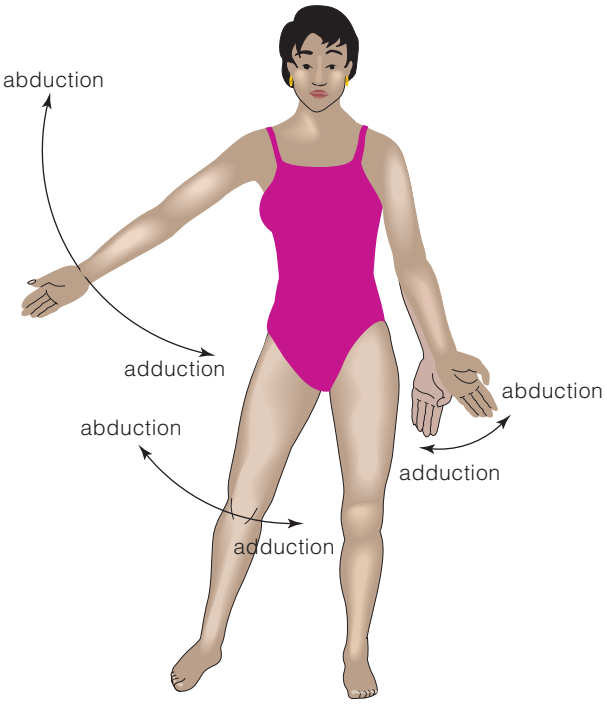


A flexion and extension
Flexion reduces the angle between two bones, while extension increases it. Hyperextension, as when you tip your head back, increases the angle beyond 180°.

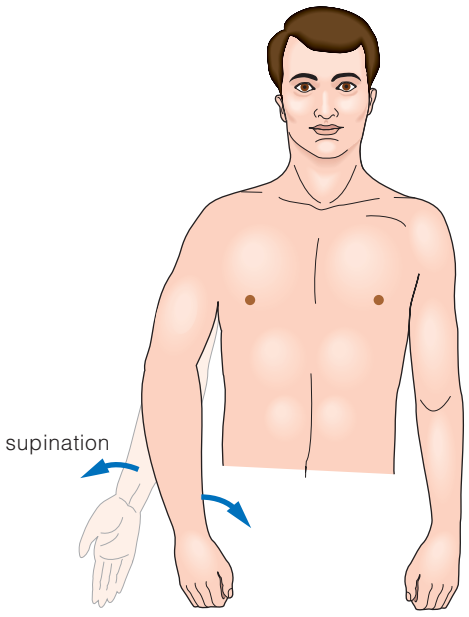




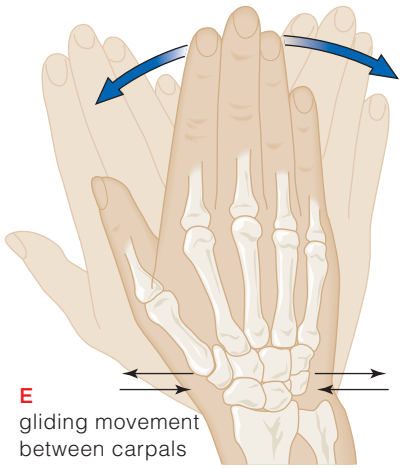
B circumduction (*above*) **and rotation** (*right*)
In circumduction a limb traces an imaginary cone. Rotation moves a body part around its axis.



C abduction and adduction
Abduction moves a limb away from the body's midline; adduction moves a limb toward the midline or beyond it.



D supination and pronation
In supination forearm bones rotate so that the palms face outward; in pronation the rotation turns the palms to the rear.



E
gliding movement between carpals

Figure 5.11 (a–e) Body parts can move in various ways at synovial joints. The synovial joint at the shoulder permits the greatest range of movement.

5.6 Disorders of the Skeleton

Inflammation is a factor in some skeletal disorders

Excessive wear on a joint is the hallmark of *osteoarthritis*. This kind of wear happens when years of use, mechanical stress, or disease wears away the cartilage covering the bone ends of freely movable joints. Often, the arthritic joint is painfully inflamed, and surgeons now routinely replace seriously arthritic hips, knees, and shoulders (Figure 5.12). Another degenerative joint condition, *rheumatoid arthritis*, results when the immune system malfunctions and mounts an attack against tissues in the affected joint. Then, the synovial membrane becomes inflamed and thickens, cartilage is eroded away, and the bones fall out of proper alignment (Figure 5.13). With time the bone ends may even fuse together.

Repetitive movements also can cause inflammation when they damage the soft tissue associated with joints. *Tendinitis*, the underlying cause of conditions such as "tennis elbow," develops when tendons and synovial membranes around joints such as the elbow, shoulders, and fingers become inflamed.

Today one of the most common repetitive motion injuries is *carpal tunnel syndrome*. The "carpal tunnel" is a slight hollow between a wrist ligament and the underside of the wrist's eight carpal bones (see Figure 5.8). Squeezed into this tunnel are several tendons and a nerve that services parts of the hand. Chronic overuse, such as long hours typing at a computer keyboard, can inflame the tendons. When the swollen tendons press on the nerve, the result can be pain, numbness, and tingling in fingers. Simply avoiding the offending motion can help relieve carpal tunnel syndrome. In more serious cases injections of an anti-inflammatory drug are helpful. Sometimes, however, the wrist ligament must be surgically cut to relieve the pressure.

Figure 5.12 Knees, hips, and some other joints may be surgically replaced. In this replacement knee a projection of the joint has been fitted into the end of the patient's femur (center) and another projection has been fitted into the tibia below. The hatlike disk at the upper left attaches to the patella—the kneecap. It may take only about 2 hours to replace a knee joint, even less for a hip. After surgery, walking and standing put stress on the new joint, so the patient's osteoblasts generate new bone that grows into pits on the prosthesis.

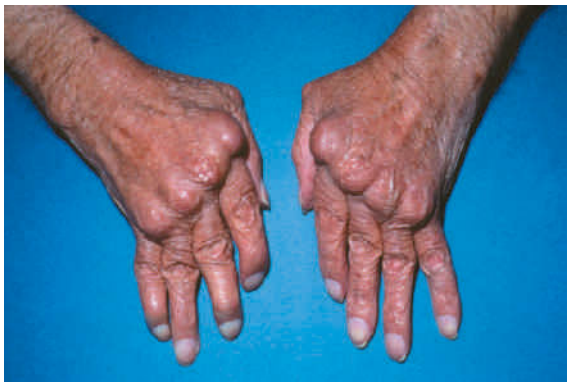


Figure 5.13 Rheumatoid arthritis may cause bones to become misaligned.

Joints are susceptible to strains, sprains, and dislocations

Synovial joints such as our knees, hips, and shoulders get a lot of use, so it's not surprising that they are vulnerable to mechanical stresses. Stretch or twist a joint suddenly and too far, and you *strain* it. Do something that makes a small tear in its ligaments or tendons and you will have a *sprain*. In fact, a sprained ankle is the most common joint injury. Sprains hurt mainly because of swelling and bleeding from broken small blood vessels. Applying cold (such as an ice pack, 30 minutes on, then 30 minutes off) for the first 24 hours will minimize these effects; after that, doctors usually advise applying heat, such as a hot pad. The warmth speeds healing by increasing blood circulation to the injured tissue.

A blow can *dislocate* a joint—that is, the two bones will no longer be in contact. During collision sports such as football, a blow to a knee often tears a ligament. If the torn part is not reattached within ten days, phagocytic cells in the knee joint's synovial fluid will attack and destroy the damaged tissue.

Bones break in various ways

Injuries severe enough to dislocate a joint also may break one or both of the bones involved. Most breaks can be classed as either a simple or closed fracture, a complete fracture, or a compound fracture. As you can probably

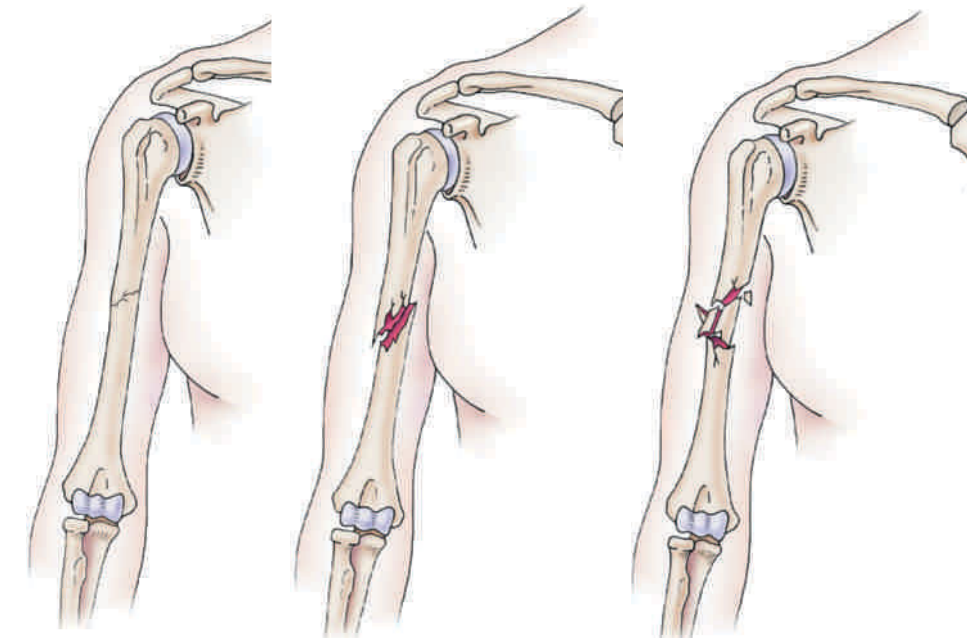


Figure 5.14 **Bone fractures range from simple to serious.**

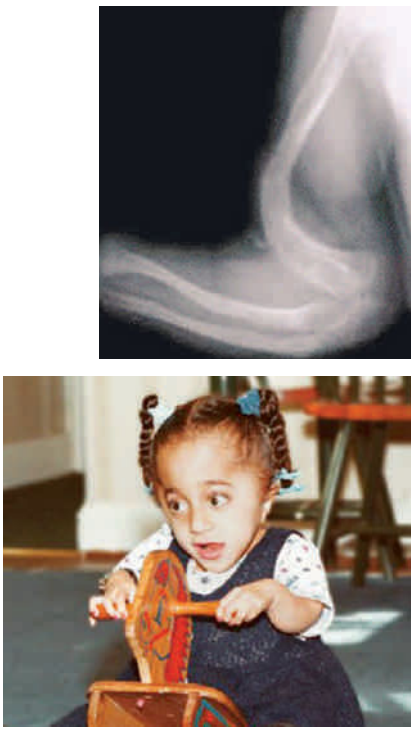


Figure 5.15 ***Osteogenesis imperfecta*** **is a genetic bone disorder.** Above: An X-ray of an arm bone deformed by OI. Below: Tiffany, who has OI, was born with fractures in her arms and legs. By age six, she had had surgery to correct more than 200 fractures and to place steel rods in her legs. She receives an experimental drug that may help strengthen her bones.

tell from the drawings in Figure 5.14, a *simple fracture* is the least serious injury because the bone ends don't do much damage to the surrounding soft tissue. A *complete fracture*, in which the bone separates into two pieces and soft tissue is damaged, is more serious. Even worse is a *compound fracture*, in part because broken ends or shards of bone puncture the skin, creating an open wound and the chance of infection. A surgeon may have difficulty reattaching all the pieces of a bone that has been shattered in this way.

When a bone breaks into pieces, the situation demands prompt medical attention. Unless the pieces are soon reset into their normal alignment, it's unlikely that the bone will heal properly. Its functioning may be impaired for the rest of a person's life. Today, in addition to the pins and casts that may be used to hold healing bones in place, the injured area may be stimulated with electricity, which speeds healing.

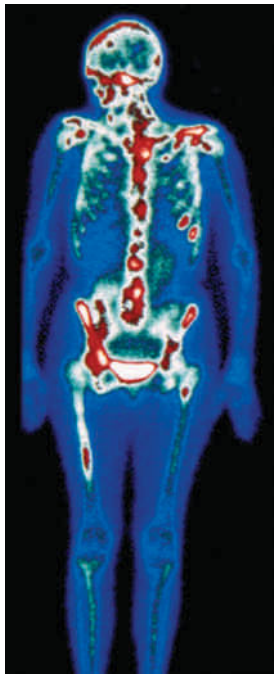
Overall, injuries to joints and bones tend to heal faster when we're younger. Changes that come with aging, and bad habits such as smoking cigarettes, slow the body's ability to repair itself.

Genetic diseases, infections, and cancer all may affect the skeleton

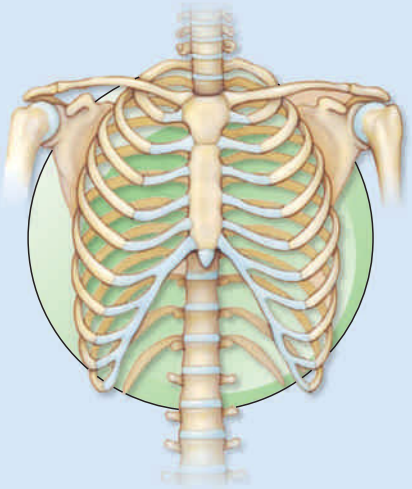
Some skeleton disorders are inherited, and a few cause lifelong difficulties for affected people. An example is *osteogenesis imperfecta* or OI (Figure 5.15). In this disease the collagen in bone tissue is defective. As a result, the bones are exceptionally brittle and break easily. Children with OI often have stunted growth and must endure repeated hospitalizations to have fractures set. In some cases where the disease has not been detected early, an affected child's parents have been wrongly suspected of child abuse. Unfortunately, there is no cure for OI, but researchers are looking for ways to improve bone strength in affected individuals.

Bones and bone marrow also can become infected by bacteria when an infection elsewhere spreads (via the bloodstream) or when the microbe enters an open wound. A heavy dose of antibiotics usually can cure the problem, although severe cases may require surgery to clean out the affected bone tissue.

The bone cancer called *osteosarcoma* can strike people young and old. It often occurs in a long bone in a limb, or in a joint such as the hip or knee. The most common treatment is amputation of the limb involved. Like many other cancers, bone cancer often is curable if caught early. Unfortunately, most bone cancer cases involve cancer that has spread from another site in the body. The image at right is of a bone scan that shows "hot spots" where cancer has spread to many sites in the patient's skeleton.

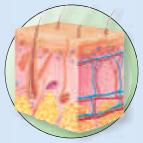
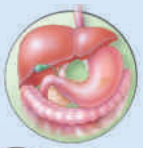
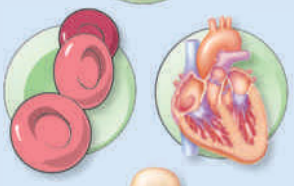
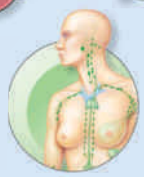
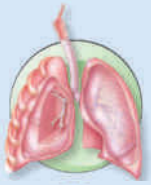
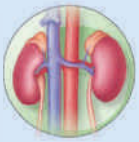
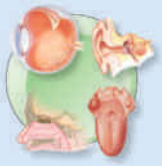
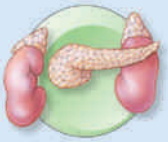


5.7 CONNECTIONS: The Skeletal System in Homeostasis



The Skeletal System

The skeleton supports and helps protect soft body parts. Bones, joints, tendons, and ligaments all have essential roles in moving the body and its parts. Bone is a reservoir for calcium, which is vital for many body functions including muscle contractions, the transmission of nerve impulses, and blood clotting. Calcium also is required for the proper functioning of some enzymes and of proteins in the cell plasma membrane.

Integumentary system		The skeleton provides support for skin and the muscles below it.
Muscular system		Skeletal muscles attach to bones, which serve as levers for body movements. Bone calcium may be released as needed to maintain blood levels required for muscle contractions.
Digestive system		Bone stores dietary calcium and phosphorus. Bones of the rib cage and pelvis protect organs including the stomach, liver, and intestines. Facial bones have sockets for teeth.
Cardiovascular system and blood		Bone calcium is available for heart contractions that pump blood. All types of blood cells form in red bone marrow.
Immunity and the lymphatic system		White blood cells that function in body defenses form in bone marrow.
Respiratory system		The rib cage and sternum protect the lungs. Muscles used in breathing attach to ribs and associated cartilages.
Urinary system		The rib cage partially protects the kidneys. The pelvis helps protect the bladder.
Nervous system		The skull protects the brain. Vertebrae the spinal cord. Bone calcium stores may be released as needed to maintain blood levels required for transmission of nerve impulses.
Sensory systems		Skull and facial bones surround and protect sensory organs in the head. Calcium in bones helps maintain blood levels required for transmission of sensory nerve impulses.
Endocrine system		Calcium may be released as needed to maintain blood levels required for the formation and secretion of many hormones.
Reproductive system		Pelvic bones protect female reproductive organs and associated glands in males. Calcium is available to help nourish a fetus and for milk production in a nursing mother.

IMPACTS, ISSUES

Creaky Joints

MANY people seeking relief from joint problems use herbs and plant extracts to self-treat their symptoms, even though there is little or no independent scientific evidence that the substances work.

How Would You Vote?

Should claims about "medicinal" plant extracts have to be backed up by independent scientific tests?

See CengageNOW for details, then vote online.

Summary

Section 5.1 Bones are organs that contain bone tissue and other connective tissues, nerves, and blood vessels.

A bone develops as osteoblasts secrete collagen fibers and a matrix of protein and carbohydrate. Calcium salts are deposited and harden the matrix. Mature living bone cells, osteocytes, are located inside spaces (lacunae) in the bone tissue.

Bone tissue has both compact bone and spongy bone. Denser compact bone is organized as thin, circular layers called osteons. In spongy bone, needlelike struts are fused together in a latticework.

A cartilage model provides the pattern for a developing bone. Long bones lengthen at their ends (epiphyses) until early adulthood when bone growth ends.

Bones grow, gain strength, and are repaired by bone remodeling. In this process, osteoblasts deposit bone and osteoclasts break it down.

- Use the animation and interaction on CengageNOW to study the structure of the femur.

Section 5.2 As the main elements of the skeleton, bones interact with skeletal muscles to move body parts. Bones also store minerals and help protect and support other body parts. Ligaments connect bones at joints; tendons attach muscles to bones or to other muscles. Some bones, including the sternum, hip bones, and femur, contain bone marrow. Blood cells are produced in red bone marrow.

Section 5.3 The skeleton is divided into an axial portion and an appendicular portion (Table 5.2). The axial skeleton forms the body's vertical axis and is a central support structure. In the spine, intervertebral disks of fibrocartilage are shock pads and flex points.

Skull bones form the brain case, which protects the brain. Sinuses in the frontal bone reduce the skull's weight.

- Use the animation and interaction on CengageNOW to explore the parts of the skeleton.

Section 5.4 The appendicular skeleton (Table 5.2) provides support for upright posture and interacts with skeletal muscles in most movements.

Section 5.5 In partnership with skeletal muscles, the skeleton works like a system of levers in which rigid rods (bones) move about at fixed points (joints).

In a synovial joint, a fluid-filled cavity separates adjoining bones. Such joints are freely movable. In cartilaginous joints, cartilage fills the space between bones and allows only slight movements. In fibrous joints, fibrous connective tissue knits the bones together.

Section 5.6 Diseases and disorders that affect the skeletal system can impair movement and hamper other functions of bones that help maintain homeostasis.

Review Questions

1. Describe the basic elements of bone tissue.
2. What are the two types of bone tissue, and how are they different?
3. Describe how bone first develops.
4. Explain why bone remodeling is important, and give its steps.
5. Name the two main divisions of the skeleton.
6. How does a tendon differ from a ligament?
7. What is the function of intervertebral disks? What are they made of?
8. What is a joint?
9. What is the defining feature of a synovial joint?

Self-Quiz *Answers in Appendix V*

1. The _____ and _____ systems work together to move the body and specific body parts.
2. Bone tissue contains _____.
   a. living cells
   b. collagen fibers
   c. calcium and phosphorus
   d. all of these
   e. only a and b

Review of the Skeleton's Parts

Appendicular skeleton

Pectoral girdles: clavicle and scapula
Arm: humerus, radius, ulna
Wrist and hand: carpals, metacarpals, phalanges (of fingers)
Pelvic girdle (6 fused bones at the hip)
Leg: femur (thighbone), patella, tibia, fibula
Ankle and foot: tarsals, metatarsals, phalanges (of toes)

Axial skeleton

Skull: cranial bones and facial bones
Rib cage: sternum (breastbone) and ribs (12 pairs)
Vertebral column: vertebrae (26)

3. _____ are shock pads and flex points.
   a. Vertebrae
   b. Cervical bones
   c. Lumbar bones
   d. Intervertebral disks

4. The hollow center of an osteon (Haversian system) provides space for what vital part of compact bone tissue?
   a. marrow
   b. collagen fibers
   c. a blood vessel
   d. osteocytes

5. _____ is a type of connective tissue; _____ form(s) in it.
   a. An osteon; collagen
   b. Bone marrow; blood cells
   c. Bone; an osteocyte
   d. A sinus; bone marrow

6. Mineralization of bone tissue requires _____.
   a. calcium ions
   b. osteoclasts
   c. elastin
   d. all of the above

7. The axial skeleton consists of the _____, while the appendicular skeleton consists of the _____.

8. Match the terms and definitions.

____ bone	a. in certain skull bones
____ collagen	b. all in the hands
____ synovial fluid	c. blood cell production
____ osteocyte	d. a fibrous protein
____ marrow	e. mature bone cell
____ metacarpals	f. lubrication
____ mandible	g. mineralized connective tissue
____ sinuses	h. the lower jaw

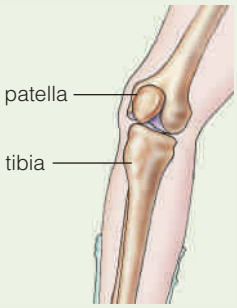
Critical Thinking

1. Growth hormone, or GH, is used clinically to spur growth in children who are unusually short because they have a GH deficiency. However, it is useless for a short but otherwise normal 25-year-old to request GH treatment from a physician. Why?
2. If bleached human bones found lying in the desert were carefully examined, which of the following would not be present? Haversian canals, a marrow cavity, osteocytes, calcium.
3. For young women, the recommended daily allowance (RDA) of calcium is 800 milligrams. During Hilde's pregnancy, the RDA is 1,200 milligrams a day. What might happen to a pregnant woman's bones without the larger amount, and why?

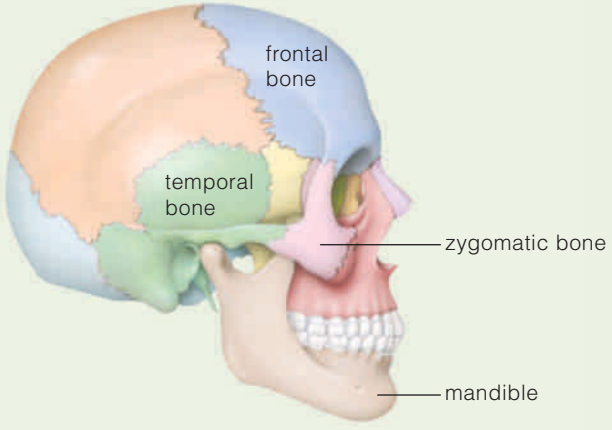
EXPLORE ON YOUR OWN

When it comes to the skeleton and joints, your body can be a great learning tool.

- Feel along the back of your neck beginning at your hairline. Can you feel any lumps made by the bony processes of your spinal vertebrae (Figure 5.7)? Locate the C7 vertebra, which in most people is the most prominent. Can you feel it at the base of your neck?
- While seated, feel your kneecap—the patella—move as you flex and extend your lower leg. Just below the patella you should also be able to feel a ligament that attaches it to your tibia. Can you find the upper protuberance of your tibia? Moving your fingers around to outside of the joint, can you feel the knobby upper part of the fibula?



- Using the diagram below as a guide, see if you can locate the ridges of your frontal bone above your eyebrows; the arching part of your zygomatic bone, which forms your "cheekbones"; and the joint where your lower jaw articulates with the temporal bone.



The Muscular System

6

IMPACTS, ISSUES

Pumping Up Muscles

WANT to "bulk up" your muscles and be stronger, with more endurance? Just swallow a pill. That is the message to bodybuilders and other athletes from the sellers of substances like "andro"—androstenedione—and THG (tetrahydrogestrinone). Several internationally renowned athletes have admitted using andro and THG. This group includes some professional football and baseball players, as well as medal-winning stars of track and field. When tests showed that THG actually is a chemical cousin of two anabolic (tissue-building) steroids banned in sports competitions, it was forced off the market.

Androstenedione occurs naturally when the human body synthesizes the sex hormone testosterone. Studies suggest, however, that andro is not an effective muscle builder, because it only raises the testosterone level for a few hours. On the other hand, andro does have side effects, including a risk of liver damage. Several years ago the FDA issued an advisory warning of these problems, and companies were ordered to stop distributing the drug.

A substance called creatine is also a performance enhancer. It is produced naturally in the body and also is present in some foods. Muscle cells use it as a quick energy source when they must contract hard and fast. Research shows that creatine supplements do improve performance during brief, high-intensity exercise. Long-term effects are not known, although there is evidence that in large amounts creatine puts a strain on the kidneys. No regulatory agency checks to see how much creatine is actually present in any commercial product.

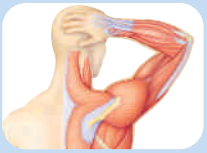
With this chapter we look at why we have muscles in the first place. We will begin by reviewing the three types of muscle tissue in the body, and then focus on skeletal muscles, which make up the **muscular system**. As you will read, their interactions with the skeleton underlie the movements and position changes that each of us performs as we go about our daily activities.

KEY CONCEPTS

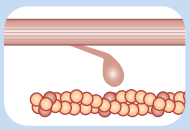
Types of Muscle Tissue

The body contains three types of muscle tissue—skeletal muscle, smooth muscle, and cardiac muscle. Muscle cells produce force by contracting. Section 6.1

What Skeletal Muscles Do



Skeletal muscles attach to and pull on bones to move body parts. They are arranged as pairs or groups. Often, the action of one muscle opposes or reverses the action of another. Section 6.2



How Muscles Work

In a muscle cell, units called sarcomeres can shorten. This action is the basis for muscle contraction, which is controlled by motor neurons. The strength and duration of muscle contractions varies. Sections 6.3–6.9

Disorders of the Muscular System and Homeostasis

Sections 6.7, 6.9

LINKS TO EARLIER CONCEPTS

- Building on what you learned about the skeleton in Chapter 5, in this chapter you will discover how skeletal muscles partner with bones to move the body and its parts.
- You will learn how two proteins, actin and myosin, work together in ways that allow muscle cells to contract (3.9). Our discussion also will draw on your knowledge of how ATP fuels cell activities (3.8), and how active transport moves substances into and out of cells (3.11).

How Would You Vote?

Dietary supplements are largely unregulated. Should they be subject to more stringent testing for effectiveness and safety? See CengageNOW for details, then vote online.

6.1 The Body's Three Kinds of Muscle

- **There are three different kinds of muscle in the body, but in all of them groups of cells contract to produce movement.**
- **Links to Muscle tissue 4.3, Nervous tissue 4.4, Tissue membranes 4.7**

The three kinds of muscle have different structures and functions

In Chapter 4 we introduced the three basic kinds of muscle tissue—skeletal muscle, smooth muscle, and cardiac muscle. Together they make up about 50 percent of the body. In all of them, cells specialized to contract bring about some type of movement.

Most of the body's muscle tissue is **skeletal muscle**, which interacts with the skeleton to move body parts. Its long, thin cells are often called muscle "fibers" (Figure 6.1*a*). And unlike other body cells, skeletal muscle fibers have more than one nucleus. As you will read later on, their internal structure gives them a striated, or striped, appearance, and bundles of them form skeletal muscles.

Smooth muscle is found in the walls of hollow organs and of tubes, such as blood vessels (Figure 6.1*b*). Its cells are smaller than skeletal muscle cells, and they do not look striped—hence the "smooth" name for this muscle tissue. Junctions link smooth muscle cells, which often are organized into sheets.

You may recall that **cardiac muscle** is found only in the heart (Figure 6.1*c*). It looks striated, like skeletal muscle. Unlike skeletal and smooth muscle, however, cardiac muscle can contract without stimulation by the the signals for nervous system. Special junctions between its cells allow the signals for contraction to pass between them so fast that for all intents and purposes the cells contract as a single unit.

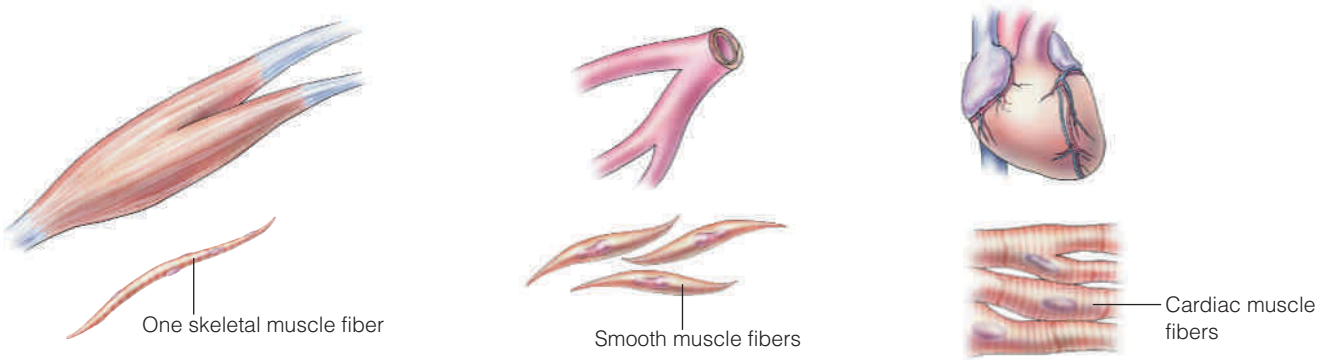
We do not have conscious control over contractions of cardiac muscle and smooth muscle, so they are said to be "involuntary" muscles. We *can* control many of our skeletal muscles, so they are "voluntary" muscles. Figure 6.2 shows the major skeletal muscles in the body. Some are close to the surface, others deep in the body wall. Some, such as facial muscles, attach to the skin. The trunk has muscles of the thorax (chest), spine, abdominal wall, and pelvic cavity. And of course, other muscle groups attach to limb bones.

When we speak of the body's "muscular system," we're talking about skeletal muscle—the focus of the rest of this chapter. Skeletal muscle interacts with the skeleton to move the body, its limbs, or other parts. Those movements range from delicate adjustments that help you keep your balance to the cool moves you might execute on a dance floor. Our skeletal muscles also help stabilize joints and generate body heat.

Take-Home Message

What are the three types of muscle tissue in the body?

- The body's muscle tissue includes skeletal, smooth, and cardiac muscle. Skeletal muscle makes up the muscular system, which partners with the skeleton to produce movement.



a Skeletal muscle **b** Smooth muscle **c** Cardiac muscle

Figure 6.1 Muscle tissue in the human body includes skeletal muscle, smooth muscle, and cardiac (heart) muscle.

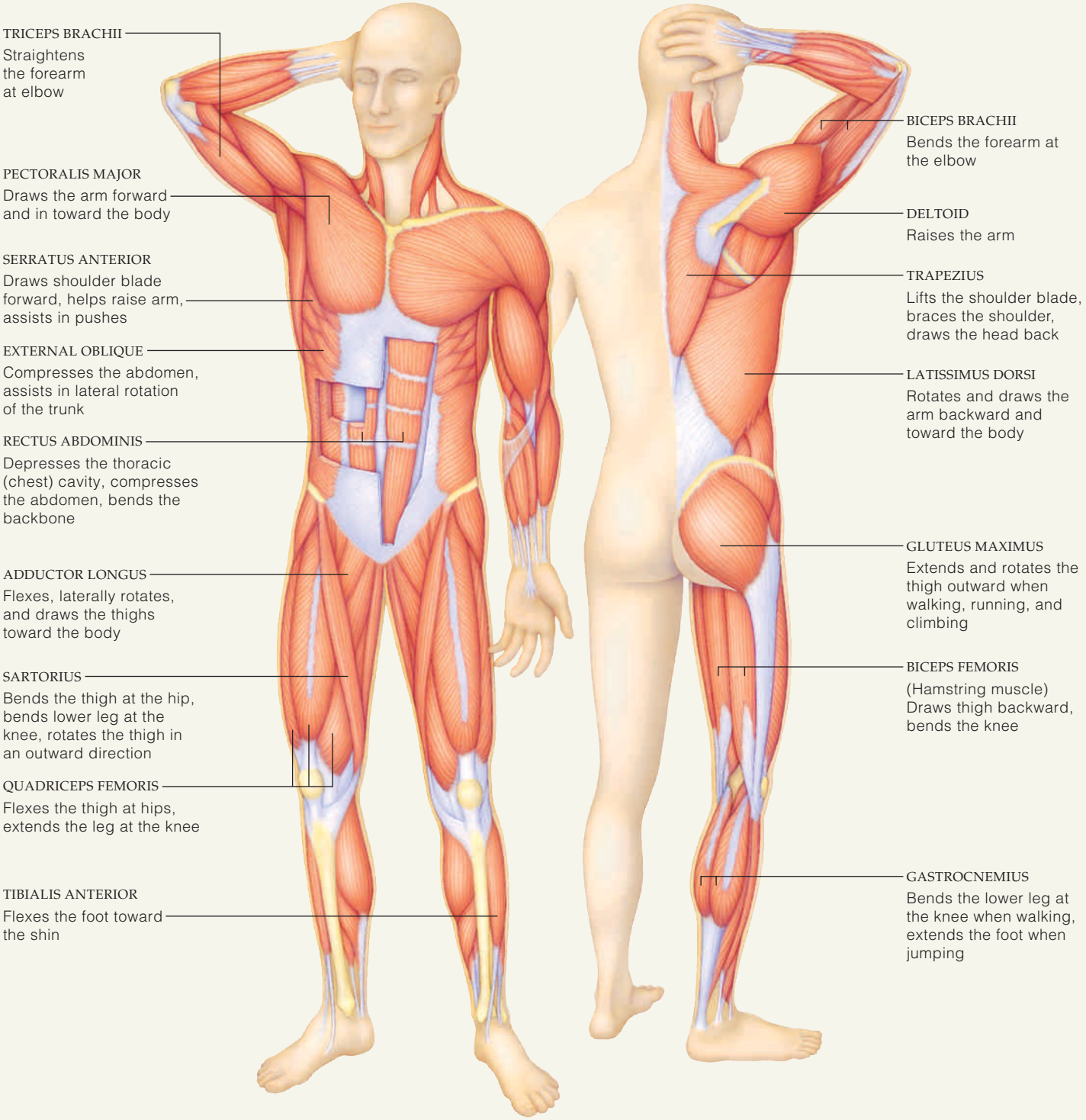


Figure 6.2 Animated! **Some of the major muscles of the muscular system.**

6.2 The Structure and Function of Skeletal Muscles

- **Muscle cells generate force by contracting. After a muscle contracts, it can relax and lengthen. As their name suggests, skeletal muscles attach to and interact with bones.**
- **Links to Metabolism 3.13, Connective tissue 4.2, Muscle tissue 4.3**

A whole skeletal muscle consists of bundled muscle cells

A skeletal muscle contains bundles of muscle cells, which look like long, striped fibers (Figure 6.3). Inside each cell are threadlike **myofibrils**, which you'll read more about in Section 6.3. There may be hundreds, even thousands, of cells in a muscle, all bundled together by connective tissue that extends past them to form tendons. A **tendon** is a strap of dense connective tissue that attaches a muscle to bone. Tendons make joints more stable by helping keep the adjoining bones properly aligned. Tendons often rub against bones, but they slide inside fluid-filled sheaths that help reduce the friction (Figure 6.4). Your knees, wrists, and finger joints all have tendon sheaths.

Bones and skeletal muscles work like a system of levers

You have more than 600 skeletal muscles, and each one helps produce some kind of body movement. In general,

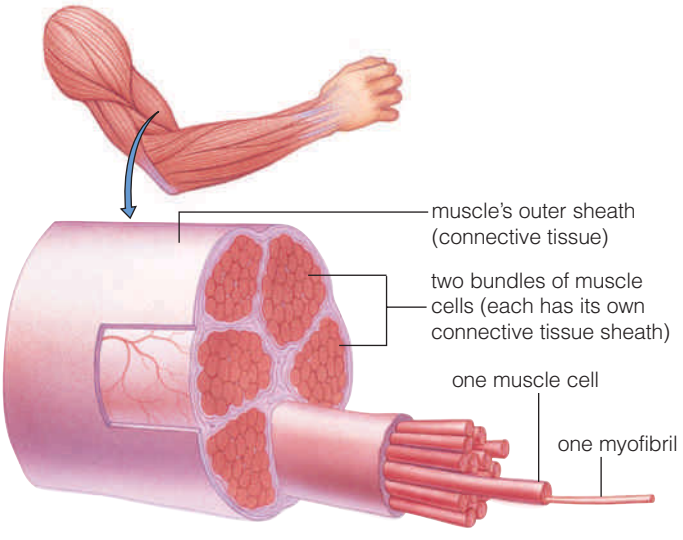


Figure 6.3 **In skeletal muscle, the muscle fibers are bundled together inside a wrapping of connective tissue.**

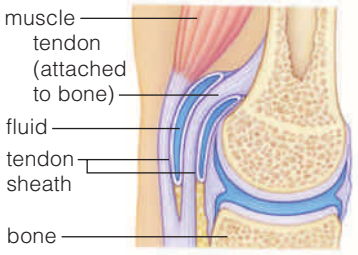


Figure 6.4 **A tendon sheath encloses lubricating fluid that prevents friction when the attached bone moves.**

one end of a muscle, called the **origin**, is attached to a bone that stays relatively motionless during a movement. The other end of the muscle, called the **insertion**, is attached to the bone that moves most (Figure 6.5). In effect, the skeleton and the muscles attached to it are like a system of levers in which bones (rigid rods) move near joints (fixed points). When a skeletal muscle contracts, it pulls on the bones it attaches to. Because muscles attach very close to most joints, a muscle only has to contract a short distance to produce a major movement.

Many muscles are arranged as pairs or in groups

Many muscles are arranged as pairs or groups. Some work in opposition (that is, antagonistically) so that the action of one opposes or reverses the action of the other. Figure 6.5 shows an antagonistic muscle pair, the biceps and triceps of the arm. Try extending your right arm in front of you, then place your left hand over the biceps in the upper arm and slowly "bend the elbow." Can you feel the biceps contract? When the biceps relaxes and its partner (the triceps) contracts, your arm straightens. This kind of coordinated action comes partly from *reciprocal innervation* by nerves from the spinal cord. When one muscle group is stimulated, no signals are sent to the opposing group, so it does not contract.

Other muscles work in a synergistic, or support, role. Their contraction adds force or helps stabilize another contracting muscle. If you make a fist while keeping your wrist straight, synergist muscles are stabilizing your wrist joint while muscles in your hand are doing the "heavy lifting" of closing your fingers.

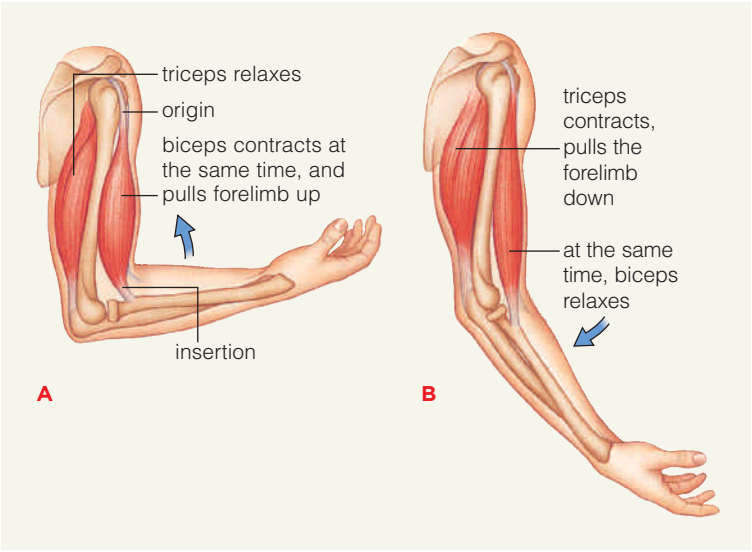


Figure 6.5 Animated! **Arm movements demonstrate the action of opposing muscle groups.** (**a**) When the triceps relaxes and its opposing partner (biceps) contracts, the elbow joint flexes and the forearm bends up. (**b**) When the triceps contracts and the biceps relaxes, the forearm is extended down.

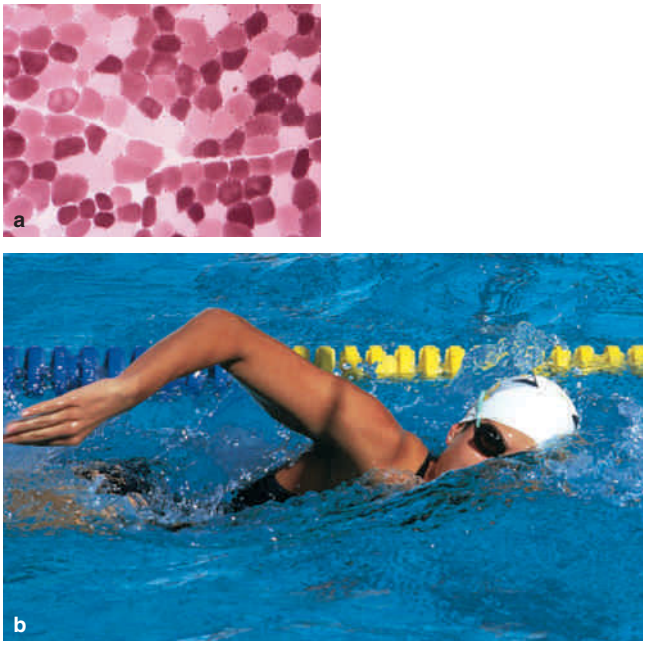


Figure 6.6 **Fast and slow skeletal muscles have slightly different structure.** (**a**) This micrograph shows a cross section of the different kinds of cells in a skeletal muscle. The lighter, "white fibers" are fast muscle. They have little myoglobin and fewer mitochondria than the dark red fibers, which are slow muscle. (**b**) A distance swimmer can work her shoulder muscles for extended periods due to the many well-developed slow muscle cells they contain.

Skeletal muscle includes "fast" and "slow" types

Your body has two basic types of skeletal muscle (Figure 6.6*a*). "Slow" or "red" muscle appears crimson because its cells are packed with myoglobin, a reddish protein that binds oxygen for the cell's use in making ATP. Red muscle also is served by larger numbers of the tiny blood vessels called capillaries. (Red muscle is the dark meat in chicken and turkey.) Red muscle contracts fairly slowly, but because its cells are so well equipped to make lots of ATP, the contractions can be sustained for a long time. For example, some muscles of the back and legs—called postural muscles because they aid body support—must contract for long periods when a person is standing. They have a high proportion of red muscle cells. By contrast, the muscles of your hand have fewer capillaries and relatively more "fast" or "white" muscle cells, in which there are fewer mitochondria and less myoglobin. Fast muscle can contract rapidly and powerfully for short periods, but it can't sustain contractions for long periods. This is why you get writer's cramp if you write long-hand for an hour or two.

When an athlete trains rigorously, one goal is to increase the relative size and contractile strength of fast or slow fibers in muscles. The type of sport determines which type of fiber is targeted. A sprinter will benefit from larger, stronger fast muscle cells in the thighs, while a distance swimmer (Figure 6.6*b*) will train to increase the number of mitochondria in the shoulder muscle cells.

Take-Home Message

What is the basic structure and function of a skeletal muscle?

- A skeletal muscle consists of hundreds or thousands of muscle cells bundled together by connective tissue. When a skeletal muscle contracts, it pulls on a bone to produce movement.
- Tendons strap skeletal muscles to bone.
- In many movements, the action of one muscle opposes or reverses the action of another.
- The cells in red or "slow" skeletal muscle have features that support slow, long-lasting contractions. The cells in white or "fast" skeletal muscle are specialized for rapid, strong bursts of contraction.

6.3 How Muscles Contract

- **Bones move—they are pulled in some direction—when the skeletal muscles attached to them contract.**

A muscle contracts when its cells shorten

A skeletal muscle contracts when the individual muscle cells in it shorten. In turn, each muscle cell shortens when units of contraction inside it are shortening. Each of these basic units of contraction is a **sarcomere**.

Bundles of cells in a skeletal muscle run parallel along the muscle's length (Figure 6.7*a*). Looking a bit deeper, each of the myofibrils in a cell is divided into bands (Figure 6.7*b*). The bands appear as an alternating light–dark pattern when they are stained and viewed under a microscope. Bands in neighboring cells line up quite closely, so a skeletal muscle cell looks striped. The dark bands are called Z bands. They mark the ends of each sarcomere (Figure 6.7*c*).

Inside a sarcomere are many filaments, some thick, others thin. Each thin filament is like two strands of pearls, twisted together, with one end attached to a Z band. The "pearls" are molecules of **actin** (Figure 6.7*d*), a globular protein that can contract. Other proteins are found near grooves on actin's surface.

Each thick filament is made of molecules of the protein **myosin**. A myosin molecule has a tail and a double head. In a thick filament many of them are bundled together so that all the heads stick out (Figure 6.7*e*), away from the sarcomere's center.

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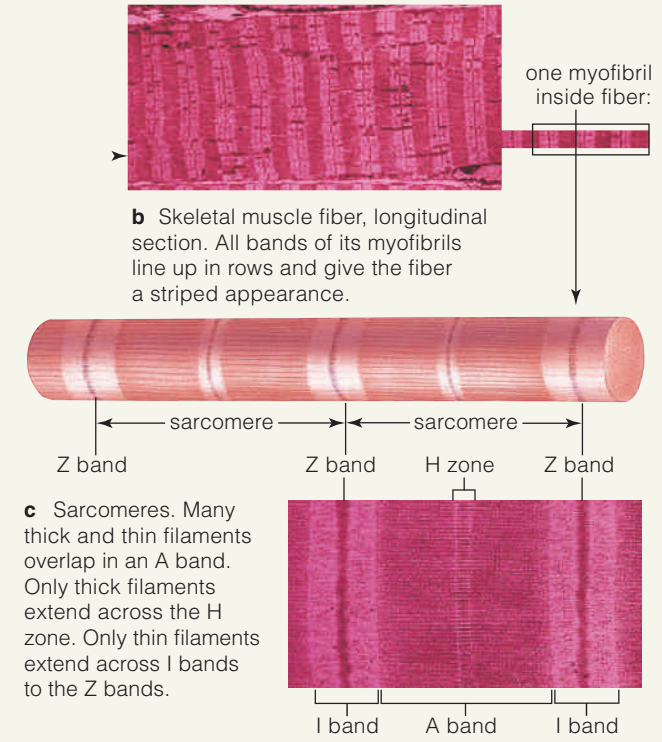
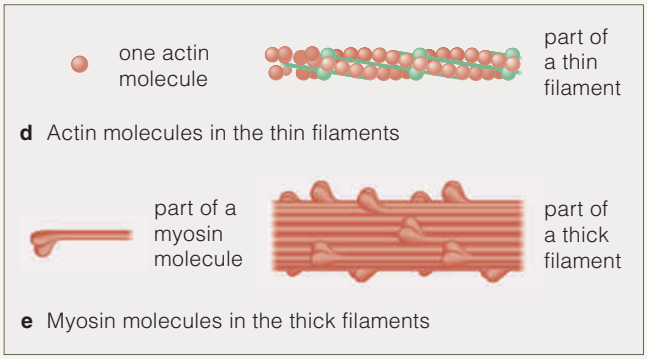


b Skeletal muscle fiber, longitudinal section. All bands of its myofibrils line up in rows and give the fiber a striped appearance.

c Sarcomeres. Many thick and thin filaments overlap in an A band. Only thick filaments extend across the H zone. Only thin filaments extend across I bands to the Z bands.



d Actin molecules in the thin filaments

e Myosin molecules in the thick filaments

As you can see in Figure 6.7, muscle bundles, muscle cells, myofibrils, and their filaments all run in the same direction. This arrangement focuses the force of a contracting muscle. All sarcomeres in all fibers of a muscle work together and pull a bone in the same direction.

Muscle cells shorten when actin filaments slide over myosin

The **sliding filament model** explains how interactions between thick and thin filaments bring about muscle contraction. All of the myosin filaments stay in place. They use short "power strokes" to slide the sets of actin filaments over them, toward the sarcomere's center. Pulling both sets of filaments shrinks the length of the sarcomere (Figure 6.8*a* and 6.8*b*). Each power stroke is driven by energy from ATP.

Each myosin head connects repeatedly to binding sites on a nearby actin filament (Figure 6.8*c*). The head is an ATPase, a type of enzyme. It binds ATP and catalyzes a phosphate-group transfer that powers the reaction.

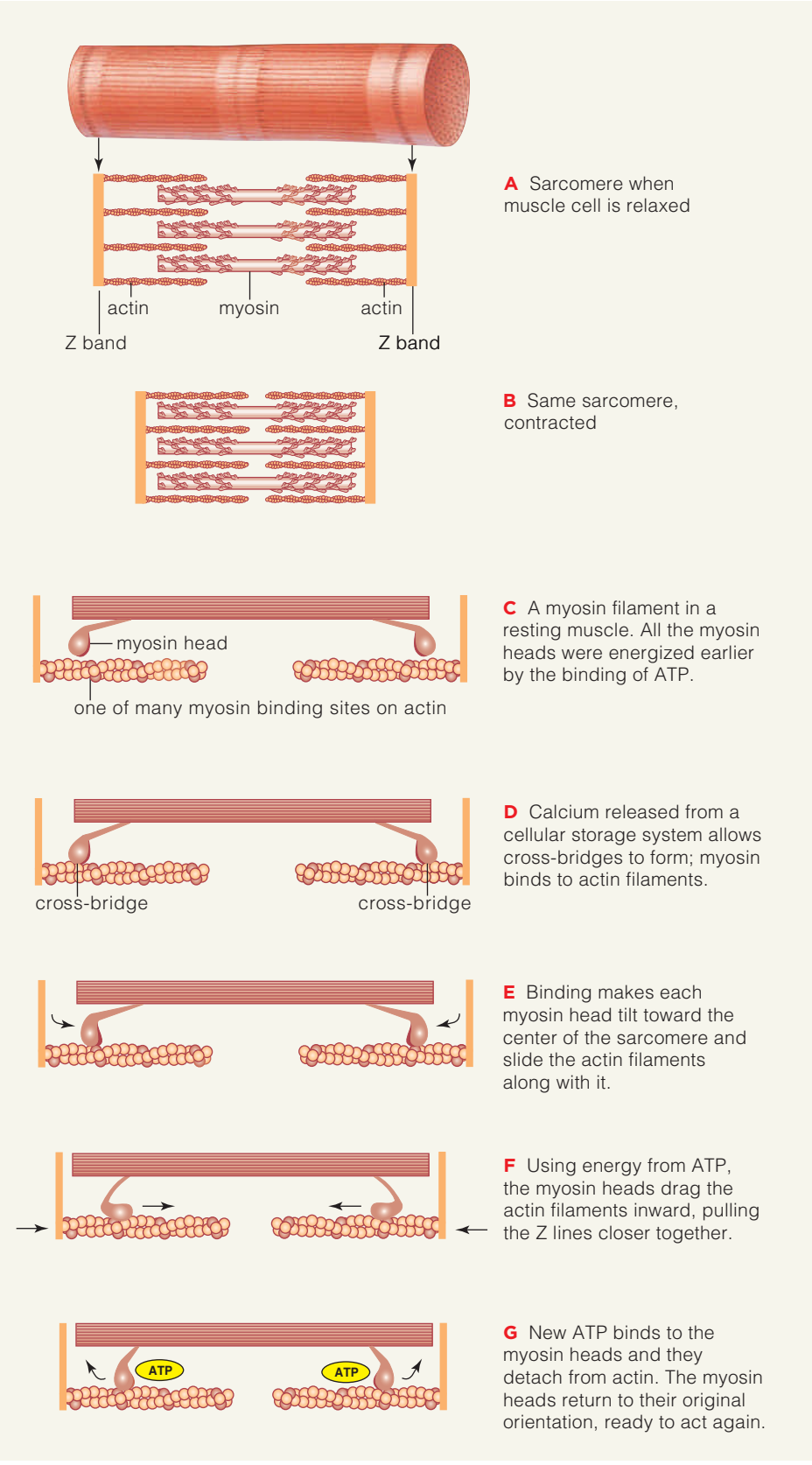
A rise in the concentration of calcium ions causes the myosin head to form a **cross-bridge** to the actin (Figure 6.8*d*). This link tilts the myosin head and pulls the actin filament toward the sarcomere's center (Figure 6.8*e-f*). Next, with the help of energy from ATP, the myosin head's grip on actin is broken and the head returns to its starting position (Figure 6.8*g*). Each time a sarcomere contracts, hundreds of myosin heads make a series of short strokes down the length of actin filaments.

When a person dies, body cells stop making ATP. In muscles this means that the myosin cross-bridges with actin can't break apart after a power stroke. As a result skeletal muscles "lock up," a stiffening called **rigor mortis** ("stiffness of death"). Rigor mortis lasts for 24 to 60 hours, or until the natural decomposition of dead tissues gets under way. Understanding this sequence helps crime investigators pinpoint when a suspicious death occurred.

Take-Home Message

How does a skeletal muscle contract?

- A skeletal muscle cell contracts when its sarcomeres shorten. Thus sarcomeres are the basic units of muscle contraction.
- Powered by ATP, interactions between myosin and actin filaments shorten the sarcomeres of a muscle cell.



A Sarcomere when muscle cell is relaxed

B Same sarcomere, contracted

C A myosin filament in a resting muscle. All the myosin heads were energized earlier by the binding of ATP.

D Calcium released from a cellular storage system allows cross-bridges to form; myosin binds to actin filaments.

E Binding makes each myosin head tilt toward the center of the sarcomere and slide the actin filaments along with it.

F Using energy from ATP, the myosin heads drag the actin filaments inward, pulling the Z lines closer together.

G New ATP binds to the myosin heads and they detach from actin. The myosin heads return to their original orientation, ready to act again.

Figure 6.8 Animated! Sarcomeres shorten when actin and myosin filaments interact. This interaction is the sliding filament model of muscle contraction.

6.4 How the Nervous System Controls Muscle Contraction

- **In response to signals from the nervous system, skeletal muscles move the body and its parts at certain times, in certain ways.**
- **Link to the Endomembrane system 3.7**

Calcium ions are the key to contraction

The nervous system controls the contraction of skeletal muscle cells. Its "orders" reach the muscles by way of motor neurons that stimulate or inhibit contraction of the sarcomeres in muscle cells (Figure 6.9).

When neural signals arrive at a muscle cell, they spread rapidly and eventually reach small extensions of the cell's plasma membrane. These **T tubules** connect with a membrane system that laces around the cell's myofibrils (Figure 6.9*d*). The system, called the **sarcoplasmic reticulum** (SR), is a modified version of the endoplasmic reticulum described in Chapter 3. SR takes up and releases calcium ions (Ca^{++}). An incoming nerve impulse triggers the release of calcium ions from the SR. The ions diffuse into myofibrils, and when they reach actin filaments the stage is set for contraction.

Two proteins, troponin and tropomyosin, are found along the surface of actin filaments (Figure 6.10). When incoming calcium binds to troponin, the binding site on the actin filament is uncovered. This allows myosin cross-bridges to attach to the site, and the cycle described in Section 6.3 continues. When nervous system signals shut off, calcium is actively transported back into the SR. Now the binding site on actin is covered up again, myosin can't bind to actin, and the muscle cell relaxes.

Neurons act on muscle cells at neuromuscular junctions

The nerve impulses that stimulate a skeletal muscle cell arrive at **neuromuscular junctions**. A motor neuron has extensions called *axons*; neuromuscular junctions are places where the branched endings of axons abut the

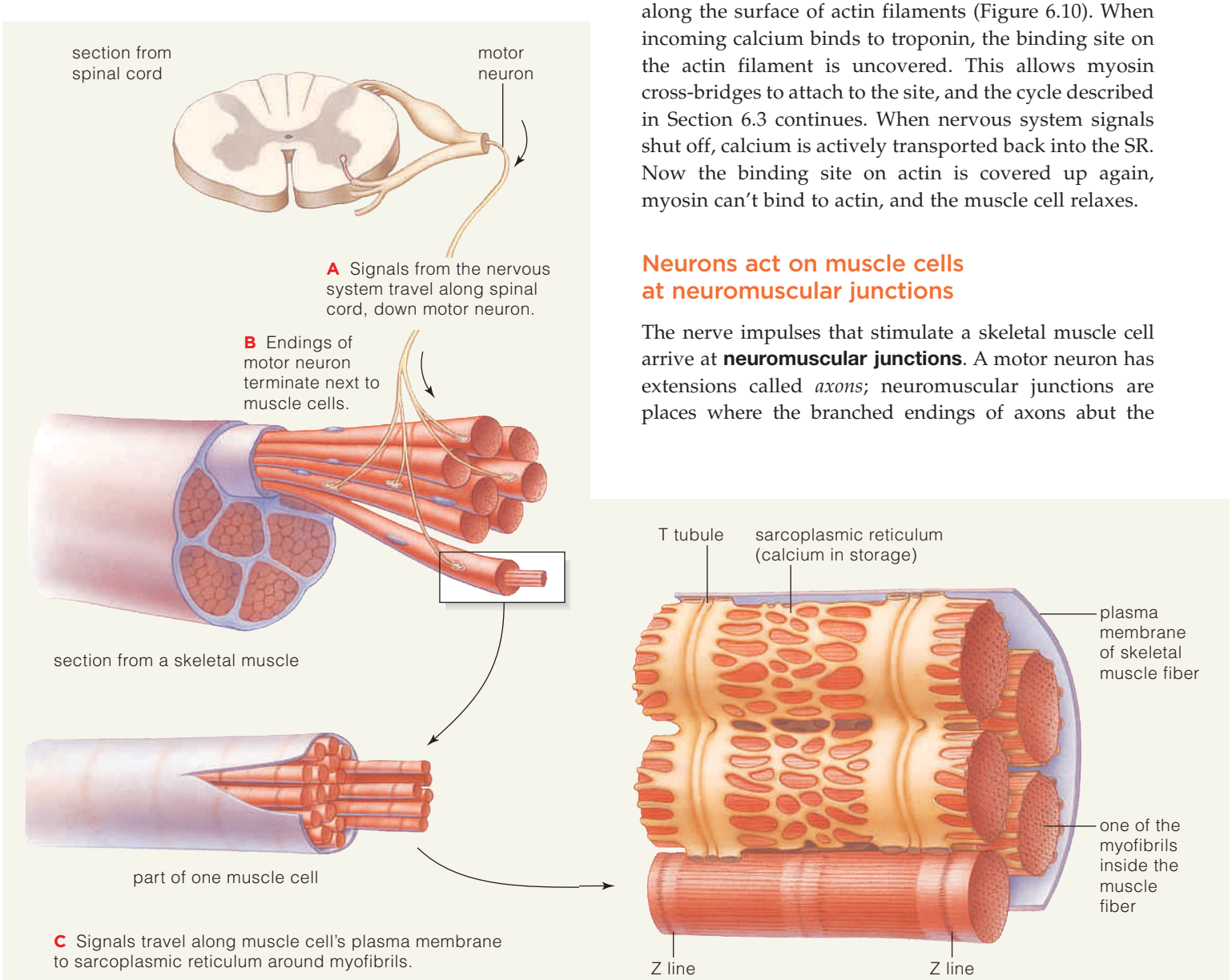


Figure 6.9 Animated! **Signals from the nervous system stimulate contraction of skeletal muscle.**

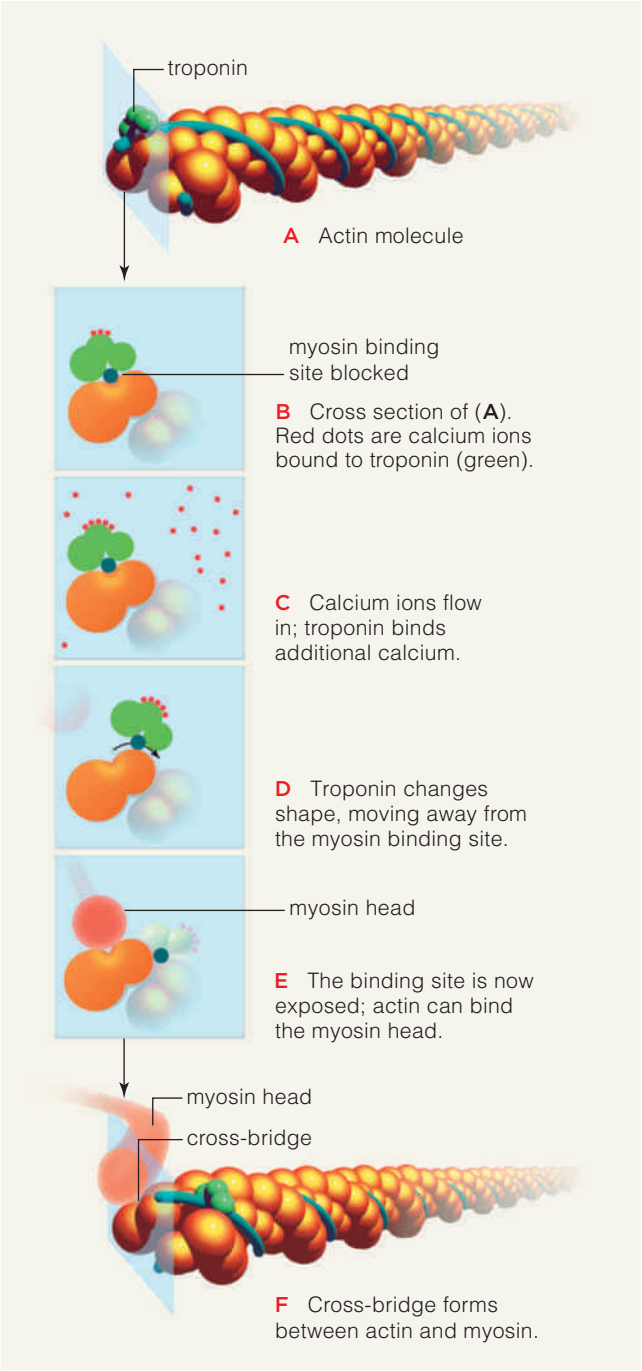


Figure 6.10 **Animated!** **Actin and proteins called tropomyosin and troponins interact in a contracting skeletal muscle cell.**

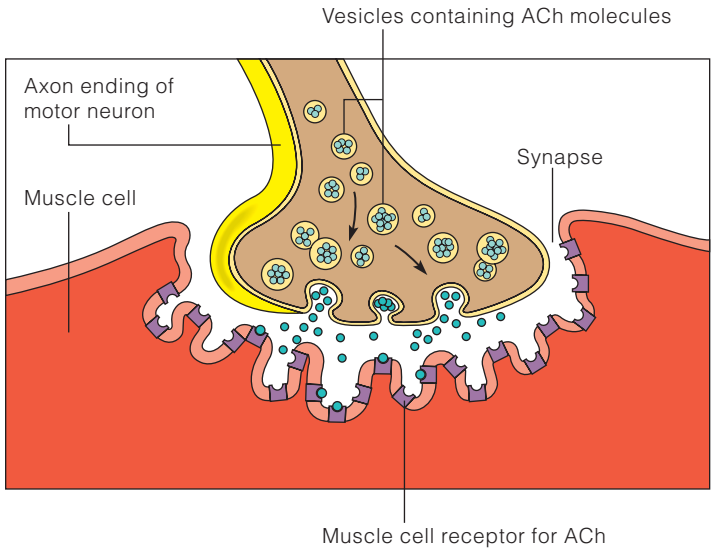


Figure 6.11 **A chemical messenger called a neurotransmitter carries a signal across a neuromuscular junction.**

muscle cell membranes, as you can see in Figure 6.9*b* and Figure 6.11. The neuron endings don't touch a muscle cell; between them there is a gap called a *synapse*. A type of chemical messenger, a **neurotransmitter** called ACh (for acetylcholine) carries signals from a motor neuron across the gap.

This signaling between a neuron and a muscle cell takes place in several steps. When the motor neuron is first stimulated, calcium channels open in the plasma membrane of the neuron's axon endings that are in the neuromuscular junction. Then, calcium ions from the extracellular fluid flow inside the axon endings, and vesicles in each ending release ACh. When ACh binds to receptors on the muscle cell membrane, it may set in motion the events that cause the muscle cell to contract. ACh can excite or inhibit muscle and gland cells, as well as some cells in the brain and spinal cord.

Each year in the United States about 2 million people have small doses of "Botox" injected to smooth out facial wrinkles. Made by the bacterium *Clostridium botulinum*, Botox blocks the release of ACh, so the muscle contractions that produce wrinkles stop for a while. The muscle-relaxing effect lasts four to six months and can have side effects, such as droopy eyelids. Botox also is used to treat disorders. For example, it may relieve abnormal muscle contractions that trouble stroke patients. Only a physician can legally prescribe Botox.

Take-Home Message

How does the nervous system control muscle contractions?

- The nervous system controls the contraction of muscle cells by way of signals that spark the release of calcium ions from a membrane system around a muscle cell's myofibrils.
- Nerve impulses pass from a neuron to a muscle cell across neuromuscular junctions.

6.5 How Muscle Cells Get Energy

- **When a resting muscle is ordered to contract, the demand for ATP in the muscle cell skyrockets.**
- **Links to How cells make ATP 3.14, Alternative energy sources 3.16**

A resting muscle cell has a small amount of ATP and much more of a substance called **creatine phosphate**. When the cell is stimulated to contract, a fast reaction transfers phosphate from creatine phosphate to ADP, to form additional ATP. This reaction can fuel contractions until a slower ATP-forming pathway can kick in (Figure 6.12).

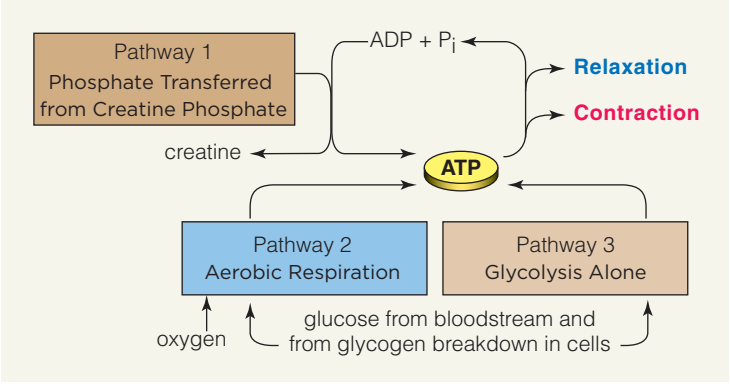


Figure 6.12 Animated! Three metabolic pathways can form ATP in active muscle cells.

Normally, most of the ATP for muscle contraction comes from the oxygen-using reactions of cellular respiration. It's the same with the first five to ten minutes of moderate exercise. For the next half hour or so of steady activity, that muscle cell depends on glucose and fatty acids delivered by the blood. Beyond that time, fatty acids are the main fuel source (Section 3.16).

If you exercise hard, your respiratory and circulatory systems may not deliver enough oxygen for aerobic cellular respiration in some muscles. Then, glycolysis (which does not use oxygen) will contribute more of the ATP being formed. Muscle cells use this alternative as long as stored glycogen can provide glucose or until **muscle fatigue** sets in. This is a state in which a muscle cannot contract, even if it is being stimulated. Fatigue may be due to an **oxygen debt** that results when muscles use more ATP than cellular respiration can deliver. The switch to glycolysis produces lactic acid. Along with the already low ATP supply, the rising acidity hampers the contraction of muscle cells. Deep, rapid breathing helps repay the oxygen debt.

Take-Home Message

Which raw materials can muscle cells use to form ATP?

- Muscle cells may use creatine phosphate, glucose and fatty acids, and fatty acids alone to form ATP.

6.6 Properties of Whole Muscles

- **A muscle may contract weakly, strongly, or somewhere in between. We can relate the properties of muscles to how individual muscle cells contract.**

Several factors determine the characteristics of a muscle contraction

A **motor neuron** supplies a number of cells in a muscle. A motor neuron and the muscle cells it synapses with form a **motor unit** (Figure 6.13). The number of cells in a motor unit depends on how precise the muscle control must be. For instance, where precise control is required, as in the tiny muscles that move the eye, motor units have only four or five muscle cells. By contrast, motor units in some large leg muscles include hundreds of cells.

A muscle contraction may last a long time or only a few thousandths of a second. When a motor neuron fires, all

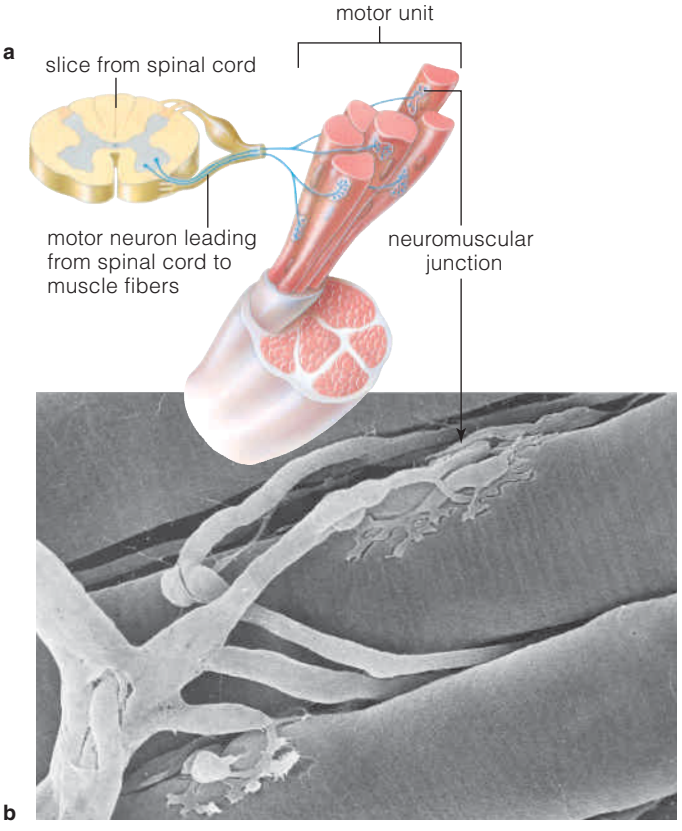


Figure 6.13 Muscle cells are organized into motor units. (**a**) Example of motor units present in muscles. (**b**) The micrograph shows the axon endings of a motor neuron that acts on individual muscle cells in the muscle.

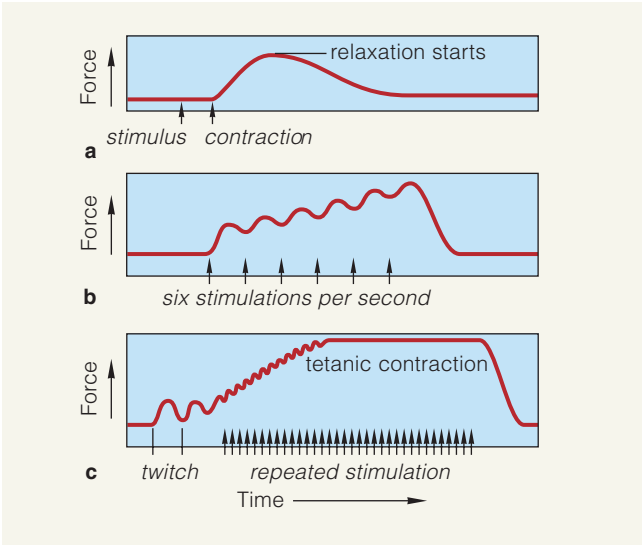


Figure 6.14 **Animated! Each contraction of a motor unit is a muscle twitch.** This figure shows recordings of twitches in muscles artificially stimulated in different ways. (**a**) A single twitch. (**b**) Six per second cause a summation of twitches, and (**c**) about 20 per second cause tetanic contraction.

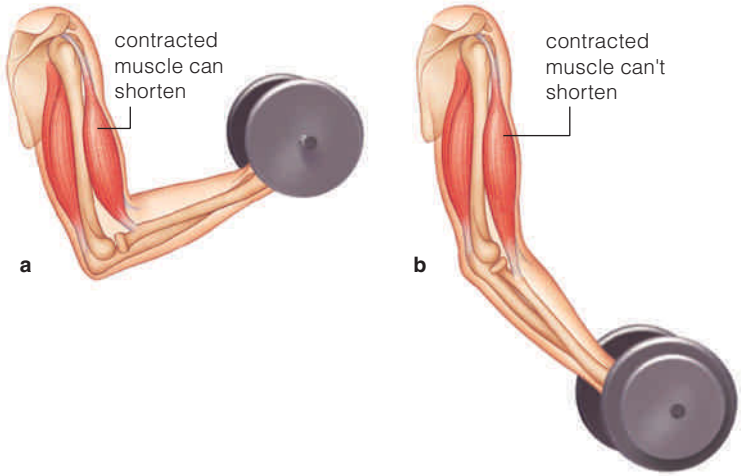


Figure 6.15 **Muscle contractions may be isotonic or isometric.** (**a**) An isotonic contraction. The load is less than a muscle's peak capacity to contract, so the muscle can contract, shorten, and lift the load. (**b**) In an isometric contraction, the load exceeds the muscle's peak capacity. It contracts, but can't shorten.

the cells in its motor unit contract briefly. This response is a **muscle twitch** (Figure 6.14*a*). If a new nerve impulse arrives before a twitch ends, the muscle twitches again. Repeated stimulation of a motor unit in a short period of time makes all the twitches run together (Figure 6.14*b*). The result is a sustained contraction called **tetanus** (Figure 6.14*c*). Our muscles normally contract in this way, which generates three or four times the force of a single twitch.

A skeletal muscle contains a large number of muscle cells, but not all of them contract at the same time. If a muscle is contracting only weakly—say, as your forearm muscles do when you pick up a pencil—it is because the nervous system is activating only a few of the muscle's motor units. In stronger contractions (when you heft a stack of books) more motor units are stimulated. Even when a muscle is relaxed, however, some of its motor units are contracted. This steady, low-level contracted state is called **muscle tone**. It helps maintain muscles in general good health and is important in stabilizing the skeleton's movable joints.

Muscle tension is the force that a contracting muscle exerts on an object, such as a bone. Opposing this force is a load, either the weight of an object or gravity's pull on the muscle. A stimulated muscle shortens only when muscle tension exceeds the opposing forces.

Isotonically contracting muscles shorten and move a load (Figure 6.15*a*). *Isometrically* contracting muscles develop tension but don't shorten. This happens when you attempt to lift an object that is too heavy (Figure 6.15*b*).

Tired muscles can't generate much force

When steady, strong stimulation keeps a muscle in a state of tetanus, the muscle eventually becomes fatigued. Muscle fatigue is a decrease in the muscle's ability to generate force (that is, to develop tension). After a few minutes of rest, a fatigued muscle will be able to contract again. How long this recovery takes depends in part on how long and how often the muscle was stimulated before. Muscles trained by a pattern of brief, intense exercise fatigue and recover rapidly. This is what happens during weight lifting. Muscles used in prolonged, moderate exercise fatigue slowly but take longer to recover, often up to a day. Exactly what causes muscle fatigue is unknown, but one factor is depletion of glycogen, the form in which muscles hold glucose in reserve for energy. The build-up of lactic acid, which makes overused muscles sore, also contributes to fatigue.

Take-Home Message

What factors determine the characteristics of a skeletal muscle contraction?

- A motor unit consists of a motor neuron and the muscle cells it serves. The cells all contract simultaneously.
- The number of motor units in a muscle correlates with how precisely the nervous system must control a muscle's activity.
- Muscles normally contract in a sustained way called tetanus.
- The force exerted by a contracting muscle is muscle tension.

6.7 Diseases and Disorders of the Muscular System

If you have ever torn a muscle or known someone with a muscle-wasting disease, you are very well aware that any problem that impairs the ability of skeletal muscles to produce movement has a serious impact on activities that most of us take for granted. In general, ills that can befall our skeletal muscles fall into three categories: injuries, disease, and disuse.

Muscle injuries include strains and tears

Given that our muscular system gets almost constant use, it's not surprising that the most common disorders of skeletal muscles are injuries. Lots of people, and athletes especially, strain a muscle at some point in their lives (Figure 6.16). The injury happens when a movement stretches or tears muscle fibers. Usually, there is some bleeding into the damaged area, which causes swelling and a painful muscle spasm. The usual first aid is an ice pack, followed by resting the affected muscle and using anti-inflammatory drugs such as ibuprofen.

When a whole muscle is torn, the aftereffects can last a lifetime. If scar tissue develops while the tear mends, the healed muscle may be shorter than before. As a result, it may not function as effectively.

Figure 6.16 **For athletes, muscle strains and tears often are "part of the game."**

Figure 6.17 **Muscular dystrophies are inherited disorders.** The child pictured here suffers from Duchenne muscular dystrophy.

Cramps and spasms are abnormal contractions

In a muscle *spasm*, a muscle suddenly and involuntarily contracts. A muscle *cramp* is a painful muscle spasm that doesn't immediately release. Any skeletal muscle can cramp, but the usual "victims" are calf and thigh muscles. In some cases the real culprit is a deficiency of potassium, which is needed for the proper transmission of nerve impulses to muscles and other tissues. Gentle stretching and massage may coax a cramped muscle to release.

Most people experience occasional muscle *tics*. These minor, involuntary twitches are common in muscles of the face and eyelids and may be triggered by anxiety or some other psycho-emotional cause.

Muscular dystrophies destroy muscle fibers

Muscular dystrophies are genetic diseases in which muscle fibers break down and the affected muscles progressively weaken and shrivel. **Duchenne muscular dystrophy** (DMD) is the most common form in children (Figure 6.17). It is caused by a single mutant gene that interferes with the ability of sarcomeres in muscle cells to contract. Affected youngsters usually are confined to a wheelchair by their teens, and most die by their early twenties.

Myotonic muscular dystrophy is usually seen in adults. It generally affects only the hands and feet and is not life-threatening. "Myo" means muscle, and the name of this disorder indicates that affected muscles contract strongly but do not relax in the normal way.

Bacterial infections can interfere with nervous system signals to muscles

Section 6.4 mentioned the use of *Clostridium botulinum* toxin for Botox injections. This microorganism normally lives in soil. When it contaminates food in unsterilized cans or jars, it produces the botulinum toxin, which causes the deadly food poisoning called **botulism**. The toxin stops motor neurons from releasing ACh, the neurotransmitter that triggers muscle contractions. As a result, muscles become paralyzed. Swift treatment with an antitoxin is the only way to prevent death due to paralysis of the heart muscle and the skeletal muscles involved in breathing.

A similar microbe, *Clostridium tetani*, lives in the gastrointestinal tract of animals such as cattle and horses. (It may also inhabit the human GI tract.) *C. tetani* spores, a resting stage of the microbe, may be in soil that contains manure. If they enter a wound, the microbe becomes active and produces a toxin that causes the disease **tetanus**.

Unlike the healthy state of steady, low-level muscle contraction of the same name (Section 6.6), the disease tetanus is life-threatening. The bacterial toxin travels to the spinal cord, where it blocks nervous system signals that release skeletal muscles from contraction. The muscles go into unending spasms called spastic paralysis. A patient's fists and jaw may stay clenched (which is why the disease sometimes is called "lockjaw") and the spine may arch in a stiff curve. Death comes when paralysis reaches the heart and respiratory muscles.

Today a tetanus vaccine can confer immunity to the disease, and in developed countries such as the United States nearly all people are immunized as children, with periodic "booster shots" recommended for adults. Vaccines were not available for soldiers who sustained battlefield wounds in early wars, and many suffered an agonizing death due to tetanus (Figure 6.18). Globally, the disease kills about 200,000 people each year, mostly women who must give birth in unsanitary conditions.

Cancer may develop in muscle tissue

Cancers that affect the body's soft tissues are a form of **sarcoma** (the prefix *sarc-* means tissue). Luckily, cancer that begins in muscle tissue is relatively rare—only about 1 percent of each year's new cancer cases. Children and young adults are most commonly affected, and about two-thirds of cases involve malignancies that develop in skeletal muscle—a cancer known as rhabdomyosarcoma.

The exact cause of rhabdomyosarcoma is not known, although, as with all cancers, genetic changes are the direct triggers. Having certain rare connective tissue disorders increases the risk. Experience shows that patients must be treated with a three-pronged therapy—surgery to remove as much of the tumor as possible, followed by chemotherapy and radiation to kill remaining cancerous cells. When patients receive this demanding treatment regimen, their chances of being cured are excellent.

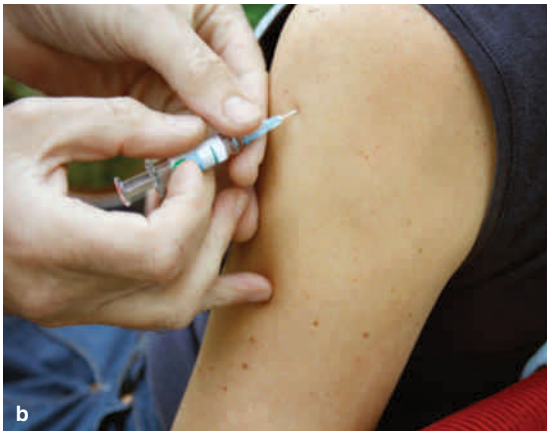


Figure 6.18 The disease tetanus "freezes" muscles in a contracted state. (**a**) This painting depicts a soldier dying of the disease tetanus in a military hospital in the 1800s after the bacterium *Clostridium tetani* infected a battlefield wound. (**b**) The tetanus vaccine has saved countless lives in countries where it is readily available.

6.8 Making the Most of Muscles

Muscle cells adapt to the activity demanded of them. When severe nerve damage or prolonged bed rest prevents a muscle from being used, the muscle will rapidly begin to waste away, or *atrophy*. Over time, affected muscles can lose up to three-fourths of their mass, with a corresponding loss of strength. More commonly, the skeletal muscles of a sedentary person stay basically healthy but cannot respond to physical demands in the same way that well-worked muscles can.

The best way to maintain or improve the work capacity of your muscles is to exercise them—that is, to increase the demands on muscle fibers to contract. To increase muscle endurance, nothing beats regular aerobic exercise—activities such as walking, biking, jogging, swimming, and aerobics classes (Figure 6.19*a*). Aerobic exercise works muscles at a rate at which the body can keep them supplied with oxygen. It affects muscle fibers in several ways:

1. There is an increase in the number and the size of mitochondria, the organelles that make ATP.
2. The number of blood capillaries supplying muscle tissue increases. This increased blood supply brings more oxygen and nutrients to the muscle tissue and removes metabolic wastes more efficiently.
3. Muscle tissues contain more of the oxygen-binding pigment myoglobin.

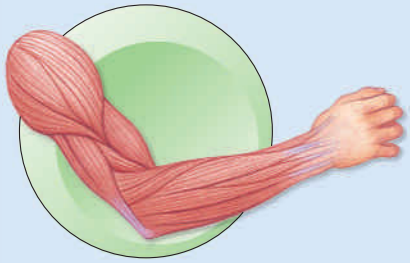
Together, these changes produce muscles that are more efficient metabolically and can work longer without becoming fatigued.

By contrast, strength training involves intense, short-duration exercise, such as weight lifting. It affects fast muscle fibers, which form more myofibrils and make more of the enzymes used in glycolysis (which forms some ATP). These changes translate into whole muscles that are larger and stronger (Figure 6.19*b*), but such bulging muscles fatigue rapidly so they don't have much endurance. Fitness experts generally recommend a workout plan that combines strength training and aerobic workouts.

Starting at about age 30, the tension, or physical force, a person's muscles can muster begins to decrease. This means that, once you enter your fourth decade of life, you may exercise just as long and intensely as a younger person but your muscles cannot adapt to the workouts to the same extent. Even so, being physically active is extremely beneficial. Aerobic exercise improves your endurance and blood circulation, and even modest strength training slows the loss of skeletal muscle tissue that is an inevitable part of aging.

Figure 6.19 Physical activity is important for muscle health throughout life. (**a**) Aerobic exercise builds endurance and improves overall muscle function. (**b**) Strength training builds larger, stronger muscles but does not improve endurance.

6.9 CONNECTIONS: Muscles and the Muscular System in Homeostasis



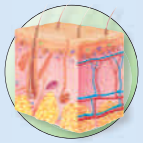
Muscle Tissue and the Muscular System

The muscular system works with the skeleton to bring about body movements. Contractions of skeletal muscles also stabilize joints and body positions. Muscle tissue produces much of the body's metabolic heat.

Smooth muscle forms the walls of hollow organs, blood vessels, ducts, and tubes. Its contractions move substances including blood and food that is being digested. Sphincters that control the passage of food, feces, and urine also consist of smooth muscle.

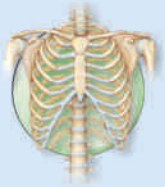
Cardiac muscle forms the wall of the heart. Its contractions move blood throughout the body via the cardiovascular system.

Integumentary system



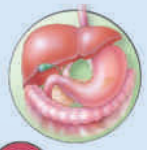
Skeletal muscle provides support for skin. Many facial muscles, especially those used for making facial expressions such as smiling, attach to skin instead of to bones.

Skeletal system



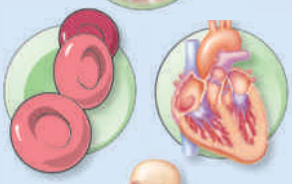
Skeletal muscles attach to bones, which serve as levers for body movements. The muscles also stabilize movable joints.

Digestive system



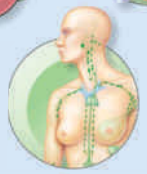
Abdominal muscles support many digestive organs. Other skeletal muscles operate in chewing and swallowing. Contractions of smooth muscle move material through the system.

Cardiovascular system and blood



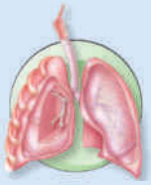
Contractions of cardiac (heart) muscle pump blood. Smooth muscle in blood vessels allows adjustments in blood flow in different body regions. Contraction of leg muscles helps return blood to the heart.

Immunity and the lymphatic system



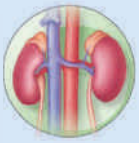
Smooth muscle forms the walls of lymphatic system vessels. Skeletal muscle helps support lymph nodes in various parts of the body.

Respiratory system



The diaphragm and skeletal muscles attached to the ribs function in breathing and help clear airways by coughing. Smooth muscle in airways allows changes in air flow to and from the lungs.

Urinary system

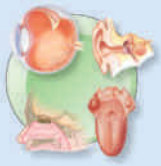


Abdominal muscles help support the kidneys and bladder. Smooth muscle in the bladder is strong and stretchable enough to store urine; its contractions move urine out of the body.

Nervous system

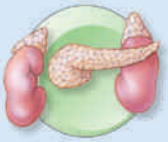
All types of muscle tissue respond to nerve impulses to carry out a wide variety of body functions. Skeletal muscles help support the spine and head.

Sensory systems



Skeletal muscles move the eyes and contain sensory receptors that provide information about changes in body position.

Endocrine system



Skeletal muscles help support endocrine organs such as the pancreas and thyroid gland.

Reproductive system

Muscle contractions move eggs and sperm. Contraction of smooth muscle in the uterus expels a fetus during childbirth and assists with shedding of the uterus lining (menstruation).

IMPACTS, ISSUES

Pumping Up Muscles

COMPETITIVE athletes and others who want to build larger, stronger muscles may be tempted to use certain performance-enhancing substances. These chemicals generally are marketed as dietary supplements, although their safety and effectiveness have not been thoroughly tested by independent laboratories.

How Would You Vote?

Dietary supplements are largely unregulated. Should they be subject to more stringent testing for effectiveness and safety? See CengageNOW for details, then vote online.

Summary

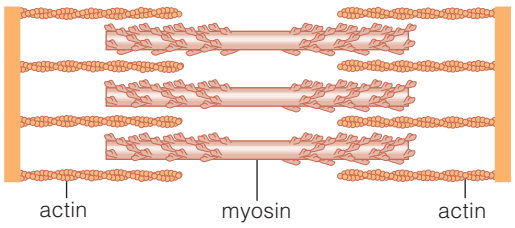
Section 6.1 Muscle tissue includes skeletal, smooth, and cardiac muscle. Despite having different functions in the body, cells in all three types of muscle generate force by contracting.

Section 6.2 The muscular system consists of more than 600 skeletal muscles, which transmit force to bones and move body limbs or other parts (Table 6.1). Skeletal muscles also help to stabilize joints and generate body heat. Each one contains bundles of muscle fibers (muscle cells) wrapped in connective tissue.

Tendons connect skeletal muscle to bones. The origin end of a muscle attaches to the bone that moves least during a movement. The insertion end attaches to the bone that moves most. Some muscles work antagonistically—the action of one opposes or reverses the action of the other. Synergist muscles assist each other's movements.

- Use the animation and interaction on CengageNOW to learn about the locations and action of skeletal muscles.

Section 6.3 Bones move when they are pulled by the shortening, or contraction, of skeletal muscles. This shortening occurs because individual muscle fibers are shortening. Skeletal muscle fibers contain threadlike myofibrils, which are divided lengthwise into sarcomeres, the basic units of contraction. Each sarcomere consists of an array of filaments of the proteins actin (thin) and myosin (thick):



To shorten a sarcomere, the myosin attaches to a neighboring actin and the actin slides over the myosin. ATP powers this interction, which is called the sliding filament mechanism of muscle contraction.

- Use the animation and interaction on CengageNOW to get an in-depth look at the structure and function of skeletal muscles.

Review of Skeletal Muscle

Function of Skeletal Muscle:

Contraction (shortening) that moves the body and its parts.

Major Components of Skeletal Muscle Cells:

Myofibrils: Strands containing filaments of the contractile proteins actin and myosin.

Sarcomeres: The basic units of muscle contraction.

Other:

Motor unit: A motor neuron and the muscle cells it controls.

Neuromuscular junction: Synapse between a motor neuron and muscle cells.

Section 6.4 Nerve impulses cause skeletal muscle cells to contract. They trigger the release of calcium ions from sarcoplasmic reticulum, a membrane system that wraps around myofibrils in the muscle fiber. The calcium alters proteins on actin filaments so that the heads of myosin molecules can bind to actin.

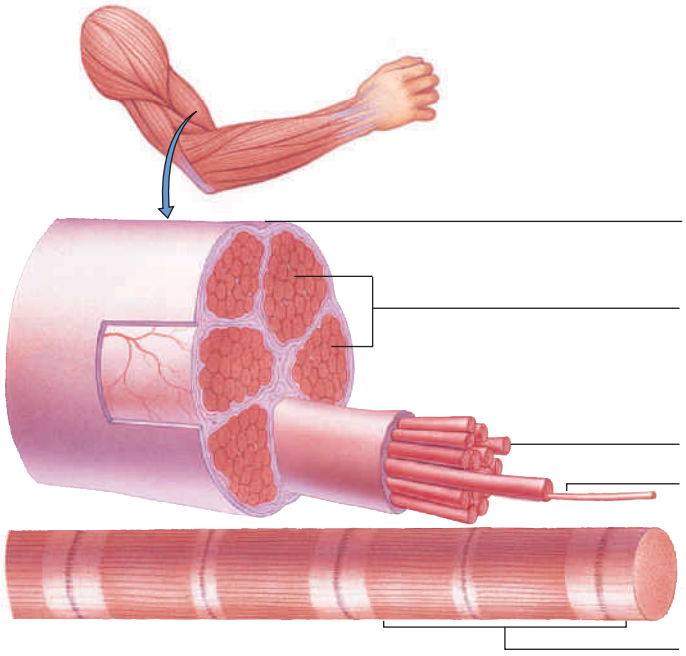
A neuromuscular junction is a synapse between a motor neuron and a muscle fiber. A nerve impulse triggers the release of a neurotransmitter called ACh into the synapse. This starts the events that cause the fiber to contract.

- Use the animation and interaction on CengageNOW to see how signals from the nervous system control muscle contraction.

Section 6.5 The ATP required for muscle contraction can come from cellular respiration, from glycolysis alone, or from the generation of ATP from creatine phosphate. When muscles use more ATP than aerobic respiration can provide, an oxygen debt may develop in muscle tissue.

- Use the animation and interaction on CengageNOW to see how a muscle gets the energy for contraction.

Section 6.6 A motor neuron and the muscle fibers it controls form a motor unit. When a stimulus activates enough motor units, it produces a muscle twitch. If a series of twitches occur close together, a sustained contraction called tetanus develops. Skeletal muscles normally operate near or at tetanus. Important functional properties of



whole muscles include the force they exert (tension), muscle tone, and fatigue.

Section 6.7 Injuries are the most common disorders of skeletal muscles, and even healthy muscles may contract abnormally, such as when they cramp. Muscular dystrophies are a set of diseases that destroy muscle fibers and cause skeletal muscles to lose function.

Review Questions

1. In a general sense, how do skeletal muscles produce movement?
2. In the diagram above, label the fine structure of a muscle, down to one of its myofibrils. Identify the basic unit of contraction in a myofibril.
3. How do actin and myosin interact in a sarcomere to bring about muscle contraction? What roles do ATP and calcium play?
4. How does a muscle cell incur an oxygen debt?
5. What is the function of the sarcoplasmic reticulum in muscle cell contraction?
6. Explain why (*a*) calcium ions and (*b*) ACh are vital for muscle contraction.
7. What is a motor unit? Why does a rapid series of muscle twitches yield a stronger overall contraction than a single twitch?
8. What are the structural and functional differences between "slow" and "fast" muscle?

Self-Quiz *Answers in Appendix V*

1. The _____ and _____ systems work together to move the body and specific body parts.
2. The three types of muscle tissue are _____, _____, and _____.
3. _____ forms cross-bridges with myosin.
   a. A muscle fiber
   b. A tendon
   c. Myoglobin
   d. Actin
4. The _____ is the basic unit of muscle contraction.
   a. myofibril
   b. sarcomere
   c. muscle fiber
   d. myosin filament
5. Skeletal muscle contraction requires _____.
   a. calcium ions
   b. ATP
   c. arrival of a nerve impulse
   d. all of the above
6. Match the M words with their defining feature.

____ muscle	a. actin's partner
____ muscle twitch	b. delivers contraction signal
____ muscle tension	c. a muscle cannot contract
____ myosin	d. motor unit response
____ motor neuron	e. force exerted by cross-bridges
____ myofibrils	f. muscle cells bundled in connective tissue
____ muscle fatigue	g. threadlike parts in a muscle fiber

Critical Thinking

1. You are training athletes for the 100-meter dash. They need muscles specialized for speed and strength, *not* endurance. What muscle characteristics would your training regimen aim to develop? How would you alter it to train marathoners?
2. In 1989, explorer Will Steger and his dogsled team crossed Antarctica, traveling some 3,741 miles. Steger said later that his polar huskies worked the hardest and pulled all the weight. A husky's limb bones and skeletal muscles are suited for long-distance load-pulling. For example, the forelegs move freely, thanks to a deep but not-too-broad rib cage, and the dog also has a well-muscled chest. What kind of muscle fibers and muscle mass would you expect to find in a husky's *hind* legs, which provide much of the brute power to propel a loaded sled?
3. Curare, a poison extracted from a South American shrub, blocks the binding of ACh by muscle cells. What do you suppose would happen to your muscles, including the ones involved in breathing, if a toxic dose of curare entered your bloodstream?
4. At the gym Sean gets on a stair-climbing machine and "climbs" as fast as he can for fifteen minutes. At the end of that time he is breathing hard and his quadriceps and other leg muscles are aching. What is the physiological explanation for these symptoms?
5. In training for a marathon, Lydia plans to take creatine supplements because she heard that they boost an athlete's energy. What is your opinion on this plan?

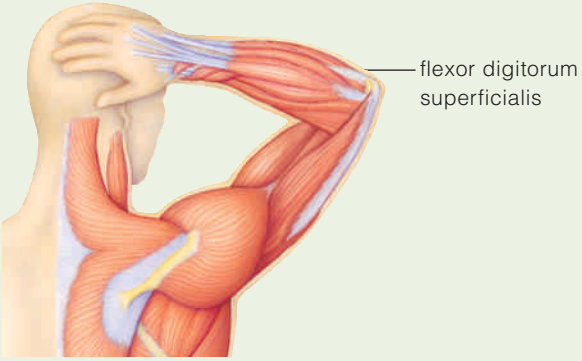
EXPLORE ON YOUR OWN

A good way to improve your understanding of your muscular system is to explore the movements of your own muscles. Try the following quick exercises.

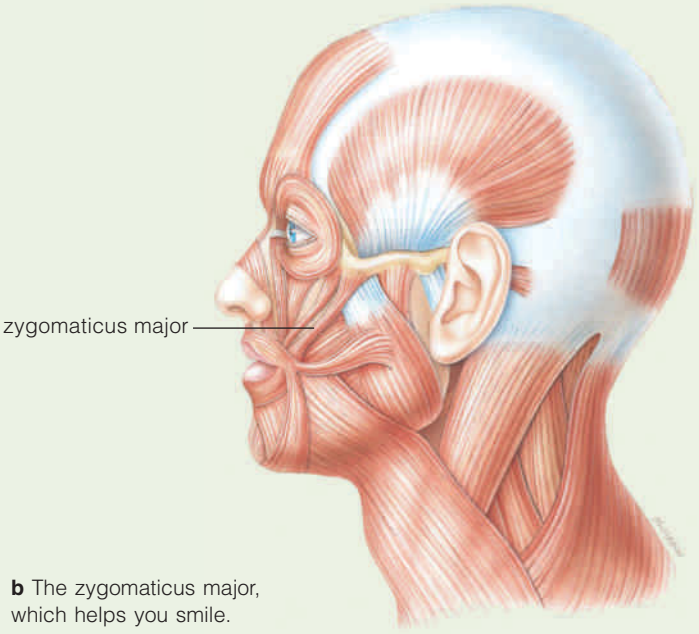
Human hands don't contain many of the muscles that control hand movements. Instead, as you can see in Figure 6.20*a*, most of those muscles are in the forearm. Tendons extending from one muscle, the flexor digitorum superficialis (the "superficial finger flexer"), bend your fingers. Place one hand on the top of the opposite forearm, and then wiggle your fingers on that side or make a fist several times. Can you feel the "finger flexer" in action?

Place your fingers on the skin above your nose, between your eyebrows. Now frown. The muscle you feel pulling your eyebrows together is the corrugator supercilii. One effect of its contraction is to "corrugate" the skin of your forehead into vertical wrinkles.

A grin calls into action other facial muscles, including the zygomaticus major (Figure 6.20*b*). On either side of the skull, this muscle originates on the cheekbones and inserts at the corners of the mouth. To feel it contract, place the tips of your index fingers at the corners of your mouth, and then smile.



a The flexor digitorum superficialis, a forearm muscle that helps move the fingers.



b The zygomaticus major, which helps you smile.

Figure 6.20 **Explore these muscles!**

Circulation: The Heart and Blood Vessels

7

IMPACTS, ISSUES

Be Not Still, My Beating Heart!

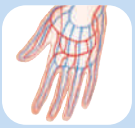
YOUR heart is the most durable muscle in your body. It begins beating about a month after conception and keeps going for a lifetime. A natural "pacemaker" in the heart's wall produces an electrical signal that stimulates each heartbeat. If this pacemaker malfunctions, the heart may stop beating—an event called sudden cardiac arrest. Each year more than 300,000 people in the United States suffer sudden cardiac arrest. In older people, heart disease is the usual cause. In those under age 35, an inborn heart defect often is to blame.

This was the case with Matt Nader, the young man shown at left. He went into sudden cardiac arrest while playing in a high school football game. Matt's parents, who were watching the game, rushed onto the field and started cardiopulmonary resuscitation (CPR) on their lifeless son. In CPR, a person alternates mouth-to-mouth respiration with chest compressions that keep the victim's blood moving. If CPR is started within 4 to 6 minutes, the victim's chances of surviving the arrest rise by 50 percent.

CPR does not restart a stopped heart. That requires a device called a defibrillator, which delivers a strong electric current to the chest. With luck the shock quickly restarts the pacemaker. In Matt's case, a bystander ran to get the school's automated external defibrillator (AED). This device, about the size of a laptop computer, provides simple voice instructions on its use and if need be generates a shock. Such a procedure helped save Matt Nader. The public health value of AEDs now is widely recognized. Many schools, senior centers, shopping malls, hotels, and airports keep one of these lifesavers on hand.

In this chapter you will learn about the structure and function of the cardiovascular system—the heart and blood vessels. Several topics will help you to understand the biology that underlies CPR and the use of an AED. If you would like to learn how to save lives with these methods, the American Heart Association, the American Red Cross, and many other community organizations provide training. Taking time to learn these skill is something we all can do for one another.

KEY CONCEPTS

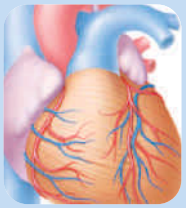


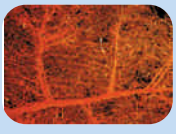
Circulating Blood

The cardiovascular system transports oxygen, nutrients, hormones, and other substances swiftly to body cells. It also carries away wastes and cell products. Section 7.1

Pumping Blood

The heart is a muscular pump. Heart contractions provide the force that drives blood through the cardiovascular system's arteries and veins. Sections 7.2–7.5





Blood Vessels

Various types of blood vessels, including arteries, arterioles, capillaries, venules, and veins, are specialized for different blood transport functions. Sections 7.6–7.9

Disorders of the Circulatory System and Homeostasis

Sections 7.8–7.10

LINKS TO EARLIER CONCEPTS

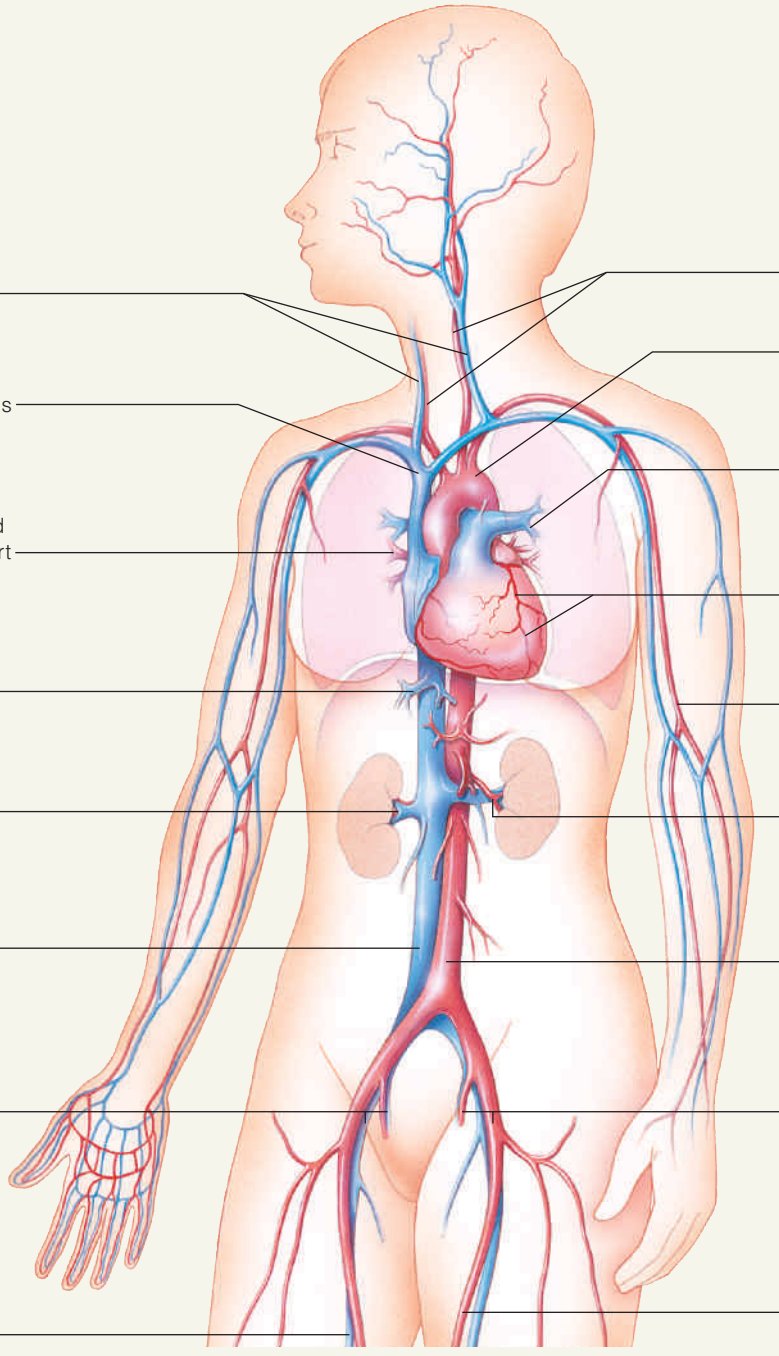
- This chapter begins our study of the body's major internal organ systems and how each contributes to homeostasis. It looks more closely at cardiac muscle (4.3) and at the specialized cell junctions in this tissue (4.6).
- You will see how the tubelike organs called blood vessels are built from layers of epithelium, connective tissue, and smooth muscle (4.1–4.3).
- We also consider cardiovascular diseases and disorders, including links between heart health and lipoproteins and cholesterol (2.10, 2.12).

How Would You Vote?

Some advocates think that CPR training should be a required mini-course in high schools. People who learn CPR also must be periodically recertified. Would you favor mandatory CPR training in high schools? See CengageNOW for details, then vote online.

7.1 The Cardiovascular System: Moving Blood through the Body

- **The cardiovascular system is built to rapidly transport blood to every living cell in the body.**
- **Links to Diffusion 3.10, Metabolism 3.13**



Jugular Veins
Receive blood from brain and from tissues of head

Superior Vena Cava
Receives blood from veins of upper body

Pulmonary Veins
Deliver oxygenated blood from the lungs to the heart

Hepatic Vein
Carries blood that has passed through small intestine and then liver

Renal Vein
Carries processed blood away from kidneys

Inferior Vena Cava
Receives blood from all veins below diaphragm

Iliac Veins
Carry blood away from the pelvic organs and lower abdominal wall

Femoral Vein
Carries blood away from the thigh and inner knee

Carotid Arteries
Deliver blood to neck, head, brain

Ascending Aorta
Carries oxygenated blood away from heart; the largest artery

Pulmonary Arteries
Deliver oxygen-poor blood from the heart to the lungs

Coronary Arteries
Service the cardiac muscle cells of heart

Brachial Artery
Delivers blood to upper limbs; blood pressure measured here

Renal Artery
Delivers blood to kidneys, where its volume, chemical make up are adjusted

Abdominal Aorta
Delivers blood to arteries leading to the digestive tract, kidneys, pelvic organs, lower limbs

Iliac Arteries
Deliver blood to pelvic organs and lower abdominal wall

Femoral Artery
Delivers blood to the thigh and inner knee

Figure 7.1 Animated! The heart and blood vessels make up the cardiovascular system. Arteries, which carry oxygenated blood to tissues, are shaded red. Veins, which carry deoxygenated blood away from tissues, are shaded blue. Notice, however, that for the pulmonary arteries and veins the roles are reversed.

The heart and blood vessels make up the cardiovascular system

"Cardiovascular" comes from the Greek *kardia* (heart) and the Latin *vasculum* (vessel). As you can see in Figure 7.1 the **cardiovascular system** has two main elements, the heart and blood vessels.

- The **heart** is a muscular pump that generates the pressure required to move blood throughout the body.
- Blood vessels are tubes of different diameters that transport blood.

The heart pumps blood into **arteries**, which have a large diameter. From there blood flows into smaller and narrower vessels called **arterioles**, which branch into even narrower **capillaries**. Blood flows from capillaries into small **venules**, then into large-diameter **veins** that return blood to the heart.

As you will read later on, the volume of blood flowing to a particular part of the body and the rate at which it flows both are adjustable. This flexibility permits the cardiovascular system to deliver blood in ways that suit conditions in different parts of the body. For example, blood flows rapidly through arteries, but in capillaries it must flow slowly so that there is time for substances moving to and from cells to diffuse into and out of extracellular fluid (Figure 7.2). This slow flow takes place in **capillary beds**, where blood moves through vast numbers of slender capillaries. By dividing up the blood flow, the capillaries handle the same total volume of flow as the large-diameter vessels, but at a slower pace.

Blood circulation is essential to maintain homeostasis

You may hear someone refer to the cardiovascular system as the "circulatory system." This name is apt because blood circulates through the system, bringing body cells such essentials as oxygen, nutrients from food, and secretions such as hormones. Circulating blood also takes away the wastes produced by our metabolism, along with excess heat. In fact, cells depend on blood to make constant pickups and deliveries of an amazingly diverse range of substances, including those that move into or out of the digestive system and the respiratory and urinary systems (Figure 7.2).

Homeostasis is one of our constant themes in this book, so it's good to keep in mind that maintaining it would be impossible were it not for our circulating blood. Cells

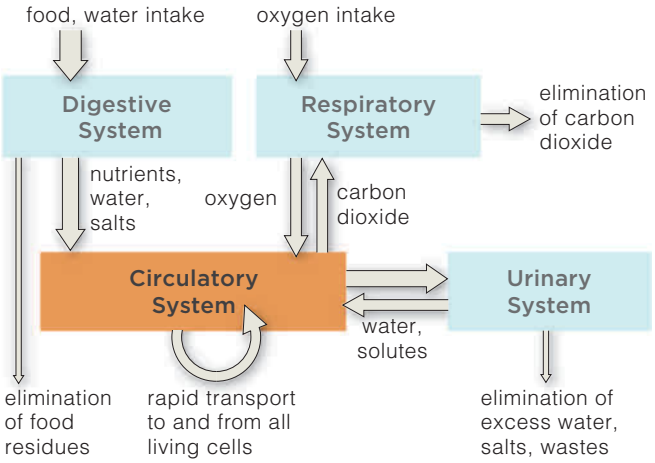


Figure 7.2 Together with the other systems shown here, the cardiovascular system helps maintain favorable operating conditions in the internal environment.

must exchange substances with blood because that is a key way cells adjust to changes in the chemical makeup of the extracellular fluid around them—part of the "internal environment" in which they live.

The cardiovascular system is linked to the lymphatic system

The heart's pumping action puts pressure on blood flowing through the cardiovascular system. Partly because of this pressure, small amounts of water and some proteins dissolved in blood are forced out and become part of interstitial fluid (the fluid between cells). An elaborate network of drainage vessels picks up excess extracellular fluid and usable substances in it—such as water and proteins—and returns them to the cardiovascular system. This vessel network is part of the lymphatic system, which we consider in Chapter 9.

Take-Home Message

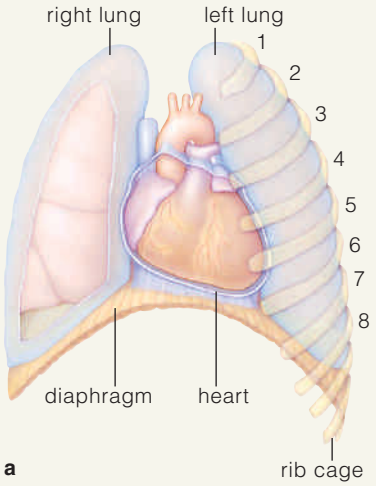
What is the cardiovascular system?

- The cardiovascular system consists of the heart and the blood vessels.
- The cardiovacular system transports substances to and from the fluid that bathes all living cells.

7.2 The Heart: A Double Pump

- **In a lifetime of 70 years, the human heart beats some 2.5 billion times. This durable pump is the centerpiece of the cardiovascular system.**
- **Links to Epithelium 4.1, Muscle tissue 4.3**

Roughly speaking, your heart is located in the center of your chest (Figure 7.3*a*). Its structure reflects its role as a long-lasting pump. The heart is mostly cardiac muscle tissue, the **myocardium** (Figure 7.3*b*). A tough, fibrous sac, the pericardium (*peri* = around), surrounds, protects, and lubricates it. The heart's chambers have a smooth lining (endocardium) composed of connective tissue and a layer of epithelial cells. The epithelial cell layer, known as endothelium, also lines the inside of blood vessels.



a

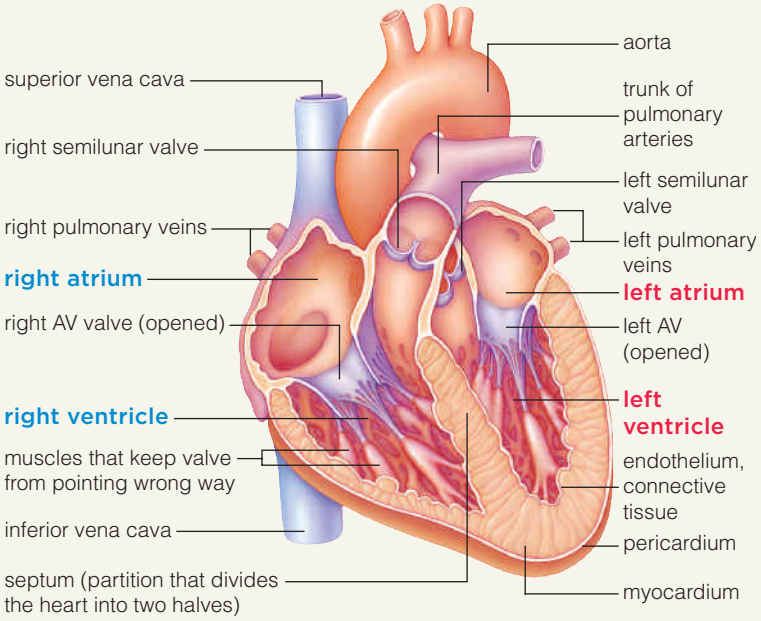
The heart has two halves and four chambers

A thick wall, the **septum**, divides the heart into two halves, right and left. Each half has two chambers: an **atrium** (plural: atria) located above a **ventricle**. Flaps of membrane separate the two chambers and serve as a one-way **atrioventricular valve** (AV valve) between them. The AV valve in the right half of the heart is called a *tricuspid valve* because its three flaps come together in pointed cusps (Figure 7.3*c*). In the heart's left half the AV valve consists of just two flaps; it is called the *bicuspid valve* or *mitral valve*. Tough, collagen-reinforced strands (chordae tendineae, or "heartstrings") connect the AV valve flaps to cone-shaped muscles that extend out from the ventricle wall. When a blood-filled ventricle contracts, this arrangement prevents the flaps from opening backward into the atrium. Each half of the heart also has a half-moon–shaped **semilunar valve** between the ventricle and the arteries leading away from it. During a heartbeat, this valve opens and closes in ways that keep blood moving in one direction through the body.

The heart has its own "coronary circulation." Two **coronary arteries** lead into a capillary bed that services most of the cardiac muscle (Figure 7.4). They branch off the **aorta**, the major artery carrying oxygenated blood away from the heart.

In a "heartbeat," the heart's chambers contract, then relax

Blood is pumped each time the heart beats. It takes less than a second for a "heartbeat"—one sequence of contraction and relaxation of the heart chambers. The sequence occurs almost simultaneously in both sides of the heart. The contraction phase is called **systole** (SISS-toe-lee), and the relaxation phase is called **diastole** (dye-ASS-toe-lee). This sequence is the **cardiac cycle** diagrammed in Figure 7.5.



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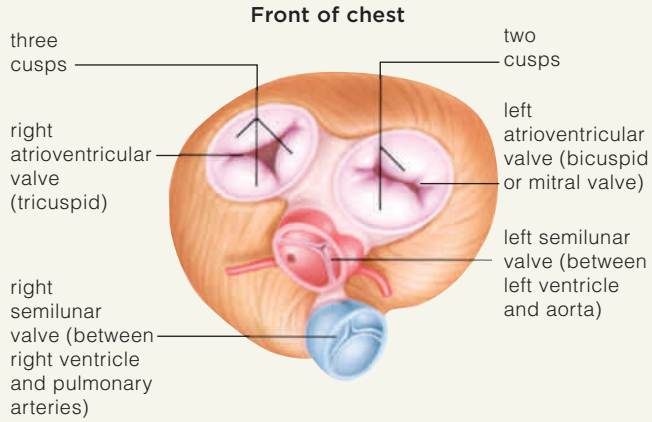
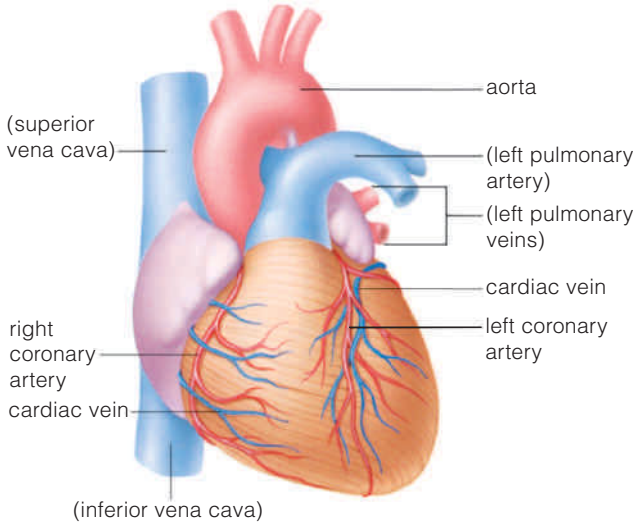


c

Figure 7.3 Animated! The heart is divided into right and left halves. (**a**) Location of the heart. (**b**) Cutaway view showing the heart's internal organization, and (**c**) valves of the heart. In this drawing, you are looking down at the heart. The atria have been removed so that the atrioventricular (AV) and semilunar valves are visible.



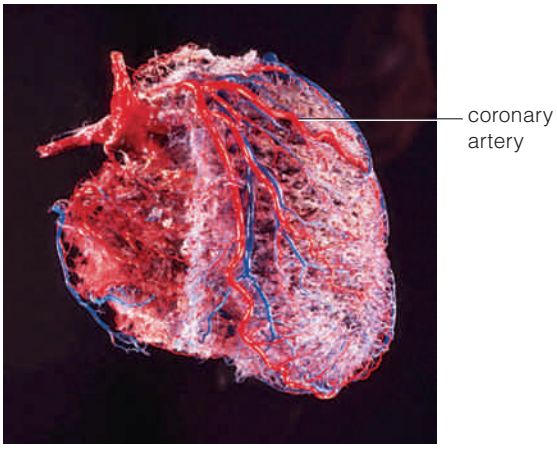


Figure 7.4 The heart itself is served by coronary arteries and veins. The photograph shows a resin cast of these vessels.

During the cycle, the ventricles relax before the atria contract, and the ventricles contract when the atria relax. When the relaxed atria are filling with blood, the fluid pressure inside them rises and the AV valves open. Blood flows into the ventricles, which are 80 percent filled by the time the atria contract. As the filled ventricles begin to contract, fluid pressure inside *them* increases, forcing the AV valves shut. The rising pressure then forces the semilunar valves open—and blood flows out of the heart and into the aorta and pulmonary artery. Now the ventricles relax, and the semilunar valves close. For about half a second the atria and ventricles are all in diastole. Then the blood-filled atria contract, and the cycle repeats.

The amount of blood each ventricle pumps in a minute is called the **cardiac output**. On average, every sixty seconds the cardiac output from each ventricle is about 5 liters—nearly all the blood in the body. This means that in a year each half of your heart pumps at least 2.5 million liters of blood. That is more than 600,000 gallons!

The blood and heart movements during the cardiac cycle generate an audible "lub-dup" sound made by the forceful closing of the heart's one-way valves. At each "lub," the AV valves are closing as the two ventricles contract. At each "dup," the semilunar valves are closing as the ventricles relax.

Take-Home Message

How does the heart work as a double pump?

- Each half of the heart is divided into an atrium and a ventricle.
- During a cardiac cycle, contraction of the atria helps fill the ventricles. Contraction of the ventricles pumps blood out the heart.

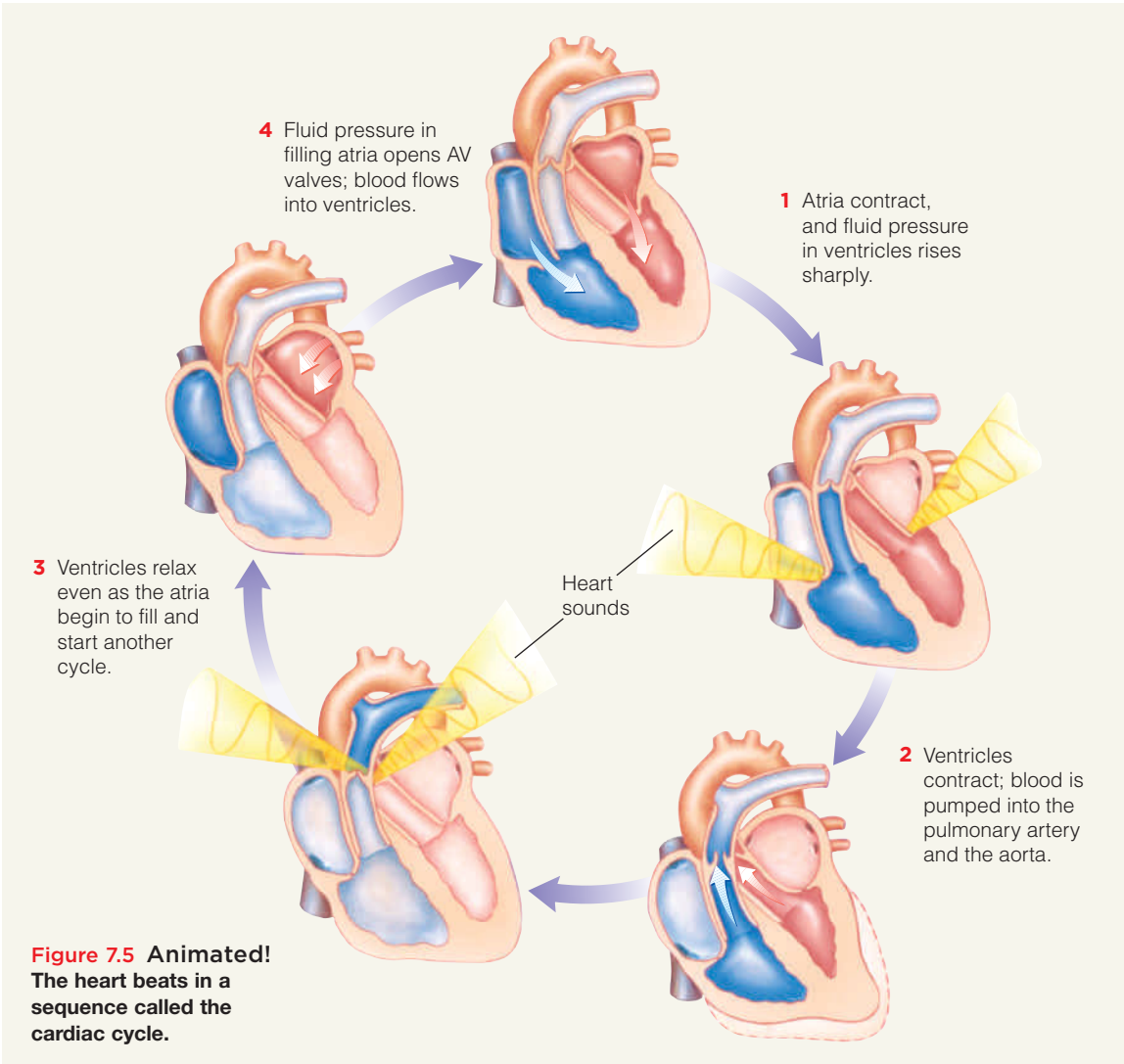


Figure 7.5 Animated! The heart beats in a sequence called the cardiac cycle.

7.3 The Two Circuits of Blood Flow

- **Each half of the heart pumps blood. The two side-by-side pumps are the basis of two cardiovascular circuits through the body, each with its own set of arteries, arterioles, capillaries, venules, and veins.**

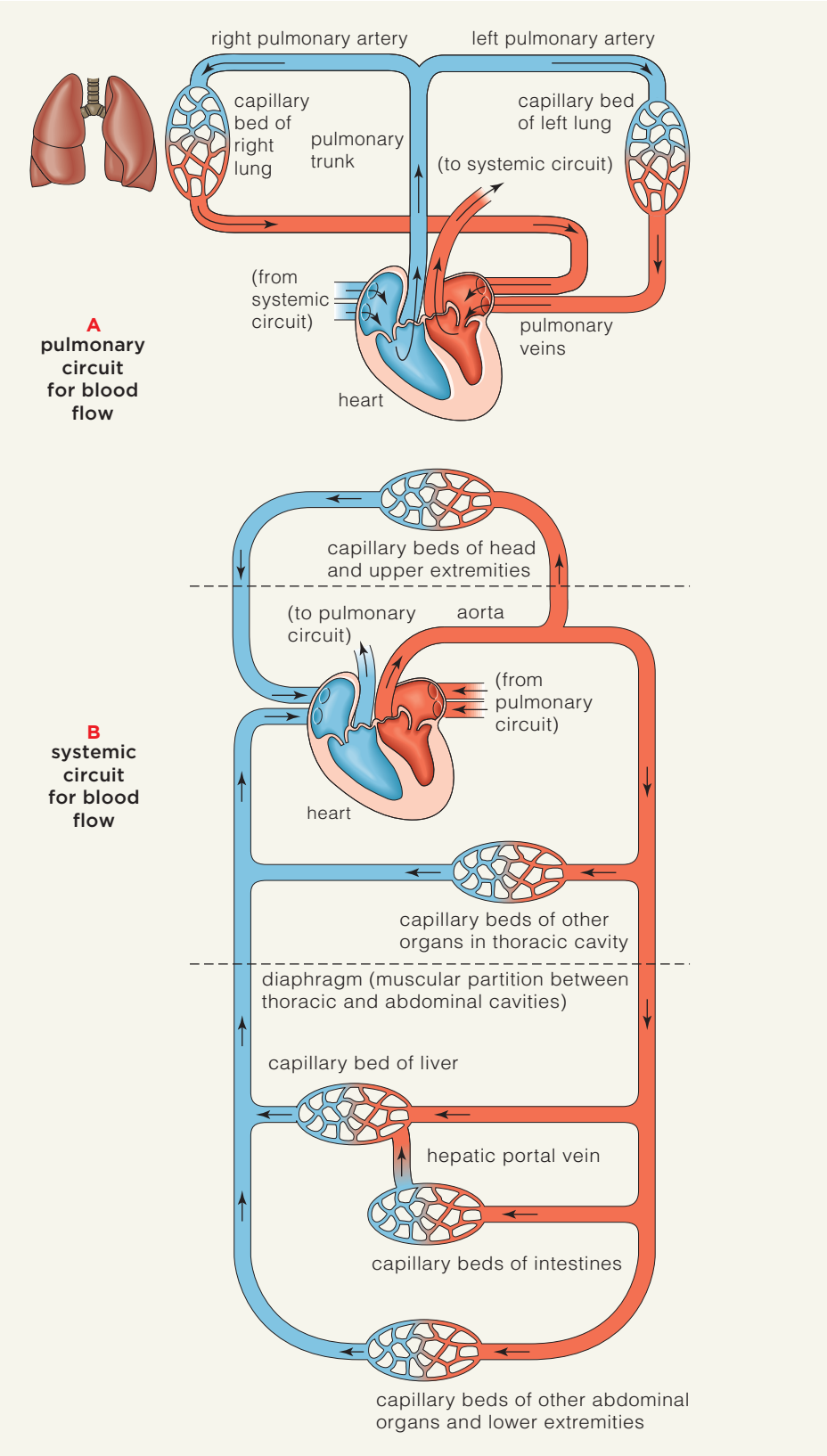
In the pulmonary circuit, blood picks up oxygen in the lungs

The **pulmonary circuit**, which is diagrammed in Figure 7.6*a* at right, receives blood from tissues and circulates it through the lungs for gas exchange. The circuit begins as blood from tissues enters the right atrium, then moves through the AV valve into the right ventricle. As the ventricle fills, the atrium contracts. Blood arriving in the right ventricle is fairly low in oxygen and high in carbon dioxide. When the ventricle contracts, the blood moves through the right semilunar valve into the *main* pulmonary artery, then into the *right* and *left* pulmonary arteries. These arteries carry the blood to the two lungs, where (in capillaries) it picks up oxygen and gives up carbon dioxide that will be exhaled. The freshly oxygenated blood returns through two sets of pulmonary veins to the heart's left atrium, completing the circuit.

In the systemic circuit, blood travels to and from tissues

In the **systemic circuit** (Figure 7.6*b*), oxygenated blood pumped by the left half of the heart moves through the body and returns to the right atrium. This circuit begins when the left atrium receives blood from pulmonary veins, and this blood moves through an AV (bicuspid) valve to the left ventricle. This chamber contracts with great force, sending blood coursing through a semilunar valve into the aorta.

As the aorta descends into the torso (see Figure 7.1), major arteries branch off it, funneling blood to organs and tissues where O_2 is used and CO_2 is produced. For example, in a resting person, each minute a fifth of the blood pumped into the systemic circulation enters the kidneys (Figure 7.6*c*) via *renal arteries*. Deoxygenated blood returns to the right half of the heart, where it enters the pulmonary circuit. Notice that in both the pulmonary and the systemic circuits, blood travels through arteries, arterioles, capillaries, and venules, finally returning to the heart in veins. Blood from the head,



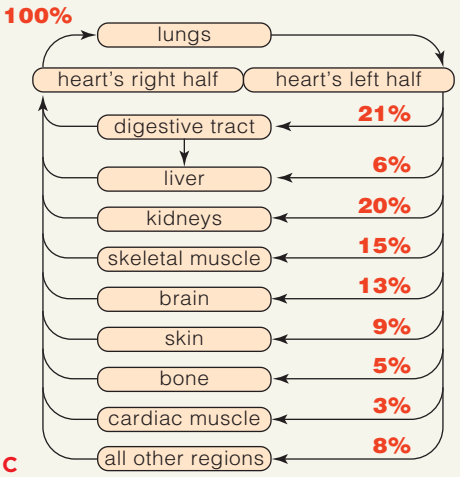


Figure 7.6 **Animated! Each half of the heart pumps blood in a different circuit.** The (**a**) pulmonary and (**b**) systemic circuits for blood flow in the cardiovascular system. (**c**) Distribution of the heart's output in people napping.

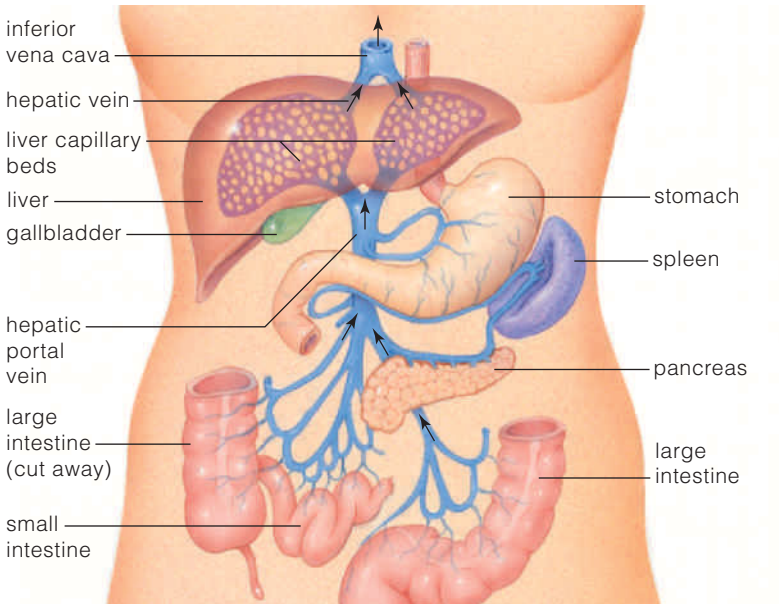


Figure 7.7 **Blood from the digestive tract detours to the liver.** Arrows show the direction in which blood flows.

arms, and chest arrives through the *superior vena cava*. The *inferior vena cava* collects blood from the lower part of the body.

Because the heart pumps constantly, the volume of flow through the entire system each minute is equal to the volume of blood returned to the heart each minute.

Blood from the digestive tract is shunted through the liver for processing

As you can see near the bottom of Figure 7.7, blood passing through capillary beds in the digestive tract travels to another capillary bed in the liver. After a meal, the **hepatic portal vein** brings nutrient-laden blood to this capillary bed. As blood seeps through it, the liver can remove impurities and process absorbed substances. The vessels involved in this detour collectively are called the *hepatic portal system* (Figure 7.7). You will read more about this topic in Chapter 11.

Blood leaving the liver's capillary bed enters the general circulation through a *hepatic vein*. The liver receives oxygenated blood via the *hepatic artery*.

Take-Home Message

What are the two circuits of blood flow in the body?

- A short pulmonary circuit carries blood through the lungs for gas exchange. A long systemic circuit transports blood to and from tissues.
- After meals, the blood in capillary beds in the GI tract is diverted to the liver for processing. It then returns to the general circulation.

7.4 How Cardiac Muscle Contracts

- **Unlike skeletal muscle, which contracts only when orders arrive from the nervous system, cardiac muscle contracts—and the heart beats—spontaneously.**
- **Link to Muscle tissue 4.3**

Electrical signals from "pacemaker" cells drive the heart's contractions

Cardiac muscle cells branch, then link to one another at their endings. Junctions called *intercalated discs* span both plasma membranes of neighboring cells (Figure 7.8). With each heartbeat, signals calling for contraction spread so rapidly across the junctions that cardiac muscle cells contract together, almost as if they were a single unit.

Where do the contraction signals come from? About 1 percent of cardiac muscle cells do not contract, but instead function as the **cardiac conduction system**. Some of these cells are self-exciting "pacemaker" cells—that is, they spontaneously generate and conduct electrical impulses. Those impulses are the signals that stimulate contractions in the heart's contractile cells. Because the cardiac conduction system is independent of the nervous system, the heart will keep right on beating even if all nerves leading to the heart are severed!

Excitation begins with a cluster of cells in the upper wall of the right atrium (Figure 7.9). About 70 times a minute, this **sinoatrial (SA) node** generates waves of excitation. Each wave spreads swiftly over both atria and causes them to contract. It then reaches the **atrioventricular (AV) node** in the septum dividing the two atria.

When a stimulus reaches the AV node, it slows a little, then quickly continues along bundles of conducting fibers that extend to each ventricle. At intervals along each bundle, conducting cells called *Purkinje fibers* pass the signal on to contractile muscle cells in each ventricle. The slow conduction in the AV node is an important part of this sequence. It gives the atria time to finish contracting before the wave of excitation spreads to the ventricles.

Of all cells of the cardiac conduction system, the SA node fires off impulses at the highest frequency and is the first region to respond in each cardiac cycle. It is called the **cardiac pacemaker** because its rhythmic firing is the basis for the normal rate of heartbeat. People whose SA node chronically malfunctions may have an artificial pacemaker implanted to provide a regular stimulus for their heart contractions.

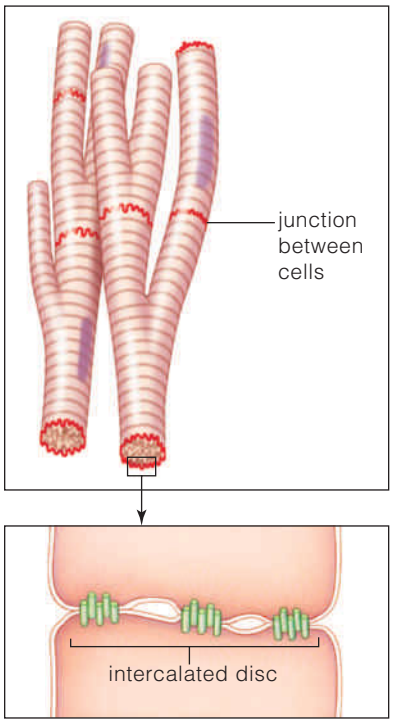


Figure 7.8 Intercalated discs form communication junctions between cardiac muscle cells. Signals travel rapidly across the junctions and cause cells to contract nearly in unison.

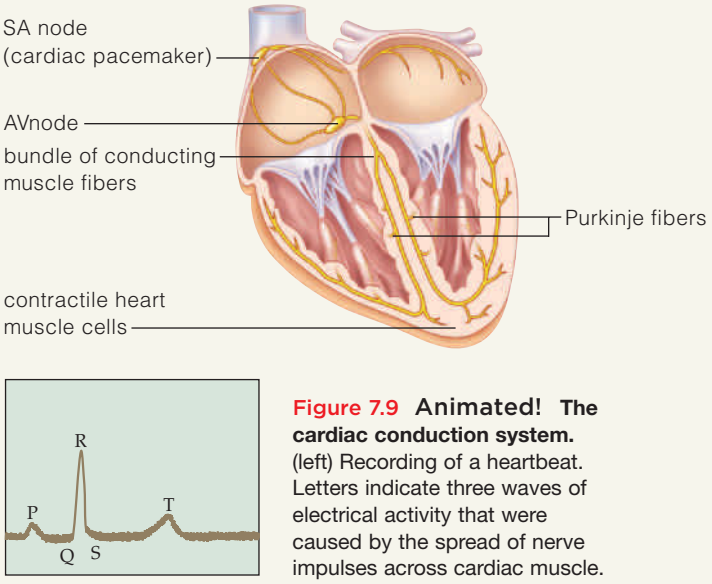


Figure 7.9 Animated! The cardiac conduction system. (left) Recording of a heartbeat. Letters indicate three waves of electrical activity that were caused by the spread of nerve impulses across cardiac muscle.

The nervous system adjusts heart activity

The nervous system initiates the contraction of skeletal muscle, but it can only *adjust* the rate and strength of cardiac muscle contraction. Stimulation by one set of nerves increases the force and rate of heart contractions, while stimulation by another set of nerves can slow heart activity. The centers for neural control of heart functions are in the spinal cord and parts of the brain. They are discussed more fully in Chapter 13.

Take-Home Message

What is the cardiac pacemaker and how does it set the heartbeat?

- The SA node is the cardiac pacemaker—it establishes a regular heartbeat. Its spontaneous, repeated excitation signals spread along a system of muscle cells that stimulate a rhythmic cycle of contraction in the heart's atria, then the ventricles.

7.5 Blood Pressure

- **Heart contractions generate blood pressure, which changes as blood moves through the cardiovascular system.**

Blood exerts pressure against the walls of blood vessels

Blood pressure is the fluid pressure that blood exerts against vessel walls. Blood pressure is highest in the aorta; then it drops along the systemic circuit. The pressure typically is measured when a person is at rest (Figure 7.10). For an adult, the National Heart, Lung, and Blood Institute has established blood pressure values under 120/80 as the healthiest (Table 7.1). The first number, *systolic pressure*, is the peak of pressure in the aorta while the left ventricle contracts and pushes blood into the aorta. The second number, *diastolic pressure*, measures the lowest blood pressure in the aorta, when blood is flowing out of it and the heart is relaxed.

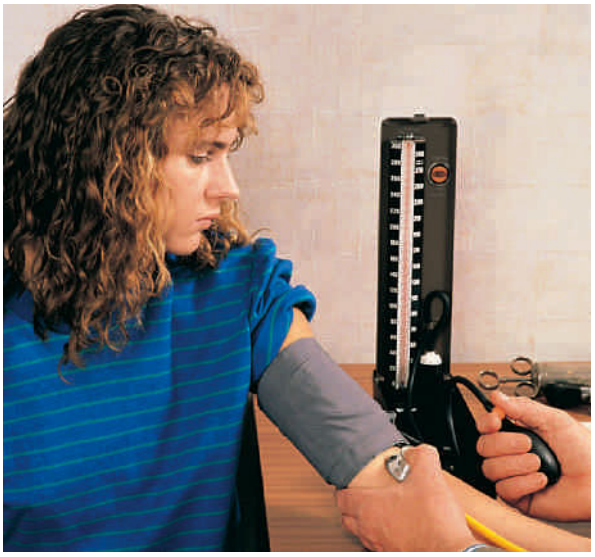


Figure 7.10 Animated! Measuring blood pressure is one way to monitor cardiovascular health. A hollow cuff attached to a pressure gauge is wrapped around the upper arm. The cuff is inflated to a pressure above the highest pressure of the cardiac cycle—at systole, when ventricles contract. Above this pressure, you can't hear sounds through a stethoscope positioned below the cuff and above the brachial artery, because no blood is flowing through the vessel. As air in the cuff is slowly released, some blood flows into the artery. The turbulent flow causes soft tapping sounds. When the tapping starts, the gauge's value is the systolic pressure, measured in millimeters of mercury (Hg). This value measures how far the pressure would force mercury to move upward in a narrow glass column.

More air is released from the cuff. Just after the sounds grow dull and muffled, blood is flowing steadily, so the turbulence and tapping end. The silence corresponds to diastolic pressure at the end of a cardiac cycle, before the heart pumps out blood. A desirable reading is under 80 mm Hg.

Blood Pressure Values (mm of Hg)

	Systolic	Diastolic
Normal	100–119	60–79
Hypotension	Less than 100	Less than 60
Prehypertension	120–139	80–139
Hypertension	140 and up	90 and up

Values for systolic and diastolic pressure provide important health information. Chronically elevated blood pressure, or *hypertension*, can be associated with a variety of ills, such as atherosclerosis (Section 7.8). The chart in Figure 7.11 lists some of the major causes and risk factors. Hypertension is a "silent killer" that can lead to a stroke or heart attack. Each year it kills about 180,000 Americans, many of whom may not have had any outward symptoms. Roughly 40 million people in the United States are unaware that they have hypertension.

Hypotension is abnormally *low* blood pressure. This condition can develop when for some reason there is not enough water in blood plasma—for instance, if there are not enough proteins in the blood to "pull" water in by osmosis. A large blood loss also can cause blood pressure to plummet. Such a drastic decrease is one sign of a dangerous condition called *circulatory shock*.

Take-Home Message

What is blood pressure?

- Heart contractions generate blood pressure. Systolic pressure is the peak of pressure in the aorta while blood pumped by the left ventricle is flowing into it. Diastolic pressure measures the lowest blood pressure in the aorta, when blood is flowing out of it.

Risk Factors for Hypertension

1. Smoking
2. Obesity
3. Sedentary lifestyle
4. Chronic stress
5. A diet low in fruits, vegetables, dairy foods, and other sources of potassium and calcium
6. Excessive salt intake (in some individuals)
7. Poor salt management by the kidneys, usually due to disease

Figure 7.11 A variety of factors may cause hypertension.

7.6 Structure and Functions of Blood Vessels

- **As with all body parts, structure is key to the functions of blood vessels. All the vessels transport blood, but there are important differences in how different kinds manage blood flow and blood pressure.**
- **Links to Epithelium 4.1, Connective tissues 4.2**

Arteries are large blood pipelines

The wall of an artery has several tissue layers (Figure 7.12*a*). The outer layer is mainly collagen, which anchors the vessel to the tissue it runs through. A thick middle layer of smooth muscle is sandwiched between thinner layers containing elastin. The innermost layer is a thin sheet of endothelium. Together these layers form a thick, muscular, and elastic wall. In a large artery the wall bulges slightly under the pressure surge caused when a ventricle contracts. In arteries near the body surface, as in the wrist, you can feel the surges as your **pulse**.

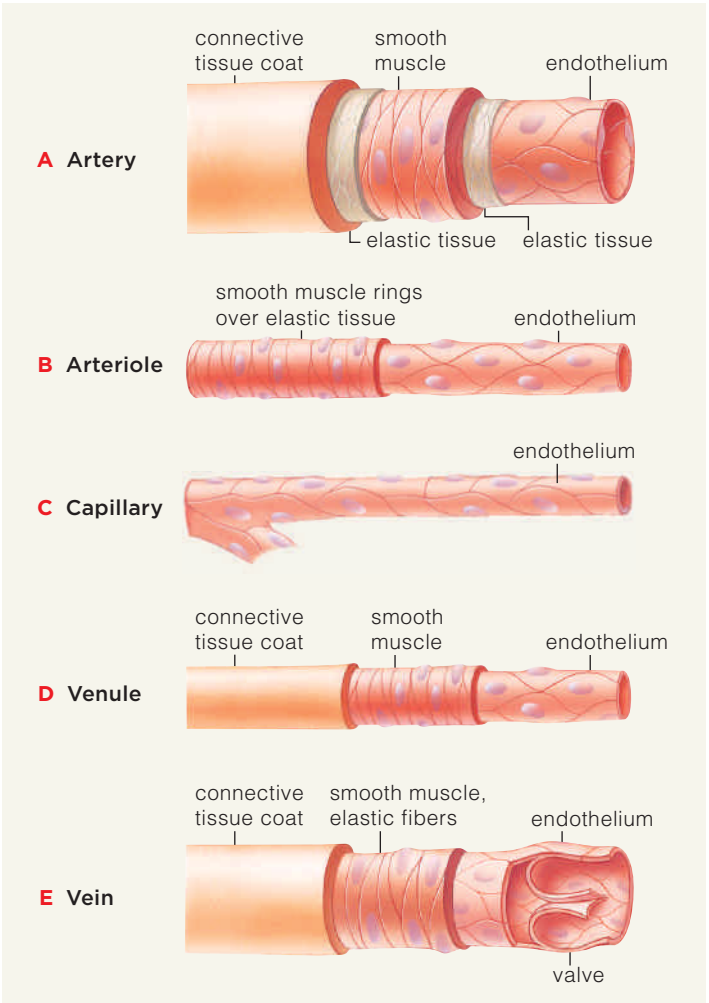


Figure 7.12 Animated! **The structure of a blood vessel matches its function.**

The bulging of artery walls helps keep blood flowing on through the system. How? For a moment, some of the blood pumped during the systole phase of each cardiac cycle is stored in the "bulge"; the elastic recoil of the artery then forces that stored blood onward during diastole, when heart chambers are relaxed. In addition to stretchable walls, arteries also have large diameters. For this reason, they present little resistance to blood flow, so blood pressure does not drop much in the large arteries of the systemic and pulmonary circuits (Figure 7.13).

Arterioles are control points for blood flow

Arteries branch into narrower arterioles, which have a wall built of rings of smooth muscle over a single layer of elastic fibers (Figure 7.12*b*). Because they are built this way, arterioles can dilate (enlarge in diameter) when the smooth muscle relaxes or constrict (shrink in diameter) when the smooth muscle contracts. Arterioles offer more resistance to blood flow than other vessels do. As the blood flow slows, it can be controlled in ways that adjust how much of the total volume goes to different body regions. For example, you become drowsy after a large meal in part because control signals divert blood away from your brain in favor of your digestive system.

Capillaries are specialized for diffusion

Your body has about 2 miles of arteries and veins but a whopping 62,000 miles of capillaries. Each capillary bed is where substances can diffuse between blood and tissue fluid. This is truly where "the rubber meets the road" when it comes to exchanges of gases (oxygen and carbon dioxide), nutrients, and wastes. As befits its function in diffusion, a capillary has the thinnest wall of any blood vessel—a single layer of flat endothelium (Figure 7.12*c*).

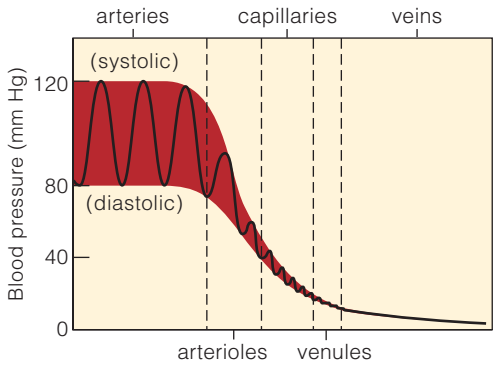


Figure 7.13 **Blood pressure changes as blood flows through different parts of the cardiovascular system.**

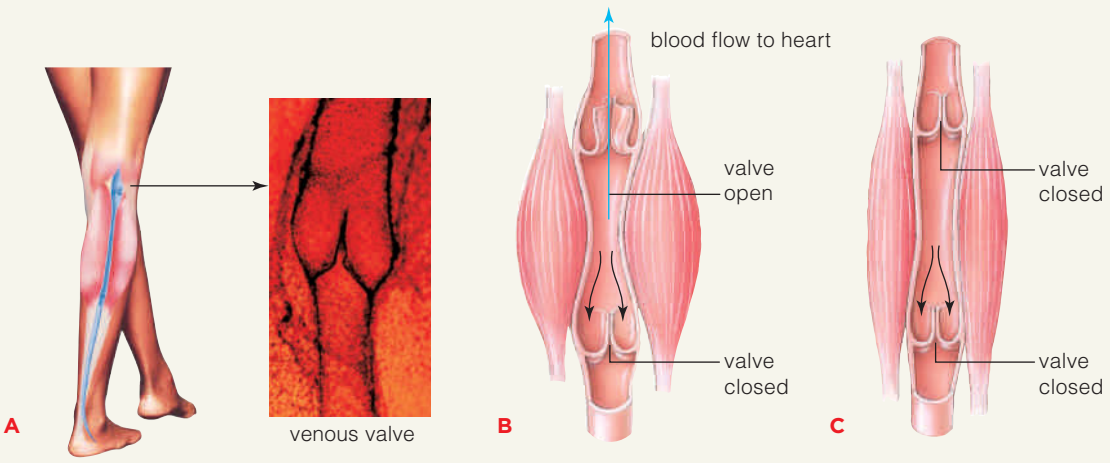


Figure 7.14 Animated! Contracting skeletal muscles can increase fluid pressure in a vein. (**a**) Valves in medium-sized veins prevent backflow of blood. (**b**) Skeletal muscles next to the vein contract, helping blood flow forward. (**c**) Skeletal muscles relax and valves in the vein shut—preventing backflow.

Blood can't move very fast in capillaries. However, because they are so extensive, capillary beds present less total resistance to flow than do the arterioles leading into them, so overall blood pressure drops more slowly in them. We'll look more closely at how capillaries function in the next section.

Venules and veins return blood to the heart

Capillaries merge into venules, or "little veins," which in turn merge into large-diameter veins. Venules function a little like capillaries, in that some solutes diffuse across their relatively thin walls (Figure 7.12*d*).

Veins are large-diameter, low-resistance transport tubes to the heart (Figure 7.12*e*). Their valves prevent backflow. When blood starts moving backward due to gravity, it pushes the valves closed. The vein wall can bulge greatly under pressure, more so than an arterial wall. Thus veins are reservoirs for variable volumes of blood. Together, the veins of an adult can hold up to 50 to 60 percent of the total blood volume.

When blood must circulate faster (as during exercise), the smooth muscle in veins contracts. The wall stiffens, the vein bulges less, and venous pressure rises—so more blood flows to the heart (Figure 7.14). Venous pressure also rises when contracting skeletal muscle—especially in the legs and abdomen—bulges against adjacent veins. This muscle activity helps return blood through the venous system.

Obesity, pregnancy, and other factors can weaken venous valves. The walls of a *varicose vein* have become overstretched because, over time, weak valves have allowed blood to pool there.

Vessels help control blood pressure

Some arteries, all arterioles, and even veins have roles in homeostatic mechanisms that help maintain adequate blood pressure over time. Centers in the brain's medulla monitor resting blood pressure. When blood pressure rises abnormally, they order the heart to contract less often and less forcefully. They also order smooth muscle in arterioles to relax. The result is **vasodilation**—an enlargement (dilation) of the vessel diameter. On the other hand, when the centers detect an abnormal *decrease* in blood pressure, they command the heart to beat faster and contract more forcefully. Neural signals also cause the smooth muscle of arterioles to contract. The result is **vasoconstriction**, a narrowing of the vessel diameter. In some parts of the body arterioles have receptors for hormones that trigger vasoconstriction or vasodilation, thus helping to maintain blood pressure.

Recall that the nervous and endocrine systems also control how blood is allocated to different body regions at different times. In addition, conditions in a particular part of the body can alter blood flow there. For instance, when you run, the amount of oxygen in your skeletal muscle tissue falls, while levels of carbon dioxide, hydrogen ions, potassium ions, and other substances rise. These chemical changes cause the smooth muscle in arterioles to relax. The vasodilation results in more blood flowing past the active muscles. At the same time, arterioles in your digestive tract and kidneys constrict.

A **baroreceptor reflex** helps provide short-term control over blood pressure. Baroreceptors are pressure receptors in the **carotid arteries** in the neck, in the arch of the aorta, and elsewhere. They monitor changes in mean arterial pressure ("mean" = the midpoint) and send signals to centers in the brain. As described in Chapter 13, this information is used to coordinate the rate and strength of heartbeats with changes in the diameter of arterioles and veins. The baroreceptor reflex helps keep blood pressure within normal limits in the face of sudden changes—such as when you leap up from a chair.

Take-Home Message

What are the different types of blood vessels?

- Arteries are the main pipelines for oxygenated blood. Because arterioles can dilate and constrict, they are control points for blood flow (and pressure).
- Capillary beds are diffusion zones. Blood moves back to the heart through venules and veins. Valves in veins prevent the backflow of blood due to gravity.

7.7 Capillaries: Where Blood Exchanges Substances with Tissues

- **Blood enters the systemic circulation moving swiftly in the aorta, but this speed has to slow in order for substances to move into and out of the bloodstream.**
- **Link to Diffusion 3.10**

A vast network of capillaries brings blood close to nearly all body cells

Your body comes equipped with one aorta, a few hundred branching arteries and veins, more than half a million arterioles and venules—and as many as 40 billion capillaries! Capillaries are so thin that it would take 100 of them to equal the thickness of a human hair. And at least one of these tiny vessels is next to living cells in nearly all body tissues.

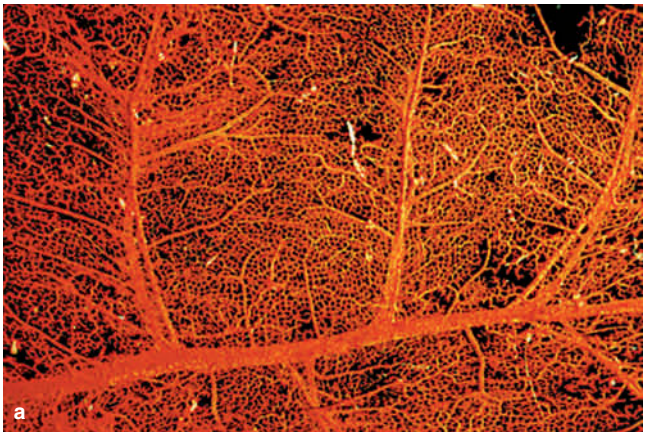
In addition to forming a vast network of vessels (Figure 7.15*a*), this branching system also affects the speed at which blood flows through it. The flow is fastest in the aorta, quickly "loses steam" in the more numerous arterioles, and slows to a relative crawl in the narrow capillaries. The flow of blood speeds up again as blood moves into veins for the return trip to the heart.

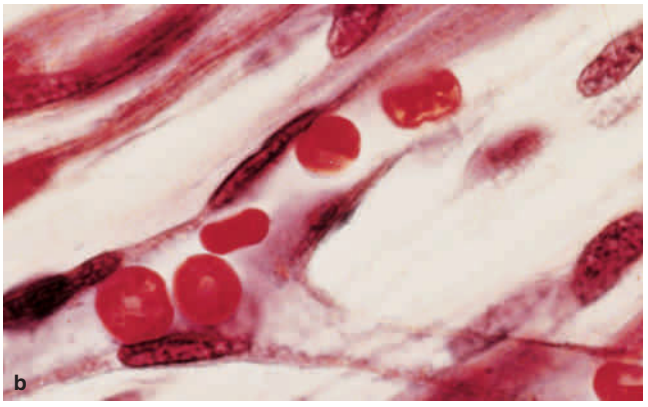
Many substances enter and leave capillaries by diffusion

Why do we have such an extensive system of capillaries in which blood slows to a snail's pace? Remember from Section 7.6 that capillaries are where all the substances that enter and leave cells are exchanged with the blood, many of them by diffusion. But diffusion is a slow process that is not efficient over long distances. In a large, multicellular organism such as a human, having billions of narrow capillaries solves both these problems. There is a capillary very close to nearly every cell, and in each one the blood is barely moving. As blood "creeps" along in capillaries, there is time for the necessary exchanges of fluid and solutes to take place. In fact, most solutes, including molecules of oxygen and carbon dioxide, diffuse across the capillary wall.

Some substances pass through "pores" in capillary walls

Some substances enter and leave capillaries by way of slitlike areas between the cells of capillary walls (Figure 7.15*c*). These "pores" are filled with water. They are passages for substances that cannot diffuse through the lipid bilayer of the cells that make up the capillary wall, but that *can* dissolve in water.





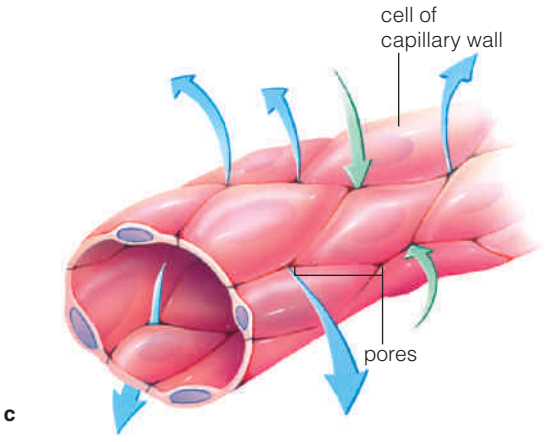


Figure 7.15 Capillaries deliver blood close to cells. (**a**) A resin cast showing a dense network of capillaries. (**b**) Red blood cells moving single file in capillaries. (**c**) How substances pass through slitlike pores in the wall of a capillary.

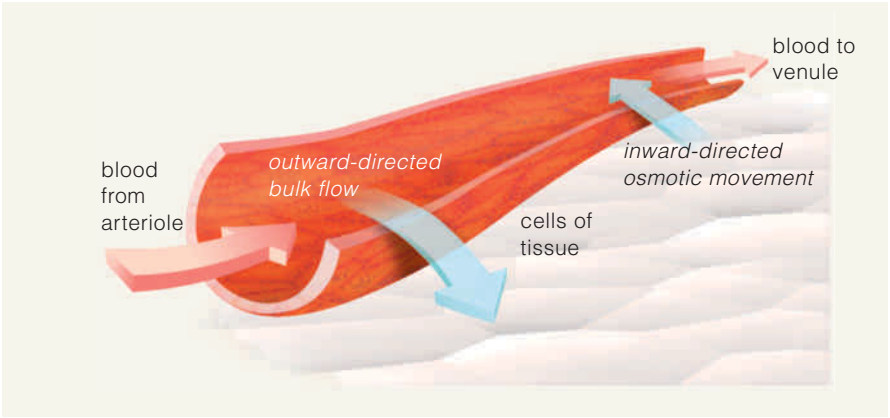


Figure 7.16 Animated! **Fluid may move by "bulk flow" into and out of a capillary bed.**

When the blood pressure inside a capillary is greater than pressure from the extracellular fluid outside, water and solutes may be forced out of the vessel—a type of fluid movement called "bulk flow" (Figure 7.16). Various factors affect this process, but on balance, a little more water leaves capillaries than enters them. The lymphatic system, which consists of lymph vessels, lymph nodes, and some other organs, returns the fluid to the blood. This system also plays a major role in body defense, and you will learn more about it in Chapter 9.

Overall, the movements of fluid and solutes into and out of capillaries help maintain blood pressure by adding water to, or subtracting it from, blood plasma. The fluid traffic also helps maintain the proper fluid balance between blood and surrounding tissues.

Blood in capillaries flows onward to venules

Capillary beds are the "turnaround points" for blood in the cardiovascular system. They receive blood from arterioles, and after the blood flows through the bed it enters channels that converge into venules—the beginning of its return trip to the heart (Figure 7.17).

At the point where a capillary branches into the capillary bed, a wispy ring of smooth muscle wraps around it. This structure, a **precapillary sphincter**, regulates the flow of blood into the capillary. The smooth muscle is sensitive to chemical changes in the capillary bed. It can contract and prevent blood from entering the capillary, or it can relax and let blood flow in.

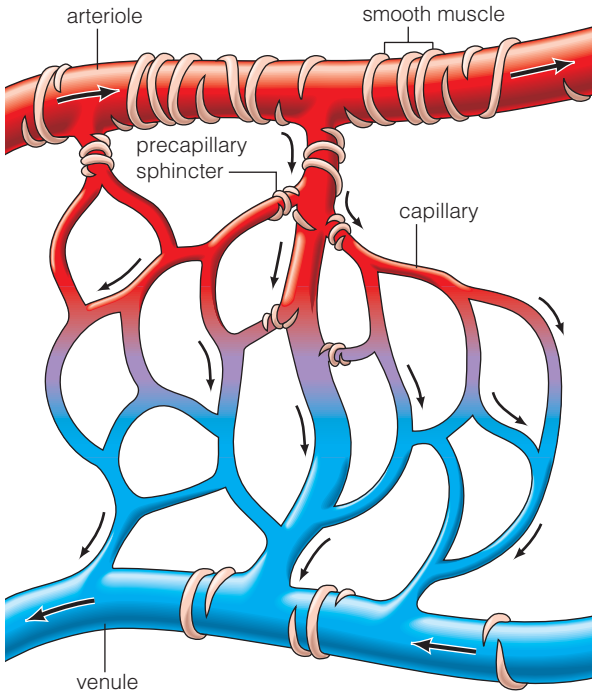


Figure 7.17 **This diagram shows the general direction of blood flow through a capillary bed.** A precapillary sphincter wraps around the base of each capillary.

For example, if you sit quietly and listen to music, only about one-tenth of the capillaries in your skeletal muscles are open. But if you decide to get up and boogie, precapillary sphincters will sense the demand for more blood flow to your muscles to deliver oxygen and carry away carbon dioxide. Many more of the sphincters will relax, allowing a rush of blood into the muscle tissue. The same mechanism brings blood to the surface of your skin when you blush or become flushed with heat.

Take-Home Message

What is the function of capillaries?

- The cardiovascular system's extensive network of narrow capillaries ensures that every living cell is only a short distance from a capillary.
- In capillary beds, substances move between the blood and extracellular fluid by diffusion, through capillary pores, or by bulk flow.
- Movements of water and other substances into and out of capillaries help maintain blood pressure and the proper fluid balance between blood and tissues.

7.8 Cardiovascular Disease

What are your chances of developing a cardiovascular disorder? Some major risk factors include a family history of heart trouble, high levels of blood lipids such as cholesterol and trans fats, hypertension, obesity, smoking, lack of exercise, and simply getting older. Interestingly, however, more than half of people who suffer heart attacks do not have any of these risk factors.

To help explain this puzzle, scientists have focused on inflammation, which is a defense response discussed in Chapter 9. Sometimes, though, inflammation does harm. In the cardiovascular system, it can promote the formation of the artery-blocking plaques described shortly. Infections can trigger inflammation, which in turn causes the liver to make *C-reactive protein*, which also is implicated in heart disease. This link is why infection-related inflammation and C-reactive protein are listed in Table 7.2.

Another suspect is homocysteine, an amino acid that is released as certain proteins are broken down. Too much of it in the blood also may cause damage that is a first step in a major cardiovascular disorder, atherosclerosis.

Arteries can clog or weaken

In *arteriosclerosis*, or "hardening of the arteries," arteries become thicker and stiffer. In **atherosclerosis**, this condition gets worse as cholesterol and other lipids build up in the artery wall. When this **atherosclerotic plaque** grows large enough to protrude into the artery, there is less room for blood (Figure 7.18).

Coronary arteries and their branches are narrow and vulnerable to clogging by plaques. When the artery is narrowed further to one-quarter of its starting diameter, symptoms can range from mild chest pain, called *angina pectoris*, to a full-scale heart attack.

Having too many lipids in the blood—often, due to a diet high in cholesterol and trans fat—is a major risk factor for atherosclerosis. In the blood, proteins called **LDLs** (*low-density lipoproteins*) bind cholesterol and other fats and carry them to body cells. Proteins called **HDLs** (*high-density lipoproteins*) pick up cholesterol in the blood and carry it back to the liver, where it is mixed into bile and eventually excreted in feces. Because HDLs help remove excess cholesterol from the body, they are called "good cholesterol."

If there are more LDLs in the blood than cells can remove, the surplus increases the risk of atherosclerosis. This is why LDLs are called "bad cholesterol." As LDLs infiltrate artery walls, cholesterol accumulates there. Other changes occur also, and eventually a fibrous net forms over the mass—an atherosclerotic plaque. Blood tests measure the relative amounts of HDLs and LDLs in a person's blood (in milligrams). A total of 200 mg or less per milliliter of blood is considered acceptable (for most people), but experts agree that LDLs should make up only about one-third of this total, or about 70 to 80 mg.

Surgery may be the only answer for a severely blocked coronary artery. In a *coronary bypass*, a section of a large vessel taken from the chest is stitched to the aorta and to the coronary artery below the affected region (Figure 7.18*c*). In *laser angioplasty*, laser beams vaporize the plaques. In *balloon angioplasty*, a small balloon is inflated inside a blocked artery to flatten a plaque so there is more room in the artery. A small wire cylinder called a stent may then be inserted to help keep the artery open. "Plaque-busting" drugs called statins, which reduce cholesterol in the blood, can help prevent new plaques from forming.

Disease, an injury, or an inborn defect can weaken an artery so that part of its wall balloons outward. This

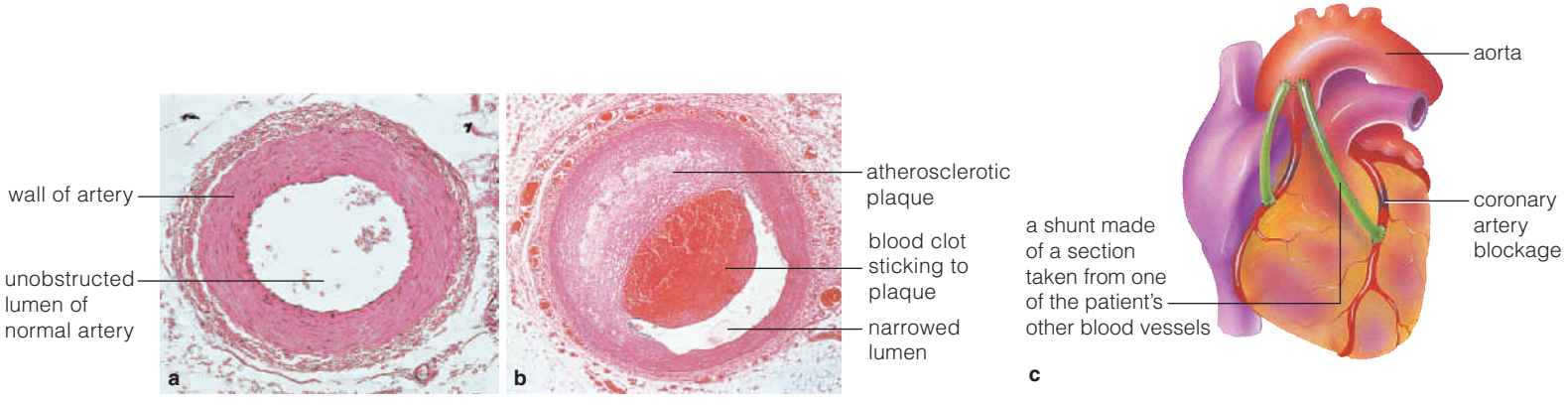
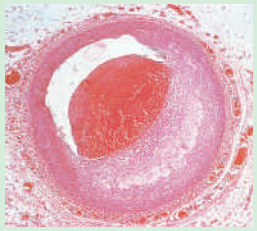


Figure 7.18 Plaques and blood clots may clog arteries. Section from (**a**) a normal artery, (**b**) a blood vessel narrowed by a plaque and clogged further by a blood clot. (**c**) Coronary bypasses.

Major Risk Factors for Cardiovascular Disease



1. Inherited predisposition
2. Elevated blood lipids (cholesterol, trans fats)
3. Hypertension
4. Obesity
5. Smoking
6. Lack of exercise
7. Age 50+
8. Inflammation due to infections by viruses, bacteria
9. High levels of C-reactive protein in blood
10. Elevated blood levels of the amino acid homocysteine

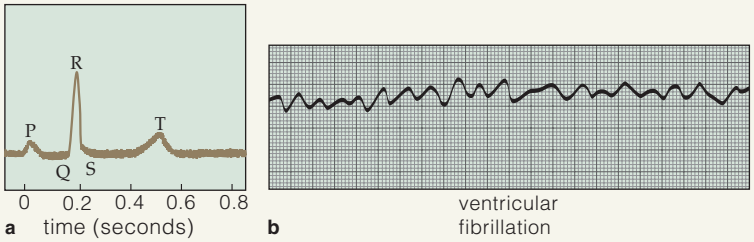


Figure 7.19 Animated! An ECG tracing can reveal abnormal heart activity. (**a**) ECG of a normal heartbeat. The P wave is generated by electrical signals from the SA node that stimulate contraction of the atria. As the stimulus moves over the ventricles, it is recorded as the QRS wave complex. The T wave marks the brief period when the ventricles are resting. (**b**) A recording of ventricular fibrillation.

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pouchlike weak spot is called an **aneurysm**. Aneurysms can develop in various parts of the cardiovascular system, including vessels in the brain, abdomen, and the aorta. If an aneurysm bursts, it can cause serious and even fatal blood loss. A minor aneurysm may not present any immediate worry, but in the brain, especially, an aneurysm is potentially so dangerous that it requires immediate medical treatment.

Heart damage can lead to heart attack and heart failure

A **heart attack** is damage to or death of heart muscle. Warning signs of a heart attack include sensations of pain or squeezing behind the breastbone, pain or numbness radiating down the left arm, sweating, and nausea. Women more often experience neck and back pain, fatigue, a sense of indigestion, a fast heartbeat, shortness of breath, and low blood pressure. Risk factors include hypertension, a circulating blood clot (also called an embolus), and atherosclerosis.

In **heart failure** (HF), the heart is weakened and so does not pump blood as well as it should. Even a basic exertion such as walking can become difficult. Because patients may require repeated hospitalization, HF has become the nation's most costly health problem.

Arrhythmias are abnormal heart rhythms

An electrocardiogram, or ECG, is a recording of the electrical activity of the cardiac cycle (Figure 7.19*a*). ECGs reveal **arrhythmias**, or irregular heart rhythms. Some arrhythmias are abnormal, others are not. For example, endurance athletes may have a below-average resting cardiac rate, or *bradycardia*, which is an adaptation to regular strenuous exercise. A cardiac rate above 100 beats per minute, called *tachycardia*, occurs normally during exercise or stressful situations. Serious tachycardia can be triggered by drugs (including caffeine, nicotine, alcohol, and cocaine), excessive thyroid hormones, and other factors.

Ventricular fibrillation is the most dangerous arrythmia. In parts of the ventricles, the cardiac muscle contracts haphazardly, so blood isn't pumped normally. This is what happens in sudden cardiac arrest, as described in the chapter introduction. Like Matt Nader's cardiac arrest described in the chapter introduction, ventricular fibrillation is a medical emergency. With luck, a strong electrical jolt to the patient's heart from an AED, or the use of defibrillating drugs, can restore a normal rhythm before the damage is too serious.

A heart-healthy lifestyle may help prevent cardiovascular disease

Everybody ages, and none of us can control the genes we inherit. Even so, each of us can take steps to improve our chances of living free of serious cardiovascular disease. Watching our intake of foods rich in cholesterol and trans fats, getting regular exercise, and not smoking are three strategies, and they provide multiple benefits. A diet that's moderate in fats may also help keep weight under control. Exercise helps with weight control, too. It also relieves stress and helps keep muscles and bones fit and strong. Smoking is bad for just about every body system; you'll get a closer look at its devastating impact on the respiratory system in Chapter 10.

7.9 Infections, Cancer, and Heart Defects

Infections may seriously damage the heart

As described in Section 7.8, bacterial and viral infections that first take hold outside the cardiovascular system may eventually harm the heart. Infections related to an untreated "strep throat," certain dental procedures, or IV drug abuse are in this category.

"Strep" infections are caused by strains of *Streptococcus* bacteria (Figure 7.20). If the illness isn't treated with an antibiotic, it may lead to *rheumatic fever*. In this disorder, the body produces defensive antibodies that attack the invading bacteria—but they also mistakenly attack heart valves. Although in affluent countries most people who develop a strep infection get treatment, rheumatic fever still is the most common cause of heart valve disease. It is an example of an autoimmune disorder, a topic we will discuss in Chapter 9.

Microbes that enter the bloodstream during dental surgery or on a contaminated IV needle may attack heart valves directly. This condition is called *endocarditis* ("inside the heart"). People who have an existing valve problem due to aging or some other heart disorder often are advised to take an antibiotic before having dental work. Endocarditis is a major hazard for IV drug users. It can rapidly destroy infected valves and cause sudden heart failure.

Heart problems also can be a complication of Lyme disease, which is caused by the bacterium *Borrelia burgdorferi* and spread by ticks. At first the body responds to a Lyme infection with a "bull's-eye" rash (Figure 7.21). Later the joints may become inflamed, and so may the heart muscle (the myocardium). Heart inflammation, called *myocarditis*, produces an irregular heart rhythm that manifests as dizzy spells and other other symptoms. Measles caused by the rubella virus in unvaccinated people can also damage the heart muscle.

Alcohol abuse and recreational drugs also may cause heart inflammation. When someone dies of a cocaine overdose, an autopsy often reveals myocarditis. Cocaine, amphetamines, and habitual, heavy alcohol use all can cause cardiomyopathy, or weakness of the heart muscle that in turn may lead to heart failure.

Is there such a thing as heart cancer?

Although the reason is a mystery, cancer almost never starts in the heart muscle or blood vessels. More often, a cancer that begins elsewhere in the body, such as the skin cancer malignant melanoma spreads to the heart. Even more commonly, the heart or vessels are damaged by cancer treatments such as radiation or chemotherapy.

Inborn heart defects are fairly common

You may have heard of "blue babies," infants born with a hole in some part of the heart wall, so that the heart doesn't pump blood efficiently. In fact, thousands of babies enter the world each year with some type of heart defect. Depending on the problem, one or more surgeries may be required to repair it.

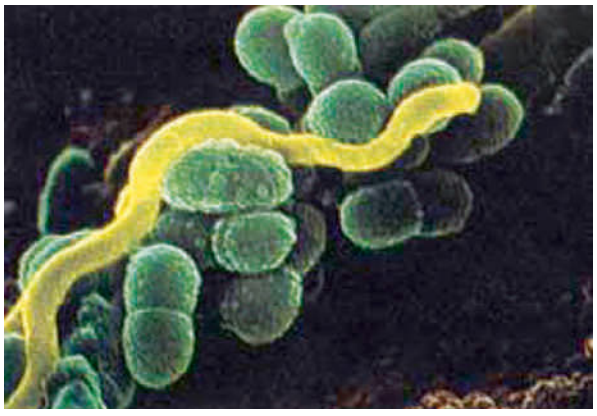
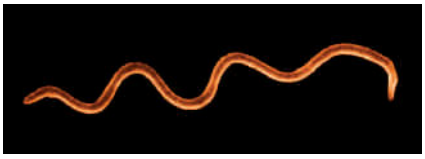


Figure 7.20 ***Streptococcus*** **bacteria cause different kinds of "strep" infections.** In this image the bacteria are colored green.



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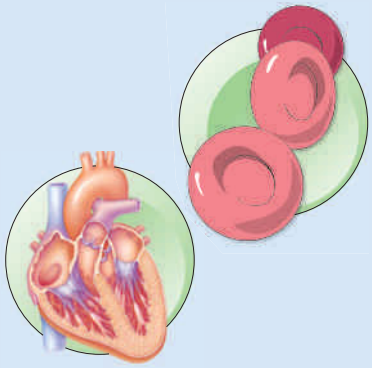
7.10 CONNECTIONS: The Cardiovascular System and Blood in Homeostasis



The Cardiovascular System and Blood

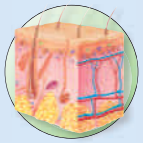
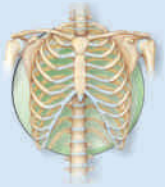
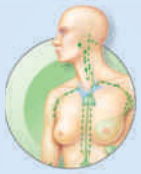
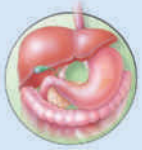
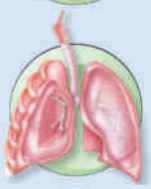
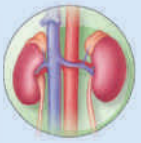
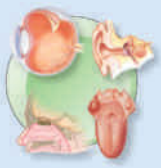
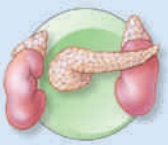
As described in Chapter 8, blood is the medium that transports nutrients, oxygen, hormones, cell wastes, and other substances. It also carries and distributes a great deal of body heat.

The heart pumps blood into blood vessels that transport blood throughout the body. In this way the system delivers blood's cargoes to body cells and carries away potentially toxic wastes and other unneeded materials.

Blood pressure generated by heart contractions helps keep blood flowing through the cardiovascular system.

Mechanisms that widen or narrow the diameter of arterioles and capillaries allow adjustments in blood flow to different body regions as conditions warrant.

Blood's ability to clot allows the body to sustain minor wounds without a serious loss of blood.

Integumentary system		Adjustments to blood flow at the skin's surface help regulate body temperature. Blood clotting mechanisms help repair skin injuries.
Skeletal system		Stem cells in bone marrow produce blood cells. Circulating blood delivers calcium and phosphate used to form bone tissue.
Muscular system		Circulating blood distributes heat produced by active skeletal muscles. Contraction of leg muscles helps return venous blood to the heart.
Immunity and the lymphatic system		Blood pumped by the heart picks up inhaled oxygen from the lungs and delivers carbon dioxide to the lungs to be exhaled.
Digestive system		The bloodstream circulates nutrients from food digestion to cells. The liver receives and processes certain nutrients via the hepatic portal system.
Respiratory system		Blood pumped by the heart picks up inhaled oxygen from the lungs and delivers carbon dioxide to the lungs to be exhaled.
Urinary system		The kidneys filter impurities and other unneeded substances from blood and form urine that removes them from the body. The kidney hormone erythropoietin stimulates the formation of red blood cells.
Nervous system		Centers in the brain and spinal cord adjust the rate and strength of heart contractions and help maintain proper blood pressure by adjusting the diameter of arterioles.
Sensory systems		Sensors in the carotid arteries help monitor blood pressure. Sensory perceptions related to mental or physiological states may trigger changes in local blood flow (as in blushing, sexual arousal).
Endocrine system		Nearly all hormones reach their targets via the bloodstream. Certain cells in the heart atria release a hormone (ANP) that helps regulate blood pressure.
Reproductive system		Reproductive hormones, including estrogens and testosterone, travel in the bloodstream. Arterioles in organs of sexual intercourse dilate at times of arousal. Blood vessels of the placenta help maintain homeostasis in a developing fetus.

IMPACTS, ISSUES

Be Not Still, My Beating Heart!

How Would You Vote?

Would you be in favor of mandatory CPR training in high schools? See CengageNOW for details, then vote online.

ALTHOUGH the benefits of CPR training are obvious, schools might need extra funding in order to add a CPR mini-course. Also, some people are uncomfortable with the idea of performing mouth-to-mouth resuscitation, especially on someone they do not know.

Summary

Section 7.1 The cardiovascular system consists of the heart and blood vessels including arteries, arterioles, capillaries, venules, and veins. The system helps maintain homeostasis by providing rapid internal transport of substances to and from cells.

- Use the animation and interaction on CengageNOW to explore the human cardiovascular system.

Section 7.2 The heart muscle is called the myocardium. A septum divides the heart into two halves, each with two chambers, an atrium and a ventricle. Valves in each half help control the direction of blood flow. These include a semilunar valve and an atrioventricular valve. Coronary arteries provide much of the heart's blood supply. They branch off the aorta, which carries oxygenated blood away from the heart.

Blood is pumped each time the heart beats, in a cardiac cycle of contraction and relaxation. Systole, the contraction phase, alternates with the relaxation phase, called diastole.

- Use the animation and interaction on CengageNOW to learn about the structure and function of the heart.

Section 7.3 The partition between the heart's two halves separates the blood flow into two circuits, one pulmonary and the other systemic.

a. In the pulmonary circuit, deoxygenated blood in the heart's right half is pumped to capillary beds in the lungs. The blood picks up oxygen, then flows to the heart's left atrium.

b. In the systemic circuit, the left half of the heart pumps oxygenated blood to body tissues. There, cells take up oxygen and release carbon dioxide. The blood, now deoxygenated, flows to the heart's right atrium.

Section 7.4 Electrical impulses stimulate heart contractions via the heart's cardiac conduction system. In the right atrium, a sinoatrial node—the cardiac pacemaker—generates the impulses and establishes a regular heartbeat. Signals from the SA node pass to the atrioventricular node, a way station for stimulation that triggers contraction of the ventricles. The nervous and endocrine systems can adjust the rate and strength of heart contractions.

Section 7.5 Blood pressure is the fluid pressure blood exerts against vessel walls. It is highest in the aorta, which receives blood pumped by the left ventricle, and drops along the systemic circuit.

- Use the animation and interaction on CengageNOW to see how blood pressure is measured.

Section 7.6

a. Arteries are strong, elastic pressure reservoirs. They smooth out pressure changes resulting from heartbeats and so smooth out blood flow. When a ventricle contracts, it causes a pressure surge, or pulse, in large arteries.

b. Arterioles are control points for distributing different volumes of blood to different regions.

c. Capillary beds are diffusion zones where blood and extracellular fluid exchange substances.

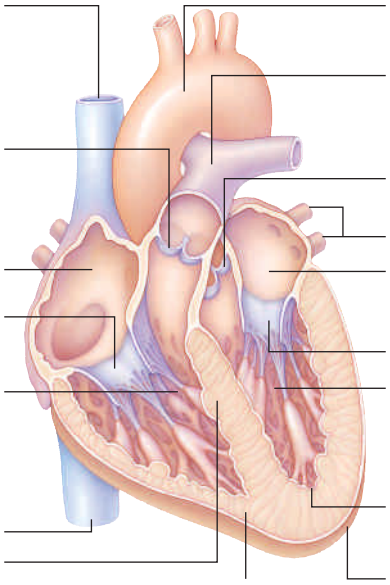
d. Venules overlap capillaries and veins somewhat in function. Some solutes diffuse across their walls.

e. Veins are blood reservoirs that can be tapped to adjust the volume of flow back to the heart. Valves in some veins, in the limbs, prevent blood returning to the heart from flowing backward due to gravity.

Blood vessels help control blood pressure. Arterioles dilate when centers in the brain detect an abnormal rise in blood pressure. If blood pressure falls below a set point, the centers trigger vasoconstriction of arterioles. Baroreceptors in carotid arteries provide short-term blood pressure control by way of signals that adjust the pressure when sudden changes occur.

Section 7.7 Capillaries are where fluids and solutes move between the bloodstream and body cells. These substances move by diffusion, through pores between cells, and by bulk flow of fluid. The movements help maintain the proper fluid balance between the blood and surrounding tissues, and also help maintain proper blood volume.

Section 7.8 Cardiovascular disorders collectively are the number one cause of death in the United States. In atherosclerosis, a buildup of cholesterol and other material develops into plaques that narrow the interior space in arteries and reduce blood flow to the heart or other tissues



and organs. HDLs (high-density lipoproteins) help transport excess blood cholesterol to the liver for disposal. High levels of LDLs (low-density lipoproteins) and trans fats, smoking, obesity, and inflammation in coronary arteries are some of the major risk factors associated with atherosclerosis.

Disease, injury, or an inborn defect can weaken an artery so that part of its wall balloons outward and forms an aneurysm.

Other serious cardiovascular disorders are heart attack (damage to or death of heart muscle) and heart failure (a weakened heart that cannot pump blood efficiently). An arrhythmia—irregular heart rhythm—can be a sign of heart problems. The most serious arrhythmia is ventricular fibrillation, haphazard contractions of the ventricles that greatly reduce blood pumping.

Section 7.9 Infections, substance abuse, and birth defects all can result in damage to the heart muscle or heart valves.

Review Questions

1. List the functions of the cardiovascular system.
2. Define a "heartbeat," giving the sequence of events that make it up.
3. Distinguish between the systemic and pulmonary circuits.
4. Explain the function of (*a*) the sinoatrial node, (*b*) the atrioventricular node, and (*c*) the cardiac pacemaker.
5. State the main function of blood capillaries. Name the main ways substances cross the walls of capillaries.
6. In the diagram above, label the heart's components.
7. State the main functions of venules and veins. What forces work together in returning venous blood to the heart?

Self-Quiz *Answers in Appendix V*

1. Cells obtain nutrients from and deposit waste into _____.
   a. blood
   b. lymph vessels
   c. each other
   d. both a and b
2. The contraction phase of the heartbeat is _____; the relaxation phase is _____.
3. In the pulmonary circuit, the heart's _____ half pumps _____ blood to capillary beds inside the lungs; then _____ blood flows to the heart.
   a. left; deoxygenated; oxygenated
   b. right; deoxygenated; oxygenated
   c. left; oxygenated; deoxygenated
   d. right; oxygenated; deoxygenated
4. In the systemic circuit, the heart's _____ half pumps _____ blood to all body regions; then _____ blood flows to the heart.
   a. left; deoxygenated; oxygenated
   b. right; deoxygenated; oxygenated
   c. left; oxygenated; deoxygenated
   d. right; oxygenated; deoxygenated
5. After you eat, blood passing through the GI tract travels through the _____ to a capillary bed in the _____.
   a. aorta; liver
   b. hepatic portal vein; liver
   c. hepatic vein; spleen
   d. renal arteries; kidneys
6. The cardiac pacemaker _____.
   a. sets the normal rate of heartbeat
   b. is the same as the AV node
   c. establishes resting blood pressure
   d. all of these are correct
7. Blood pressure is highest in _____ and lowest in _____.
   a. arteries; veins
   b. arteries; relaxed atria
   c. arteries; ventricles
   d. arterioles; veins
8. _____ contraction drives blood through the systemic and pulmonary circuits; outside the heart, blood pressure is highest in the _____.
   a. Atrial; ventricles
   b. Atrial; atria
   c. Ventricular; arteries
   d. Ventricular; aorta
9. Match the type of blood vessel with its major function.
   ____ arteries
   ____ arterioles
   ____ capillaries
   ____ veins
   a. diffusion
   b. control of blood distribution
   c. transport, blood volume reservoirs
   d. blood transport and pressure regulators

10. Match these three circulation components with their descriptions.

____ capillary beds	a. two atria, two ventricles
____ heart chambers	b. driving force for blood
____ heart contractions	c. zones of diffusion

Critical Thinking

1. A patient suffering from hypertension may receive drugs that decrease the heart's output, dilate arterioles, or increase urine production. In each case, how would the drug treatment help relieve hypertension?

2. Heavy smokers often develop abnormally high blood pressure. The nicotine in tobacco is a potent vasoconstrictor. Explain the connection between these two facts, including what kind of blood vessels are likely affected.

3. Before antibiotics were available, it wasn't uncommon for people in the United States (and elsewhere) to develop rheumatic fever. The infection can trigger an inflammation that ultimately damages valves in the heart. How must this disease affect the heart's functioning? What kinds of symptoms would arise as a consequence?

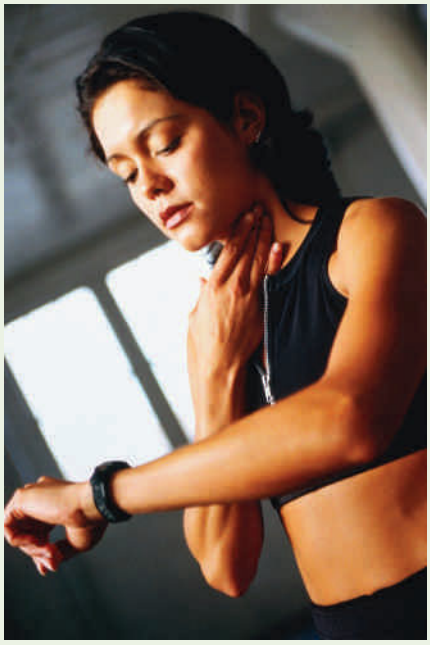
4. The highly publicized deaths of several airline travelers led to warnings about "economy-class syndrome." The idea is that economy-class passengers don't have as much leg room as passengers in more costly seating, so they are more likely to sit essentially motionless for long periods on flights—conditions that may allow blood to pool and clots to form in the legs. This condition is called deep-vein thrombosis, or DVT. In addition, low oxygen levels in airplane cabins may increase clotting. If a clot gets large enough to block blood flow or breaks free and is carried to the lungs or brain, it can lethally block an artery.

There could be a time lag between when a clot forms and health problems, so an air traveler who later develops DVT might easily overlook the possible connection with a flight. Studies are now under way to determine whether economy-class travel represents a significant risk of DVT. Given what you know about blood flow in the veins, explain why periodically getting up and moving around in the plane's cabin during a long flight may lower the risk that a clot will form.

EXPLORE ON YOUR OWN

As described in Section 7.6, a pulse is the pressure wave created during each cardiac cycle as the body's elastic arteries expand and then recoil. Common pulse points—places where an artery lies close to the body surface—include the inside of the wrist, where the radial artery travels, and the carotid artery at the front of the neck. Monitoring your pulse is an easy way to observe how a change in your posture or activity affects your heart rate.

To take your pulse, simply press your fingers on a pulse point and count the number of "beats" during one minute. For this exercise, take your first measurement after you've been lying down for a few minutes. If you are a healthy adult, it's likely that your resting pulse will be between 65 and 70 beats per minute. Now sit up, and take your pulse again. Did the change in posture correlate with a change in your pulse? Now run in place for 30 seconds and take your pulse rate once again. In a short paragraph, describe what changes in your heart's activity led to the pulse differences.



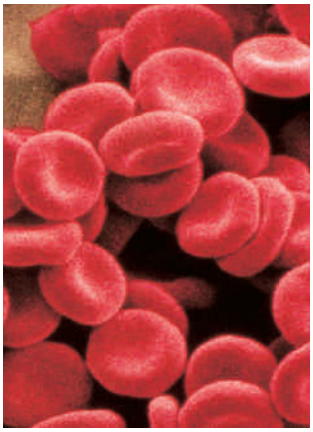
Blood

8

IMPACTS, ISSUES

Chemical Questions

SEVERAL years ago a team of scientists at the Centers for Disease Control (CDC) in Atlanta found 116 pollutants in the blood and urine of more than 2,500 healthy people who had volunteered to be tested for contaminated body fluids. The volunteers were selected to provide a statistically reliable cross section of the U.S. population. Many of the pollutants that turned up were substances known or strongly suspected to be harmful—toxic metals, chemicals in cigarette smoke, residues of pesticides and herbicides, and by-products of manufacturing processes.



A similar study by staff at the Environmental Working Group in Washington, D.C., found a whopping 167 contaminants in the body fluids of volunteers. None of those people reported any unusual exposure to polluting chemicals.

Few of the chemicals tracked in these tests even existed when you were born. Most are recent inventions that are designed to enhance products ranging from lipstick to electronic equipment or to improve farm productivity.

Many researchers are concerned that too little is known about the health impacts of many synthetic chemicals. For example, in the CDC study the majority of subjects, including children, had traces of phthalates in their fluids. Phthalates are used in cosmetics and plastics and aren't regulated in the United States. Yet studies using laboratory animals produced strong evidence that phthalates cause cancer and various abnormalities of the reproductive system.

How serious is the problem? In general, say environmental scientists, children and fetuses are most at risk, because many pollutants affect development. Also, little is known about the effect of long-term exposure to many synthetic chemicals. The metal lead is an example: Levels of lead in blood that were deemed safe in 1970 were later found to pose a major health threat to children. Ultimately lead was banned for use in paints and some other products.

Clearly, our blood can transport substances good and not so good. In this chapter you will get a better idea of its functions and why it is a key player in maintaining homeostasis.

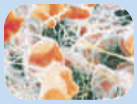
KEY CONCEPTS

Components and Functions of Blood

Blood consists of plasma, red blood cells, white blood cells, and platelets. Red blood cells carry O_2 and CO_2, white blood cells function in defense, and platelets help clot blood. Circulating blood helps maintain proper pH and body temperature. Sections 8.1–8.3

Blood Types

Proteins on red blood cells establish each person's blood type. Sections 8.4–8.6



Blood Clotting

Mechanisms that clot blood help prevent blood loss. Section 8.7

Disorders of the Blood

Section 8.8

LINKS TO EARLIER CONCEPTS

- This chapter expands on our survey of the cardiovascular system (Chapter 7). You also will learn more about the function of hemoglobin, the oxygen-carrying protein in red blood cells (2.12) and about the kinds of blood cells that arise from stem cells in bone marrow (5.2).
- This chapter's discussion of blood typing shows a key function of recognition proteins that are embedded in cell plasma membranes (3.4).
- Section 8.7 on blood clotting provides good examples of how enzymes catalyze chemical reactions that are vital to life (2.8).

How Would You Vote?

Government regulation of substances such as lead seems to be effective: In recent years the levels of several pollutants in the general population have fallen. Should other suspect industrial chemicals be regulated? See CengageNOW for details, then vote online.

8.1 Blood: Plasma, Blood Cells, and Platelets

- **Human blood is a sticky fluid that consists of water, blood cells, and other substances.**
- **Links to Properties of water 2.5, Proteins 2.11, Osmosis 3.10, Skeleton 5.2**

The old saying is true—**blood** really is thicker than water. This unusual fluid consists of plasma, blood cells, and cell fragments called platelets. If you are an adult woman of average size, your body has about 4 to 5 liters of blood; males have slightly more. In all, blood amounts to about 6 to 8 percent of your body weight.

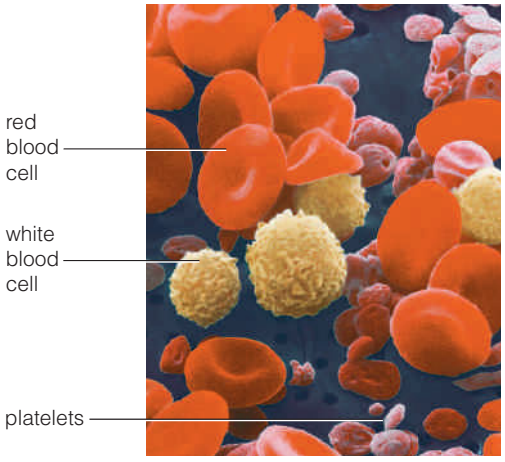
Plasma is the fluid part of blood

If you fill a test tube with blood, treat it so it doesn't clot, and whirl it in a centrifuge, the tube's contents should look like what you see in Figure 8.1. About 55 percent of whole blood is **plasma**. Plasma is mostly water. It transports blood cells and platelets, and more than a hundred other substances. Most of these "substances" are different plasma proteins, which have a variety of functions.

Plasma proteins determine the fluid volume of the blood—how much of it is water. Two-thirds of plasma proteins are albumin molecules made in the liver. Because there is so much of it—that is, because its concentration is so high—albumin has a major influence on the osmotic movement of water into and out of blood. Albumin also carries many chemicals in blood, from metabolic wastes to therapeutic drugs. Too little albumin can be one cause of *edema*, swelling that occurs when water leaves the blood and enters tissues.

Other plasma proteins include protein hormones and proteins involved in immunity and blood clotting. Lipoproteins carry lipids, and still other plasma proteins transport fat-soluble vitamins.

Plasma also contains ions, glucose and other simple sugars, amino acids, various communication molecules, and dissolved gases—mostly oxygen, carbon dioxide, and nitrogen. The ions (such as Na^+, Cl^-, H^+, and K^+) help maintain the volume and pH of extracellular fluid.



Red blood cells carry oxygen and CO_2

About 45 percent of whole blood—the bottom portion in your centrifuged test tube—consists of **erythrocytes**, or **red blood cells**. Each red blood cell is a biconcave disk, like a thick pancake with a dimple on each side. The cell's red color comes from the iron-containing protein **hemoglobin**. Hemoglobin transports oxygen that the

Components	Relative Amounts	Functions
Plasma Portion (*50%–60% of total volume*):		
1. Water	91%–92% of plasma volume	Solvent
2. Plasma proteins (albumin, globulins, fibrinogen, etc.)	7%–8%	Defense, clotting, lipid transport, roles in extracellular fluid volume, etc.
3. Ions, sugars, lipids, amino acids, hormones, vitamins, dissolved gases	1%–2%	Roles in extracellular fluid volume, pH, etc.
Cellular Portion (*40%–50% of total volume*):		
1. White blood cells:		
Neutrophils	3,000–6,750	Phagocytosis during inflammation
Lymphocytes	1,000–2,700	Immune responses
Monocytes (macrophages)	150–720	Phagocytosis in all defense responses
Eosinophils	100–360	Defense against parasitic worms
Basophils	25–90	Secrete substances for inflammatory response and for fat removal from blood
2. Platelets	250,000–300,000	Roles in clotting
3. Red blood cells	4,800,000–5,400,000 per microliter	Oxygen, carbon dioxide transport

Figure 8.1 Blood consists of cells, platelets, and plasma. In the micrograph the dark red cells are red blood cells. Platelets are pink. The fuzzy gold balls are white blood cells.

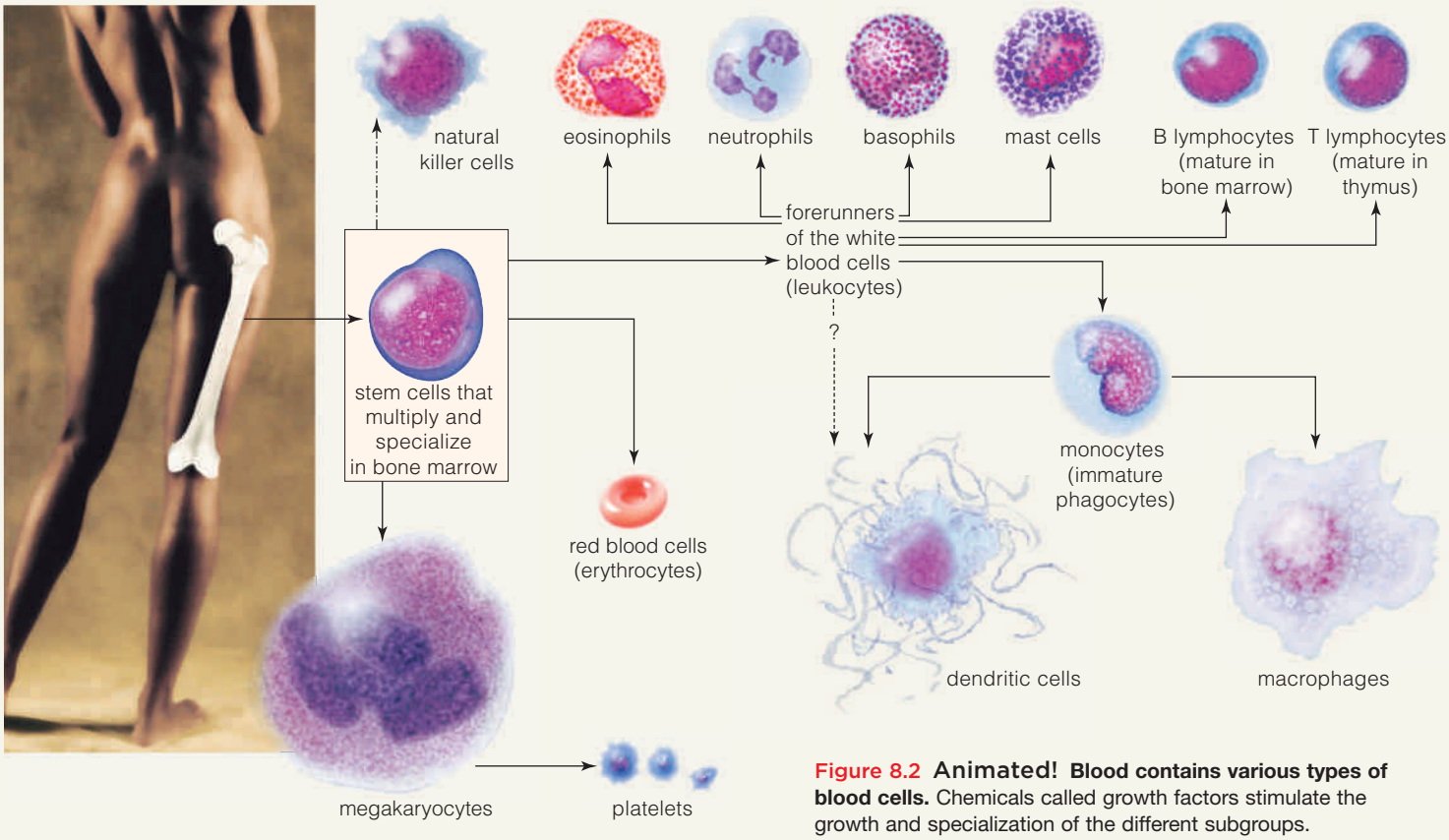


Figure 8.2 Animated! Blood contains various types of blood cells. Chemicals called growth factors stimulate the growth and specialization of the different subgroups.

body requires for aerobic respiration. Red blood cells also carry away some carbon dioxide wastes.

Red blood cells arise from stem cells in bone marrow. You may recall that a **stem cell** stays unspecialized and retains the ability to divide. Some of the daughter cells, however, do become specialized for particular functions, as you can see in Figure 8.2.

White blood cells perform defense and cleanup duties

Leukocytes, or **white blood cells**, make up a tiny fraction of whole blood. (With platelets, they are the thin, pale, middle layer in your test tube.) Leukocytes function in housekeeping and defense. Some scavenge dead or worn-out cells, or material identified as foreign to the body. Others target or destroy disease agents such as bacteria or viruses. Most go to work after they squeeze out of blood vessels and enter tissues. The number of them in the body varies, depending on whether a person is sedentary or highly active, healthy or fighting an infection.

All white blood cells develop from stem cells in bone marrow. In the various kinds of cells, the nucleus varies in its size and shape, and there are other differences as well. **Granulocytes** include neutrophils, eosinophils, and basophils. When this type of cell is stained, various types of granules are visible in its cytoplasm. The majority of leukocytes are neutrophils. They and eosinophils, basophils, and mast cells have roles in body defenses that you will read more about in Chapter 9.

The leukocytes called **agranulocytes** don't have visible granules in their cytoplasm. One type, called monocytes, develops into macrophages, "big eaters" that engulf and destroy invading microbes and debris. Another type, lymphocytes (B cells, T cells, and natural killer cells), operates in immune responses. Most types of white blood cells live for only a few days or, during a major infection, perhaps a few hours. Others may live for years.

Platelets help clot blood

Some stem cells in bone marrow develop into "giant" cells called megakaryocytes (mega = large). These cells shed bits of cytoplasm that become enclosed in a plasma membrane. The fragments, known as **platelets**, last only about a week, but millions are always circulating in our blood. Platelets release substances that begin the process of blood clotting described in Section 8.7.

Take-Home Message

What is human blood?

- Blood consists of plasma, in which proteins and other substances are dissolved; red blood cells; white blood cells; and platelets.

8.2 How Blood Transports Oxygen

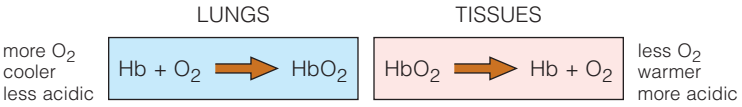
- **A key function of blood is transporting oxygen, and the key to oxygen transport is the protein called hemoglobin.**
- **Link to Protein function 2.12**

Hemoglobin is the oxygen carrier

If you were to analyze a liter of blood drawn from an artery, you would find only a quarter teaspoon of oxygen dissolved in the plasma—just 3 milliliters. Yet, like all large, active, warm-bodied animals, humans require a lot of oxygen to maintain the metabolic activity of their cells. Hemoglobin (Hb) meets this need. In addition to the small amount of dissolved oxygen, a liter of arterial blood usually carries around 65 times more O_2 bound to the heme groups of hemoglobin molecules. This oxygen-bearing hemoglobin is called **oxyhemoglobin**.

What determines how much oxygen hemoglobin can carry?

As conditions change in different tissues and organs, so does the tendency of hemoglobin to bind with and hold on to oxygen. Several factors influence this process. The most important factor is how much oxygen is present relative to the amount of carbon dioxide. Other factors are the temperature and acidity of tissues. Hemoglobin is most likely to bind oxygen in places where blood plasma contains a relatively large amount of oxygen, where the temperature is relatively cool, and where the pH is roughly neutral. This is exactly the environment in our lungs, where the blood must take on oxygen. By contrast, metabolic activity in cells *uses* oxygen. It also increases both the temperature and the acidity (lowers the pH) of tissues. Under those conditions, the oxyhemoglobin of red blood cells arriving in tissue capillaries tends to release oxygen, which then can enter cells. We can summarize these events this way:



The protein portion of hemoglobin also carries some of the carbon dioxide wastes that cells produce, along with hydrogen ions (H^+) that affect the pH of body fluids. You'll read more about hemoglobin in Chapter 10, where we consider the many interacting elements that enable the respiratory system to transport gases efficiently to and from body cells.

You can see the structure of a hemoglobin molecule in Figure 8.3. Notice that it has two parts: the protein globin, and heme groups that contain iron. Globin is built of four linked polypeptide chains, and each chain is associated with a heme group. It is the iron molecule at the center of each heme group that binds oxygen.

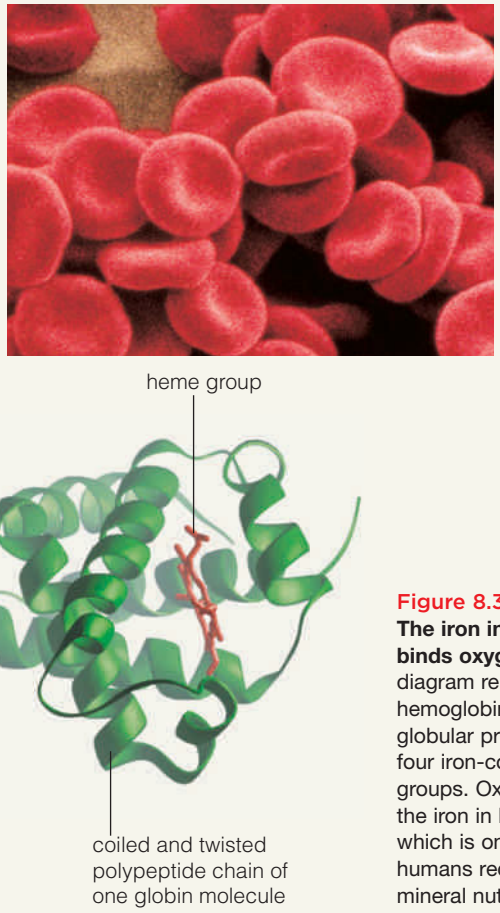


Figure 8.3 Animated! The iron in hemoglobin binds oxygen. This diagram represents hemoglobin, which is a globular protein that has four iron-containing heme groups. Oxygen binds to the iron in heme groups, which is one reason why humans require iron as a mineral nutrient.

Oxygen in the lungs diffuses into the blood plasma and then into individual red blood cells. There it binds with the iron in hemoglobin. This oxyhemoglobin is deep red. Hemoglobin that is depleted of oxygen looks purplish, especially when it is observed through skin and the walls of blood vessels.

Take-Home Message

How does blood transport oxygen?

- Hemoglobin in red blood cells transports oxygen. The oxygen is bound to iron in heme groups in each hemoglobin molecule.
- The relative amounts of oxygen and carbon dioxide present in blood, and the temperature and acidity of tissues, affect how much oxygen hemoglobin binds—and therefore the amount of oxygen available to tissues.

8.3 Making New Red Blood Cells

- **Red blood cells do not live long. In response to hormones, stem cells in bone marrow constantly produce new ones.**

Each second, about 3 million new red blood cells enter your bloodstream. They gradually lose their nucleus and other organelles, structures that are unnecessary because red blood cells do not divide or make new proteins.

Red blood cells have enough enzymes and other proteins to function for about 120 days. As they near the end of their life, die, or become damaged or abnormal, phagocytes called macrophages ("big eaters") remove them from the blood. Much of this cleanup occurs in the spleen, which is located in the upper left abdomen. As a macrophage dismantles a hemoglobin molecule, amino acids from its proteins return to the bloodstream and the iron in its heme groups returns to red bone marrow, where it may be recycled in new red blood cells. The rest of the heme group is converted to the orangish pigment bilirubin. Liver cells take up this pigment, which is mixed with bile that is released into the small intestine during digestion.

Steady replacements from stem cells in bone marrow keep a person's red blood cell count fairly constant over time. A **cell count** is a tally of the number of cells in a microliter of blood. On average, an adult male's red blood cell count is around 5.4 million. In an adult female the count averages about 4.8 million red blood cells.

Having a stable red blood cell count is important for homeostasis, because body cells need a reliable supply of oxygen. Your kidneys make erythropoietin (EPO). This hormone stimulates the production of new red blood cells when they are needed.

The process relies on a negative feedback loop (Figure 8.4). In this loop, the kidneys monitor the level of oxygen in your blood. When it falls below a set point, kidney cells detect the change and soon release EPO. It stimulates stem cells in bone marrow to produce more red blood cells. As new red blood cells enter your bloodstream, the blood can carry more oxygen and the oxygen level rises in your blood and tissues. This information feeds back to the kidneys. They make less erythropoietin, and production of red blood cells in bone marrow drops.

In "blood doping," some of an athlete's blood is withdrawn and stored. Erythropoietin then stimulates the production of replacement red blood cells. The stored blood is reinjected several days prior to an athletic event, so that the athlete has more than the normal number of red blood cells to carry oxygen to body muscles—and an unethical competitive advantage. Some cyclists, runners and other "distance" athletes have used lab-made EPO, even though it is a banned performance-enhancing drug. Better drug testing is helping to curb this practice.

Take-Home Message

How does the body make new red blood cells?

- When more red blood cells are needed to carry oxygen, the kidneys release erythropoietin, a hormone that stimulates the production of new red blood cells by stem cells in bone marrow.

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8.4 Blood Types: Genetically Different Red Blood Cells

- **The different human blood types are due to variations in the surface markers on red blood cells.**
- **Link to the Plasma membrane 3.4**

Each of your body cells has proteins on its surface that mark the cell as "self." Your genes have determined the chemical characteristics of these self markers, which vary from person to person. The variations are medically important because the markers on cells and substances that are *not* part of an individual's own body are antigens. An **antigen** is a chemical characteristic of a cell, particle, or substance that causes the immune system to mount an immune response. Defensive proteins called *antibodies* identify and attack antigens in a process that is a major topic of Chapter 9.

Human red blood cells bristle with self markers. To date biologists have identified at least 30 common ones, and many more rare ones. Because each kind of marker can have several forms, they are often called "blood groups." Two of them, the Rh blood group and the ABO blood group, are extremely important in situations where the blood of two people mixes. We will consider the Rh blood group in Section 8.5. For now, let's look more closely at the ABO blood group, which is a vital consideration in blood transfusions.

Self markers on red blood cells include the ABO group of blood types

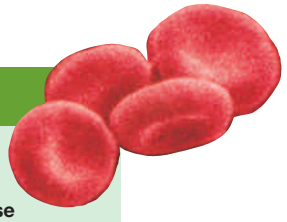
One of our genes carries the instructions for building the ABO self markers on red blood cells. Different versions of this gene carry instructions for different markers, called type A and type B. A third version of the gene does not call for a marker, and red blood cells of someone who has this gene are dubbed type O. Collectively, these markers make up the ABO blood group.

In type A blood, red blood cells bear A markers. Type B blood has B markers, and type AB has both A and B. Type AB blood is quite rare, but a large percentage of people have type O red blood cells—they have neither A nor B markers. Depending on your ABO blood type, your blood plasma also will contain antibodies to other blood types, even if you have never been exposed to them. As you will read shortly, a severe immune response takes place when incompatible blood types are mixed. This is why donated blood must undergo a chemical analysis called **ABO blood typing** (Table 8.1).

Mixing incompatible blood types can cause the clumping called agglutination

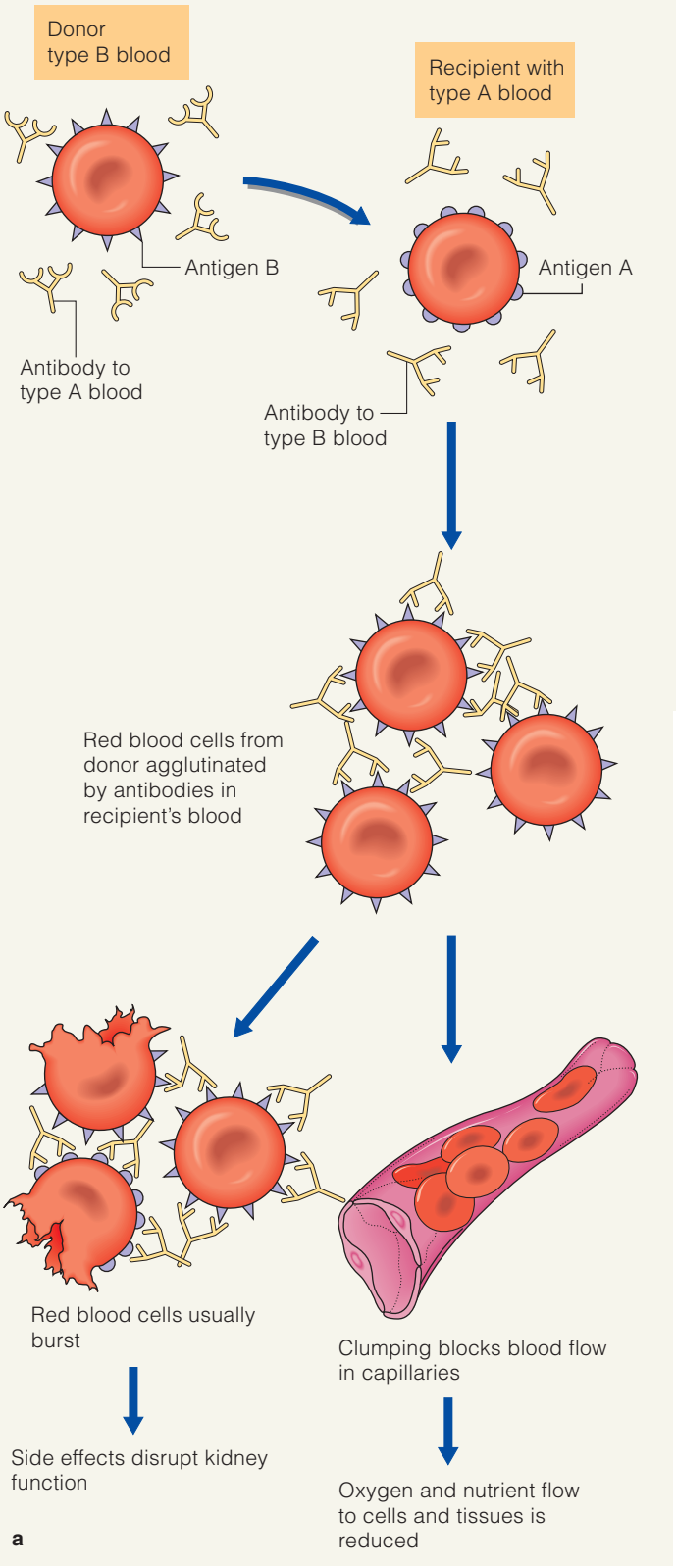
As you can see in Table 8.1, if you are type A, your body does not have antibodies against A markers but does have them against B markers. If you are type B, you don't have antibodies against B markers, but you do have antibodies against A markers. If you are type AB, you do not have antibodies against either form of the marker. If you are type O, however, you have antibodies against *both* forms of the marker, so you can only receive blood from another type O individual.

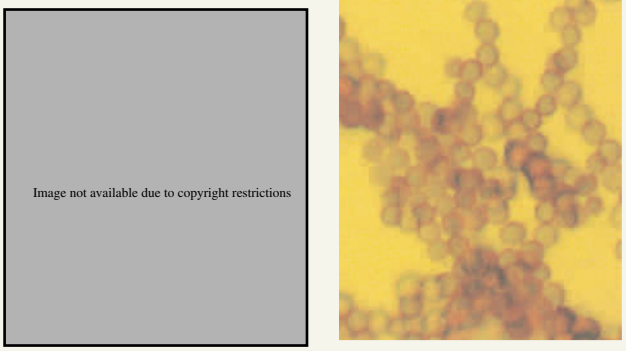
In theory, type O people are "universal donors," because they have neither A nor B antigens, and—again, only in theory—type AB people are "universal recipients." In fact, however, as already noted, there are *many* markers



Summary of ABO Blood Types

Blood Type	Antigens on Plasma Membranes of RBCs	Antibodies in Blood	Safe to Transfuse To	Safe to Transfuse From
A	A	Anti-B	A, AB	A, O
B	B	Anti-A	B, AB	B, O
AB	A + B	none	AB	A, B, AB, O
O	—	Anti-A Anti-B	A, B, AB, O	O





incompatible blood cells

Figure 8.5 **Animated! Mixing incompatible blood types causes agglutination, or clumping.** (**a**) Example of an agglutination reaction. This diagram shows what happens when type B blood is transfused into a person who has type A blood. (**b**) What an agglutination reaction looks like. In the micrograph on the left, commingled red blood cells are compatible and have not clumped. The cells on the right are a mix of incompatible ABO types, and they have clumped together. Donated blood is typed in order to avoid an agglutination response when the blood is transfused into another person.

associated with our red blood cells, and any of them can trigger the defense response called **agglutination** (Figure 8.5). When the mixing of incompatible blood causes agglutination, antibodies act against the "foreign" cells and cause them to clump. The clumps can clog small blood vessels, severely damaging tissues throughout the body and sometimes even causing death.

We turn next to the Rh blood group. As you will now read, agglutination is also a danger when mismatched Rh blood types mix.

Take-Home Message

What is a blood type?

- Like all cells, red blood cells bear genetically determined proteins on their surface. These proteins serve as self markers and determine a person's ABO (and Rh) blood type.
- When incompatible blood types mix, an agglutination response occurs in which antibodies cause potentially fatal clumping of red blood cells.

8.5 Rh Blood Typing

- **Another surface marker on red blood cells that can cause agglutination is the Rh factor, so named because it was first identified in the blood of Rhesus monkeys.**

Rh blood typing looks for an Rh marker

Rh blood typing determines the presence or absence of an Rh marker. If your blood cells bear this marker, you are Rh^+ (positive). If they don't have the marker, you are Rh^- (negative). When a person's blood type is determined, the ABO blood type and Rh type are usually combined. For instance, if your blood is type A and Rh negative, your blood type will be given as type A^-.

Most people don't have antibodies against the Rh marker. But an Rh^- person who receives a transfusion of Rh^+ blood will make antibodies against the marker, and these will continue circulating in the person's bloodstream.

If an Rh^- woman becomes pregnant by an Rh^+ man, there is a chance the fetus will be Rh^+. During pregnancy or childbirth, some of the fetal red blood cells may leak into the mother's bloodstream. If they do, her body will produce antibodies against Rh (Figure 8.6). If she gets pregnant *again*, Rh antibodies will enter the bloodstream of this new fetus. If its blood is Rh^+, its mother's antibodies will cause its red blood cells to swell and burst.

In extreme cases, called *hemolytic disease of the newborn*, so many red blood cells are destroyed that the fetus dies. If the condition is diagnosed before or during a live birth, the baby can survive by having its blood replaced with transfusions free of Rh antibodies.

Currently, a known Rh^- woman can be treated after her first pregnancy with an anti-Rh gamma globulin (RhoGam) that will protect her next fetus. The drug will inactivate Rh^+ fetal blood cells circulating in the mother's bloodstream before she can become sensitized and begin producing anti-Rh antibodies. In non-maternity cases, an Rh^- person who receives a transfusion of Rh^+ blood also can have a severe negative reaction if he or she has previously been exposed to the Rh marker.

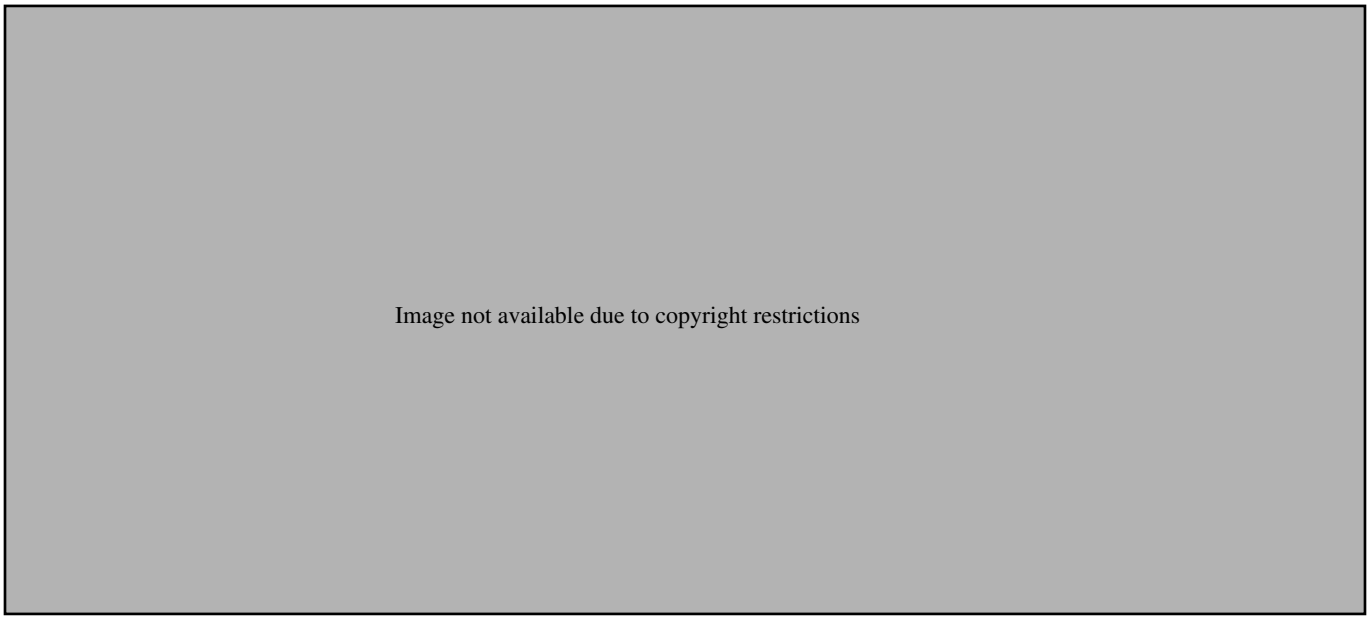
There are also many other markers on red blood cells

Besides the Rh and AB blood marker proteins, hundreds of others are now known to exist. These markers are a bit like needles in a haystack—they are widely scattered within the human population and usually don't cause problems in transfusions. Reactions do occur, though, and except in extreme emergencies, hospitals use a method called *cross-matching* to exclude the possibility that blood to be transfused and that of a patient might be incompatible due to the presence of a rare blood cell marker outside the ABO and Rh groups.

Take-Home Message

What is the purpose of Rh blood typing?

- In some people, red blood cells are marked with an Rh protein. If this Rh^+ blood mixes with the Rh^- blood of someone else, the Rh^- individual will develop antibodies against it. The antibodies will trigger an immune response against Rh^+ red blood cells if the person is exposed to them again.



8.6 New Frontiers of Blood Typing

- **Because blood types are genetically determined, they can be used to help establish a person's genetic heritage.**

Blood and DNA are used to investigate crimes and identify mom or dad

In addition to helping ensure that a blood transfusion will be safe or that a mother's antibodies will not harm her fetus, the markers on red blood cells have a variety of other uses. For example, investigations of rapes, murders, and sometimes other crimes often compare the blood groups of victims and any possible perpetrators.

Today, blood samples often are used for DNA testing, which provides the most definitive information about a person's genetic heritage. For instance, there is a lot of similarity in the blood types found in and among people of different ethnic backgrounds (Table 8.2). Notice that AB is the rarest blood type.

At one time blood typing was also commonly used to help determine the identity of a child's father or mother in cases where parentage was disputed. This is another area in which DNA testing is now the norm.

For safety's sake, some people bank their own blood

A blood transfusion is inherently risky. There is the need for an accurately matched blood type, and the risk of being exposed to blood-borne pathogens such as hepatitis viruses and HIV, the human immunodeficiency virus that causes AIDS. Although in general hospital blood supplies are carefully screened, some people who are slated for elective surgery take the extra precaution of pre-donating blood for an *autologous transfusion* (Figure 8.7). This means they have some of their own blood removed and stored before the procedure so it can be used during the surgery if a transfusion is necessary.

ABO Blood Groups in the U.S. Population (percentages)

Blood Group	White	Black	Asian	Native American
AB	4	4	5	<1
B	11	20	27	4
A	40	27	28	16
O	45	49	40	79

Blood substitutes have pros and cons

For years medical researchers have been trying to develop a safe, effective blood substitute that can be used in emergencies when matching a person's blood type isn't feasible, as in an ambulance or on a battlefield. A substitute might also be acceptable to people who refuse blood transfusions on religious grounds. As you've read, however, blood is extremely complex, and red blood cells, which are the crucial oxygen transporters, have many different self markers on their plasma membranes. Under these circumstances, it has been a tall order to find the right recipe for a blood substitute.

To date the most promising approach seems to be a substitute oxygen carrier that will not trigger an immune response. The more we explore options for blood substitutes, the more we understand just what a remarkable substance we have coursing through our arteries and veins.

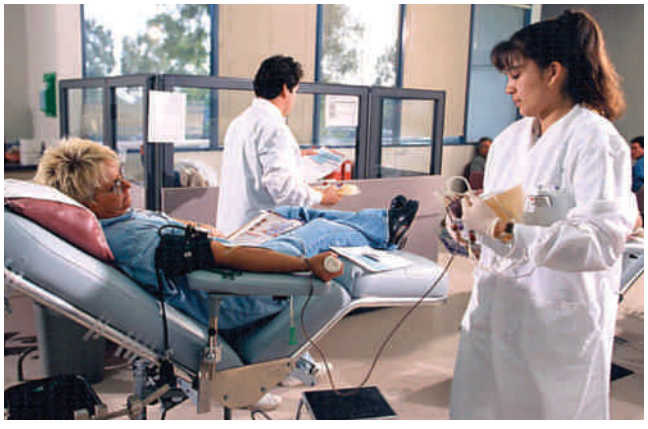


Figure 8.7 **Blood can be donated to help others or stored for personal use.**

Take-Home Message

What are some uses and problems related to blood typing?

- The presence of self markers on red blood cells allows blood to be used to help identify individuals.
- The markers also make transfusions risky, so some patients opt for transfusions of their own blood.
- The complexity of blood presents a challenge in the development of blood substitutes.

8.7 Hemostasis and Blood Clotting

- **Small blood vessels can easily tear or be damaged by a cut or blow. To maintain homeostasis, it is essential for small tears to be quickly repaired.**

Hemostasis prevents blood loss

Hemostasis is the name of a process that stops bleeding and so helps prevent the excessive loss of blood. In this process, an affected blood vessel constricts, platelets plug up the tear, and blood coagulates, or clots (Figure 8.8). Although hemostasis can only seal tears or punctures in relatively small blood vessels, most cuts and punctures fall into this category.

When a blood vessel is ruptured, smooth muscle in the damaged vessel wall contracts in an automatic response called a spasm. The muscle contraction constricts the blood vessel, so blood flow through it slows or stops. This response can last for up to half an hour, and it is vital in stemming the immediate loss of blood. Then, while the flow of blood slows, platelets arrive and clump together, creating a temporary plug in the damaged wall. They also release the hormone serotonin and other chemicals that help prolong the spasm and attract more platelets. Lastly, blood coagulates—that is, it converts to a gel—and forms a clot.

Factors in blood are one trigger for blood clotting

Two different mechanisms can cause a blood clot to form. The first is called an "intrinsic" clotting mechanism because it involves substances that are in the blood itself. Figure 8.8 diagrams this process. It gets under way when a protein in the blood plasma, called "factor X," is activated. This triggers reactions that produce thrombin. This is an enzyme that acts on a rod-shaped protein called fibrinogen. The fibrinogen rods stick together, forming long threads of fibrin. The fibrin threads also stick to one another. The result is a net that entangles blood cells and platelets, as you can see in the micrograph in Figure 8.8. The entire mass is a blood clot. With time, the clot becomes more compact, drawing the torn walls of the vessel back together.

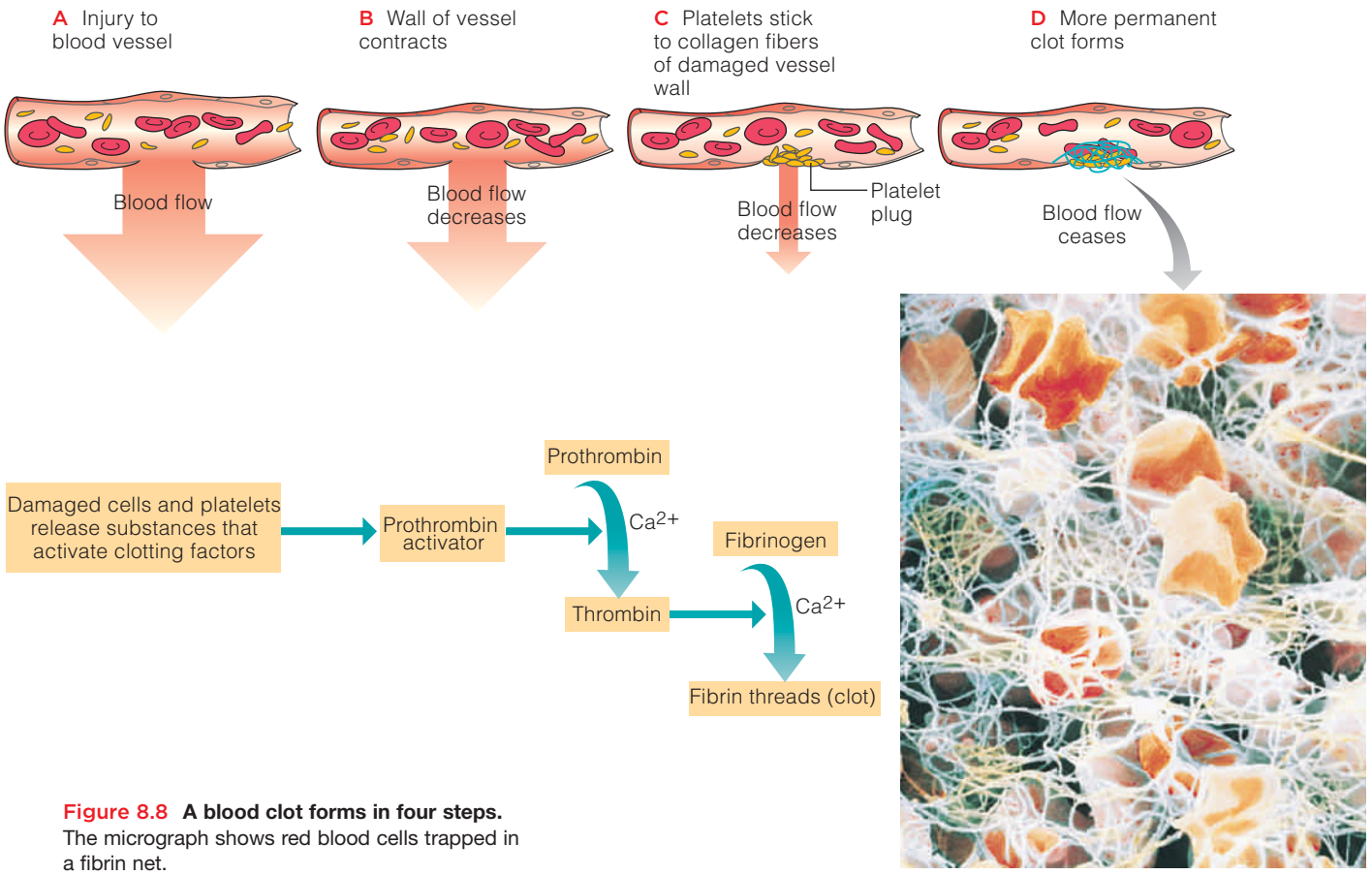


Figure 8.8 A blood clot forms in four steps. The micrograph shows red blood cells trapped in a fibrin net.

Factors from damaged tissue also can cause a clot to form

Blood also can coagulate through an extrinsic clotting mechanism. "Extrinsic" means that the reactions leading to clotting are triggered by the release of enzymes and other substances *outside* the blood. These chemicals come from damaged blood vessels or from tissue around the damaged area. The substances lead to the formation of thrombin, and the remaining steps are like the steps of the intrinsic pathway.

Because aspirin reduces the aggregation of platelets, it is sometimes prescribed in small doses to help prevent blood clots. A clot that forms in an unbroken blood vessel can be a serious threat because it can block the flow of blood. A clot that stays where it forms is called a *thrombus*, and the condition is called a *thrombosis*.

Even worse is an *embolus*, a clot that breaks free and circulates through the bloodstream. A person who suffers an *embolism* in the heart, lungs, brain, or some other organ may suddenly die when the roving clot shuts down the organ's blood supply. This is what happens when a person suffers a **stroke**. A blood clot blocks the flow of blood to some part of the brain and the affected brain tissue dies. Strokes can be mild to severe. In serious cases the person may be paralyzed on one side of the body and have trouble speaking. Physical therapy and speech therapy may help minimize the long-term effects.

The disease **hemophilia** is a genetic disorder in which the blood does not contain the usual clotting factors and so does not clot properly. You will read more about this disorder in Chapter 20.

The formation of a blood clot is a first step in healing wounds

When the skin is punctured or torn, blood clotting gets under way immediately to help seal the breach (Figure 8.9). With minor cuts, it usually takes less than 30 minutes for a clot to seal off injured vessels. In a few more hours, phagocytes are at work cleaning up debris and a scab has begun to form. This quick action is vital to minimize blood loss and the chances of infection.

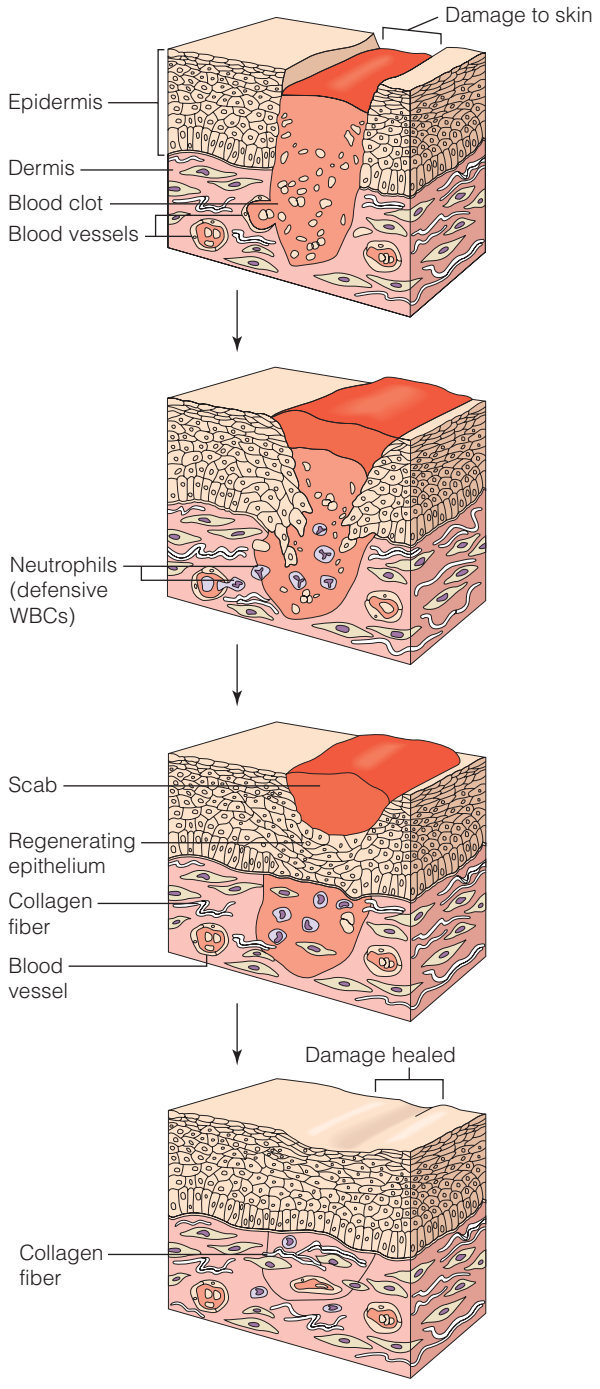


Figure 8.9 **Blood clotting helps heal a wound in the skin.**

Take-Home Message

What are hemostasis and blood clotting?

- Hemostasis refers to processes that slow or stop the flow of blood from a ruptured vessel.
- The mechanisms include spasms that constrict blood vessel walls, the formation of platelet plugs, and blood clotting.
- Blood clotting can be triggered by substances in the blood itself or by way of reactions involving substances in damaged tissue.

8.8 Blood Disorders

Anemias are red blood cell disorders

At least half a dozen **anemias** (meaning "no blood") are signs that red blood cells are not delivering enough oxygen to meet body needs. All anemias result from other, underlying problems. To varying degrees they make a person feel tired and listless, among other symptoms.

Two common types of anemia result from nutrient deficiencies. For example, *iron-deficiency anemia* develops when the body's iron supply is too low to form enough hemoglobin (with its iron-containing heme groups). Folic acid and vitamin B_{12} both are needed for the production of red blood cells in bone marrow. A deficiency of either one can lead to *pernicious anemia*. A balanced diet usually provides both nutrients, but other conditions can prevent them from being absorbed.

The rare malady *aplastic anemia* arises when red bone marrow, including the stem cells that give rise to red and white blood cells and platelets, has been destroyed by radiation, drugs, or toxins.

"Hemolytic" means "blood breaking," and *hemolytic anemias* develop when red blood cells die or are destroyed before the end of their normal useful life. The root cause may be an inherited defect, as in sickle-cell anemia, in which red blood cells take a sickle shape (Figure 8.10*a* and 8.10*b*) and can burst. Chapter 20 looks more fully at the genetic trigger for these changes.

Worldwide, **malaria** is a major cause of hemolytic anemia. It is caused by a protozoan that is transmitted by mosquitoes. One life stage of this pathogen multiplies inside red blood cells, leading to disease symptoms such as fever, chills, and trembling. Eventually the red blood cells burst (Figure 8.10*c*).

Like people who have sickle-cell anemia, those with *thalassemia* produce abnormal hemoglobin. Too few red blood cells form, and those that do form are thin and extremely fragile.

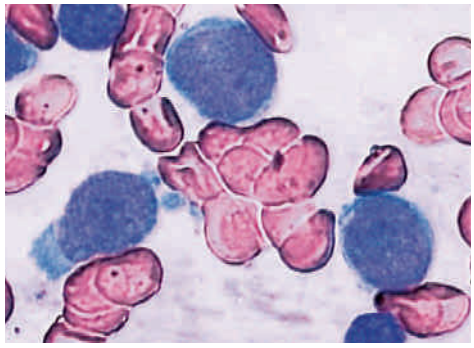


Figure 8.11 This image shows blood from a person with chronic myelogenous leukemia. Abnormal white blood cells (*purple*) are starting to crowd out normal cells.

Carbon monoxide poisoning prevents hemoglobin from binding oxygen

Carbon monoxide, or CO, is a colorless odorless gas. It is present in auto exhaust fumes and in smoke from burning wood, coal, charcoal, and tobacco. It binds to hemoglobin at least 200 times more tightly than oxygen does. As a result, breathing even tiny amounts of it can tie up half of the body's hemoglobin and prevent tissues from receiving the oxygen they need. CO poisoning is especially dangerous because an affected person may not realize that the symptoms—headache and feeling "woozy"—are signs of life-threatening distress.

Mononucleosis and leukemias affect white blood cells

Our white blood cells also can be affected by disease. For example, **infectious mononucleosis** is caused by the Epstein-Barr virus, which causes overproduction of lymphocytes. The patient feels achy and tired and runs a low-grade fever for several weeks as the highly contagious disease runs its course.

Far more serious are **leukemias**, which result from bone marrow cancer. The word "leukemia" means "white blood," and the hallmark of leukemias (like other cancers) is runaway multiplication of the abnormal cells and destruction of healthy bone marrow.

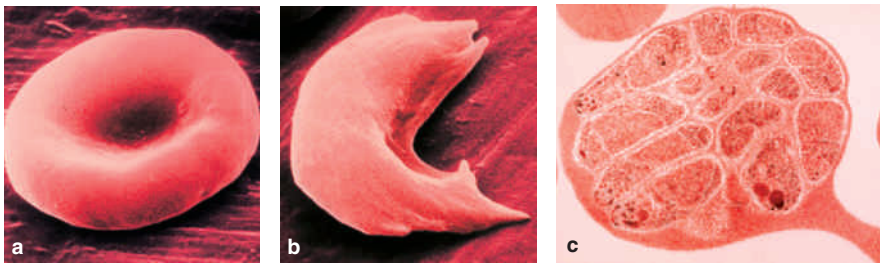


Figure 8.10 In hemolytic anemias red blood cells are destroyed. Here you are looking at scanning electron micrographs of (**a**) normal and (**b**) sickled red blood cells. In (**c**) a multiplying life stage of the microorganism that causes malaria is about to burst open a red blood cell.

IMPACTS, ISSUES

Chemical Questions

DUE to government regulations, in recent years the levels of lead and some other potentially dangerous industrial chemicals in the general population have fallen. Industry representatives say that any new regulations should be on hold until we have more evidence about health effects of some other suspect substances.

How Would You Vote?

Should the government limit the use of certain industrial chemicals before their possible harmful effects on human health are confirmed? See CengageNOW for details, then vote online.

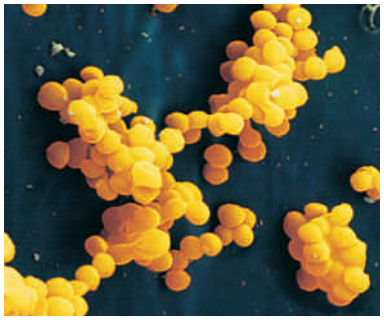


Figure 8.12 ***Staphylococcus aureus*** **bacteria destroy red blood cells and stop blood from clotting.**

In the most serious forms of leukemia, which tend to strike children, the marrow cavities in bones become choked with cancerous white blood cells. As other types of blood cells (and stem cells) are excluded, leukemia's symptoms develop—fever, weight loss, anemia, internal bleeding, pain, and susceptibility to infections. Modern treatments now save thousands of lives, and there is hope that experimental gene therapies may provide more help. Figure 8.11 shows cells of one type of leukemia, called **chronic myelogenous leukemia**.

Viral infections also can harm white blood cells. The most notorious is HIV, the human immunodeficiency virus, which causes AIDS. Its ability to kill lymphocytes of the immune system is a major topic in Chapter 9.

Toxins can poison the blood

Some bacteria release toxins into the blood, a condition called **septicemia**. One of our scariest bacterial foes is *Staphylococcus aureus*, or simply "staph A" (Figure 8.12). This microbe produces enzymes that destroy red blood cells and prevent blood clotting. Some strains have become highly resistant to antibiotics. One of them, MRSA (for methicillin resistant staph A) can kill, and it is most common where you might least expect it—in health care facilities, including hospitals.

Metabolic poisons in the body cause *toxemia*. For example, the kidneys normally remove many toxic wastes from blood. In a person whose kidneys do not function well due to disease or some other cause, the buildup of certain wastes prevents the normal replacement of red blood cells. It also prevents platelets from functioning. Thus the person becomes anemic and blood does not clot properly.

Summary

Section 8.1 Blood is a fluid connective tissue. It helps maintain homeostasis by transporting oxygen and other substances to and from the extracellular fluid that bathes cells. Proteins (such as albumin) in blood help maintain proper fluid volume of blood. Ions in blood help stabilize the pH of extracellular fluid.

Blood consists of liquid plasma, red and white blood cells, and cell fragments called platelets. Blood cells and platelets arise from stem cells in bone marrow.

Plasma transports blood cells and platelets. Proteins, simple sugars, amino acids, mineral ions, vitamins, hormones, and oxygen and carbon dioxide gases all are dissolved in plasma water.

Red blood cells carry oxygen and platelets produce substances that initiate blood clotting. Major categories of white blood cells are granulocytes and agranulocytes. Granulocytes, such as neutrophils, operate in body defense. Agranulocytes include a type that develops into macrophages, which scavenge dead or worn-out cells and other debris and cleanse tissues of "non-self" material. Lymphocytes destroy specific microbes and other agents of disease.

Section 8.2 Red blood cells contain hemoglobin, an iron-containing pigment molecule that binds reversibly with oxygen, forming oxyhemoglobin. Red blood cells also carry some carbon dioxide (also bound to hemoglobin) back to the lungs to be exhaled.

Section 8.3 Red blood cells live for about 120 days. A cell count measures the number of them in a microliter of blood. Macrophages remove dead or damaged red blood cells while stem cells provide replacements.

Section 8.4 Blood type is determined by proteins on the surface of red blood cells. The four main human blood types are A, B, AB, and O. Agglutination is a defense response activated when a person's blood mixes with an incompatible type. Rh blood typing determines the presence or absence of Rh factors (+ or −) on red blood cells.

- Use the animation and interaction on CengageNOW to learn about ABO and Rh blood types.

Section 8.7 Mechanisms of hemostasis slow or stop bleeding. These events include spasms that constrict blood vessels, the formation of platelet plugs, and blood clotting.

Review Questions

1. What is blood plasma, and what is its function?
2. What are the cellular components of blood? Where do the various kinds come from?
3. Add the missing labels to Figure 8.13 at right. Then, on a separate sheet of paper, list the factors that affect the tendency of hemoglobin to bind with oxygen.
4. Explain what an agglutination response is, and how it can be avoided when blood is transfused.
5. What is the function of hemostasis? What are the two ways a blood clot can form?

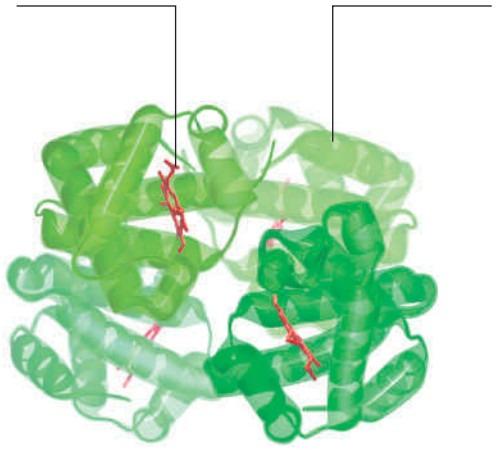


Figure 8.13 **A hemoglobin molecule.**

Self-Quiz *Answers in Appendix V*

1. Which are *not* components of blood?
   a. plasma
   b. blood cells and platelets
   c. gases and other dissolved substances
   d. all of the above are components of blood
2. The _____ produces red blood cells, which transport _____ and some _____.
   a. liver; oxygen; mineral ions
   b. liver; oxygen; carbon dioxide
   c. bone marrow; oxygen; hormones
   d. bone marrow; oxygen; carbon dioxide
3. The _____ produces white blood cells, which function in _____ and _____.
   a. liver; oxygen transport; defense
   b. lymph glands; oxygen transport; stabilizing pH
   c. bone marrow; day-to-day housekeeping; defense
   d. bone marrow; stabilizing pH; defense
4. In the lungs, the main factor in boosting the tendency of hemoglobin to bind with and hold oxygen is _____.
   a. temperature
   b. the amount of O_2 relative to the amount of CO_2 in plasma
   c. acidity (pH)
   d. all are equally important
5. Match the blood terms with the best description.

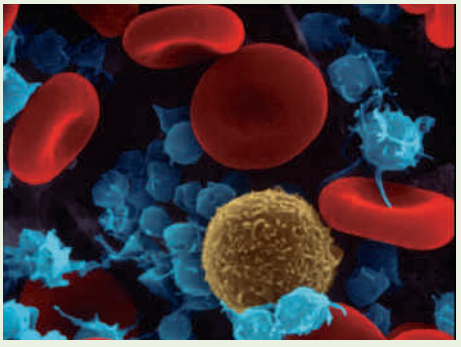
____ red blood cell	a. plug leaks
____ platelets	b. blood markers
____ stem cell	c. blood cell source
____ plasma	d. erythrocyte
____ A, B, O	e. more than half of whole blood

Critical Thinking

1. Thrombocytopenia (throm-bo-sye-tow-PEE-ne-ah) is a disorder that develops when certain drugs, bone marrow cancer, or radiation destroys red bone marrow, including stem cells that give rise to platelets. Predict a likely symptom of this disorder.
2. As the text described, when a person's red blood cell count drops, the kidneys receive less oxygen. In response they release erythropoietin, which prompts the bone marrow to make more red blood cells. As the rising number of red blood cells carry more oxygen to the kidneys, they stop releasing the hormone. What type of homeostatic control mechanism are we talking about in this case?

EXPLORE ON YOUR OWN

What is your "Blood IQ"? To find out how much you know about blood and public blood supplies, visit www.RedCross.org or www.givelife.org. Both are sponsored by the American Red Cross. At the GIVELIFE website, take the ten-question Blood IQ test and see how much you know about blood types and other issues. The websites offer information about blood, blood donation, and even current research on blood substitutes and other topics.



Immunity and Disease

9

IMPACTS, ISSUES

Frankie's Wish

IN April of 2000, life for Frankie McCullough (below, waving) was happy chaos. At 31 Frankie was an active working wife and mother. Except for some mild abdominal pain and a little vaginal spotting, she felt healthy, and way too busy to worry about minor physical discomforts. When the pain gradually got worse, she found time in her schedule for a quick visit to a gynecologist. The appointment brought a shock: Frankie had advanced cancer of the cervix, the lower part of the uterus where it joins the vagina.

The **human papillomavirus**, or **HPV**, is one cause of cervical cancer. There are about 100 strains of HPV, which infect skin and mucous membranes. "Genital" strains are found in nearly all cervical cancers. Sexual contact easily spreads the virus. An estimated 80 percent of women over 50 are infected.

A procedure called a Pap test, which is a standard part of an annual gynocological checkup, is a simple way to detect precancerous changes or early, curable cervical cancer. Another weapon against this cancer is Gardasil, a recent vaccine that works against the genital strains of HPV. Gardasil is most effective in girls who are not yet sexually active.

The vaccine came too late for Frankie McCullough, and she also did not take time for yearly gynocological checkups. Before she died in 2001, she expressed the wish that her story would raise awareness among young women of the importance of having an annual exam. She knew her message might save lives. In addition to such external defenses, several body systems also constantly work to maintain our health despite the threats from infection and other dangers. In this chapter you will see how these systems work—and some of the consequences when they fail.

KEY CONCEPTS

Body Defenses

The body has physical, chemical, and cellular defenses against disease threats. Some defenses are inborn, others are acquired as we encounter pathogens. Sections 9.1–9.4

Adaptive Immunity

White blood cells mount immune responses against specific bacteria or other pathogens. The lymphatic system plays important roles in these defense mechanisms. Sections 9.5–9.9

Faulty Defenses

Allergies, autoimmune disorders, cancer, and immune deficiencies result from faulty or failed immune mechanisms. Sections 9.10, 9.11

Patterns of Infectious Disease

Infectious diseases spread in predictable ways. Understanding these patterns is helpful in avoiding infections. Section 9.12

Disorders of the Immune System

Section 9.10

LINKS TO EARLIER CONCEPTS

- In this chapter you will see how several body systems and cells, including the skin (4.9) and white blood cells (8.1), work to fight infection. You will be using what you have learned about proteins (2.11) and the processes of endocytosis and phagocytosis (3.10).
- You will see how circulating blood (7.3) serves as a highway for defensive cells and how it interacts with the lymphatic system—the body-wide network of vessels and organs where the white blood cells called lymphocytes acquire their ability to recognize threats.

How Would You Vote?

Several states have mandated that girls be vaccinated with Garadasil to prevent cervical cancer. Typically, programs call for vaccination before age 13. Some people object, citing worries about possible side effects. Others fear that vaccination might encourage early sexual activity. Should parents be able to "opt out" of vaccination programs? See CengageNOW for details, then vote online.

9.1 Overview of Body Defenses

- **Every day we encounter a vast number of health threats. Body defenses include physical barriers and two interacting sets of cells and proteins.**
- **Links to Skin 4.9, Blood cells 8.1**

We are born with some general defenses and acquire other, specific ones

Viruses, bacteria, fungi, protozoa, and parasitic worms that cause disease are all **pathogens**. We can't really avoid pathogens. They are in the air we breathe, the food we eat, and on everything we touch. This means that our survival depends on having effective defenses against them.

You may remember from Section 8.4 that an **antigen** is something that the body identifies as nonself and that triggers an immune response. Virus particles, foreign cells, toxins, and cancer cells all have antigens on their surface. Most antigens are proteins, lipids, or the large sugar molecules called oligosaccharides.

Immunity is the body's overall ability to resist and combat something that is nonself. The responses involved in immunity all are governed by genes, and they fall into two categories. Each of us is born with some preset responses, which provide **innate immunity**. These responses are launched quickly when tissue is damaged or when the body detects general chemical signals that microbes have invaded. Certain white blood cells and proteins in blood plasma carry out innate responses.

Other immune responses develop only after the body detects antigens of specific pathogens, toxins, or abnormal body cells. These responses provide **adaptive immunity**, in which armies of specialized lymphocytes and proteins mount a counterattack against invasion. They take longer to develop, but as you will read later on, every adaptive immune response leaves behind cells that "remember" a pathogen and protect against it for a long time, perhaps even for life. Also, some versatile genetic mechanisms underlie adaptive immune responses. They can produce lymphocytes sensitive to billions of different antigens. As a result, adaptive responses can combat billions of possible threats. Table 9.1 summarizes the features of innate and adaptive immunity.

Innate and Adaptive Immunity

	Innate Immunity	Adaptive Immunity
Response time:	Immediate	Slower
How antigen is detected:	About 1,000 preset receptors	Billions of different receptors
Triggers:	Damage to tissues; proteins on microbes	Pathogens, toxins, altered body cells
Memory:	None	Long-term

Three lines of defense protect the body

Biologists often portray the protections of immunity as three "lines of defense." This approach can make it easier to remember what each "line" does, even though in fact all our defenses function as parts of a whole.

The first barrier to invasion is physical. Intact skin and the linings of body cavities and tubes effectively bar most pathogens from entering the body. We'll take a closer look at these barriers in Section 9.3.

The innate immune system is the second line of defense. It swings into action as soon as an antigen has been detected internally. The responses are general; they don't target specific intruders. Still, innate responses can wipe out many pathogens before an infection becomes established. Section 9.4 describes these countermeasures, which include inflammation. When an innate immune response gets under way, it also unleashes the third line of defense, the adaptive immune system.

White blood cells and their chemicals are the defenders in immune responses

You probably recall from Section 8.1 that stem cells in bone marrow give rise to white blood cells (WBCs). White blood cells, the core of the **immune system**, have crucial roles in both the innate and adaptive immune responses.

Several types of white blood cells are phagocytes, and all of them release chemical signals that help muster or strengthen defense responses. These chemicals include several types of **cytokines**, "cell movers" that promote and regulate many aspects of immunity (Table 9.2). Examples are **interleukins**, which cause inflammation and fever and also stimulate the activity of various kinds of white blood cells. **Interferons** help defend against viruses and activate certain lymphocytes. **Tumor necrosis factor** ("necrosis" means death) triggers inflammation and kills tumor cells. Some white blood cells also secrete enzymes and toxins that kill microbes.

Another chemical weapon is a set of proteins called the **complement system**. There are about 30 complement proteins. They are carried in the blood and can kill microbes or flag them for phagocytes such as macrophages, which then engulf and destroy the invader.

Many white blood cells also circulate in the blood as well as in lymph, a pale fluid that circulates in vessels of the lymphatic system. As you will read in the following

Chemical Weapons of Immunity	
Complement	Directly kills cells; stimulates lymphocytes
Cytokines	Cell–cell and cell–tissue communication:
Interleukins	Cause inflammation and fever, cause T cells and B cells to divide and specialize; stimulate bone marrow stem cells, attract phagocytes, activate NK cells
Interferons	Confer resistance to viruses; activate NK cells
Tumor Necrosis Factor	Causes inflammation; kills tumor cells, causes T cells to accumulate in lymph nodes during infection
Other Chemicals	Various antimicrobial and defensive effects
	Enzymes and peptides; clotting factors; protease inhibitors; toxins; hormones

section, this system, which has major rroles in defense, works with the cardiovascular system in moving many substances throughout the body.

Figure 9.1 gives a visual summary of white blood cells. About two-thirds of our WBCs are **neutrophils**. They follow chemical trails to infected, inflamed, or damaged tissues. **Basophils** that circulate in blood and **mast cells** in tissues release enzymes and chemicals called histamines when they detect an antigen. **Macrophages** are phagocytes that patrol the bloodstream; each of these "big eaters" can engulf as many as one hundred bacteria! **Eosinophils** target worms, fungi, and other pathogens that are too big for phagocytosis. **Dendritic cells** alert the adaptive immune system when an antigen is present in tissue fluid in the skin and body linings. The cells known as **B** and **T lymphocytes**—or simply B and T cells—have the most important roles in adaptive immunity. They are the only defensive cells that have receptors for specific antigens. **Natural killer cells** (NK cells) also are lymphocytes. Their most important role is destroying cancer cells and cells that have been infected by a virus.

Take-Home Message

What are the three lines of body defenses?

- The body's three lines of defense are physical barriers, innate immunity, and adaptive immunity.
- Immune responses are executed by white blood cells and the chemicals they release.

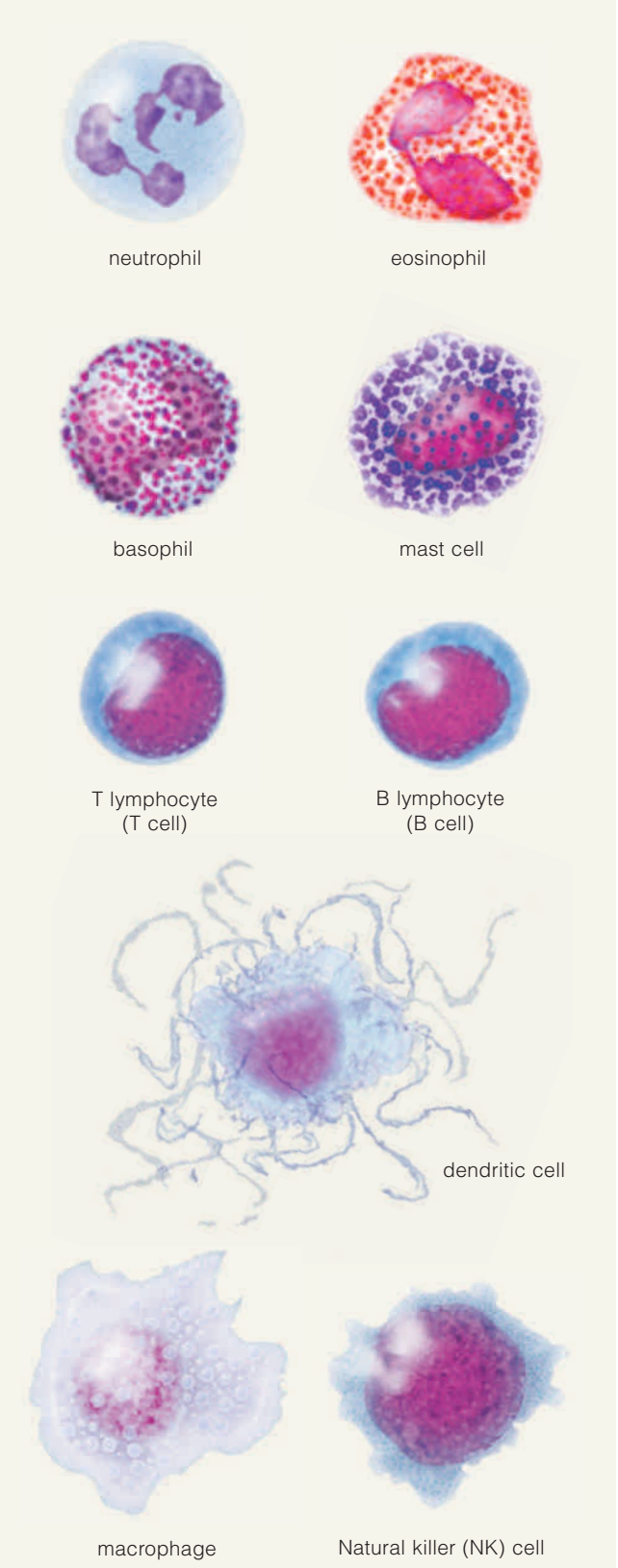


Figure 9.1 Animated! White blood cells, including lymphocytes, carry out immune responses.

9.2 The Lymphatic System

■ Link to Blood vessel function 7.6

As you've just read, the **lymphatic system** does several things in the body. It works with the cardiovascular system by picking up fluid that is lost from capillaries and returning it to the bloodstream. The lymphatic system's other key task is defense. As sketched in Figure 9.2, the system consists of drainage vessels, **lymphoid organs** such as the spleen and lymph nodes, and lymphoid tissues. The tissue fluid that has moved into lymph vessels is aptly called **lymph**.

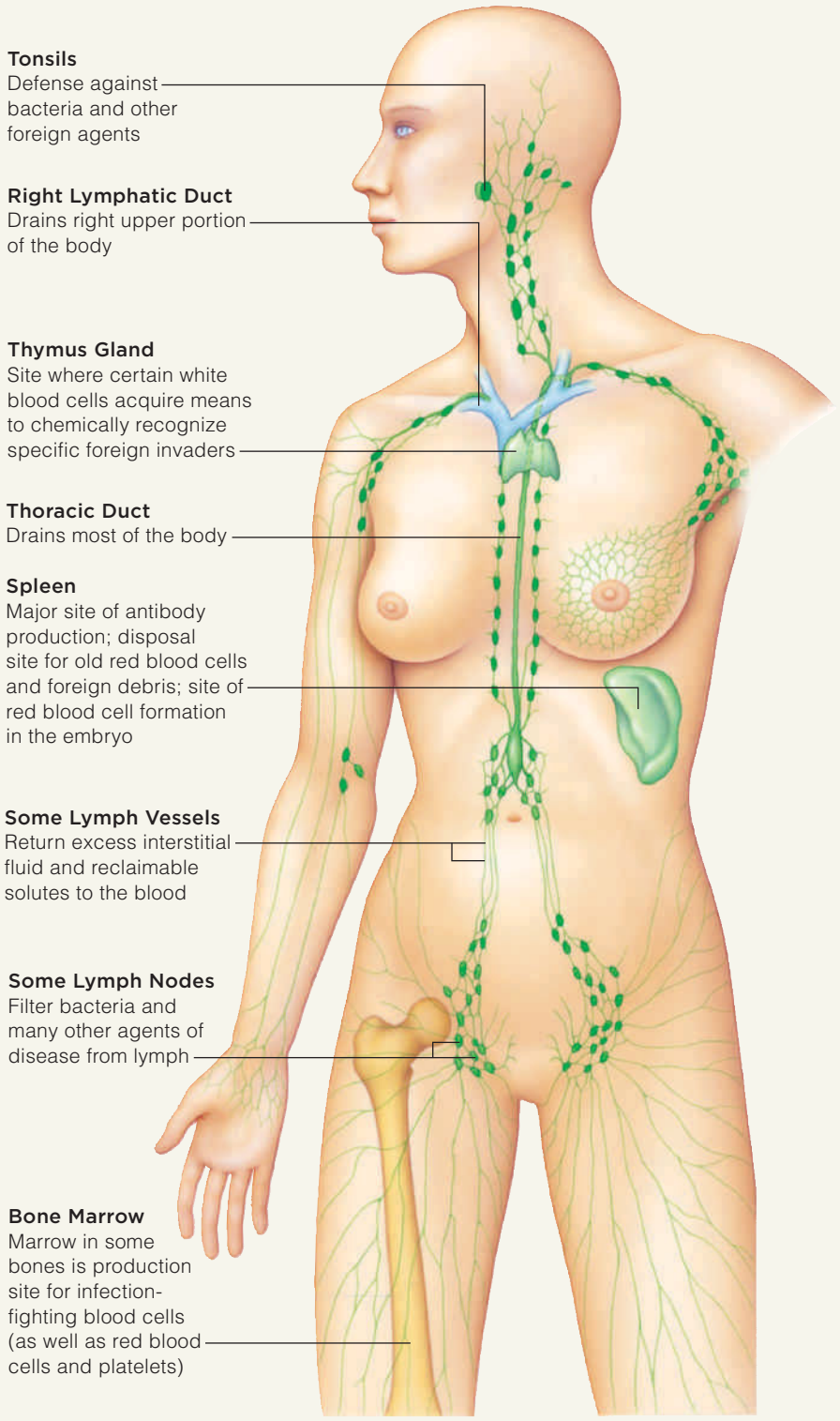


Figure 9.2 Animated! The lymphatic system collects fluid and functions in defense. The small green ovals show where some of the major lymph nodes are located. The system also includes patches of lymphoid tissue in the small intestine and in the appendix.

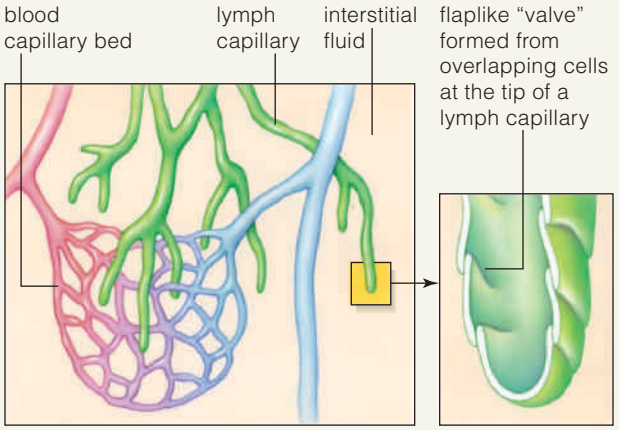
The lymph vascular system functions in drainage, delivery, and disposal

The **lymph vascular system** consists of lymph capillaries and other vessels that collect water and dissolved substances from tissue fluid and transport them to ducts of the cardiovascular system. The lymph vascular system has three functions, which we could call the "three Ds"—drainage, delivery, and disposal.

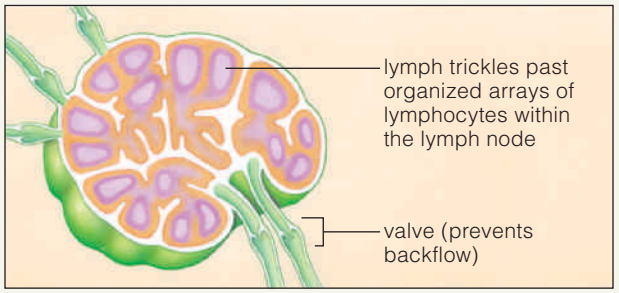
To begin with, the system's vessels are drainage channels. They collect water and solutes that have leaked out of the blood in capillary beds (due to fluid pressure there) and return those substances to the bloodstream. The system also picks up fats that the body has absorbed from the small intestine and delivers them to the bloodstream. Finally, lymphatic vessels transport foreign material and cellular debris from body tissues to the lymph vascular system's disposal centers, the lymph nodes.

The lymph vascular system starts at capillary beds (Figure 9.3*a*), where fluid enters the lymph capillaries. These capillaries don't have an obvious entrance. Instead, water and solutes move into their tips at flaplike "valves." These are areas where endothelial cells overlap (see Figure 7.12*c*).

Lymph capillaries merge into larger lymph vessels. Like veins, these vessels have smooth muscle in their walls and valves that prevent backflow. They converge into collecting ducts that drain into veins in the lower neck. This is how the lymph fluid is returned to circulating blood. Movements of skeletal muscles and of the rib cage (during breathing) help move fluid through the lymph vessels, just as they do for veins.



a Lymph capillaries



b A lymph node, cross section

Figure 9.3 Animated! Lymph capillaries collect fluid and direct it through lymph nodes. (**a**) Lymph capillaries at the start of the drainage network called the lymph vascular system. (**b**) Cutaway diagram of a lymph node. Its inner chambers are packed with infection-fighting white blood cells.

Lymphoid organs and lymphatic tissues are specialized for body defense

Several elements of the lymphatic system operate in body defenses. These parts include the lymph nodes, the spleen, and the thymus. They also include the tonsils and patches of tissue in the small intestine, in the appendix, and in airways leading to the lungs.

The **lymph nodes** are strategically located at intervals along lymph vessels (Figures 9.2 and 9.3*b*). Before lymph enters the bloodstream, it trickles through at least one of these nodes. A lymph node has several chambers where white blood cells accumulate after they have been produced in bone marrow. During an infection, lymph nodes become battlegrounds where armies of lymphocytes form and where foreign agents are destroyed. Macrophages in the nodes help clear the lymph of bacteria and other unwanted substances.

The **spleen** is the lymphatic system's largest organ. It filters blood and also serves as a holding station for lymphocytes. The spleen has inner chambers filled with soft red and white tissue called "pulp." The red pulp is a storage reservoir of red blood cells and macrophages. (In a developing embryo, the spleen produces red blood cells.) In the white pulp, masses of lymphocytes are arrayed close to blood vessels. If an invader reaches the spleen during an infection, the lymphocytes are mobilized to destroy it, just as in lymph nodes.

The **thymus** is where T cells multiply and become specialized to combat specific foreign antigens. You will soon be learning more about how these cells function.

Take-Home Message

What are the functions of the lymphatic system?

- The lymphatic system includes lymph vessels that carry tissue fluid to the blood, transport fats, and carry debris and foreign material to lymph nodes.
- Lymph nodes, the spleen, and the thymus all function in body defenses.

9.3 Surface Barriers

- **Pathogens usually cannot get past the skin or the linings of other body surfaces such as the digestive tract.**
- **Links to Tissue membranes 4.7, Skin 4.9**

Even if you showered today, there are probably thousands of microorganisms on every square inch of your skin. They usually are harmless as long as they stay outside the body. Some types grow so densely that they help prevent more harmful species from gaining a foothold (Figure 9.4).

Normally "friendly" bacteria in the mucosal lining of the digestive tract also help protect you. In females, lactate produced by *Lactobacillus* bacteria in the vaginal mucosa helps maintain a low vaginal pH that most bacteria and fungi cannot tolerate. Any change in the conditions in which these organisms grow can cause an infection. For example, some antibiotics used to cure bacterial infections can trigger a vaginal yeast infection because the drug also kills *Lactobacillus*. The fungus that causes *athlete's foot* may begin to grow between your toes if the skin there is often moist and warm.

The inner walls of the respiratory airways leading to your lungs are coated with sticky mucus. That mucus contains protective substances such as **lysozyme**, an enzyme that chemically attacks and helps destroy many bacteria. Broomlike cilia in the airways sweep out the pathogens.

Lysozyme and some other chemicals in tears, saliva, and gastric fluid offer more protection. Urine's low pH and flushing action help bar pathogens from the urinary tract. In adults, mild diarrhea can rid the lower GI tract of irritating pathogens. (In children, however, diarrhea must be controlled to prevent dangerous dehydration.)

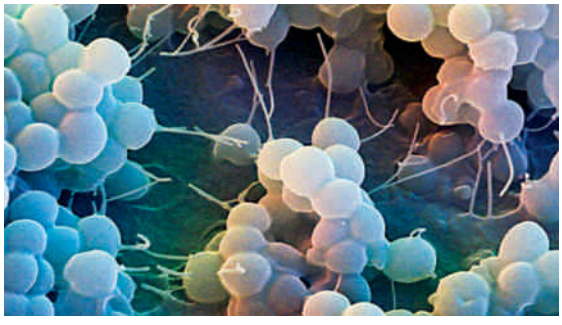


Figure 9.4 Many types of bacteria live on body surfaces. This image shows *Staphylococcus epidermis*, the most common species of bacterium on human skin.

Take-Home Message

What are the surface barriers to infection?

- Intact skin, mucous membranes, lysozyme, and other physical barriers all help prevent pathogens from infecting the internal environment of the body.

9.4 Innate Immunity

- **Phagocytosis, inflammation, and fever are the body's "off-the-shelf" mechanisms that act at once to counter threats in general and prevent infection.**
- **Links to Cells 3.1, Homeostasis 4.10, Blood cells 8.1**

If a pathogen manages to enter the body, macrophages in tissue fluid are usually the first defenders on the scene. They engulf and destroy virtually anything other than undamaged body cells. If they detect an antigen, they release cytokines—chemical signals that attract dendritic cells, neutrophils, and more macrophages.

Complement proteins are another important aspect of innate immunity. As they circulate in blood and tissue fluid, they can chemically detect pathogens. The encounter activates a complement protein, which then activates more, and so on. The cascade of reactions quickly floods a damaged area with complement molecules.

Activated complement molecules attract phagocytes, such as macrophages and neutrophils, to damaged tissues. They also attach themselves to invaders. Phagocytes have receptors that bind to the complement proteins. An invader that is coated with complement molecules sticks to the phagocyte, which ingests and kills it. Some complement proteins form **membrane attack complexes** (Figure 9.5). When an attack complex is inserted into the plasma membrane of a pathogen, it forms a pore—that is, a hole—in the membrane and the punctured cell quickly disintegrates.

Activated complement and cytokines secreted by macrophages both trigger acute (sudden) **inflammation**,

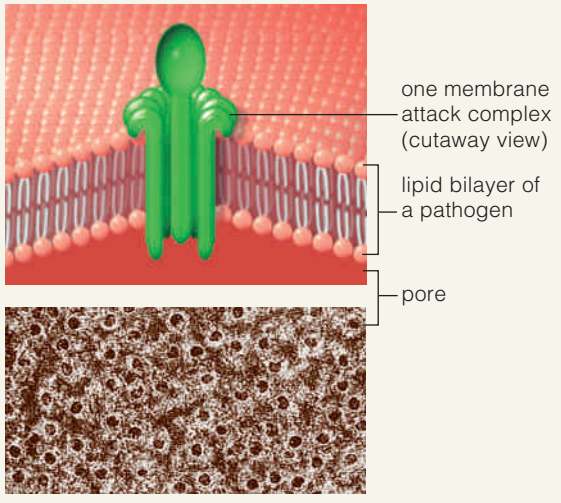


Figure 9.5 Animated! Membrane attack complexes can form holes in the plasma membrane of bacteria. The damaged cell then dies.

a fast, local, general response to tissue invasion (Figure 9.6). Symptoms of inflammation are redness, swelling, warmth, and pain, all caused by a series of internal events.

First, mast cells in tissues respond to complement proteins or to an antigen by releasing histamines and cytokines into tissue fluid. Histamines make arterioles in the tissue dilate. As a result, more blood flows through them and the tissue reddens and warms with blood-borne metabolic heat.

Histamine also makes capillaries leaky. The narrow gaps between the cells of the capillary wall become a bit wider, so plasma proteins and phagocytes slip out through them (Figure 9.7). Water flows out as well. As a result of these and other changes, the tissue balloons with fluid. This swelling is called *edema*. The pain that comes with inflammation is due to edema and the effects of inflammatory chemicals.

The plasma proteins leaking into tissue fluid include factors that cause blood to clot. Clots can wall off inflamed areas and delay the spread of microbes into nearby tissues.

A **fever** is a core body temperature above the normal 37°C (98.6°F). Fever develops when cytokines released by macrophages stimulate the brain to release prostaglandins. These signaling molecules can raise the set point on the hypothalamic thermostat, which controls core temperature.

Fevers are not usually harmful. A fever of about 39°C (100°F) is actually helpful. Among other benefits, it increases body temperature to a level that is too hot for many pathogens to function normally.

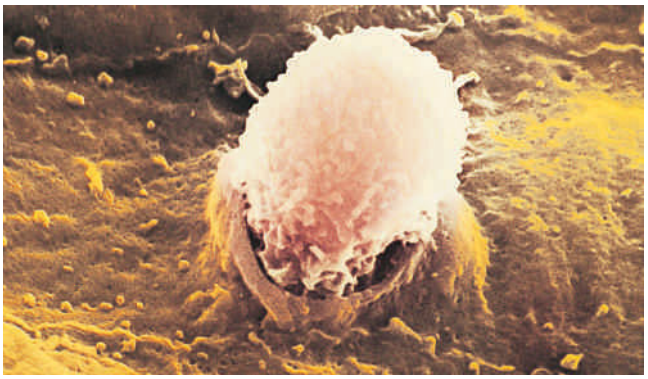


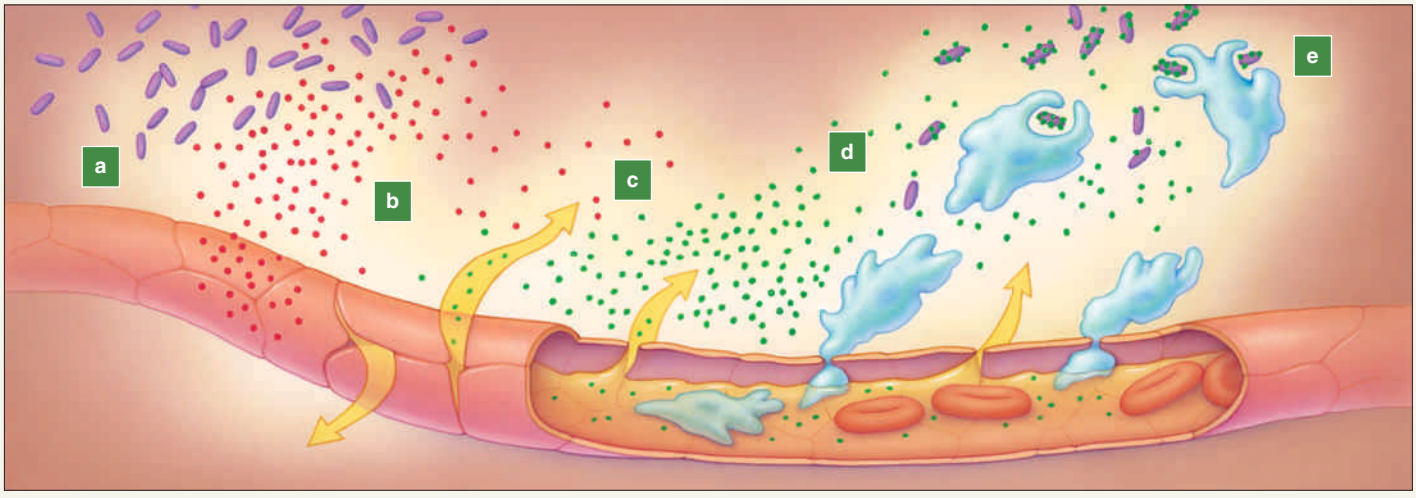
Figure 9.7 A white blood cell can squeeze through the wall of a capillary.

Phagocytosis, inflammation, and fever rid the body of most pathogens before they do major harm. If an infection does take hold, the adaptive immune system takes over. Three defenders we have been discussing—dendritic cells, macrophages, and complement proteins—also take part in adaptive immunity, the topic we turn to next.

Take-Home Message

What are the "weapons" of innate immunity?

- Phagocytes (such as macrophages), inflammation, and fever are the body's "first strike" weapons against infection. They are the tools of innate immunity, which is a general response to health challenges by pathogens.



A Bacteria invade a tissue and directly kill cells or release metabolic products that damage tissue.

B Mast cells in tissue release histamine, which then triggers arteriolar vasodilation (hence redness and warmth) as well as increased capillary permeability.

C Fluid and plasma proteins leak out of capillaries; localized edema (tissue swelling) and pain result.

D Plasma proteins attack bacteria. Clotting factors wall off inflamed area.

E Neutrophils, macrophages, and other phagocytes engulf invaders and debris. Activated complement attracts phagocytes and directly kills invaders.

Figure 9.6 Animated! Acute inflammation is a general response to tissue damage. This diagram illustrates how invading bacteria might trigger inflammation. In addition to combating the attack, the process helps prepare the damaged tissue for repair.

9.5 Overview of Adaptive Defenses

- **When physical barriers and inflammation don't prevent an invasion, the adaptive immune system is mobilized.**
- **Links to White blood cells 8.1, Self markers 8.4**

Adaptive immunity has three key features

Adaptive immunity is the body's third line of defense. It mobilizes B and T cells, which attack foreign intruders they recognize as antigens. The three defining feaures of adaptive immunity are:

1. **Specificity:** Each B or T cell makes receptors for only one kind of antigen.
2. **Diversity:** B and T cells collectively may have receptors for at least a billion different specific threats.
3. **Memory:** Some of the B and T cells formed during a first response to an invader are held in reserve for future battles with it.

When a B cell or T cell recognizes an antigen, the meeting stimulates round after round of cell division. In the end, a huge number of identical T cells or B cells form. Each one of them can now counterattack the pathogen.

All the new cells produced by dividing B or T cells are sensitive to the same antigen. Some become **effector cells** that can immediately begin destroying the enemy, while others become **memory cells** (Figure 9.8). Instead of joining the first battle, memory cells are set aside. If the threat returns, they mount a larger, faster response to it. Memory cells are what make you "immune" to a given cold or flu virus once you have recovered from the first infection.

B cells and T cells attack invaders in different ways

You will recall that lymphocytes arise from stem cells in bone marrow. Cells that are destined to specialize as B cells continue developing in bone marrow, but cells that will specialize as T cells travel via the blood to the thymus gland. As they complete their development, they split into two groups—**helper T cells** and effector cells known as **cytotoxic** ("killer") **T cells**.

When B and T cells are mature, most move into lymph nodes, the spleen, and other lymphoid tissues. Some B and T cells are said to be "naive" until they are activated. Like a defensive light bulb blinking on, this activation happens when the cell recognizes an antigen.

When B cells and T cells identify intruders, they attack in different ways. Instead of directly engaging a pathogen, B cells produce defensive proteins called **antibodies**. For this reason their response is called **antibody-mediated immunity**. By contrast, cytotoxic T cells do attack invaders directly, so the T cell response is called **cell-mediated immunity** (Figures 9.9 and 9.10). Helper T cells help launch both responses, and we consider them both in more detail later. For the moment we will complete this overview with a closer look at how T and B cells "learn" they have encountered an antigen.

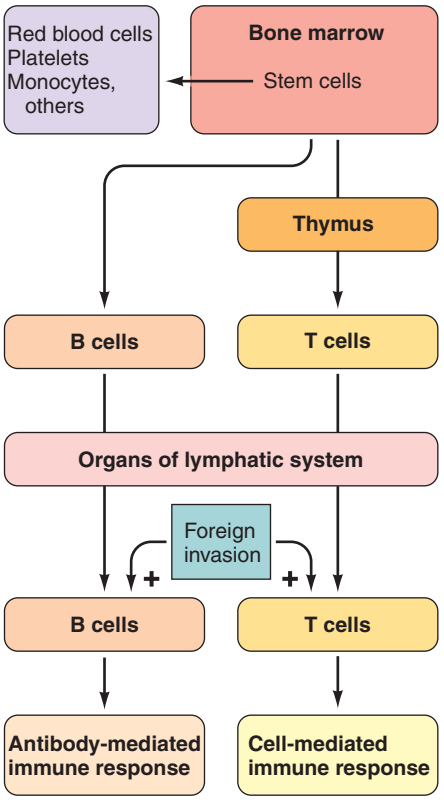


Figure 9.9 **A "life history" of B cells and T cells.**

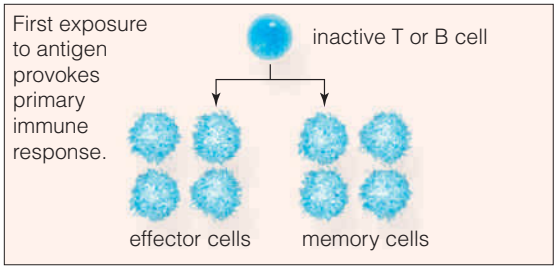


Figure 9.8 **Activated lymphocytes produce effector cells and memory cells.**

MHC markers label body cells as self

Chapter 8 described the APO self markers on red blood cells. All body cells also have **MHC markers**. These self markers—named after the genes that code for them (*M*ajor *H*istocompatibility *C*omplex genes)—are some of the proteins that stick out above the plasma membrane of body cells. T cells have receptors that recognize MHC markers and other self tags on body cells. Part of the receptor also can recognize a particular antigen, so the antigen can be linked up with an MHC marker. As it turns out, this is a key step in starting specific immune responses, as you will read in Section 9.6.

Antigen-presenting cells introduce antigens to T cells and B cells

T cells and B cells can't detect an enemy by themselves. They must meet the threat after it has been "processed" by an **antigen-presenting cell**, an APC. The adaptive immune system allows plenty of opportunities for this to happen, for macrophages, dendritic cells, and B cells all can present antigens. To begin the process, the APC engulfs something bearing an antigen (Figure 9.11*a*). Then enzymes (made by the APC's lysosomes) break the antigen into pieces. Some of the fragments are joined with MHC markers inside the cell. These antigen–MHC complexes move to the plasma membrane and are displayed like "come and get me" flags at the cell's surface.

When a helper T cell binds to an antigen–MHC complex, it releases cytokines. These chemicals trigger the repeated rounds of division that produce huge armies of activated B or T cells. They also stimulate activated B and T cells to form specialized subgroups of effector and memory cells.

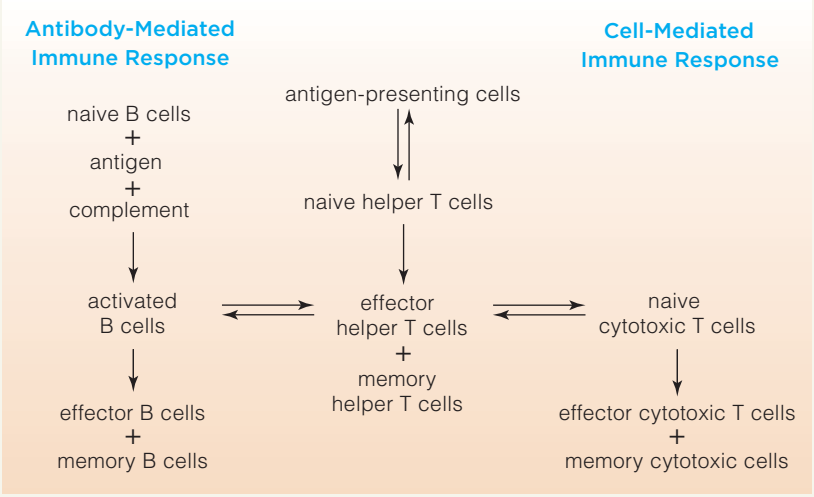
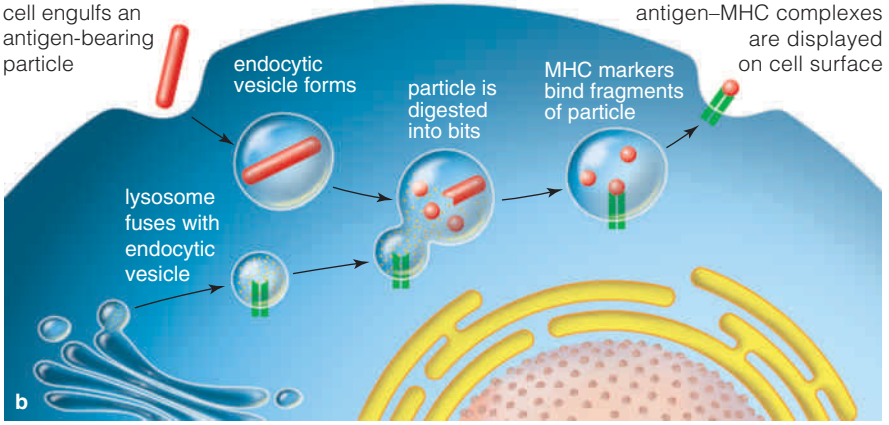


Figure 9.10 Animated! The two arms of adaptive immunity are the antibody-mediated response and the cell-mediated response.

Figure 9.11 B and T cells can recognize antigens that are presented to them.

(**a**) A macrophage engulfs a foreign cell. Macrophages, B cells, and dendritic cells all can present antigens.



(**b**) This diagram shows how an antigen-presenting cell forms an antigen-MHC complex—the chemical flag that can launch an immune response by lymphocytes.

Take-Home Message

What are adaptive immune responses?

- Adaptive immune responses are carried out mainly by T and B cells.
- Adaptive responses are specific and amazingly diverse. They also produce memory cells that can mount a faster, stronger response to an antigen that enters the body again.
- Macrophages, dendritic cells, and B cells can serve as antigen-presenting cells, which expose T and B cells to processed antigens they can recognize.
- Cytokines from helper T cells stimulate activated T and B cells to multiply and produce armies of effector cells (helper T cells, cytotoxic T cells, and B cells that make antibodies).

9.6 Antibody-Mediated Immunity: Defending against Threats Outside Cells

- **Different kinds of antibodies have roles in body defenses.**
- **Link to Endocytosis 3.11**

Antibodies develop while B cells are in bone marrow

While a B cell is in bone marrow, it develops antibodies. Figure 9.12 shows the typical Y shape of a simple one. The place where an antibody can bind an antigen usually is near the tip of the two "arms," and its shape and other characteristics are determined by genes. The genetic mechanisms involved ensure that no two B cells will make antibodies that are alike. This is the source of the diversity and specificity of antibody-mediated immunity.

As a B cell matures, it makes copies of its antibodies that become embedded in its plasma membrane so that the two arms stick out. Before long the B cell bristles with antibodies. Each one can bind to just one kind of antigen.

Antibodies target pathogens that are outside cells

Antibodies can't enter cells and bind to enemies hidden there. Instead, antibodies target pathogens and toxins that are circulating in tissues or body fluids.

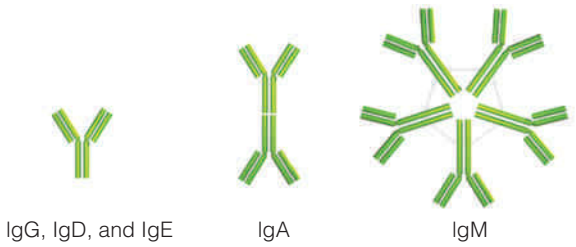
Let's follow a B cell that has made its antibodies but that is not yet activated. In this state, a B cell can function as an antigen-presenting cell. When an antigen binds with some of the B cell's antibodies, it links them together. This linking triggers endocytosis, which moves the antigen into the cell. There, antigen–MHC complexes form and are displayed at the B cell surface.

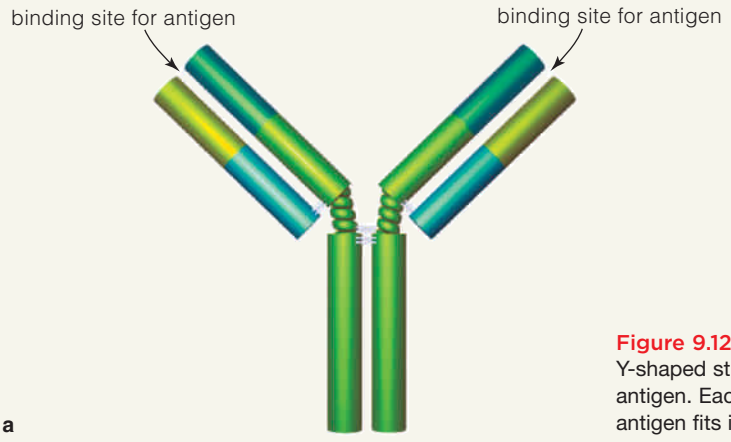
When receptors of a responding helper T cell bind to the antigen–MHC complex, the T and B cells exchange signals. Then they disengage. This step activates the B cell. Now when the B cell meets an antigen that is *not* part of a complex, the B cell's antibodies bind to it. The binding helps spur the B cell to divide; a boost comes from cytokines secreted from nearby helper T cells. The B cell's descendants become specialized as effectors called **plasma cells** or as memory B cells (Figure 9.13).

The plasma cells release huge numbers of antibodies in the bloodstream—up to 2,000 of them each minute. When any of these antibodies binds to an antigen, it flags the invader for destruction by phagocytes and complement proteins. The memory B cells do not engage in battle but are available to respond rapidly to the antigen if it attacks the body another time (Section 9.8).

There are five classes of antibodies, each with a particular function

B cells produce five classes of antibodies. Collectively they are called **immunoglobulins**, or Igs. They are the proteins that result from the gene shuffling that takes place while B cells mature and while an immune response is under way. We abbreviate them as IgM, IgD, IgG, IgA, and IgE. Each type has antigen-binding sites and other sites with special roles. When B cells secrete immunoglobulins, they have roughly these shapes:





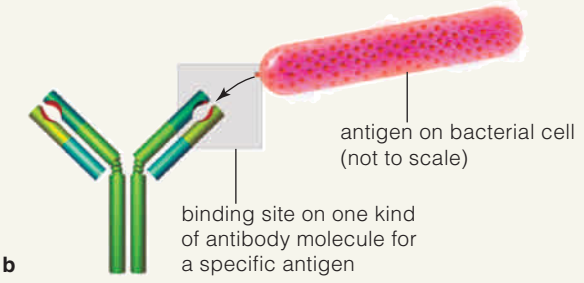


Figure 9.12 **Animated! Antibodies can bind to antigens.** (**a**) The Y-shaped structure of many antibodies. (**b**) How an antibody binds to an antigen. Each kind of antibody can bind only one kind of antigen. The antigen fits into grooves and bumps on the antibody molecules.

A The B cell receptors on an inactive (naive) B cell bind to the antigen on a bacterium. Then the B cell engulfs it. Fragments of the bacterium bind MHC markers, and the complexes are displayed at the surface of the now-activated B cell.

B A dendritic cell engulfs the same kind of bacterium that the B cell encountered. Digested fragments of the bacterium bind to MHC markers, and the complexes are displayed at the dendritic cell's surface. The dendritic cell is now an antigen-presenting cell.

C The antigen–MHC complexes on the antigen-presenting cell are recognized by antigen receptors on an inactive T cell. The T cell now divides and gives rise to effector and memory helper T cells.

D Antigen receptors of one of the effector helper T cells bind antigen–MHC complexes on the B cell. Binding makes the T cell secrete cytokines.

E The cytokines stimulate the B cell to divide, giving rise to many identical B cells. The cells give rise to effector B cells and memory B cells.

F The effector B cells begin making and secreting huge numbers of IgA, IgG, or IgE, all of which recognize the same antigen as the original B cell receptor. The new antibodies circulate throughout the body and bind to any remaining bacteria.

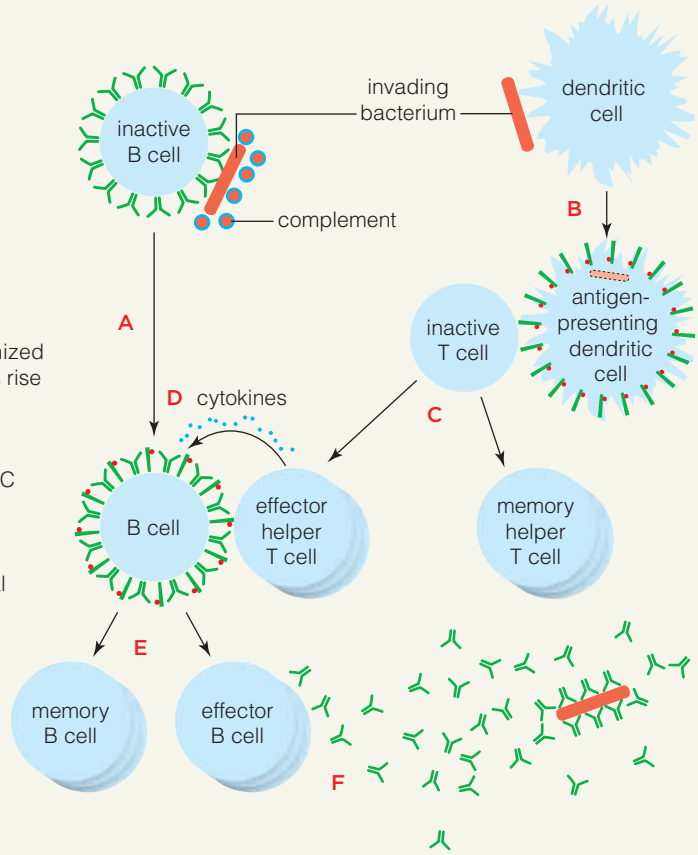


Figure 9.13 Animated! **An antibody-mediated immune response occurs when B cells make antibodies to a foreign antigen.** In this example, the invader is a bacterium.

IgM is the first antibody secreted during immune responses and the first one produced by newborns. IgM molecules cluster into a structure with ten antigen-binding sites. This makes it more efficient at binding clumped targets, such as agglutinating red blood cells (Section 8.4) and clumps of virus particles.

Along with IgM, *IgD* is the most common antibody bound to inactive B cells. It may help activate helper T cells.

IgG makes up about 80 percent of the antibodies in your blood. It's the most efficient one at turning on complement proteins, and it neutralizes many toxins. This long-lasting antibody easily crosses the placenta. It helps protect the developing fetus with the mother's acquired immunities. IgG secreted into early milk is also absorbed into a suckling newborn's bloodstream.

IgA is the main immunoglobulin in the secretions of exocrine glands, such as tears, saliva, and breast milk. It also is in mucus that coats the respiratory, digestive, and reproductive tracts—areas to which microbes have easy access. Bacteria and viruses can't attach to the cells of mucous membranes when IgA is bound to them. In this way, IgA is effective in fighting the pathogens that cause salmonella, cholera, gonorrhea, influenza, and polio.

The *IgE* antibody is involved in allergic reactions, including asthma, hay fever, and hives. IgE also triggers inflammation after attacks by parasitic worms and other pathogens. When it binds to an antigen, basophils and mast cells release histamine, a chemical that promotes inflammation.

Take-Home Message

What are antibodies and how do they help defend body tissues?

- B cells secrete five classes of antibodies (immunoglobulins) that help protect the body against diverse threats.
- Antibodies bind to antigens of pathogens or toxins that are outside cells and flag them for destruction by other defenders.

9.7 Cell-Mediated Responses: Defending against Threats Inside Cells

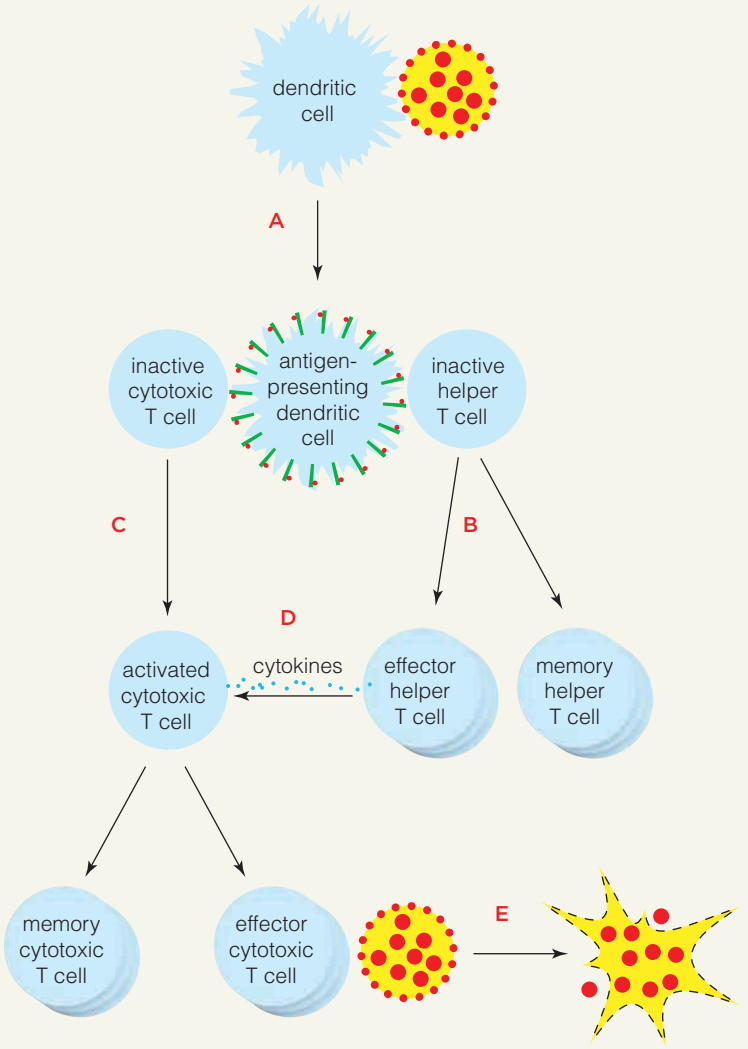
- **Responses by antibodies can't reach threats inside cells. Accordingly, when cells become infected or altered in harmful ways, other "warrior" cells must come to the defense.**
- **Link to Blood types 8.4**

Many pathogens evade antibodies. They hide in body cells, kill them, and often reproduce inside them. They are exposed only briefly after they slip out of one cell and before they infect others. Viruses, bacteria, and some fungi and protozoans all can enter cells. Cell-mediated immune responses are the body's weapons against these dangers as well as abnormal body cells such as cancer cells.

Figure 9.14 gives an overview of how a cell-mediated immune response takes place. Like an antibody-mediated response, it gets under way when an APC such as a dendritic cell presents an antigen to T cells. The response also produces memory T cells.

Some of the warriors in cell-mediated immunity are helper T cells and cytotoxic T cells, which respond to particular antigens. Others, including NK cells and macrophages, make more general responses.

Helper T cell cytokines stimulate NK cells. These killer cells don't need to have an antigen presented to them. Instead, they simply attack any body cell that has too few or altered MHC markers, or that antibodies have tagged



A A dendritic cell engulfs a virus-infected cell. Digested fragments of the virus bind to MHC markers, and the complexes are displayed at the dendritic cell's surface. The dendritic cell, now an antigen-presenting cell, migrates to a lymph node.

B Receptors on an inactive helper T cell bind to antigen–MHC complexes on the dendritic cell. This activates the helper T cell, which then begins to divide. Effector and memory cells form. All have T cell receptors that recognize the same antigen.

C Receptors on an inactive cytotoxic T cell bind to the antigen–MHC complexes on the surface of the dendritic cell. This activates the cytotoxic T cell.

D The activated cytotoxic T cell recognizes cytokines secreted by the effector helper T cells as signals to divide. Effector and memory cells form. All have T cell receptors that recognize the same antigen.

E The new cytotoxic T cells circulate through the body. They recognize and touch-kill any body cell that displays the viral antigen–MHC complexes on its surface.

Figure 9.14 Animated! T cells are the warriors in cell-mediated immune responses.

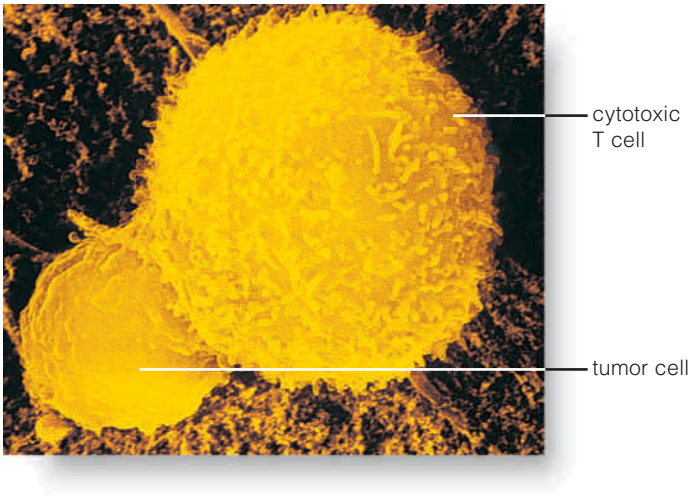


Figure 9.15 **This image shows a cytotoxic T cell touch-killing a tumor cell.**

Figure 9.16 **Kelly Perkins, a mountaineering heart transplant patient, received her donor heart in 1995.** She has written a best-selling book about her experience.

for destruction. They also kill body cells flagged with chemical "stress markers" that develop when a cell is infected or has become cancerous.

Cytotoxic T cells are so sensitive to antigen–MHC complexes and altered body cells that they don't need further signals to start multiplying. They release molecules that can touch-kill infected and abnormal body cells (Figure 9.15). Cytotoxic cells also secrete chemicals that cause the genetically programmed death of a target cell. This programmed cell death is called **apoptosis** (a-poh-TOE-sys). The term comes from a Greek word meaning to fall apart, and that's what happens to the cell. Its cytoplasm dribbles out and its DNA and organelles are broken up. After a cytotoxic T cell makes its lethal hit, it disengages from the doomed cell and moves on.

Cytotoxic T cells cause the body to reject transplanted tissue

Cytotoxic T cells cause the rejection of tissue and organ transplants. This is partly because features of the MHC markers on donor cells differ enough from the recipient's to be recognized as antigens.

To help prevent rejection, before an organ is transplanted the MHC markers of a potential donor are analyzed to determine how closely they match those of the patient. Because such tissue grafts generally succeed only when the donor and recipient share at least 75 percent of their MHC markers, the best donor is a close relative of the recipient, such as a parent or sibling, who is likely to have a similar genetic makeup.

More commonly, however, the donated organ comes from a fresh cadaver. In addition to having well-matched MHC markers, the donor and recipient also must have compatible blood types (Section 8.4).

After surgery, the organ recipient receives drugs that suppress the immune system. The treatment also may include other therapies designed to fend off an attack by B and T cells. Suppression of the immune system means that the patient must take large doses of antibiotics to control infections. In spite of the difficulties, many organ recipients survive for years beyond the surgery and lead highly active lives (Figure 9.16).

Interestingly, not all transplanted tissues provoke a recipient's immune defenses. Two examples are tissues of the eye and the testicles. In simple terms, the plasma membrane of cells of these organs is thought to bear receptors that can detect activated lymphocytes. Before such a defender can launch an attack, the protein signals the soon-to-be-besieged cell to secrete a chemical that triggers apoptosis in the approaching lymphocytes—so the attack is averted. Our ability to readily transplant the cornea—the outermost layer of the eye that is vital to clear vision—depends on this mechanism.

Take-Home Message

How does a cell-mediated immune response fight infection?

- Cell-mediated immune responses are mounted against infected or altered body cells.
- Helper T cells and cytotoxic T cells target antigens. NK cells, macrophages, and various other white blood cells make nonspecific responses.

9.8 Immunological Memory

- **The memory cells produced during an adaptive immune response can provide many years of immunity to a pathogen.**

Memory cells that form during a primary (first) immune response circulate in the blood for years, even decades. Compared to the B and T cells that initiate a primary response, these patrolling battalions have many more cell "soldiers," so they intercept antigens far sooner. Plasma cells and effector T cells form sooner, in greater numbers, so the infection is ended before the host—you—gets sick (Figure 9.17). Even more memory T and plasma cells form during a secondary adaptive response.

The kinds of memory T and plasma cells in the body are determined by the antigens you are exposed to. That is why people generally are not immune to a bacterium or virus that is not in their usual surroundings. A common example of this phenomenon is vacationers who get "traveler's diarrhea" when they drink "foreign" water, even though the local people drink the same water and do not get sick.

Take-Home Message

What are the surface barriers to infection?

- Memory cells enable the adaptive immune system to make a faster, more powerful secondary response to another encounter with a pathogen.

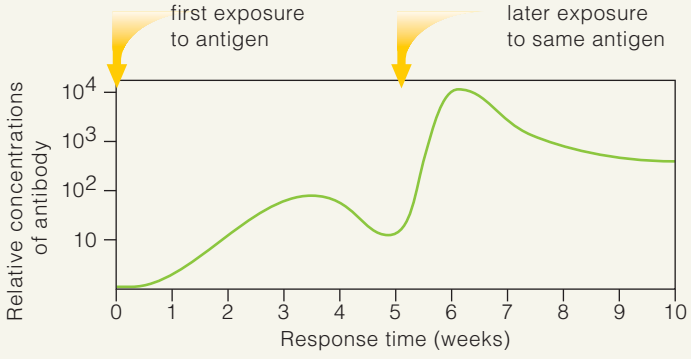


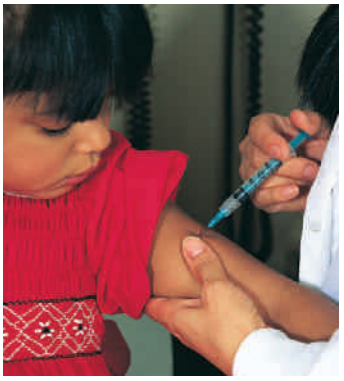
Figure 9.17 Animated! Memory cells allow the body to mount a faster, stronger secondary immune response. The graph tracks a primary and secondary immune response.

9.9 Applications of Immunology

- **Modern science has developed powerful weapons that can enhance the immune system's functioning or harness it in new ways to treat disease.**

Immunization gives "borrowed" immunity

Immunization is a way to increase immunity against specific diseases. In active immunization, a vaccine is injected into the body or taken orally, sometimes according to a schedule (Table 9.3). A **vaccine** is a prepared substance that contains an antigen. The first injection elicits a primary immune response. A "booster shot" given later elicits a secondary response, in which more effector cells and memory cells form and can provide long-lasting disease protection.



Recommended Immunization Schedule for Children

Vaccine	Age of Vaccination
Hepatitis B	Birth to 2 months
Hepatitis B boosters	1–4 months and 6–18 months
Rotavirus	2, 4, and 6 months
DTP: diphtheria, tetanus, and pertussis (whooping cough)	2, 4, and 6 months
DTP boosters	15–18 months, 4–6 years, and 11–12 years
HiB (*Haemophilus influenzae*)	2, 4, and 6 months
HiB booster	12–15 months
Pneumococcal	2, 4, and 6 months
Pneumococcal booster	12–15 months
Inactivated poliovirus	2 and 4 months
Inactivated poliovirus boosters	6–18 months and 4–6 years
Influenza	Yearly, 1–18 years
MMR (measles, mumps, rubella)	12–15 months
MMR booster	4–6 years
Varicella (chicken pox)	12–15 months
Varicella booster	4–6 years
Hepatitis A series	1–2 years
Human papillomavirus	11–12 years
Meningococcal	11–12 years

Source: Centers for Disease Control (CDC), 2007

Many vaccines are made from killed or extremely weakened pathogens. For example, weakened poliovirus particles are used for the Sabin polio vaccine. Other vaccines are based on inactivated forms of natural toxins, such as the bacterial toxin that causes tetanus. Today many vaccines are made with genetically engineered viruses (Chapter 21). These harmless "transgenic" viruses incorporate genes from three or more different viruses in their genetic material. After a person is vaccinated with an engineered virus, body cells use the new genes to produce antigens, and immunity is established.

Passive immunization often helps people who are already infected with pathogens, such as those that cause tetanus, measles, hepatitis B, and rabies. A person receives injections of antibodies that have been purified from another source, preferably someone who already has produced a large amount of the antibody. The effects don't last long because the recipient's own B cells are not producing antibodies. However, the injected antibodies may counter the immediate attack.

Vaccines are powerful weapons, but they can fail or have adverse effects. In rare cases, a vaccine can damage the nervous system or result in chronic immunological problems. A physician can explain the risks and benefits.

Monoclonal antibodies are used in research and medicine

Commercially prepared **monoclonal antibodies** harness antibodies for medical and research uses (Figure 9.18). The term "monoclonal antibody" refers to the fact that the antibodies are made by cells cloned from just a single antibody-producing B cell.

At one time laboratory mice were the "factories" for making monoclonal antibodies. Today most monoclonal antibodies are produced using genetically altered bacteria. Genetically engineered plants such as corn also are being used to make antibodies that may be both cost-effective and safe (few plant pathogens can infect people). The first "plantibody" to be used on human volunteers prevented infection by a bacterium that causes tooth decay.

Monoclonal antibodies have become useful tools in diagnosing health conditions. Because they can recognize and bind to specific antigens, they can detect substances in the body—a bacterial cell, another antibody, or a chemical—even if only a tiny amount is present. Uses include home pregnancy tests and screening for prostate cancer and some sexually transmitted diseases. As you'll read next, monoclonal antibodies also have potential uses as "magic bullets" to deliver drugs used to treat certain forms of cancer.

Figure 9.18 Cells that produce monoclonal antibodies are stored in liquid nitrogen.

Immunotherapies reinforce defenses

Immunotherapy bolsters defenses against infections and cancer cells by manipulating the body's own immune mechanisms. Cytokines that activate B and T cells are being used to treat some cancers. Monoclonal antibodies are another weapon. For example, some aggressive breast cancers have telltale HER2 proteins at their surface. The drug Herceptin is a monoclonal antibody that binds to the proteins and draws a response from NK cells. The drug can be a double-edged sword, however, because some healthy body cells also have HER2 proteins, and they are attacked as well.

Monoclonal antibodies also can be bound to poisons to make *immunotoxins*. When these substances bind to an antigen on a cancer cell, they enter the cell and block processes that allow it to survive and multiply. Some experimental immunotoxins are being tested against HIV, the virus that causes AIDS.

Various body cells, including ones infected by a virus, can make and secrete interferons. When these cytokines reach an uninfected cell, they trigger a chemical attack that prevents the virus from multiplying. *Gamma* interferon, which is made by T cells, has other functions, too. It calls NK cells into action and also boosts the activity of macrophages. Genetically engineered gamma interferon is used to treat hepatitis C, a chronic, potentially lethal viral disease. Some kinds of cells (not lymphocytes) produce *beta* interferon. This protein has recently been approved for the treatment of a type of **multiple sclerosis**, a disease in which the immune system mounts an attack on parts of the nervous system.

Take-Home Message

What are some major applications of immunology?

- Immunization can enhance immunity to specific diseases by stimulating the production of both effector and memory lymphocytes.
- Monoclonal antibodies and cytokines such as interferons are important tools in medical research, testing, and the treatment of disease.

9.10 Disorders of the Immune System

In allergies, harmless substances provoke an immune attack

Most allergies won't kill you, but they sure can make you miserable. In at least 15 percent of the people in the United States, normally harmless substances can provoke immune responses. These substances are **allergens**, and the response to them is an **allergy**. Common allergens are pollen (Figure 9.19*a*), a variety of foods and drugs, dust mites, fungal spores, insect venom, and ingredients in cosmetics. Some responses start within minutes; others are delayed. Either way, the allergens trigger mild to severe inflammation of mucous membranes and in some cases other tissues as well.

Some people are genetically predisposed to develop allergies. Infections, emotional stress, or changes in air temperature also may cause the reactions. When an allergic person first is exposed to certain antigens, IgE antibodies are secreted and bind to mast cells (Figure 9.19*b*). When the IgE binds an allergen, mast cells secrete prostaglandins, histamine, and other substances that fan inflammation. They also cause an affected person's airways to constrict. In **hay fever**, the allergic response produces stuffed sinuses, a drippy nose, and sneezing.

Like other allergies, food allergies are skewed immune responses in which a particular food is interpreted as an "invader." The most common culprits are shellfish, eggs, and wheat. Depending on the person and the food involved, symptoms typically include diarrhea, vomiting, and sometimes swelling or tingling of mucous membranes. Some food allergies can be lethal. For example, in people who are allergic to peanuts even a tiny amount can trigger **anaphylactic shock**—a whole-body allergic response that produces frightening symptoms. Within moments air passages to the lungs close almost completely. Fluid gushes from dilated blood vessels all over the body. Blood pressure plummets, which can lead to the collapse of the person's cardiovascular system (Figure 9.20).

Anaphylactic shock is also a concern for people who are allergic to wasp or bee venom, for a single sting can kill them. One emergency treatment is an injection of the

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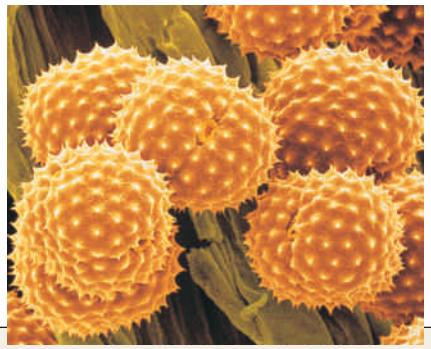

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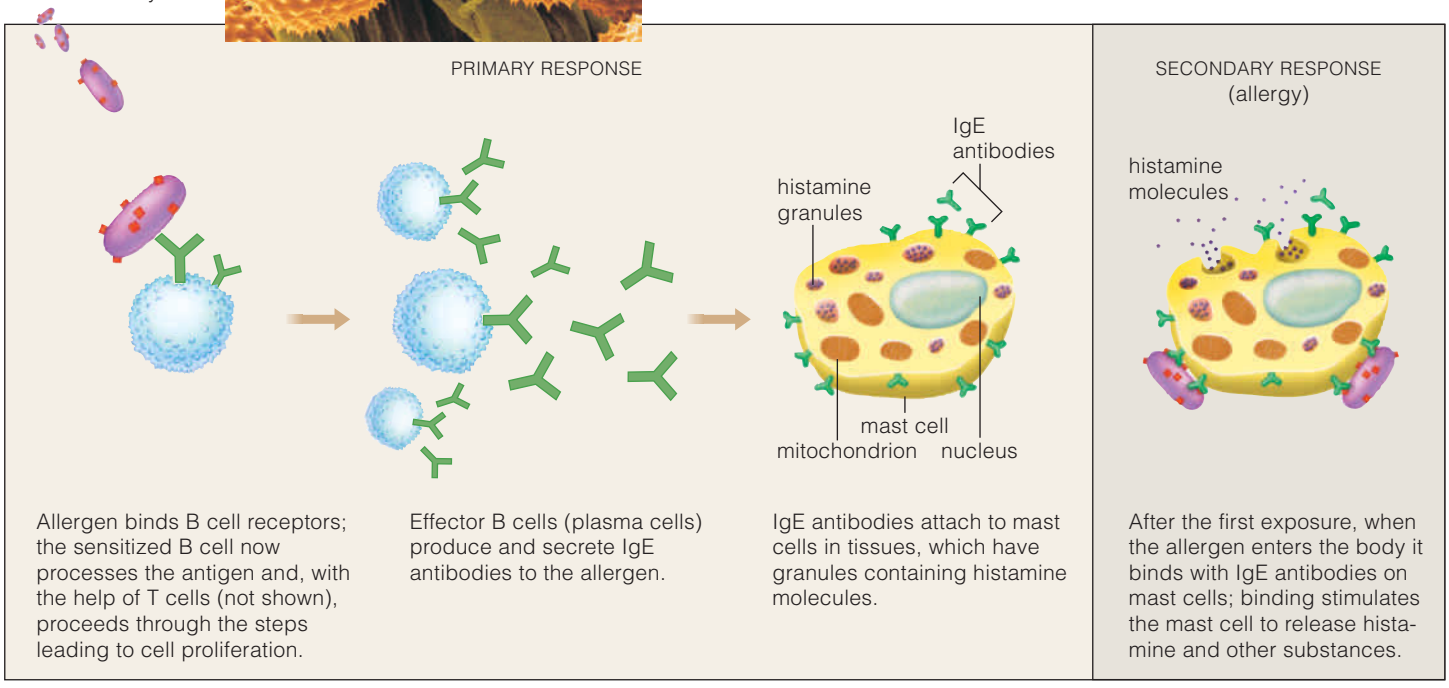


Figure 9.19 Allergies are misguided immune responses. (**a**) Micrograph of ragweed pollen. (**b**) The basic steps leading to an allergic response.

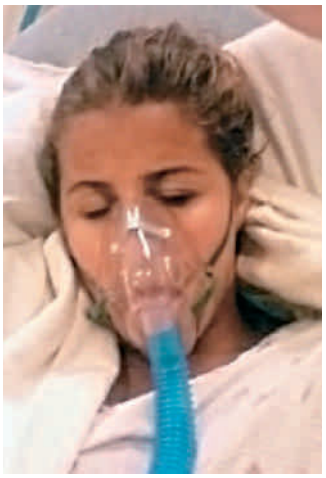


Figure 9.20 For a patient with anaphylactic shock, an emergency treatment includes receiving oxygen.

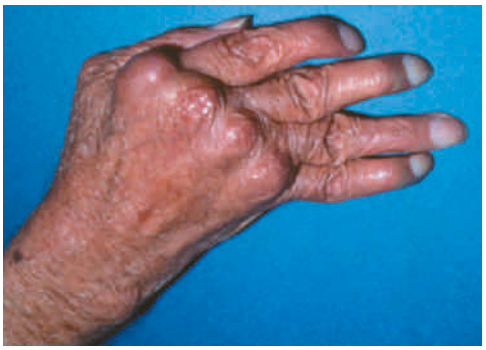


Figure 9.21 This person's hand is crippled by rheumatoid arthritis.

hormone epinephrine. People who know they are at risk (usually because they've already had a bad reaction to an allergen) can carry the necessary medication with them, just in case.

Antihistamines are anti-inflammatory drugs that are often used to relieve short-term allergy symptoms. In some cases a person may opt to undergo a desensitization program. Following skin tests that identify offending allergens, inflammatory responses to some of them can be blocked if the patient's body can be stimulated to make IgG instead of IgE. Gradually, larger and larger doses of specific allergens are administered. Each time, the person's body produces more IgG molecules and memory cells. The IgG will bind with an allergen and block its attachment to IgE. As a result, inflammation is blocked, too.

Autoimmune disorders attack "self"

In **autoimmunity**, the immune system's weapons are unleashed against normal body cells or proteins. An example is *rheumatoid arthritis* (RA). People with RA are genetically predisposed to it. Their macrophages and T and B cells become activated by antigens associated with the joints. Immune responses are mounted against their body's collagen molecules and also apparently against antibodies that have bound to an (as yet unknown) antigen. Joint tissues suffer more damage from inflammation and the complement system (Figure 9.21). Malfunctioning repair mechanisms make the problem worse. Eventually the affected joints become immobile.

Another autoimmune disease is *type 1 diabetes*. This is a type of *diabetes mellitus*, in which the pancreas does not secrete enough of the hormone insulin for proper absorption of glucose from the blood. For reasons that are still being investigated, the immune system attacks and destroys the insulin-secreting cells. A viral infection may trigger the response. Chapter 15 looks at the various forms of diabetes in more detail.

Systemic lupus erythematosus (SLE) primarily affects young women, but males may also develop it. A typical symptom is a rash on the face that extends from cheek to cheek, roughly in the shape of a butterfly. The rash is one sign that the affected person has developed antibodies to her or his own DNA and other "self" components. Antigen–antibody complexes accumulate in joints, blood vessel walls, the skin, and the kidneys. Other symptoms include fatigue, painful arthritis, and in some cases a near-total breakdown of kidney function. Therapeutic drugs can help relieve many SLE symptoms, but there is no cure.

Autoimmunity is far more common in women. We know that the receptor for estrogen is involved in certain genetic controls. Is the receptor also implicated in autoimmune responses? Researchers are exploring the question.

Immune responses can be deficient

The term **immunodeficiency** applies when a person's immune system is weakened or lacking altogether. When the body has too few properly functioning lymphocytes, its immune responses are not effective. Both T and B cells are in short supply in the disorder known as **severe combined immune deficiency** (SCID). SCID usually is inherited, and infants born with it may die early in life. Lacking adequate immune responses, they are extremely vulnerable to infections that are not life-threatening to other people. One type of SCID is now being treated by gene therapy (Chapter 21).

You probably know that infection by the human immunodeficiency virus (HIV) causes AIDS (acquired immunodeficiency syndrome). The next section looks at the current status of the global AIDS epidemic and efforts to fight it.

9.11 HIV and AIDS

- **HIV, the human immunodeficiency virus, cripples the immune system by destroying lymphocytes.**

AIDS (acquired immune deficiency syndrome) is a group of diseases caused by infection with **HIV**, the human immunodeficiency virus. HIV infects cells that have a certain type of surface receptor. Macrophages, dendritic cells, and helper T cells have this receptor. Because HIV kills lymphocytes, it leaves the body vulnerable to infections and rare forms of cancer.

There is no way to rid the body of the known forms of the virus, HIV-I and HIV-II. Sooner or later, people who are infected begin to develop symptoms of illness. Diagnostic signs of AIDS include having a severely depressed immune system, a positive HIV test, and having an "indicator disease," including types of pneumonia, recurrent yeast infections, cancer, and drug-resistant tuberculosis. Worldwide, HIV has infected an estimated 33.2 million people (Table 9.4).

Global HIV and AIDS Cases

Region	AIDS Cases	New HIV Cases
Sub-Saharan Africa	22,500,000	1,700,000
South/Southeast Asia	4,000,000	340,000
Central Asia/East Europe	1,600,000	150,000
Latin America	1,600,000	100,000
North America	1,300,000	46,000
East Asia	800,000	92,000
Western/Central Europe	760,000	31,000
Middle East/North Africa	380,000	35,000
Caribbean Islands	230,000	17,000
Australia/New Zealand	75,000	14,000
Worldwide total	33,200,000	2,500,000

Source: Joint United Nations Programme HIV/AIDS, 2007 data

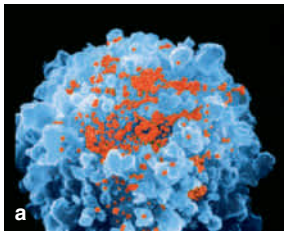
HIV is transmitted in body fluids

HIV is transmitted when body fluids, especially blood and semen, of an infected person enter another person's tissues. The virus can enter through any kind of cut or abrasion, anywhere on or in the body. HIV-infected blood also can be present on toothbrushes and razors; on needles used to inject drugs, pierce ears, do acupuncture, and on contaminated medical equipment.

The most common mode of transmission is sex with an infected partner. HIV in semen and vaginal secretions enters a partner's body through epithelium lining the penis, vagina, rectum, or (rarely) mouth. Anything that damages the linings, such as other sexually transmitted diseases, anal intercourse, or rough sex, increases the odds that the virus will be transmitted.

HIV is not effectively transmitted by food, air, water, casual contact, or insect bites. However, infected mothers can transmit HIV to their babies during pregnancy, birth, and breast-feeding (Figure 9.22).

Almost half of HIV-infected adults worldwide are women. Some of those infections are due to intravenous drug abuse, but most are the result of sexual contact with infected men. Young people are also being hit hard. In recent years, more young adults in the United States have died from AIDS than from any other single cause.



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HIV infection begins a fateful struggle

HIV is a retrovirus, which means that its primary genetic instructions are in the form of RNA, not DNA. Each virus particle has a lipid envelope, a bit of plasma membrane that enclosed it as it budded from an infected cell. Proteins spike from the envelope, extend across it, or line its inner surface. Inside the envelope, so-called "viral coat" proteins enclose RNA and an enzyme called *reverse transcriptase*. This enzyme uses RNA as a template for making DNA (the reverse of a more common process in

Figure 9.22 HIV disables the immune system. (**a**) A human T cell (*blue*) infected with HIV (*red*). (**b**) This Romanian baby contracted AIDS from his mother's breast milk and later died.

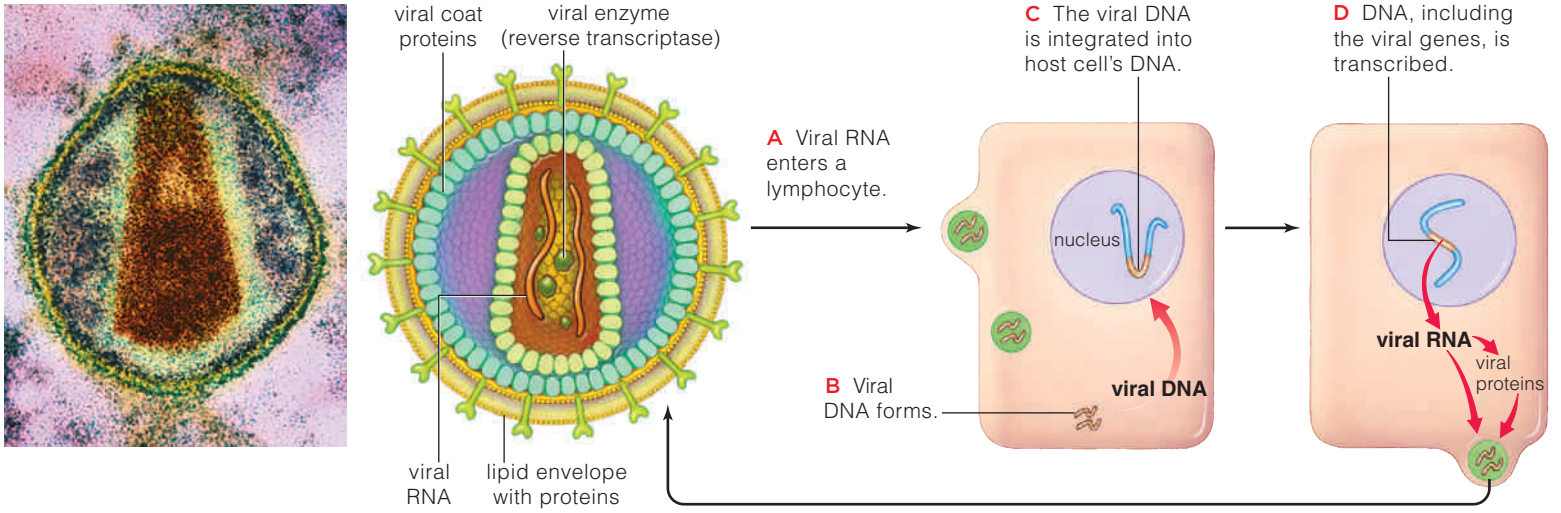


Figure 9.23 This diagram summarizes the steps by which HIV replicates inside a cell.

which DNA is the template for making RNA). The newly formed DNA makes up genes that are then inserted into one of the host cell's chromosomes. Eventually the genetic message in the DNA is "rewritten" back into RNA, and these RNA instructions are then translated into protein (Figure 9.23). Chapter 21 explains this process more fully.

After HIV infects a person, virus particles enter the bloodstream. At this stage, many people have flulike symptoms as the adaptive immune response begins. B cells make antibodies that can be detected by an HIV test. Armies of helper T cells and killer T cells also form. With time, however, the adaptive immune response begins to slow as up to 1 billion new virus particles are built every day. They bud from the plasma membrane of an infected helper T cell or are released when the membrane ruptures.

Over time, billions of HIV particles and masses of infected T cells accumulate in lymph nodes. The number of circulating virus particles also increases and the body produces fewer and fewer helper T cells to replace those it has lost. As the number of healthy helper T cells drops, the person may lose weight and experience symptoms such as fatigue, nausea, heavy night sweats, enlarged lymph nodes, and a series of minor infections. With time, one or more of the typical AIDS indicator diseases appear. These are the diseases that eventually kill the individual.

Can drugs and vaccines be used to help fight HIV?

Drugs can't cure infected people, because there is no way to remove HIV genes that are already inserted into someone's DNA. Also, HIV mutates rapidly, so it can rapidly develop resistance to drugs. Even so, researchers have developed a fairly effective arsenal of anti-HIV drugs. Protease inhibitors block the action of HIV protease, an enzyme required for the assembly of new virus particles. Other drugs inhibit an enzyme that allows the virus to replicate itself.

At present the preferred treatment is a drug "cocktail" that often consists of a protease inhibitor and two anti-HIV drugs. This regimen can sometimes suppress HIV, at least for a time. The drug cocktails are expensive, though, and they may have serious side effects. The search also is on for compounds that might prevent HIV from entering human cells. Such "entry inhibitors" are now being tested.

Making an effective HIV vaccine has proven to be a tall order. Because HIV mutates rapidly, there may be many different genetic forms in a single person, and each presents the immune system with a different antigen. No single vaccine can keep up with this challenge. Despite the obstacles, researchers are not giving up. At present, 35 HIV vaccines are undergoing clinical trials in various parts of the world.

At present, our only real option for halting the spread of HIV appears to be prevention, by teaching people how to avoid being infected. Most HIV infections result from a personal choice to have unprotected sex, or to use a shared needle for intravenous drugs. Education programs around the world are having an effect on the spread of the virus. In many—but not all—countries, the incidence of new cases of HIV each year is slowing. Even so, overall we still are not winning our global battle against AIDS.

Take-Home Message

What is AIDS?

- AIDS is a group of diseases that may develop as a result of infection by HIV, a virus that infects T cells and so cripples the human immune system.

9.12 Patterns of Infectious Disease

- **Infections that can threaten health spread in predictable ways and occur in predictable patterns. This knowledge is useful in efforts to combat disease.**
- **Links to Antibiotic resistance 1.7, Blood disorders 8.8**

Our innate and adaptive defenses evolved to protect the body from pathogens and dangerous abnormalities such as cancerous cells. This is how defense responses make a vital contribution to homeostasis. In this section we look at some basic characteristics of infectious microbes, including how they spread.

Pathogens spread in four ways

By definition, an infectious disease can be transmitted from person to person. There are four common modes of transmission:

1. **Direct contact** with a pathogen, as by touching open sores or body fluids from an infected person. (This is where "contagious" comes from; the Latin contagio means touch or contact.) Infected people can transfer pathogens from their hands, mouth, or genitals.
2. **Indirect contact**, as by touching doorknobs, tissues (or handkerchiefs), diapers, or other objects previously in contact with an infected person. As already noted, food, water and surfaces can be contaminated by pathogens. Some extremely common infections are caused by organisms that are nearly always present in our surroundings (Figure 9. 24*a*).
3. **Inhaling pathogens**, such as cold and flu viruses, that have been spewed into the air by uncovered coughs and sneezes (Figure 9.24b). This is the most common mode of transmission.
4. **Contact with a vector**, such as mosquitoes, flies, fleas, and ticks. A disease vector carries a pathogen from an infected person or contaminated material to new hosts. In some cases, part of the pathogen's life cycle must take place inside the vector, which is an intermediate host. For example, mosquitoes are the intermediate hosts for the West Nile virus and the *Plasmodium* parasites that cause malaria.

Every year 5 to 10 percent of hospital patients come down with a **nosocomial infection**—one that is acquired in a hospital, usually by direct contact with a microbe. The MRSA infection mentioned in Section 8.8 is an example. Why are nosocomial infections so common? Anyone sick enough to be hospitalized may have a compromised (and therefore less effective) immune system, and invasive medical procedures give bacteria easy access to tissues. Also, the intensive use of antibiotics in hospitals increases the chances that antibiotic-resistant pathogens will be present there. Hospitals usually are careful to monitor patients likely to be vulnerable to nosocomial infection.

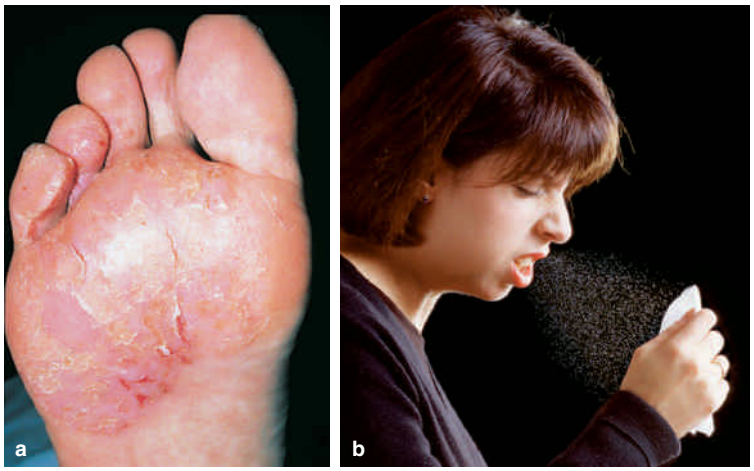


Figure 9.24 Many infections are spread by contact or when a pathogen is inhaled. (**a**) Athlete's foot, caused by a fungus that lives in warm, damp places such as shower stalls. (**b**) Sneezes, used tissues, and contaminated hands all may spread a virus.

Infectious Diseases: Global Health Threats*

Disease	Type of Pathogen	Estimated Deaths per Year
Diarrheas (includes amoebic dysentery, cryptosporidiosis)	Protozoa, virus, and bacteria	31 million
Various respiratory infections (pneumonia, viral influenza, diphtheria, strep infections)	Virus, bacteria	71 million
Malaria	Protozoan	2.7 million
Tuberculosis	Bacterium	2.4 million
Hepatitis (includes A, B, C, D, E)	Virus	1–2 million
Measles	Virus	220,000
Schistosomiasis	Worm	200,000
Whooping cough	Bacterium	100,000
Hookworm	Worm	50,000+

*Does not include AIDS-related deaths.

Diseases occur in four patterns

Infectious diseases sometimes are described in terms of the patterns in which they occur. In an **epidemic**, a disease rate increases to a level above what we would predict, based on experience. When cholera broke out all through Peru in 1991, that was an epidemic. When epidemics break out in several countries around the world in a given time span, they collectively are called a **pandemic**. AIDS is a pandemic; it has spread worldwide since the first cases were identified in 1981.

A **sporadic disease**, such as whooping cough, breaks out irregularly and affects relatively few people. An **endemic disease**, such as the common cold, occurs more or less continuously. Many of the diseases noted in Table 9.5 are endemic in various parts of the world.

Virulence is a measure of pathogen damage

Pathogens are ranked according to their **virulence**—how likely it is that the pathogen will make its host seriously ill. Virulence depends on how fast the pathogen can invade tissues, how severe is the damage it causes, and which tissues it targets. For example, a virus that can cause pneumonia is more virulent than one that causes the sniffles. Rabies viruses are highly virulent because they target the brain. Antibiotic resistance in some bacteria has made those microbes highly virulent. Infectious disease specialists have instituted a worldwide surveillance system to identify new resistant strains before they can become well established.

There are many public and personal strategies for preventing infection

The best way to combat any disease is to prevent it in the first place. With infectious diseases, prevention depends on knowing how a disease is transmitted and what the pathogen reservoir is.

Figure 9.25 lists general strategies for preventing the transmission of pathogens that are present on the skin, in the respiratory tract, in the GI tract, and in blood. These strategies recognize that the human body, soil, water, and other animals all are reservoirs for a range of pathogens. Notice that regular hand washing tops the list for limiting your exposure to all except blood-borne pathogens. Public health measures include vaccination programs, standards for processing or treating supplies of food, drinking water, and blood products, and public dissemination of information on proper food-handling methods. Chapter 16 describes strategies for protecting against sexually transmitted disease.

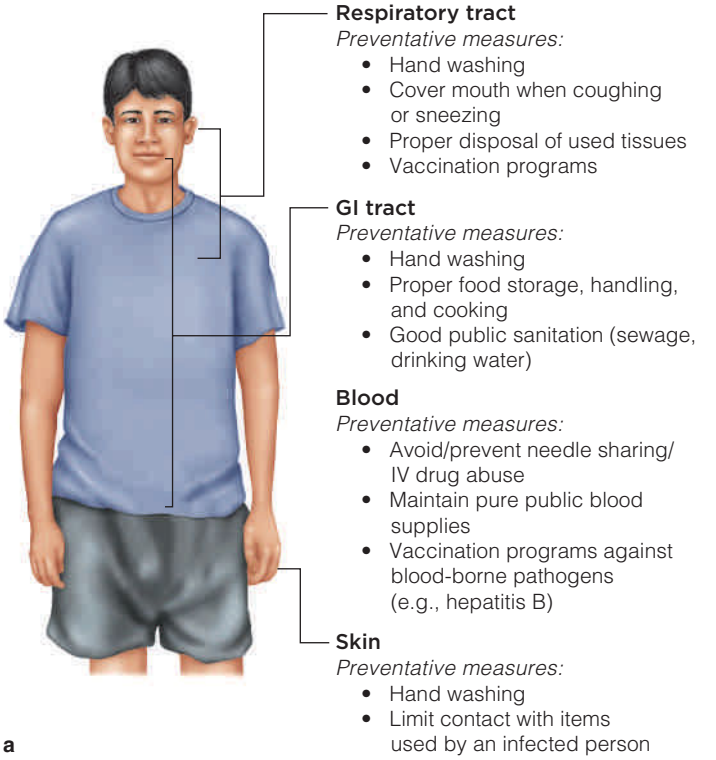


Figure 9.25 It is helpful to know how pathogens spread and what their reservoirs are. (**a**) Some recommended strategies for preventing the spread of infectious disease. (**b**) *Staphylococcus aureus* bacteria (*yellow* balls) sticking to cilia of a person's nasal epithelium. This strain is common on the skin and living on the epithelial lining of the nose, throat, and intestines. It is the leading cause of bacterial disease in humans.

Take-Home Message

How do infectious diseases spread?

- Infectious diseases are spread by direct or indirect contact, by being inhaled, or by vectors.
- Some disease organisms are extremely virulent—they can cause severe illness.
- Simple hand washing is a good strategy for avoiding many common infectious organisms.

IMPACTS, ISSUES

Frankie's Wish

SEVERAL states have launched programs to vaccinate young girls with the HPV vaccine Gardasil in order to prevent possible cervical cancer later in life. Gardasil is the first anticancer vaccine and has strong backing from most in the medical community. Some parents have raised objections on personal grounds or due to worries about unforeseen side effects.

How Would You Vote?

Should parents be able to "opt out" of state-mandated Gardasil vaccination programs? See CengageNow for details, then cast your vote online.

Summary

Section 9.1 The body protects itself from pathogens with general and specific responses of white blood cells and chemicals they release. Inborn responses provide innate immunity. Responses after the body detects antigens of specific pathogens provide adaptive immunity (Table 9.6). An antigen is a protein or other type of molecule that triggers an immune response against itself.

Chemicals called cytokines help organize or strengthen immune responses. They include interleukins, interferons, and complement proteins.

Section 9.2 T and B cells are stationed in lymph nodes, the spleen, the tonsils, and other parts of the lymphatic system. Lymph vessels also recover water and dissolved substances that have escaped from the bloodstream and return them to the general circulation.

- Use the animation and interaction on CengageNOW to learn more about how the lymphatic system functions.

Section 9.3 Physical barriers, such as intact skin and mucous membranes lining body surfaces, are the first line of defense against pathogens. Lysozyme in mucus attacks many bacteria. Chemical barriers also include tears, saliva, and gastric juice. Urine and diarrhea can help flush pathogens from the urinary tract and GI tract.

Section 9.4 Innate immune responses counter threats in a general way. They may stop an infection from setting in.

Macrophages are "first responders" that engulf and digest foreign agents and clean up damaged tissue. Complement proteins bind to pathogens and kill them by inserting membrane attack complexes into the invader's plasma membrane. They also attract phagocytes.

Activated complement and cytokines from macrophages trigger inflammation, a fast, local response to tissue damage. Signs of inflammation include redness, warmth, and pain.

Chemical signals triggered by an infection can increase the body temperature set point and cause a fever.

Section 9.5 Adaptive defenses work against specific pathogens. They can combat a great diversity of antigens, and generate memory T and B cells that provide extended immunity. When B cells and T cells recognize an antigen, they are activated and multiply to form large populations of identical cells.

Activated B cells produce antibodies that bind specific antigens and flag them to be destroyed by phagocytes or other defender cells. Effector B cells, called plasma cells, can release floods of antibodies.

The response by T cells provides cell-mediated immunity. T cells recognize combinations of antigen fragments and MHC self markers. These complexes are produced by antigen-presenting cells (dendritic cells, macrophages, B cells). Cytotoxic T cells are the effectors that attack intruders directly. Helper T cells release cytokines that mobilize and strengthen defense responses.

Section 9.6 Antibodies target pathogens outside cells. In the antibody-mediated response, plasma cells secrete

The Human Body's Three Lines of Defense against Pathogens

Barriers at Body Surfaces (*nonspecific* targets)

Intact skin; mucous membranes at other body surfaces

Infection-fighting chemicals in tears, saliva, gastric fluid

Normally harmless bacteria on body surfaces, which outcompete pathogens

Flushing effect of tears, saliva, urination, diarrhea, sneezing, and coughing

Innate Immune Responses (*nonspecific* targets)

Inflammation

1. Fast-acting white blood cells (neutrophils, eosinophils, and basophils)
2. Macrophages (also take part in immune responses)
3. Complement proteins, blood-clotting proteins, and other infection-fighting cytokines

Organs with pathogen-killing functions (such as lymph nodes)

Some cytotoxic cells (e.g., NK cells) with a range of targets

Adaptive Immune Responses (*specific* targets only)

1. White blood cells (T cells, B cells, and macrophages that interact with them)
2. Communication signals (e.g., interleukins) and chemical weapons (e.g., antibodies, perforins)

large numbers of antibodies that circulate in the bloodstream. Antibodies are proteins, often Y-shaped, and each binds one kind of antigen. The five classes of antibodies—IgG, IgD, IgE, IgA, and IgM—are immunoglobulins.

- Use the animation and interaction on CengageNOW to see how antibodies combat pathogens in the blood and lymphatic system.

Section 9.7 Cell-mediated responses destroy infected cells, tumor cells, and cells of tissue or organ transplants. Cytotoxic T cells secrete chemicals that can trigger apoptosis, or programmed cell death, in an invading cell.

- Use the animation and interaction on CengageNOW to see the steps of a cell-mediated immune response.

Section 9.8 Memory cells that form during a primary adaptive response circulate in the blood for years. They can mount a stronger, faster secondary response to a pathogen if it invades the body again.

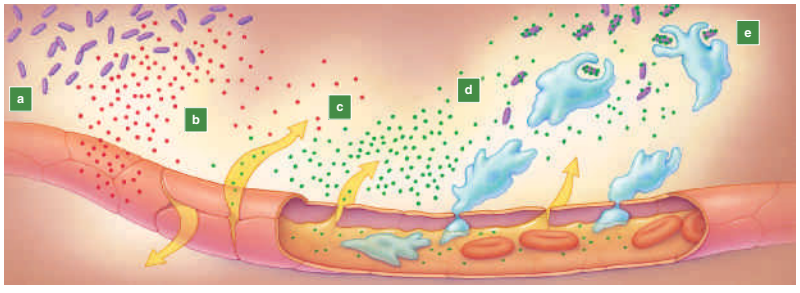
Section 9.9 In active immunization, a vaccine provokes an immune response, including the production of memory cells. Passive immunization uses injections of purified antibodies to help combat an infection. Monoclonal antibodies are used in medical research, testing, and the treatment of various diseases.

Sections 9.10, 9.11 An allergy is an immune response to a generally harmless substance. An autoimmune response is an attack by lymphocytes on normal body cells. Immunodeficiency is a weakened or nonexistent capacity to mount an immune response. A prime example is AIDS, caused by the HIV virus.

- Use the animation and interaction on CengageNOW to see how HIV invades a cell and replicates inside it.

Review Questions

1. While you're jogging in the surf, your toes land on a jellyfish. Soon the bottoms of your toes are swollen, red, and warm to the touch. Using the diagram below as a guide, describe how these signs of inflammation came about.
2. Distinguish between:
   a. neutrophil and macrophage
   b. cytotoxic T cell and natural killer cell
   c. effector cell and memory cell
   d. antigen and antibody



3. What is the difference between innate immunity and adaptive immunity?
4. How does a macrophage or a dendritic cell become an antigen-presenting cell?
5. What is the difference between an allergy and an autoimmune response?

Self-Quiz *Answers in Appendix V*

1. _____ are barriers to pathogens at body surfaces.
   a. Intact skin and mucous membranes
   b. Tears, saliva, and gastric fluid
   c. Resident bacteria
   d. all are correct
2. Complement proteins function in defense by _____.
   a. neutralizing toxins
   b. enhancing resident bacteria
   c. promoting inflammation
   d. forming pores that cause pathogens to disintegrate
   e. both a and b are correct
   f. both c and d are correct
3. _____ are molecules that lymphocytes recognize as foreign and that elicit an immune response.
   a. Interleukins
   b. Antibodies
   c. Immunoglobulins
   d. Antigens
   e. Histamines
4. Another term for antibodies is _____; there are _____ classes of these molecules.
   a. B cells; three
   b. immunoglobulins; three
   c. B cells; five
   d. immunoglobulins; five
5. Antibody-mediated responses work best against _____.
   a. pathogens inside cells
   b. pathogens outside cells
   c. toxins
   d. both b and c
   e. all are correct
6. The most common antigens are _____.
   a. nucleotides
   b. triglycerides
   c. steroids
   d. proteins
7. The ability to develop a secondary immune response is based on _____.
   a. memory cells
   b. circulating antibodies
   c. plasma cells
   d. effector cytotoxic T cells
   e. mast cells
8. Tears are part of the body's defensive arsenal. What defense category do they fall into, and why?
9. Match the immunity concepts:
   ____ inflammation
   ____ antibody secretion
   ____ phagocyte
   ____ immunological memory
   ____ vaccination
   ____ allergy
   a. neutrophil
   b. plasma cell
   c. nonspecific response
   d. purposely causing memory cell production
   e. basis of secondary immune response
   f. nonprotective immune response

Critical Thinking

1. New research suggests a link between some microbes that normally live in the body and seemingly unrelated major illnesses. The gum disease called periodontitis itself is not life-threatening, for instance, but it is a fairly good predictor for heart attacks. Bacteria that cause gum disease can trigger inflammation. Thinking back to your reading in Chapter 7, how do you suppose that this response also may be harmful to the heart?
2. Given what you now know about how foreign invaders trigger immune responses, explain why mutated forms of viruses, which have altered surface proteins, pose a monitoring problem for a person's memory cells.
3. Researchers have been trying to develop a way to get the immune system to accept foreign tissue as "self." Can you think of some clinical applications for such a development?
4. Elena developed chicken pox when she was in kindergarten. Later in life, when her children developed chicken pox, she stayed healthy even though she was exposed to countless virus particles each day. Explain why.
5. In 1796 the English physician Edward Jenner (right) injected a young boy with material from cowpox scabs. Cowpox is a mild, smallpox-like disease that is not nearly so dangerous as smallpox. Jenner had noticed that people who got cowpox never later got smallpox, which was a major killer at the time. He suspected—rightly as it turned out—that having cowpox somehow made a person immune to smallpox. The boy was his test subject for this hypothesis. After the boy's bout of cowpox was over, Jenner injected him with pus from a smallpox sore. The boy stayed healthy, and the episode led to the discovery of vaccination—a term that literally means "encowment." What do you think would happen if a physician tried this experiment today?

EXPLORE ON YOUR OWN

The photograph in Figure 9.26 shows a reaction to a skin test for tuberculosis. For this test, a health care worker scratches a bit of TB antigen into a small patch of a patient's skin. In people who have a positive reaction to the test, a red swelling develops at the scratch site, usually within a day or two. Even in a person with no medical history of the disease, this response is visible evidence of immunological memory. It shows that there has been an immune response against the tuberculosis bacterium, which the person's immune system must have encountered at some time in the past. Tests for allergies work the same way.

In many communities, a TB test is required for people who are applying for jobs that involve public contact, such as teaching in the public schools. To learn more about this public health measure, find out if the test is required in your community, where it is available, and why public health authorities believe it is important.

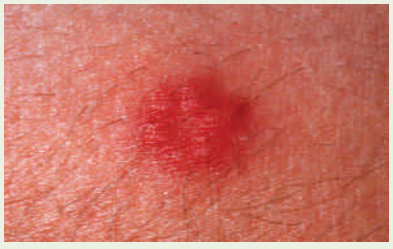


Figure 9.26 **This skin eruption indicates a positive reaction to a tuberculosis skin test.**

The Respiratory System

10

IMPACTS, ISSUES

Up in Smoke

EACH day, about 3,000 teenagers, most younger than 15, join the ranks of smokers in the United States. The first time a person lights up, they typically cough and choke on the irritants in smoke, and they may feel dizzy and nauseated. These responses are threat signals that tobacco smoke is toxic to human tissues.

So why do smoking "recruits" keep on lighting up? Research tells us that teens take up the habit in order to fit in socially. At the time, the threat that tobacco use poses to their health and survival seems remote. And of course, the nicotine in cigarette smoke is extremely addictive.

Tobacco smoke is really bad news for the respiratory sysem, our topic in this chapter. Cilia that line the airways to the lungs normally sweep away airborne pollutants and microbes. Unfortunately, smoke from a single cigarette may immobilize them for hours. Smoke also kills white blood cells that patrol and defend the respiratory tract. Microbes may start living there, leading to more colds, bronchitis, and even asthma attacks.

You're probably aware that smoking also is a major risk factor for lung cancer. It also is linked with other cancers. For example, females who start smoking in their teens are about 70 percent more likely to develop breast cancer than those who don't smoke. Other negative effects of of smoking include increased blood pressure, higher levels of LDL ("bad") cholesterol, and lower levels of "good" cholesterol (HDL).

The **respiratory system** has one basic job—to help maintain homeostasis by bringing in oxygen for body cells and to carry away cells' carbon dioxide wastes. Structures such as lungs and functions such as breathing allow the respiratory system to perform this essential gas exchange.

LINKS TO EARLIER CONCEPTS

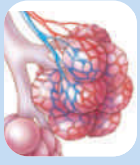
- In this chapter your knowledge of concentration gradients and diffusion (3.10) will help you understand the mechanisms that move oxygen into and carbon dioxode out of the body.
- You will see how the respiratory system works together with the cardiovascular system (7.1) to supply oxygen and remove carbon dioxide.
- You will learn how hemoglobin and red blood cells function in gas exchange (8.1).

KEY CONCEPTS

The Respiratory System

Respiration provides the body with the oxygen for aerobic respiration in cells. It also removes waste carbon dioxide. These gases enter and leave the body by way of the respiratory system. Sections 10.1–10.3

Gas Exchange



Oxygen and carbon dioxide are exchanged across the thin walls of microscopic sacs in the lungs called alveoli. The cardiovascular system carries gases to and from the lungs. Section 10.4

Breathing Controls

Various controls regulate respiration. The nervous system controls the rate, depth, and rhythmic pattern of breathing. Section 10.5

Disorders of the Respiratory System and Homeostasis

Sections 10.6–10.8

How Would You Vote?

Tobacco is both a worldwide threat to health and a profitable product for American companies. As tobacco use by its citizens declines, should the United States encourage international efforts to reduce tobacco use? See CengageNOW for details, then vote online.

10.1 The Respiratory System: Built for Gas Exchange

- **Getting oxygen from air and releasing carbon dioxide wastes are the basic functions of the respiratory system.**

Airways are pathways for oxygen and carbon dioxide

Body cells need oxygen for aerobic respiration and must get rid of the carbon dioxide they produce as a waste. The respiratory system handles these key tasks (Figure 10.1).

When a person breathes quietly, air typically enters and leaves the respiratory system by way of the nose. Hairs at the entrance to the nasal cavity and in its ciliated epithelial lining filter out large particles, such as dust, from incoming air. The air also is warmed in the nose and picks up moisture from mucus. A septum (wall) of bone and cartilage separates the nasal cavity's two chambers. Channels link the cavity with paranasal sinuses above and behind it (which is why nasal sprays for colds or allergies can relieve mucus-clogged sinuses). Tear glands produce moisture that drains into the nasal cavity. Crying increases the flow, which is why your nose "runs" when you cry.

From the nasal cavity, air moves into the **pharynx**. This is the entrance to both the **larynx** (an airway) and

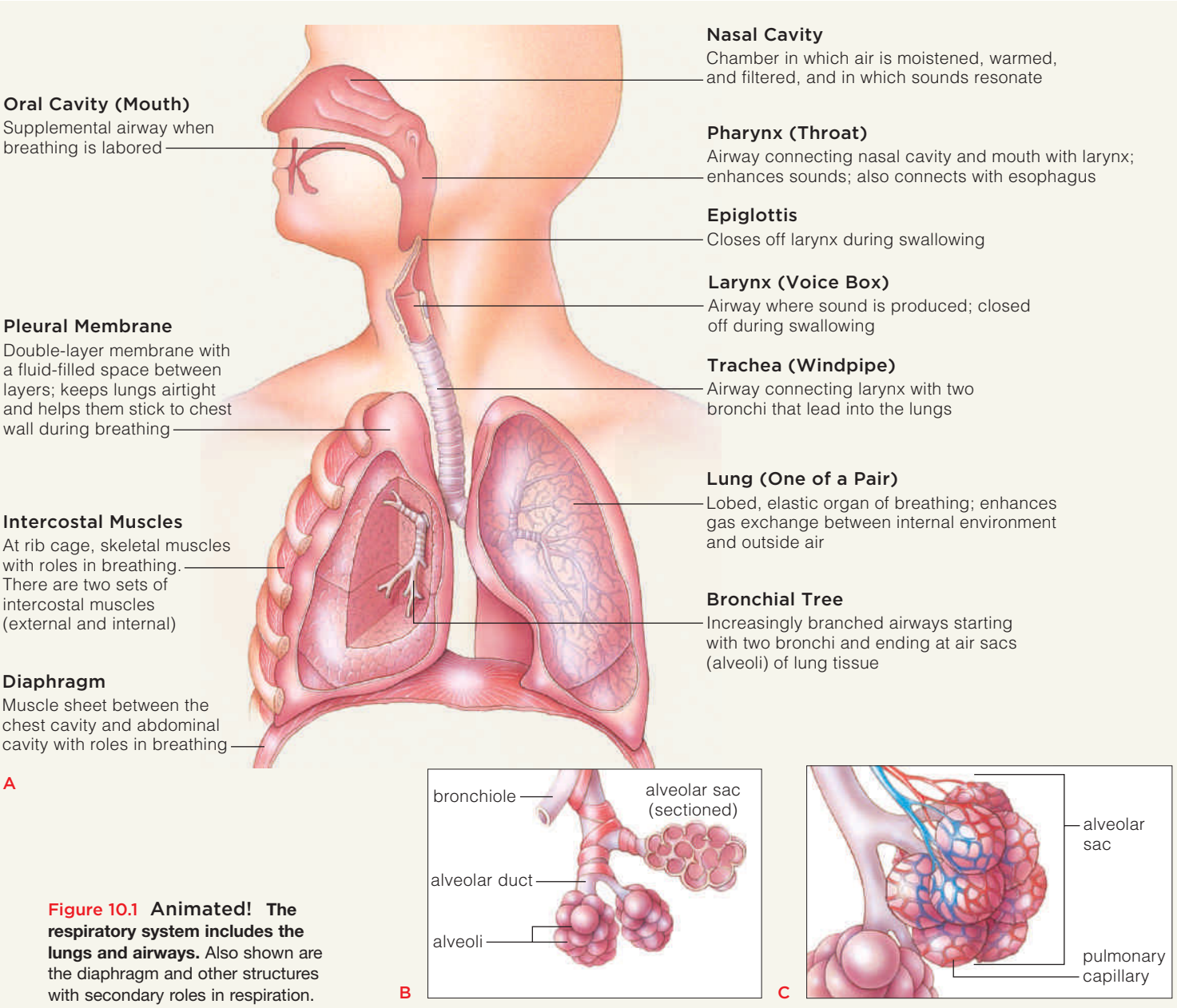


Figure 10.1 Animated! The respiratory system includes the lungs and airways. Also shown are the diaphragm and other structures with secondary roles in respiration.

Figure 10.2 **The lining of the airways includes mucus-secreting cells (*orange*) and hairlike cilia.**

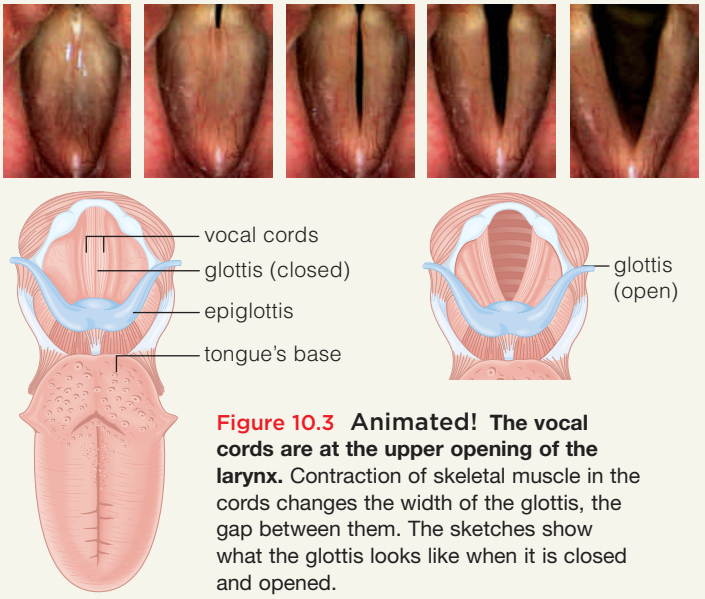


Figure 10.3 **Animated! The vocal cords are at the upper opening of the larynx.** Contraction of skeletal muscle in the cords changes the width of the glottis, the gap between them. The sketches show what the glottis looks like when it is closed and opened.

the esophagus (which leads to the stomach). Nine pieces of cartilage form the larynx. One of these, the thyroid cartilage, is the "Adam's apple."

Luckily, our airways are nearly always open. The flaplike **epiglottis**, attached to the larynx, points up during breathing. When you swallow, the larynx moves up so that the epiglottis partly covers the opening of the larynx. This helps prevent food from entering the respiratory tract and causing choking.

From the larynx, air moves into the "windpipe" or **trachea** (TRAY-key-uh). Press gently at the lower front of your neck, and you can feel some of the bands of cartilage that ring the tube, adding strength and helping to keep it open. The trachea branches into two airways, one leading to each lung. Each airway is a **bronchus** (BRAWN-kus; plural: bronchi). The epithelial lining of bronchi includes mucus-secreting cells and cilia. Figure 10.2 shows a close-up view of these cilia. Bacteria and airborne particles stick in the mucus; then the upward-beating cilia sweep the debris-laden mucus toward the mouth.

Near the entrance to the larynx, part of a mucous membrane forms horizontal folds that are the **vocal cords** (Figure 10.3). When you exhale, air is forced through the *glottis*, a gap between the vocal cords that is the opening to the larynx. Air moving through it makes the cords vibrate. By controlling the vibrations we can make sounds. Using our lips, teeth, tongue, and the soft roof over the tongue (the soft palate), we can modify these sounds into speech, song, and other vocalizations.

Lungs are elastic and provide a large surface area for gas exchange

Your **lungs** are elastic cone-shaped organs separated from each other by the heart. The left lung has two lobes, the right lung three. The lungs are located inside the rib cage above the **diaphragm**, a sheet of muscle between the thoracic (chest) and abdominal cavities. The lungs are soft and spongy, and they don't attach directly to the chest cavity wall. Instead, each lung is enclosed by a pair of thin membranes called **pleurae** (singular: pleura). You can visualize this arrangement if you think of pushing your fist into an inflated balloon. A lung occupies the same kind of position as your fist, and the pleural membrane folds back on itself (as the balloon does) to form a closed pleural sac. An extremely narrow intrapleural space (*intra-* means between) separates the membrane's two facing surfaces. A thin film of lubricating intrapleural fluid in the space reduces chafing between the membranes. Inside each lung, the bronchi narrow as they branch and form "bronchial trees." These narrowing airways are **bronchioles**. Their narrowest portions deep in the lungs are **respiratory bronchioles**. Tiny air sacs bulge out from their walls. Each sac is an **alveolus** (plural: alveoli). Each lung has about 150 million alveoli. Alveoli are where gases diffuse between the lungs and blood capillaries (Figures 10.1*b* and 10.1*c*).

Together the milions of alveoli provide a huge surface area for the diffusion of gases. If they were stretched out as a single layer, they would cover the body several times over—or the floor of a racquetball court!

Take-Home Message

What are the parts of the respiratory system?

- The lungs and airways are the main components of the respiratory system.
- The respiratory system's main functions are taking in oxygen and removing carbon dioxide.
- In alveoli inside the lungs, oxygen enters lung capillaries and carbon dioxide leaves them to be exhaled.

10.2 Respiration = Gas Exchange

- **All living cells in the body rely on respiration to supply them with oxygen and dispose of carbon dioxide wastes.**
- **Links to Mitochondria 3.7, Cellular respiration 3.14**

Chapter 3 discussed how aerobic cellular respiration inside cell mitochondria uses oxygen and produces carbon dioxide wastes that must be removed from the body. **Respiration**, in contrast, is the overall exchange of oxygen inhaled from the air for waste carbon dioxide, which is exhaled (Figure 10.4).

As you just read in Section 10.1, gas exchange takes place in alveoli in the lungs. The alveoli are where the respiratory system's role in respiration ends. From there, the cardiovascular system takes over the task of moving gases (Figure 10.5), which it transports along with other substances arriving from the digestive system and moving into and out of the urinary system.

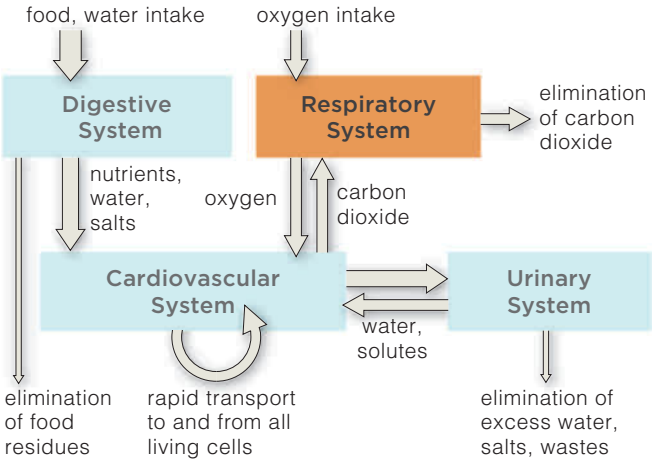


Figure 10.5 The cardiovascular system transports oxygen and carbon dioxide that are exchanged in the lungs. It is the link between the respiratory system and other organ systems.

In gas exchange, oxygen and carbon dioxide diffuse down a concentration gradient

Gas exchange in the body relies on the tendency of oxygen and carbon dioxide to diffuse down their respective concentration gradients—or, as we say for gases, their *pressure gradients*. When molecules of either gas are more concentrated outside the body, they tend to move into the body, and vice versa.

At sea level the air is about 78 percent nitrogen, 21 percent oxygen, 0.04 percent carbon dioxide, and 0.96 percent other gases. Atmospheric pressure at sea level is about 760 mm Hg, as measured by a mercury barometer (Figure 10.6). Each gas accounts for only *part* of the total pressure exerted by the whole mix of gases. Oxygen's partial pressure is 21 percent of 760, about 160 mm Hg. Carbon dioxide's partial pressure is about 0.3 mm Hg.

Gas exchange must be efficient in order to meet the metabolic needs of a large, active animal such as a human. Various factors influence the process. To begin with, gases enter and leave the body by crossing a thin **respiratory surface** of epithelium. In addition, the respiratory surface must be moist, because gases can't diffuse across it unless they are dissolved in fluid.

Two factors affect how many gas molecules can move across the respiratory surface in a given period of time. The first is surface area, and the second is the partial pressure gradient across it. Diffusion occurs faster when the surface area is large and the gradient is steep. The millions of thin-walled alveoli in your lungs provide a huge surface area for gas exchange. As you'll now read, the interaction between hemoglobin and oxygen helps maintain a steep gradient that in turn helps bring oxygen into the lungs.

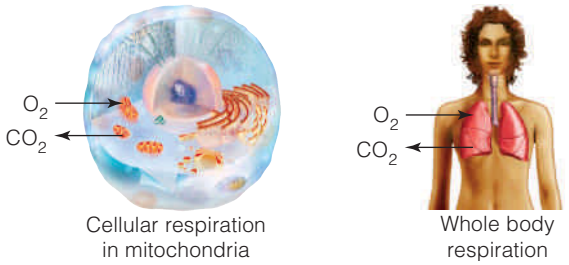


Figure 10.4 Respiration is the exchange of inhaled oxygen for waste carbon dioxide, which is exhaled.

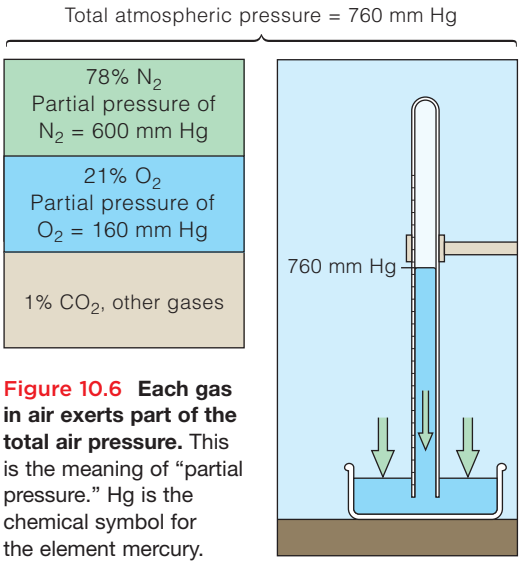


Figure 10.6 Each gas in air exerts part of the total air pressure. This is the meaning of "partial pressure." Hg is the chemical symbol for the element mercury.

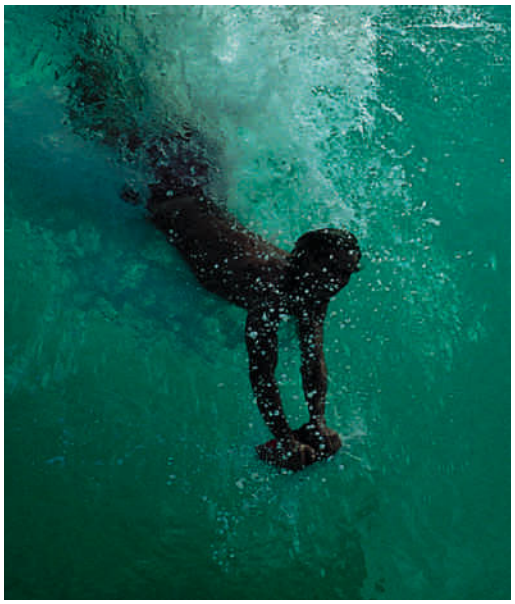


Figure 10.7 High altitudes and underwater environments present major challenges to breathing. (**a**) A climber approaches the summit of Chomolungma (Mt. Everest), where the air contains only a small amount of oxygen. (**b**) The human body is unable to extract the oxygen dissolved in water.

When hemoglobin binds oxygen, it helps maintain the steep pressure gradient

Gas exchange also gets a boost from the hemoglobin in red blood cells. Each hemoglobin molecule binds with as many as four oxygen molecules in the lungs, where the oxygen concentration is high. When blood carries red blood cells into tissues where the oxygen concentration is low, hemoglobin *releases* oxygen. Thus, by carrying oxygen away from the respiratory surface, hemoglobin helps maintain the pressure gradient that helps draw oxygen into the lungs—and into the blood in lung capillaries. Later in this chapter you will learn more about the way oxygen binds to and is released from hemoglobin.

Gas exchange "rules" change when oxygen is scarce

In environments where there is less oxygen than normal, such as at high altitude or underwater, the rules of gas exchange change. For instance, the partial pressure of oxygen falls the higher you go (Figure 10.7*a*). A person who isn't acclimatized to the thinner air at high altitude can become *hypoxic*—meaning that tissues are chronically short of oxygen. Above 2,400 meters (about 8,000 feet), the brain's respiratory centers trigger the response known as *hyperventilation*—faster, deeper breathing—to compensate for the oxygen deficiency. People with heart disease (which impairs blood pumping) or respiratory problems such as asthma may experience severe symptoms at high altitides, such as the heart pain called angina. Such pain indicates that the heart muscle is receiving too little oxygen.

When you swim or dive, there may be plenty of oxygen dissolved in the water but the body has no way to extract it. (Gills do this for a fish.) People trained to dive without oxygen tanks can stay submerged only for about three minutes (Figure 10.7*b*).

Deep divers risk "raptures of the deep" or *nitrogen narcosis*. This condition develops because water pressure increases the deeper you go, and at about 45 meters (150 feet) dangerous amounts of nitrogen gas (N_2) start to become dissolved in tissue fluid and move into cells. In brain cells the nitrogen interferes with nerve impulses, and the diver becomes euphoric and drowsy. If a diver ascends from depth too quickly, the falling pressure causes N_2 to enter the blood faster than it can be exhaled, so nitrogen bubbles may form in blood and tissues. The resulting pain (especially in joints) is called *decompression sickness*, or "the bends."

Take-Home Message

What is respiration?

- Respiration is the exchange of two gases, oxygen (O_2) and carbon dioxide (CO_2), with the outside world.
- The cardiovascular system transports O_2 and CO_2 between the lungs and tissues.
- Gas exchange in the respiratory system depends on steep partial pressure gradients between the outside and inside of the body.
- The larger the respiratory surface and the larger the partial pressure gradient, the faster gases diffuse.
- When hemoglobin in red blood cells binds oxygen, it helps maintain the pressure gradient that draws air into the lungs.

10.3 Breathing: Air In, Air Out

- **You will take about 500 million breaths by age 75—and even more if you consider that young children breathe faster than adults do.**
- **Links to the Axial skeleton 5.3, Skeletal muscles 6.2**

When you breathe, air pressure gradients reverse in a cycle

Breathing ventilates the lungs in a continuous, in/out pattern called a **respiratory cycle**. Ventilation has two phases. First, **inspiration**—or inhalation—draws a breath of air into the airways. Then, in the phase of **expiration**, or exhalation, a breath moves out.

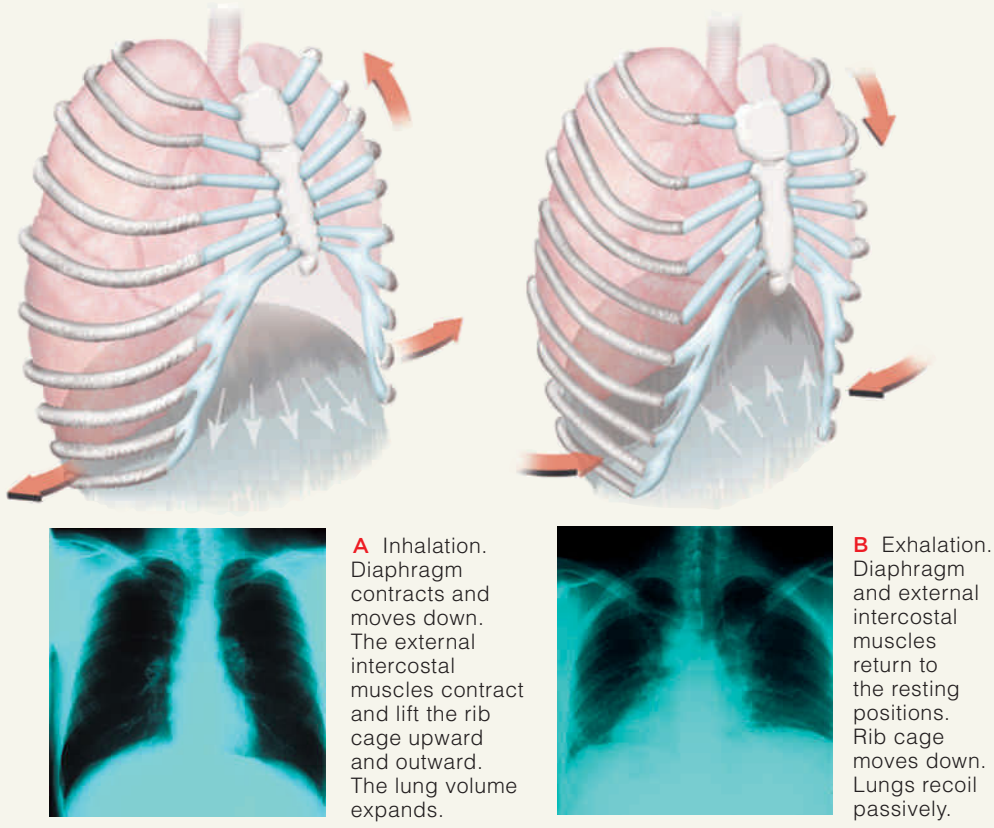
In each respiratory cycle, the volume of the chest cavity increases, then decreases (Figure 10.8). At the same time, pressure gradients between the lungs and the air outside the body are *reversed*. To understand how this shift affects breathing, it helps to remember that air in your airways (oxygen, carbon dioxide, and the other atmospheric gases) is at the same pressure as the outside atmosphere. Before you inhale, the pressure inside all your alveoli (called *intrapulmonary pressure*) is also the same as that of outside air.

The basic respiratory cycle As you start to inhale, the diaphragm contracts and flattens, and external intercostal muscle movements lift the rib cage up and out (Figure 10.8*a*). As the chest cavity expands, the lungs expand too. At that time, the air pressure in alveoli is lower than the atmospheric pressure. Fresh air follows this gradient and flows down the airways, then into the alveoli. If you take a deep breath, the volume of the chest cavity increases even more because contracting neck muscles raise the sternum and the first two ribs.

During normal, quiet breathing, expiration is passive. The muscles that contracted to bring about inspiration simply relax and the lungs recoil, like a stretched rubber band. As the lung volume shrinks, the air in the alveoli is compressed. Because pressure in the sacs now is greater than the outside atmospheric pressure, air follows the gradient and moves out of the lungs (Figure 10.8*b*).

If your lungs must rapidly expel more air—for instance, when you huff and puff while working out—expiration becomes active. Muscles in the wall of the abdomen contract, pushing your diaphragm upward, and other muscle movements reduce the volume of the chest cavity even more. Add to these changes the natural recoil of the lungs, and a great deal of air in the lungs is pushed outward.

Another pressure gradient aids the process A negative pressure gradient *outside* the lungs contributes to the respiratory cycle. Atmospheric pressure is a little bit higher than the pressure in the pleural sac that wraps around the lungs. The pressure difference is enough to make the lungs stretch and fill the expanded chest cavity. It keeps the



A Inhalation. Diaphragm contracts and moves down. The external intercostal muscles contract and lift the rib cage upward and outward. The lung volume expands.

B Exhalation. Diaphragm and external intercostal muscles return to the resting positions. Rib cage moves down. Lungs recoil passively.

Figure 10.8 Animated! The size of the chest cavity changes during a respiratory cycle. The X-ray image in (**a**) shows how taking a deep breath changes the volume of the chest (thoracic) cavity. Part (**b**) shows how the volume shrinks after exhalation.

lungs snug against the chest wall even when air is being exhaled, when the lung volume is much smaller than the space inside the chest cavity. As a result, when the chest cavity expands with the next breath, so do the lungs.

You may recall from Chapter 2 that the hydrogen bonds between water molecules prevent them from being easily pulled apart. This cohesiveness of water molecules in the fluid in the pleural sac also helps your lungs hug the chest wall, in much the same way that two wet panes of glass resist being pulled apart.

Pneumothorax, or a "collapsed lung" is caused by an injury or illness that allows air to enter the pleural cavity. The lungs can't expand normally and breathing becomes difficult and painful.

How much air is in a "breath"?

About 500 milliliters (two cupfuls) of air enters or leaves your lungs in a normal breath. This volume of air is called **tidal volume**. You can increase the amount of air you inhale or exhale, however. In addition to air taken in as part of the tidal volume, a person can forcibly inhale roughly 3,100 milliliters of air, called the *inspiratory reserve volume*. By forcibly exhaling, you can expel an additional *expiratory reserve volume* of about 1,200 milliliters of air. **Vital capacity** is the maximum volume of air that can move out of the lungs after you inhale as deeply as possible. It is about 4,800 milliliters for a healthy young man and about 3,800 milliliters for a healthy young woman. As a practical matter, people rarely take in more than half their vital capacity, even when they breathe deeply during strenuous exercise. At the end of your deepest exhalation, your lungs still are not completely emptied of air; another roughly 1,200 milliliters of *residual volume* remains (Figure 10.9).

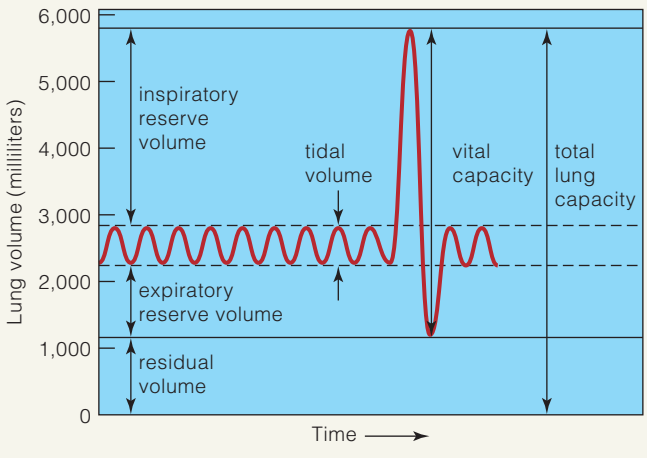
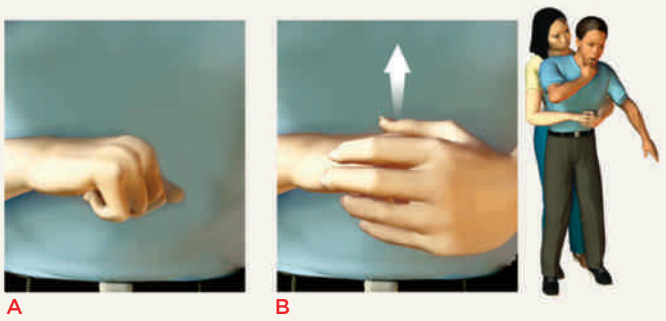


Figure 10.9 Animated! Lung volume changes during quiet breathing and during forced inspiration and expiration. In this graph you can see "spikes" above and below the normal tidal volume.

How much of the 500 milliliters of inspired air is actually available for gas exchange? Between breaths, about 150 milliliters of exhaled "dead" air remains in the airways and never reaches the alveoli. Thus only about 350 (500 − 150) milliliters of fresh air reaches the alveoli each time you inhale. An adult typically breathes at least twelve times per minute. This rate of ventilation supplies the alveoli with 4,200 (350 × 12) milliliters of fresh air every 60 seconds. This is about the volume of soda pop in four 1-liter bottles.

When food "goes down the wrong way" and enters the trachea (instead of the esophagus), air can't be inhaled or exhaled normally. A choking person can suffocate in just a few minutes. The emergency procedure called the Heimlich maneuver can dislodge food from the trachea by elevating the diaphragm muscle. This reduces the chest volume, forcing air up the trachea. Figure 10.10 shows how to perform the maneuver. With luck, the air will rush out with enough force to eject the obstruction.



1. Determine that the person is actually choking; a person who has an object lodged in their trachea cannot cough or speak.
2. Stand behind the person and place one fist below his or her rib cage, just above the navel, with your thumb facing inward as in (**a**).
3. Cover the fist with your other hand and thrust inward and upward with both fists as in (**b**). Repeat until the object is expelled.

Figure 10.10 Animated! The Heimlich maneuver is designed to save the life of an adult who is choking.

Take-Home Message

What is the respiratory cycle?

- In the respiratory cycle, the air movements of breathing occur as the volume of the chest cavity expands and shrinks. These changes alter the pressure gradients between the lungs and outside air.

10.4 How Gases Are Exchanged and Transported

- **Gas exchange during respiration provides body cells with oxygen for cellular respiration and picks up the carbon dioxide cells produce as a waste product.**
- **Links to Acid and base balance 2.7, Diffusion 3.10, How cells make ATP 3.14, How blood transports oxygen 8.2**

Physiologists divide respiration into "external" and "internal" phases. *External* respiration moves oxygen from alveoli into the blood and moves carbon dioxide in the opposite direction. During *internal* respiration, oxygen moves from the blood into tissues, and carbon dioxide moves from tissues into the blood.

Alveoli are built for gas exchange

The alveoli in your lungs are ideally constructed for their function of gas exchange. The wall of each alveolus is a single layer of epithelial cells, supported by a gossamer-thin basement membrane. Hugging the alveoli are lung capillaries (Figure 10.11*a*). They, too, have an extremely thin basement membrane around their wall. In between the two basement membranes is a film of fluid. It may seem like a lot of layers, but the **respiratory membrane** they form is far narrower than even a fine baby hair. This is why oxygen and carbon dioxide can diffuse rapidly across it—oxygen moving in and carbon dioxide moving out (Figures 10.11*b* and 10.11*c*).

Some cells in the epithelium of alveoli secrete *pulmonary surfactant*. This substance reduces the surface tension of the watery film between alveoli. Without it, the force of surface tension can collapse the delicate alveoli. This can happen to premature babies whose underdeveloped lungs do not yet have working surfactant-secreting cells. The result is a dangerous disorder called *infant respiratory distress syndrome*.

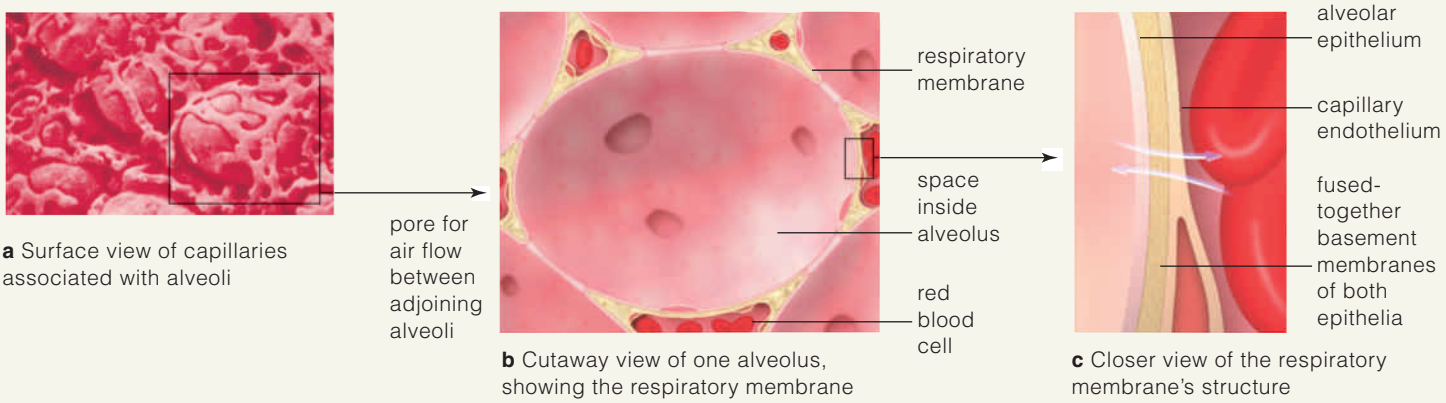
Hemoglobin is the oxygen carrier

Blood plasma can carry only so much dissolved oxygen and carbon dioxide. To meet the body's requirements, the gas transport must be improved. The hemoglobin in red blood cells binds and transports both O_2 and CO_2. This pigment enables blood to carry some 70 times more oxygen than it otherwise would and to transport 17 times more carbon dioxide away from tissues.

Air inhaled into your alveoli contains plenty of oxygen and relatively little carbon dioxide. Just the opposite is true of blood arriving from tissues—which, remember, enters lung capillaries at the "end" of the pulmonary circuit (Section 7.3). Thus, in the lungs, oxygen diffuses down its pressure gradient into the blood plasma and then into red blood cells, where up to four oxygen molecules rapidly form a weak, reversible bond with each molecule of hemoglobin. Hemoglobin with oxygen bound to it is called **oxyhemoglobin**, or HbO_2.

The amount of HbO_2 that forms depends on several factors. One is the partial pressure of oxygen—that is, the relative amount of oxygen in blood plasma. In general, the higher its partial pressure, the more oxygen will be picked up by hemoglobin, until oxygen is attached to all hemoglobin binding sites. HbO_2 will give up its oxygen in tissues where the partial pressure of oxygen is lower than in the blood. Figure 10.12 will give you an idea of the pressure gradients in different areas of the body.

In tissues with high metabolic activity—and therefore a greater demand for oxygen—the chemical conditions loosen hemoglobin's "grip" on oxygen. For example, the binding of oxygen weakens as temperature rises or as acidity increases and pH falls. Several events contribute to a falling pH. The reaction that forms HbO_2 releases hydrogen ions (H^+), making the blood more acidic. Blood



a Surface view of capillaries associated with alveoli

b Cutaway view of one alveolus, showing the respiratory membrane

c Closer view of the respiratory membrane's structure

Figure 10.11 Animated! Gases are exchanged between blood in pulmonary capillaries and air in alveoli.

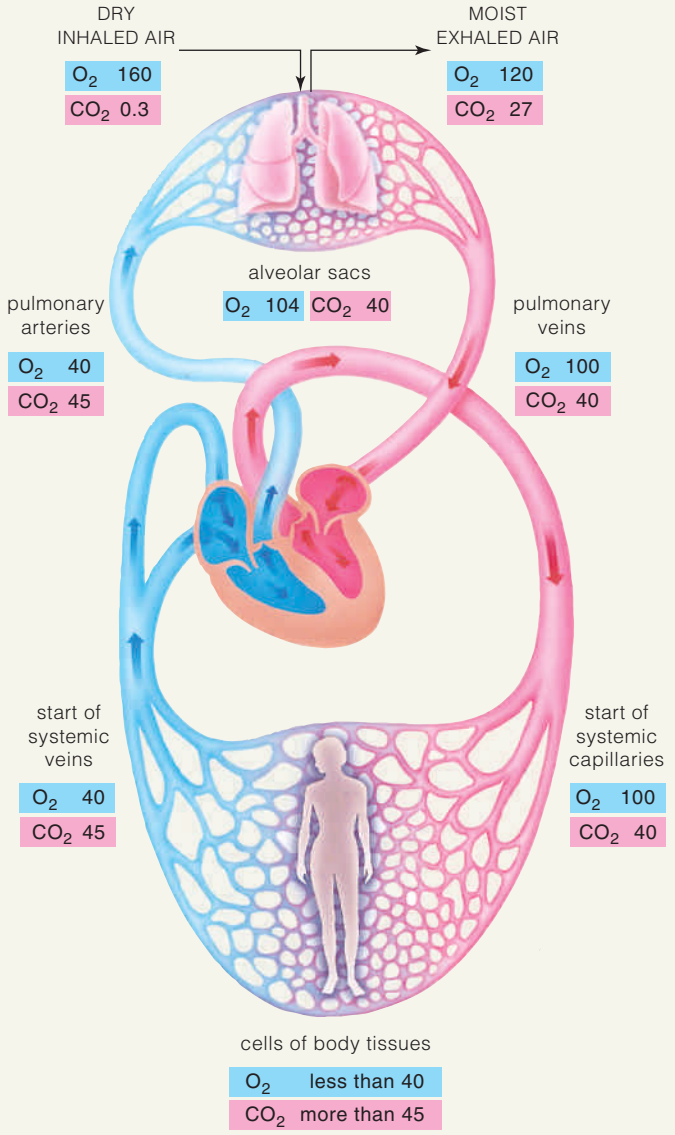


Figure 10.12 Animated! Partial pressure gradients for oxygen and carbon dioxide change as blood travels through the cardiovascular system. Remember that each gas moves from regions of higher to lower partial pressure.

pH also falls as the level of carbon dioxide given off by active cells increases.

When tissues chronically receive too little oxygen, red blood cells increase their production of a compound called 2,3-diphosphoglycerate, DPG for short. DPG reversibly binds hemoglobin. The more of it that is bound to hemoglobin, the *more loosely* hemoglobin binds oxygen—and thus the more oxygen is available to tissues.

Hemoglobin and blood plasma both carry carbon dioxide

As you know, aerobic respiration in cells produces carbon dioxide as a waste. For this reason, there is more carbon dioxide in metabolically active tissues than in the blood in the nearby capillaries. So, following its pressure gradient, carbon dioxide diffuses into these capillaries. It will be carried toward the lungs in three ways. About 7 percent stays dissolved in plasma. About another 23 percent binds with hemoglobin in red blood cells, forming the compound **carbaminohemoglobin** ($HbCO_2$). Most of the carbon dioxide, about 70 percent, combines with water to form bicarbonate (HCO_3^-). The reaction has two steps. First carbonic acid (H_2CO_3) forms; then it dissociates (that is, it separates) into bicarbonate ions and hydrogen ions:

$$CO_2 + H_2O \rightleftharpoons \underset{\text{carbonic acid}}{H_2CO_3} \rightleftharpoons \underset{\text{bicarbonate}}{HCO_3^-} + H^+$$

This reaction occurs in blood plasma and in red blood cells. However, it is faster in red blood cells, which contain carbonic anhydrase. This enzyme increases the reaction rate by at least 250 times. Newly formed bicarbonate in red blood cells diffuses into the plasma, which will carry it to the lungs. The reactions rapidly reduce the amount of carbon dioxide in the blood. By "sopping up" CO_2, the reactions help maintain the gradient that keeps carbon dioxide diffusing from tissue fluid into the bloodstream.

The reactions that make bicarbonate are reversed in alveoli, where the partial pressure of carbon dioxide is *lower* than it is in surrounding capillaries. The CO_2 that forms as the reactions go in reverse diffuses into the alveoli and is exhaled.

If you look again at the chemical reactions outlined in the pink shaded area above, you can see that the steps that form bicarbonate also produce some H^+, which makes blood more acid. What happens to these hydrogen ions? Hemoglobin binds some of them and thus acts as a buffer (Chapter 2). Certain proteins in blood plasma also bind H^+. These buffering mechanisms are extremely important in homeostasis, because they help prevent an abnormal decline in blood pH.

Take-Home Message

How are oxygen and CO_2 exchanged and transported?

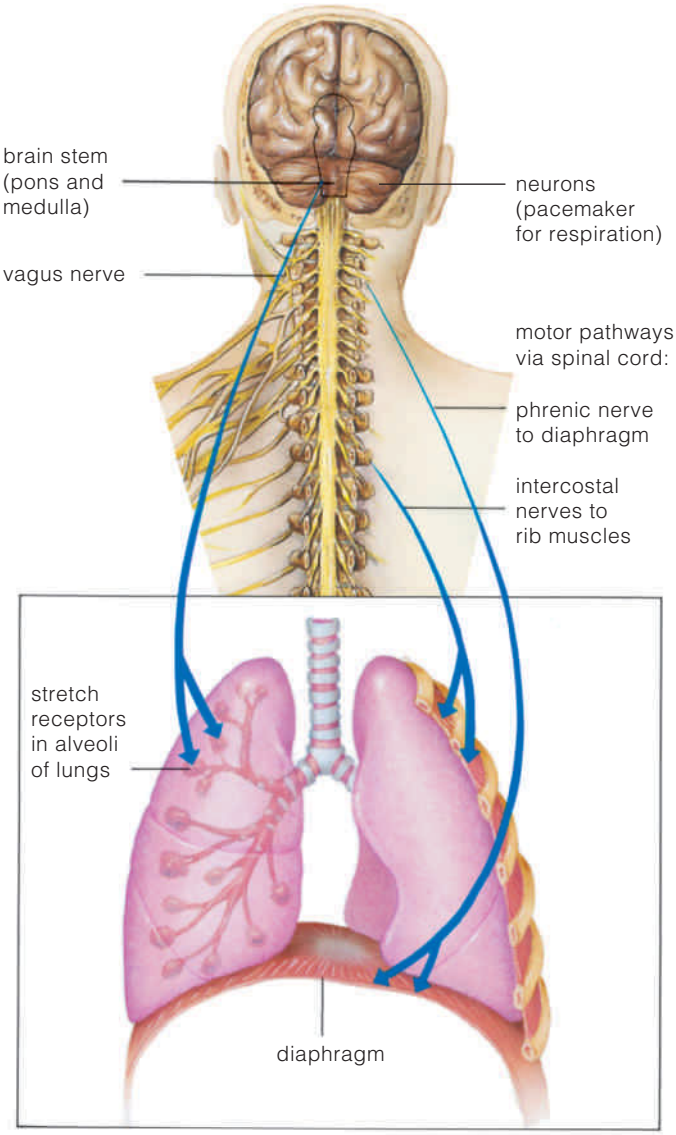
- Driven by its partial pressure gradient, oxygen diffuses from alveoli, through tissue fluid, and into lung capillaries. Carbon dioxide diffuses in the opposite direction, driven by its partial pressure gradient.
- Hemoglobin in red blood cells greatly increases the oxygen-carrying capacity of the blood.
- Hemoglobin and blood plasma also carry carbon dioxide.
- In plasma, most carbon dioxide is transported in the form of bicarbonate.
- Buffers help prevent the blood from becoming too acid due to H^+ that is released when bicarbonate forms.

10.5 Homeostasis Depends on Controls over Breathing

- **The nervous system controls muscle movements that lead to the normal rhythm of breathing. It also controls how often and how deeply you breathe.**
- **Links to the pH Scale 2.7, Structure and function of skeletal muscles 6.2, The two circuits of blood flow 7.3**

A respiratory pacemaker in the brain sets the basic rhythm of breathing

Adults usually take about 12 to 15 breaths a minute. If you had to remember to inhale and exhale each time, could you do it, even when you sleep? Luckily for us all, a respiratory center in the medulla in the brain stem, at the lower rear of the brain, provides this service. Like the heart's SA node, this center contains neurons that fire spontaneously. They are the pacemaker for respiration.



As Figure 10.13 suggests, signals from the respiratory center travel nerve pathways to the diaphragm and chest. These signals stimulate the rib cage muscles and diaphragm to contract. As you read in Section 10.3, this causes the rib cage to expand, and you inhale a breath as air moves into the lungs. In between nerve impulses, the diaphragm and chest muscles relax. Elastic recoil returns the rib cage to its unexpanded state, and you exhale as air in the lungs moves out.

Carbon dioxide is the main trigger for controls over the rate and depth of breathing

While the respiratory center governs the basic operations of breathing, other controls determine how rapidly and deeply the lungs are ventilated. Overall, these controls monitor three aspects blood chemistry: the levels of carbon dioxide and oxygen in the bloodstream, and the acidity or pH of blood. Sensory receptors that respond to chemicals are called *chemoreceptors*. Some of the sensors are in the brain stem, while others monitor the blood flowing through arteries.

You might guess that the amount of oxygen in blood is the most important factor in respiratory control systems, but actually brain stem chemoreceptors are more sensitive to levels of carbon dioxide. The receptors also detect hydrogen ions that are produced when dissolved CO_2 leaves the bloodstream and enters fluid that bathes the medulla. In this fluid (called *cerebrospinal fluid*) the drop in pH that goes along with increasing H^+ indicates that the blood is becoming more acidic. The brain's respiratory centers respond to this signal (Figure 10.14). In short order breathing becomes more rapid and deeper. Soon the blood level of CO_2 falls—and so does the blood's acidity. Notice that this is another example of a negative feedback loop helping to maintain homeostasis.

The brain also receives information about blood gases and pH from chemoreceptors in arteries. These receptors include **carotid bodies**, where the carotid arteries branch to the brain, and **aortic bodies** in artery walls near the heart. Both types of receptors detect changes in levels of carbon dioxide and oxygen in the blood. They also detect changes in blood pH. When there is too little oxygen in the blood relative to carbon dioxide and hydrogen ions, the brain responds by increasing the ventilation rate, so more oxygen can be delivered to tissues.

Figure 10.13 Several controls regulate breathing. In quiet breathing, centers in the brain stem coordinate signals to the diaphragm and muscles that move the rib cage, triggering inhalation. When a person breathes deeply or rapidly, another center receives signals from stretch receptors in the lungs and coordinates signals for exhalation.

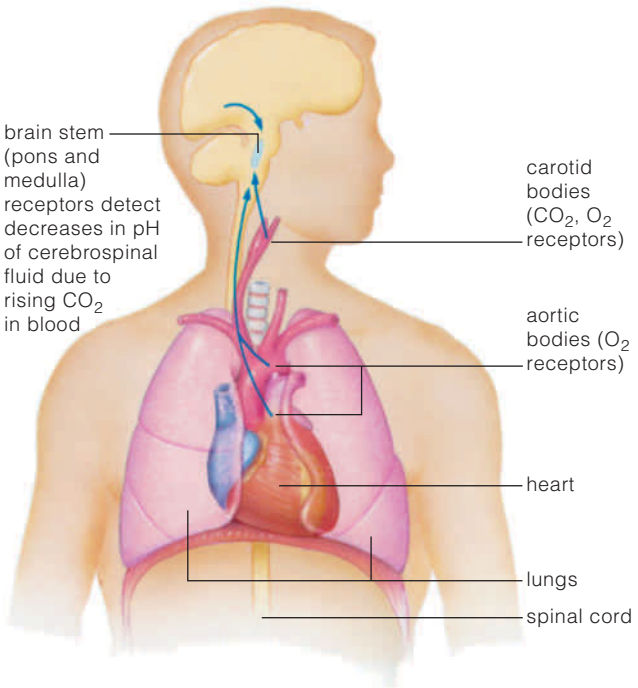


Figure 10.14 **Sensors in arteries and the brain monitor carbon dioxide, oxygen, and blood pH.**

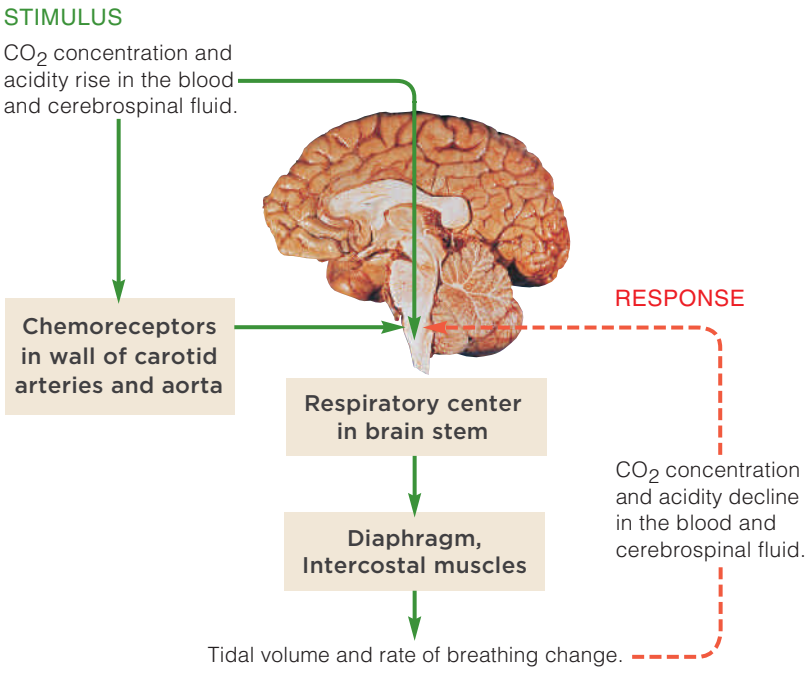


Figure 10.15 **Breathing patterns change with a person's activity level.**

Overall, the mechanisms that control our breathing allow gas exchange to match the body's activity level. For example, if you start exercising, your skeletal muscles immediately require more oxygen and begin producing more CO_2. As you have just read, these changes prompt the brain's respiratory center to step up its signals to the breathing muscles (Figure 10.15).

Other controls help match air flow to blood flow

Controls over air flow also operate in the millions of lung alveoli. For example, if you get nervous, your heart may start pumping hard and fast but your lungs may not be ventilating at a corresponding pace. If too little carbon dioxide is moving out of the lungs, the rising blood level of CO_2 makes smooth muscle in the walls of bronchioles relax and widen, so more air flows through them. On the other hand, an abnormal *decrease* in the level of carbon dioxide in the lungs causes the bronchiole walls to constrict, so less air flows through them. Shifting oxygen levels have a similar effect. If you breathe in oxygen faster than it can enter blood capillaries, the oxygen level rises in parts of the lungs, capillaries dilate. As more blood flows through them, it can pick up more oxygen. When less oxygen is available in the lungs, the vessels constrict and less blood moves through them.

Only minor aspects of breathing are under conscious control

Reflexes such as swallowing or coughing briefly halt breathing. You also can deliberately alter your breathing pattern, as when you change your normal breathing rhythm to talk, laugh, or sing, or when you hold your breath underwater. At most, however, you can only hold your breath for two or three minutes. As CO_2 builds up and your blood's chemistry shifts, "orders" from the nervous system force you to take a breath.

Take-Home Message

What automatic controls regulate breathing?

- Respiratory centers in the brain stem control the rhythmic pattern of breathing.
- Brain centers that adjust the rate and depth of breathing receive information mainly from sensors that monitor blood levels of carbon dioxide.
- These controls contribute to homeostasis by helping to maintain proper levels of carbon dioxide, oxygen, and hydrogen ions in arterial blood.

10.6 Disorders of the Respiratory System

A variety of infections and other disorders can prevent the respiratory system from functioning properly. Some of these problems develop when we inadvertantly inhale a pathogen or noxious substances, while others we bring on ourselves.

Tobacco is a major threat

People who start smoking tobacco begin wreaking havoc on their lungs. Smoke from a single cigarette can prevent cilia in bronchioles from beating for hours. Toxic particles smoke contains can stimulate mucus secretion and kill the infection-fighting phagocytes that normally patrol the respiratory epithelium.

Today we know that cigarette smoke, including "secondhand smoke" inhaled by a nonsmoker, causes lung cancer and contributes to other ills. In the body, some compounds in coal tar and cigarette smoke are converted to carcinogens (cancer-causing substances); they trigger genetic damage leading to lung cancer. Susceptibility to lung cancer is related to the number of cigarettes smoked per day and how often and how deeply the smoke is inhaled. In all, cigarette smoking causes at least 80 percent of all lung cancer deaths. Figure 10.16 lists the known health risks associated with tobacco smoking, as well as the benefits of quitting.

Irritants cause other disorders

In cities, in certain occupations, and anywhere near a smoker, airborne particles and irritating gases put extra workloads on the lungs.

Bronchitis can be brought on when air pollution increases mucus secretions and interferes with ciliary

RISKS ASSOCIATED WITH SMOKING	REDUCTION IN RISKS BY QUITTING
SHORTENED LIFE EXPECTANCY: Nonsmokers live 8.3 years longer on average than those who smoke two packs daily from the mid-twenties on.	Cumulative risk reduction; after 10 to 15 years, life expectancy of ex-smokers approaches that of nonsmokers.
CHRONIC BRONCHITIS, EMPHYSEMA: Smokers have 4–25 times more risk of dying from these diseases than do nonsmokers.	Greater chance of improving lung function and slowing down rate of deterioration.
LUNG CANCER: Cigarette smoking is a major contributing factor.	After 10 to 15 years, risk approaches that of nonsmokers.
CANCER OF MOUTH: 3–10 times greater risk among smokers.	After 10 to 15 years, risk is reduced to that of nonsmokers.
CANCER OF LARYNX: 2.9–17.7 times more frequent among smokers.	After 10 years, risk is reduced to that of nonsmokers.
CANCER OF ESOPHAGUS: 2–9 times greater risk of dying from this.	Risk proportional to amount smoked; quitting should reduce it.
CANCER OF PANCREAS: 2–5 times greater risk of dying from this.	Risk proportional to amount smoked; quitting should reduce it.
CANCER OF BLADDER: 7–10 times greater risk for smokers.	Risk decreases gradually over 7 years to that of nonsmokers.
CORONARY HEART DISEASE: Cigarette smoking is a major contributing factor.	Risk drops sharply after a year; after 10 years, risk reduced to that of nonsmokers.
EFFECTS ON OFFSPRING: Women who smoke during pregnancy have more stillbirths, and weight of liveborns averages less (hence, babies are more vulnerable to disease, death).	When smoking stops before fourth month of pregnancy, risk of stillbirth and lower birthweight eliminated.
IMPAIRED IMMUNE SYSTEM FUNCTION: Increase in allergic responses, destruction of defensive cells (macrophages) in respiratory tract.	Avoidable by not smoking.
BONE HEALING: Evidence suggests that surgically cut or broken bones require up to 30 percent longer to heal in smokers, possibly because smoking depletes the body of vitamin C and reduces the amount of oxygen reaching the tissues. Reduced vitamin C and reduced oxygen interfere with production of collagen fibers, a key component of bone. Research in this area is continuing.	Avoidable by not smoking.

Figure 10.16 **From the American Cancer Society, a list of the risks incurred by smoking and the benefits of quitting.** The photograph shows swirls of cigarette smoke at the entrance to the two bronchi that lead into the lungs.

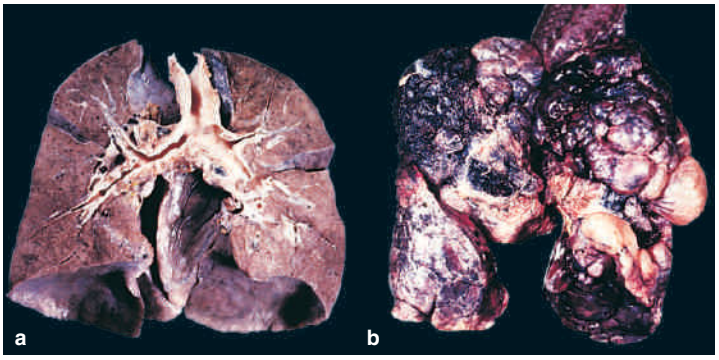


Figure 10.17 **Emphysema ravages the lungs.** (**a**) Normal human lungs that have been chemically preserved. (**b**) Lungs from a person with emphysema.

action in the lungs. Ciliated epithelium in the bronchioles is especially sensitive to cigarette smoke. Mucus and the particles it traps—including bacteria—accumulate in airways, coughing starts, and the bronchial walls become inflamed. Bacteria or chemical agents start destroying the wall tissue. Cilia in the lining die, and mucus-secreting cells multiply as the body attempts to get rid of the accumulating debris. Eventually scar tissue forms and can block parts of the respiratory tract.

In an otherwise healthy person, even acute bronchitis is easily treated with antibiotics. When inflammation continues, however, scar tissue builds up and the bronchi become chronically clogged with mucus. Also, the walls of some alveoli break down and become surrounded by stiffer fibrous tissue. The result is **emphysema**, in which the lungs are so distended and inelastic that gases cannot be exchanged efficiently (Figure 10.17). Running, walking, even exhaling can be difficult. About 1.3 million people in the United States have emphysema.

Smoking, frequent colds, and other respiratory ailments sometimes make a person susceptible to emphysema. Many emphysema sufferers lack a normal gene coding for a protein that inhibits tissue-destroying enzymes made by bacteria. Emphysema can develop over 20 or 30 years. Unfortunately, by the time the disease is detected, the lungs are permanently damaged.

Millions of people suffer from **asthma**, a disorder in which the bronchioles suddenly narrow when the smooth muscle in their walls contracts in strong spasms. At the same time, mucus gushes from the bronchial epithelium, clogging the constricted passages even more. Breathing can become extremely difficult so quickly that the victim may feel in imminent danger of suffocating. The triggers include allergens such as pollen, dairy products, shellfish, pet hairs, flavorings, or even the dung of tiny mites in house dust. In susceptible people, attacks also can be triggered by noxious fumes, stress, strenuous exercise, or a respiratory infection. While the reasons aren't fully understood, the incidence of asthma in the United States has grown rapidly in the last several decades. Some researchers believe that increased air pollution is at least partly to blame.

Figure 10.18 **Many asthma sufferers must use an aerosol inhaler.**

Many asthma sufferers rely on aerosol inhalers, which squirt a fine mist into the airways (Figure 10.18). A drug in the mist dilates bronchial passages and helps restore free breathing. Some devices contain powerful steroids that can harm the immune system, so inhalers should be used only with medical supervision.

Apnea is a condition in which breathing controls malfunction

As described in Section 10.5, respiration usually is on "autopilot,"controlled by the brain's respiratory center. In some situations, however, a person can fail to breathe in the usual pattern. Breathing that stops briefly and then resumes spontaneously is called *apnea*. During certain times in the normal sleep cycle (see Section 13.11), breathing may stop for one or two seconds or even minutes—in extreme cases, as often as 500 times a night. This *sleep apnea* may be a contributing factor in heavy snoring.

Aging also takes a toll on the respiratory system. Sleep apnea is a common problem in the elderly, because the mechanisms for sensing a change in oxygen and carbon dioxide levels gradually become less effective over the years. Also, as we age, our lungs lose some of their elasticity. This along with other changes makes ventilation of the lungs less efficient. Obese people may also have a problem with sleep apnea when fat deposits in the neck obstruct the airways. Staying physically fit, and maintaining a "lung-healthy" lifestyle in other ways, can go a long way toward keeping the respiratory system functioning well throughout life.

10.7 Pathogens and Cancer in the Respiratory System

Airborne pathogens have easy access to the airways and lungs

Inhaled viruses, bacteria, or fungi all can infect respiratory organs. A dry cough, chest pain, and shortness of breath are symptoms of **pneumonia**. The infection inflames lung tissue, and then fluid (from edema) builds up in the lungs and makes breathing difficult.

Strains of the bacterium *Streptococcus pneumoniae* can cause pneumonia and other infections. This microbe often causes outbreaks of illness among children at day care centers. Penicillin or some other antibiotic is the usual treatment for bacterial pneumonia. Unfortunately, today half of all strains of *S. pneumoniae* are resistant.

Sometimes the trigger for pneumonia is **influenza**, in which an infection that began in the nose or throat spreads to the lungs. There are many flu viruses, but several have made headlines in recent years. Figure 10.19*a* shows the virus that causes SARS, short for severe acute respiratory syndrome. A 2003 outbreak of SARS was a short-lived pandemic that began in China and eventully made its way around the globe. Government-ordered quarantines stopped its spread, but not before thousands were sickened and hundreds died. So-called "bird flu," or avian influenza, is caused by th H5N1 virus. To date it has killed nearly 200 people, nearly all of whom had close contact with infected birds. Public health authorities worry that the virus may mutate in a way that makes it transmissible between humans.

Tuberculosis (TB) is a serious lung infection caused by the bacterium *Mycobacterium tuberculosis* (Figure 10.19*b*). It starts with flulike symptoms but eventually can destroy patches of lung tissue and can spread to other parts of the body.

Although TB usually is curable with antibiotics, newer drug-resistant strains of *M. tuberculosis* have made treatment much more challenging. Untreated TB can be fatal.

A microscopic fungus causes **histoplasmosis**. The symptoms include cough, fever, and inflammation in the lungs and airways. Antifungal drugs can cure "histo," but the infection may spread to the retina of the eye, leading to permanently impaired vision or blindness.

Lung cancer is a major killer

Lung cancer kills more people than any other cancer. Long-term tobacco smoking is the overwhelming risk factor. Other risk factors are exposure to asbestos, to industrial chemicals such as arsenic, and to radiation. For a smoker, a combination of these factors greatly boosts the odds of developing cancer. For nonsmokers, especially spouses and children of smokers, inhaling tobacco smoke also poses a significant cancer risk. The Environmental Protection Agency estimates that lung cancer resulting from regularly breathing secondhand smoke kills 3,000 people in the United States each year.

In recent years, the incidence of lung cancer has fallen among men. However, a rise in the relative number of female smokers in the past several decades is now reflected in the fact that lung cancer is by far the leading cancer killer of women. Warning signs include a nagging cough, shortness of breath, chest pain, blood in coughed-up phlegm, unexplained weight loss, and frequent respiratory infections or pneumonia.

Four types of lung cancer account for 90 percent of cases. About one-third of lung cancers are **squamous cell carcinomas**, affecting squamous epithelium in the bronchi. Another 48 percent are either **adenocarcinomas** or **large-cell carcinomas**. The most aggressive type, **small-cell carcinoma**, spreads rapidly and kills most patients within 5 years. Figure 10.19*c* shows an X-ray from a patient with an advanced lung cancer.

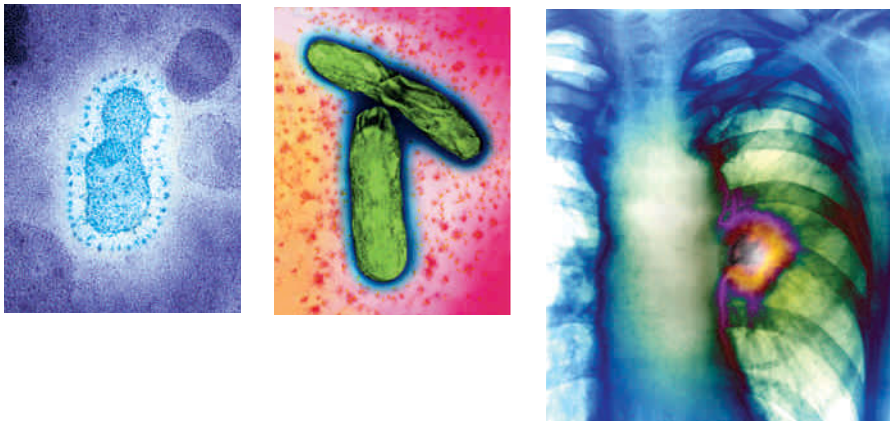
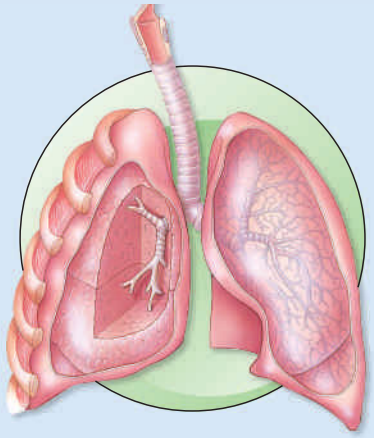


Figure 10.19 Many microbes can infect the lungs. (**a**) The SARS virus, which causes a form of influenza. (**b**) *Mycobacterium tuberculosis* causes TB. (**c**) Colored X-ray of a malignant lung tumor (*purple* and *orange*).

10.8 CONNECTIONS: The Respiratory System in Homeostasis



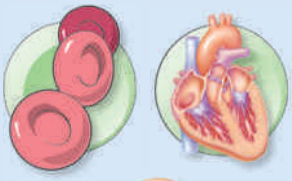
The Respiratory System

The airways and lungs bring in air and deliver the oxygen it contains into the bloodstream for transport to all living body cells. Exhaled air eliminates waste carbon dioxide that is produced as cells make ATP.

Muscular system

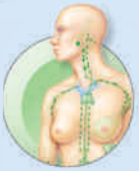
Respiratory controls over the rate and depth of breathing adjust oxygen intake and removal of carbon dioxide to service the changing demands of muscle tissue.

Cardiovascular system and blood



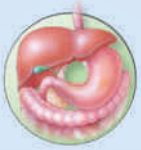
Adjustments in elimination of CO_2 help manage hydrogen ions (H^+) in blood and so help maintain blood pH (acid-base balance).

Immunity and the lymphatic system



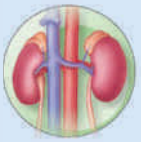
Cilia and mucus in airways trap foreign material, functioning as physical barriers to infection.

Digestive system



Voluntary contraction of the diaphragm muscle may aid voiding of feces from the large intestine/rectum.

Urinary system

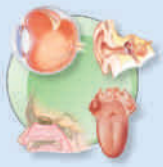


Binding H^+ by hemoglobin complements kidney functions that help maintain pH of blood and tissue fluid.

Nervous system

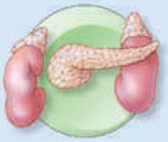
Air vibrating vocal cords allows an individual to produce spoken language.

Sensory systems



Epithelium in the nose contains sensory receptors for smell (olfaction).

Endocrine system



Cells in the lungs form an enzyme (angiotensin-converting enzyme) that acts in the formation of the hormone angiotensin II, which influences formation of urine in the kidneys.

Reproductive system

Via the mother's cardiovascular system and the placenta, supplies oxygen to and removes carbon dioxide from the blood of a developing fetus.

IMPACTS, ISSUES

Up in Smoke

How Would You Vote?

Do you believe that the United States government should support international efforts to reduce tobacco use? See CengageNOW for details, then vote online.

AMERICAN companies profit from the sale of tobacco products abroad, even while U.S. sales are declining in response to public education programs about the health dangers of tobacco use. Critics charge that the companies are simply exporting tobacco-related health problems to countries where education efforts are weaker.

Summary

Section 10.1 The respiratory system brings air, which contains oxygen, into the body and disposes of carbon dioxide.

Airways include the nasal cavity, pharynx, larynx, trachea, bronchi, and bronchioles. Gas exchange occurs in millions of saclike alveoli located at the end of the terminal respiratory bronchioles. The vocal cords are located near the entrance to the larynx.

Airways lead to the lungs, which are elastic organs located in the rib cage above the diaphragm. Membranes called pleurae enclose the lungs.

- Use the animation and interaction on CengageNOW to explore the respiratory system's parts and their functions.

Section 10.2 Respiration brings oxygen from air into the blood and removes carbon dioxide from blood. Both these processes occur in the lungs. The cardiovascular system partners with the respiratory system as it circulates blood throughout the body.

Air is a mixture of oxygen, carbon dioxide, and other gases. Each gas exerts a partial pressure, and each tends to move (diffuse) from areas of higher to lower partial pressure. Following pressure gradients, oxygen tends to diffuse into deoxygenated blood in the lungs, and carbon dioxide tends to diffuse out of the blood and into the lungs to be exhaled.

In respiration, oxygen and carbon dioxide diffuse across a respiratory surface—a moist, thin layer of epithelium in the alveoli of the lungs. Airways carry gases to and from one side of the respiratory surface, and blood vessels carry gases to and away from the other side.

- Use the animation and interaction on CengageNOW to investigate the effects of partial pressure gradients in the body.

Section 10.3 Breathing ventilates the lungs in a respiratory cycle. During inspiration (inhalation), the chest cavity expands, pressure in the lungs falls below atmospheric pressure, and air flows into the lungs. During normal expiration (exhalation), these steps are reversed.

The volume of air in a normal breath, called the tidal volume, is about 500 milliliters. Vital capacity is the maximum volume of air that can move out of the lungs after you inhale as deeply as possible.

- Use the animation and interaction on CengageNOW to learn more about the respiratory cycle.

Section 10.4 Driven by its partial pressure gradient, oxygen in the lungs diffuses from alveoli into pulmonary capillaries. Then it diffuses into red blood cells and binds with hemoglobin, forming oxyhemoglobin. In tissues where cells are metabolically active, hemoglobin gives up oxygen, which diffuses out of the capillaries, across tissue fluid, and into cells.

Hemoglobin binds with or releases oxygen in response to shifts in oxygen levels, carbon dioxide levels, pH, and temperature.

Driven by its partial pressure gradient, carbon dioxide diffuses from cells across tissue fluid and into the bloodstream. Most CO_2 reacts with water to form bicarbonate; the reactions are speeded by the enzyme carbonic anhydrase. They are reversed in the lungs, where carbon dioxide diffuses from lung capillaries into the air spaces of the alveoli, then is exhaled.

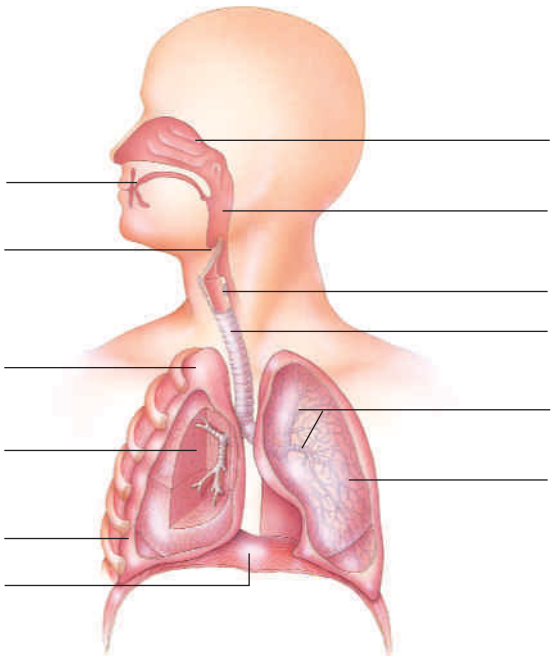
Section 10.5 Gas exchange is regulated by the nervous system and by chemical controls in the lungs. A respiratory pacemaker in the medulla (part of the brain stem) sets the normal, automatic rhythm of breathing in and out (ventilation).

The nervous system monitors the levels of oxygen and carbon dioxide in arterial blood by way of sensory receptors. These include carotid bodies (at branches of carotid arteries leading to the brain), aortic bodies (in an arterial wall near the heart), and receptors in the medulla of the brain. Blood levels of carbon dioxide are most important in triggering nervous system commands that adjust the rate and depth of breathing.

Sections 10.6, 10.7 Infections, toxins in tobacco smoke and polluted air, and damage from inflammation cause respiratory disorders including bronchitis, emphysema, pneumonia, asthma, tuberculosis, and cancer.

Review Questions

1. In the diagram on the next page, label the parts of the respiratory system and the structures that enclose some of its parts.
2. What is the difference between respiration and aerobic cellular respiration?



3. Explain what a partial pressure gradient is and how such gradients figure in gas exchange.

4. What is oxyhemoglobin? Where does it form?

5. What drives oxygen from the air spaces in alveoli, through tissue fluid, and across capillary epithelium? What drives carbon dioxide in the opposite direction?

6. How does hemoglobin help maintain the oxygen partial pressure gradient during gas transport in the body?

7. What reactions enhance the transport of carbon dioxide throughout the body? How is carbon dioxide moved out of the body?

8. How do nerve impulses from the brain regulate ventilation of the lungs? How are the rate and depth of breathing controlled?

9. Why does your breathing rate increase when you exercise? What happens to your heart rate at the same time—and why?

Self-Quiz *Answers in Appendix V*

1. A partial pressure gradient of oxygen exists between _____.
   a. air and lungs
   b. lungs and metabolically active tissues
   c. air at sea level and air at high altitudes
   d. all of the above

2. The _____ is an airway that connects the nose and mouth with the _____.
   a. oral cavity; larynx
   b. pharynx; trachea
   c. trachea; pharynx
   d. pharynx; larynx

3. Oxygen in air must diffuse across _____ to enter the blood.
   a. pleural sacs
   b. alveolar sacs
   c. a moist respiratory surface
   d. both b and c

4. Each lung encloses a _____.
   a. diaphragm
   b. bronchial tree
   c. pleural sac
   d. both b and c

5. Gas exchange occurs at the _____.
   a. two bronchi
   b. pleural sacs
   c. alveoli
   d. both b and c

6. Breathing _____.
   a. ventilates the lungs
   b. draws air into airways
   c. expels air from airways
   d. causes reversals in pressure gradients
   e. all of the above

7. After oxygen diffuses into lung capillaries it also diffuses into _____ and binds with _____.
   a. tissue fluid; red blood cells
   b. tissue fluid; carbon dioxide
   c. red blood cells; hemoglobin
   d. red blood cells; carbon dioxide

8. Due to its partial pressure gradient, carbon dioxide diffuses from cells into interstitial fluid and into the _____; in the lungs, carbon dioxide diffuses into the _____.
   a. alveoli; bronchioles
   b. bloodstream; bronchioles
   c. alveoli; bloodstream
   d. bloodstream; alveoli

9. Hemoglobin performs which of the following respiratory functions?
   a. transports oxygen
   b. transports some carbon dioxide
   c. acts as a buffer to help maintain blood pH
   d. all of the above

10. Most carbon dioxide in the blood is in the form of _____.
    a. carbon dioxide
    b. carbon monoxide
    c. carbonic acid
    d. bicarbonate

Critical Thinking

1. People occasionally poison themselves with carbon monoxide by building a charcoal fire in an enclosed area. Assuming help arrives in time, what would be the *most* effective treatment: placing the victim outdoors in fresh air, or administering pure oxygen? Explain your answer.

2. Skin divers and swimmers sometimes purposely hyperventilate. Doing so doesn't increase the oxygen available to tissues. It does increase blood pH (making it more alkaline), and it decreases the blood level of carbon dioxide. Based on your reading in this chapter, what effect is hyperventilation likely to have on the neural controls over breathing?

3. Underwater, we humans can't compete with whales and other air-breathing marine mammals, which can stay submerged for extended periods. At the beach one day you meet a surfer who tells you that special training could allow her to swim underwater without breathing for an entire hour. From what you know of respiratory physiology, explain why she is mistaken.
4. When you sneeze or cough, abdominal muscles contract suddenly, pushing your diaphragm upward. After reviewing the discussion of the respiratory cycle in Section 10.3, explain why this change forcefully expels air out your nose and mouth.
5. Physiologists have discovered that the nicotine in tobacco is as addictive as heroin. The cigarette-smoking child in Figure 10.20 probably is already addicted, and for sure has already begun to endanger her health. Based on the discussion in Section 10.6, what negative health effects might beset her in the coming years?

Figure 10.20 **This child in Mexico City is already "a pro" at smoking cigarettes.**

EXPLORE ON YOUR OWN

Air pollution is a serious problem in many parts of the world. Even if you don't live near a large urban area, you may be breathing the kinds of air pollutants shown in the chart in Figure 10.21. The ultrafine particulates can stay in the air for weeks or months before they settle to Earth or are washed down by rain, and all of them are known to cause respiratory problems, especially in people who have asthma or emphysema.

Explore this health issue by finding out if your community monitors its air quality. If so, what do authorities consider to be the greatest threats to the health of you and your fellow citizens? Where do these pollutants come from?

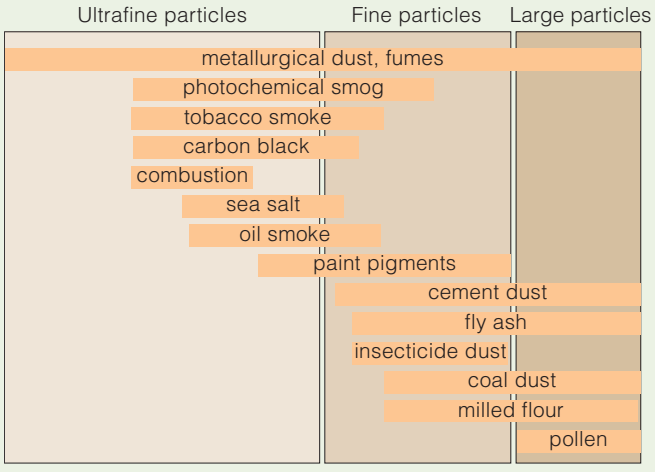


Figure 10.21 **Numerous types of particles may be present in the air you breathe.**

Digestion and Nutrition

11

IMPACTS, ISSUES

Food for Thought

IN the United States, 60 percent of adults are overweight or obese. Excess weight is a risk factor for diabetes, heart disease, diabetes, and some forms of cancer. A few extremely obese people, like the young woman pictured at left, have gastric bypass surgery. The procedure closes off much of the stomach and part of the small intestine. Those who have the surgery can eat only a small amount before feeling full, which reduces the amounts of nutrients that can be absorbed.

Like other mammals, we have fat-storing cells concentrated in adipose tissue. This energy warehouse evolved among our early ancestors, who did not have reliable sources of food. Stored body fat helped them through lean times. Once these cells form, they are in the body to stay. When you take in more calories than you burn, the cells fill with fat droplets.

Adipose cells make a hormone called leptin, which acts on a part of the brain that deals with appetite. Laboratory mice that can't make leptin eat nonstop. Does a lack of leptin also make overweight people eat too much? Unfortunately, no. Tests show that many overweight people have *more* leptin in their blood. It's possible that their leptin receptors are not functioning properly. Or maybe their body cells just don't have enough of the receptors.

The stomach also weighs in on your eating habits. Some stomach cells secrete a hormone called ghrelin, which triggers hunger. When your stomach is empty, more ghrelin is released. The level falls again after a meal.

Researchers have discovered that some hormones promote weight loss. One is cholecystokinin (CCK). Could a drug that promotes CCK secretion help prevent obesity? That question is under study.

Appetite, eating, and body weight are all part of the bigger picture of digestion and nutrition. This chapter discusses how the digestive system brings into the body the nutrients cells need to survive. The digestive system interacts with other organ systems as it makes this important contribution to homeostasis.

KEY CONCEPTS

The Digestive System

The digestive system mechanically and chemically breaks down food, absorbs nutrients, and eliminates the residues. Sections 11.1–11.8

Disorders of the Digestive System and Homeostasis

Sections 11.9–11.11

Nutrition and Body Weight

Food should supply the nutrients, vitamins, and minerals body cells require. Sections 11.12, 11.13

Body weight depends on the balance between energy from food and energy used by the body. Section 11.14

LINKS TO EARLIER CONCEPTS

- This chapter explains how digestion breaks down carbohydrates (2.9), proteins (2.11), and lipids (2.10) in food.
- Nutrient molecules enter the bloodstream by way of transport mechanisms described in Chapter 3, including diffusion and osmosis (3.10) and active transport (3.11).
- The chapter also builds on what you have learned about different sources that can supply the body's energy needs (3.16).
- Food digestion and the absorption of nutrients support homeostasis by providing many of the raw materials cells use to build and operate their parts (2.8, 3.2).

How Would You Vote?

Obesity may soon replace smoking as the main cause of preventable deaths in the United States. Fast food is contributing to the problem. Should fast-food items be required to carry health warnings? See CengageNOW for details, then vote online.

11.1 Overview of the Digestive System

- **The digestive system is a long tube where food is broken down and nutrients in it are absorbed.**
- **Link to Exocrine glands 4.1**

Our **digestive system** is a tube with two openings and many specialized organs. It extends from the mouth to the anus and is also called the **gastrointestinal (GI) tract**. Stretched out, the gastrointestinal tract would be 6.5 to 9 meters (21 to 30 feet) long in an adult.

An interesting fact about the GI tract is that while food or lefotover residues are in it, technically the material is still outside the body. Nutrients don't "officially" enter the body until they move from the *lumen*—the space inside the digestive tube into the bloodstream. Blood delivers nutrients to cells throughout the body.

From beginning to end, epithelium lines the surfaces facing the lumen. The lining is coated with thick, moist mucus that protects the wall of the tube and enhances the diffusion of substances across it.

When we eat, food advances in one direction, from the mouth (the oral cavity) through the pharynx, the esophagus, stomach, small intestine, and large intestine. The large intestine ends in the rectum, anal canal, and anus. Figure 11.1 diagrams an adult's digestive system.

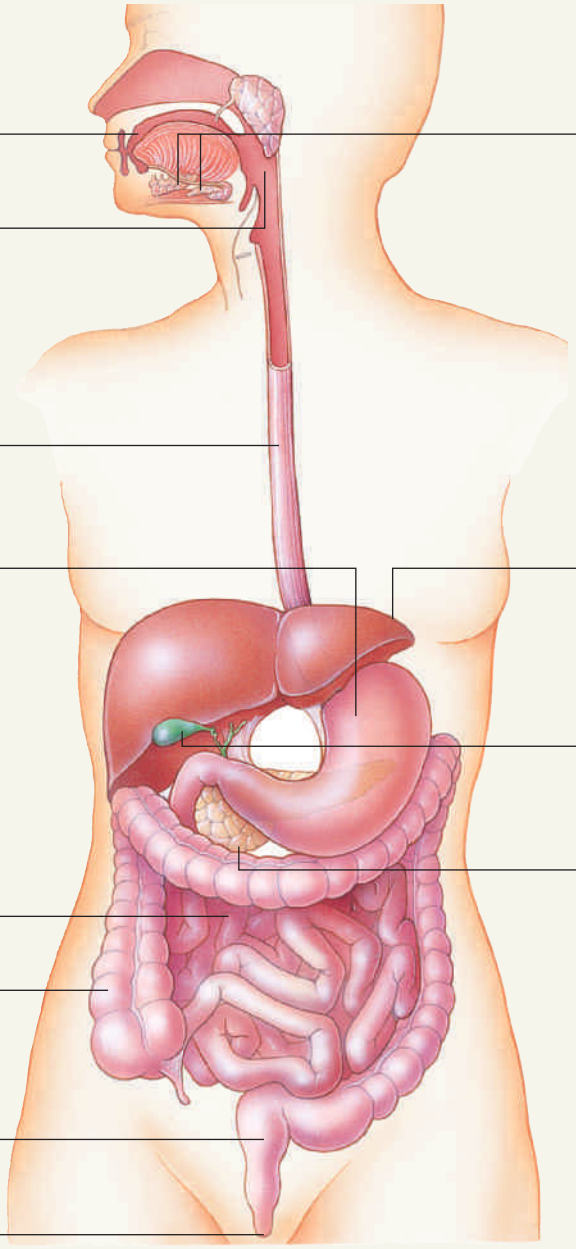


Figure 11.1 Animated! The digestive system has major and accessory organs.

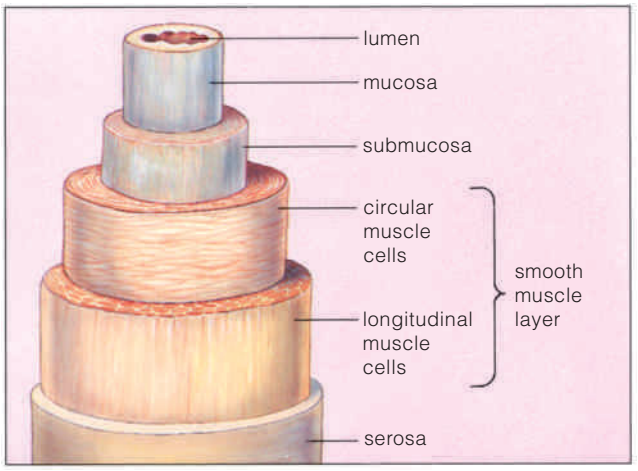


Figure 11.2 Four layers make up the wall of the digestive tract. The layers are not drawn to scale in this diagram.

The digestive tube has four layers

From the esophagus onward, the digestive tube wall has four layers (Figure 11.2). The innermost layer is a mucosa of epithelial cells. It lines the lumen, the space through which food passes. The mucosa is surrounded by the submucosa, a layer of connective tissue with blood and lymph vessels and nerve cells. The next layer is smooth muscle—usually two sublayers, one circling the tube and the other oriented lengthwise. An outer layer, the serosa, is a very thin serous membrane (Section 4.7). Circular arrays of smooth muscle at the junctions between sections of the GI tract are **sphincters**. Sphincter contractions can close off a passageway. In your stomach, for example, they help pace the forward flow of food and prevent it from moving backward.

The digestive system has five core tasks

Overall the digestive system performs five functions:

1. **Mechanical processing** and **motility.** Movements of various parts, such as the teeth, tongue, and muscle layers, break up, mix, and propel food material.
2. **Secretion.** Digestive enzymes and other substances are released into the digestive tube.
3. **Digestion.** Food is chemically broken down into nutrient molecules small enough to be absorbed.
4. **Absorption.** Digested nutrients and fluid pass across the tube wall and into blood or lymph.
5. **Elimination.** Undigested and unabsorbed residues are excreted from the end of the GI tract.

Several structures release enzymes or other chemicals used in various aspects of digestion and absorption. These accessory organs include glands in the GI tract wall; the salivary glands; and the liver, gallbladder, and pancreas.

Homeostasis overview

The flow diagram in Figure 11.3 gives a general idea of how the digestive system fits into the larger picture of homeostasis in the body. For instance, once nutrients from food have entered the bloodstream, the circulating blood carries them throughout the body. The respiratory system keeps all body cells, including those of digestive system tissues and organs, supplied with the oxygen they need for aerobic respiration and removes carbon dioxide wastes. And although food residues are eliminated by the digestive system itself, the urinary system disposes of many other wastes or unneeded substances (such as excess salt) that enter the blood from the GI tract. Together these adjustments help maintain the proper volume and chemical makeup of the extracellular fluid. With this overview in mind, let's now see how each major part of the digestive system performs its functions.

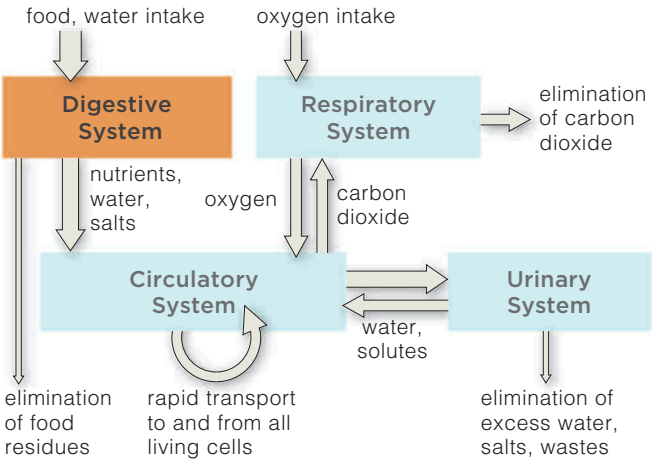


Figure 11.3 The digestive system works together with other organ systems. This diagram is an overview of links between the digestive system and the circulatory system, respiratory system, and urinary system.

Take-Home Message

What are the basic structures and functions of the digestive system?

- The digestive tube extends from the mouth to the anus. The tube also is called the gastrointestinal tract.
- For most of its length the tube wall consists of four layers, including smooth muscle.
- The digestive system's core tasks are mechanical processing and motility, secretion of substances such as enzymes, chemical digestion of food, absorption of nutrients, and elimination of residues.
- The digestion and absorption of food make a vital contribution to homeostasis as interactions among the digestive, circulatory, respiratory, and urinary systems supply cells with raw materials and dispose of wastes.

11.2 Chewing and Swallowing: Food Processing Begins

- **Food processing begins the moment food enters your mouth, where enzymes begin chemical digestion of starches.**
- **Link to Carbohydrates 2.9**

The teeth tear and grind bulk food into smaller chunks

In the oral cavity, or mouth, the food you eat begins to be broken apart by chewing. Most adults have thirty-two teeth (Figure 11.4*a*). Young children have just twenty so-called primary teeth. A tooth's crown (Figure 11.4*b*) is coated with tooth enamel. It consists of hardened calcium deposits and is the hardest substance in the body. The enamel covers a living, bonelike layer called dentin. Dentin and an inner pulp extend into the root. The pulp cavity contains blood vessels and nerves.

The shape of a tooth fits its function. Chisel-shaped incisors bite off chunks of food, and cone-shaped canines (cuspids) tear it. Premolars and molars, with broad crowns and rounded cusps, grind it.

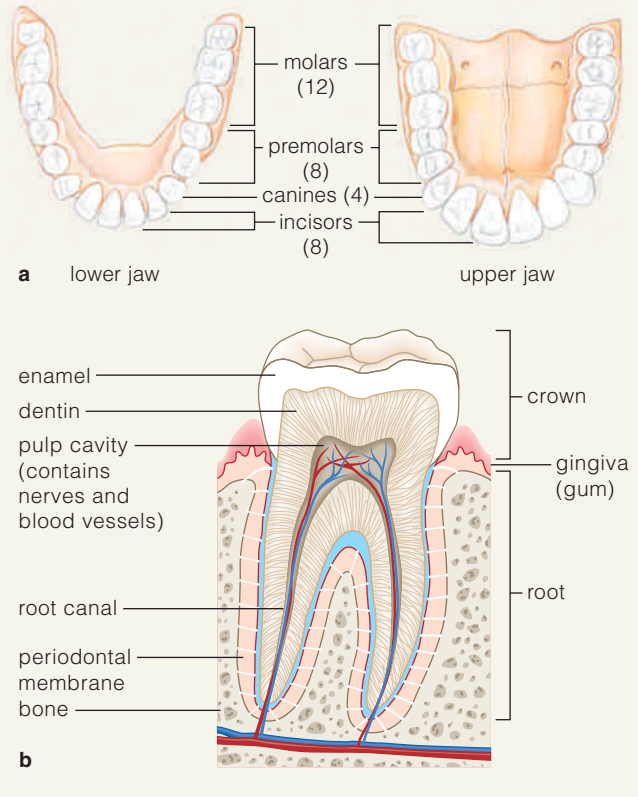


Figure 11.4 Animated! The structure of a tooth, including its shape, fits its function.

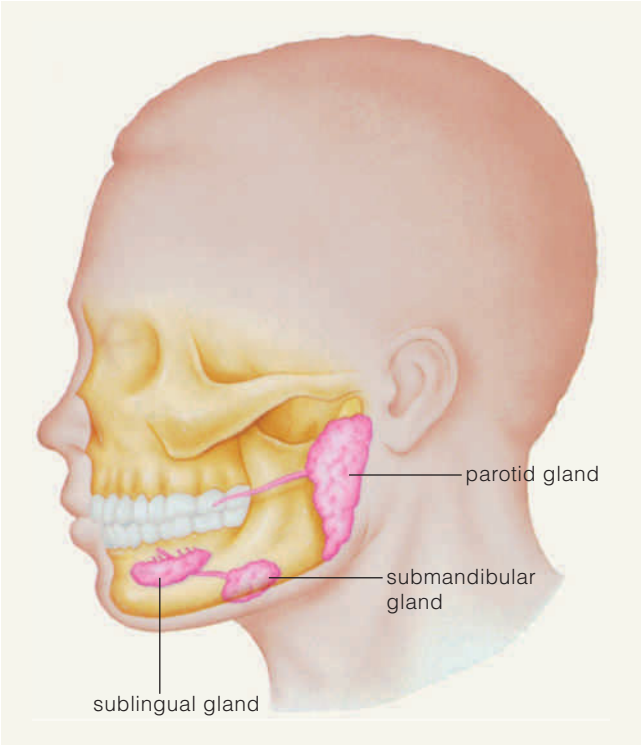


Figure 11.5 Animated! Salivary glands release saliva into various regions of the mouth.

Enzymes in saliva begin the chemical digestion of food

Chewing mixes food with saliva from several **salivary glands** (Figure 11.5). A large parotid gland nestles just in front of each ear. Submandibular glands lie just below the lower jaw in the floor of the mouth, and sublingual glands are under your tongue. The tongue itself is skeletal muscle covered by a membrane. As described in Chapter 14, its taste receptors respond to dissolved chemicals.

Saliva is mostly water, but it includes other important substances. One, the enzyme **salivary amylase**, breaks down starch; chew on a soda cracker and you can feel it turning to mush as salivary amylase goes to work. A buffer, bicarbonate (HCO_3^-), keeps the pH of your mouth between 6.5 and 11.5, a range within which salivary amylase can function. Saliva also contains mucins, proteins that help bind food bits into a lubricated ball called a **bolus** (boe-lus). Starch digestion continues in the stomach until acids there inactivate salivary amylase.

The roof of the mouth, a bone-reinforced section of the **palate**, provides a hard surface against which the tongue can press food as it mixes it with saliva. Tongue muscle contractions force the bolus into the **pharynx** (FARE-inks; throat). This passageway connects with the windpipe, or *trachea*

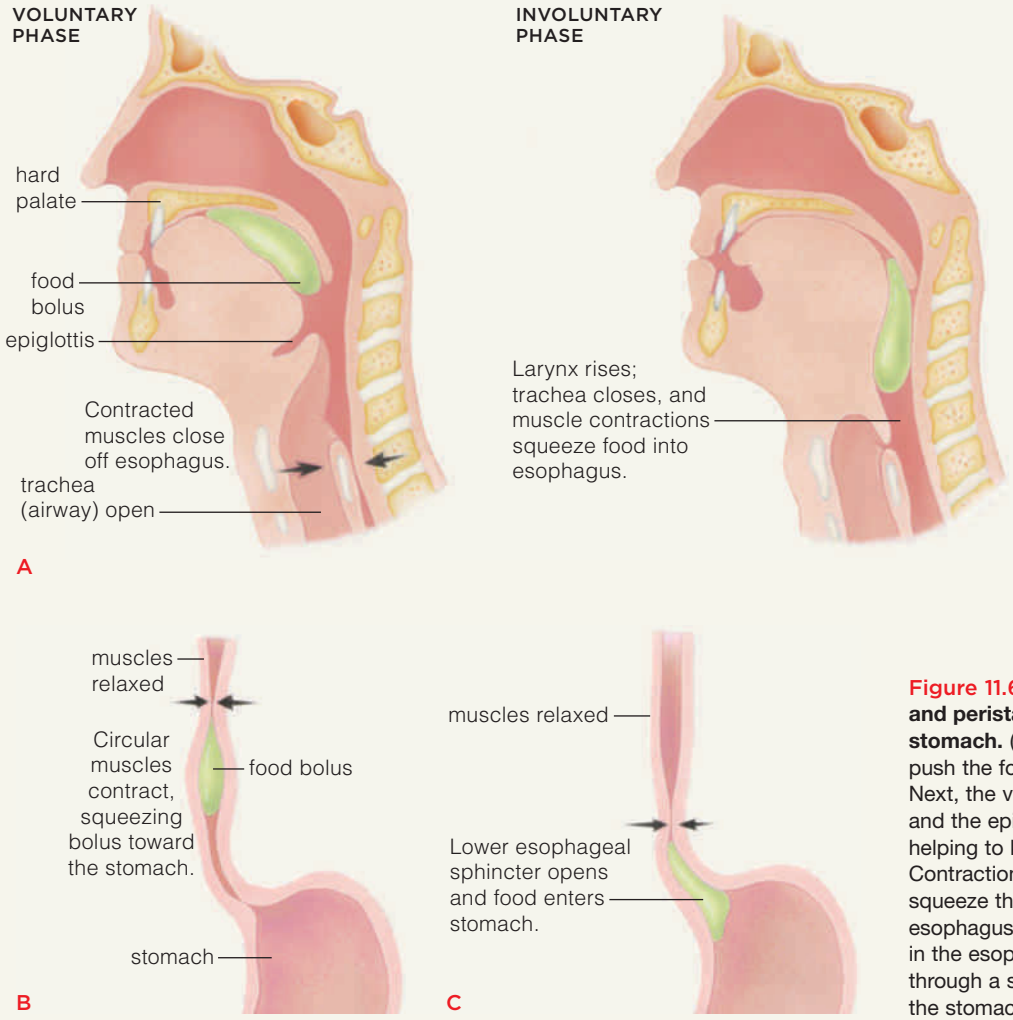


Figure 11.6 **Animated! Swallowing and peristalsis move food toward the stomach.** (**a**) Contractions of the tongue push the food bolus into the pharynx. Next, the vocal cords seal off the larynx, and the epiglottis bends downward, helping to keep the trachea closed. Contractions of throat muscles then squeeze the food bolus into the esophagus. (**b**,**c**) Finally, peristalsis in the esophagus moves the bolus through a sphincter, and food enters the stomach.

(Figure 11.6), which leads to the lungs. It also connects with the **esophagus**, which leads to the stomach. Mucus secreted by the membrane lining the pharynx and esophagus lubricates the bolus, helping move food on its way.

Swallowing has voluntary and involuntary phases

Swallowing food might seem simple, but it involves a sequence of events (Figure 11.6). Swallowing begins when voluntary skeletal muscle contractions push a bolus into the pharynx, stimulating sensory receptors in the pharynx wall. The receptors trigger a reflex in which involuntary muscle contractions keep food from moving up into your nose and down into the trachea. As this reflex occurs, the vocal cords are stretched tight across the entrance to the larynx (your "voice box"). Then, the flaplike epiglottis is pressed down over the vocal cords as a secondary seal. For a moment, breathing stops as food moves into the esophagus, so you normally don't choke when you swallow. When swallowed food reaches the lower esophagus, it passes through a sphincter into the stomach (Figures 11.6*b* and 11.6*c*). Waves of muscle contractions called **peristalsis** (pare-ih-STAL-sis) help push the food bolus along.

Take-Home Message

What are the roles of chewing and swallowing in digestion?

- As food is chewed, the teeth and tongue start breaking it up mechanically.
- Enzymes in saliva begin the chemical digestion of starches.
- Swallowed food moves down the esophagus, through the lower esophageal sphincter, and into the stomach.

11.3 The Stomach: Food Storage, Digestion, and More

- **The stomach is a complex organ with multiple functions in processing food.**
- **Links to Exocrine glands 4.1, Epithelial membrane 4.6**

The **stomach** is a muscular, stretchable sac (Figure 11.7*a*) with three functions:

1. It mixes and stores ingested food.
2. It produces secretions that help dissolve and break down food particles, especially proteins.
3. It helps control the passage of food into the small intestine.

The surface of the stomach wall facing the lumen is lined with glandular epithelium. Each day, gland cells in the lining release about two liters (1 quart) of hydrochloric acid (HCl), mucus, and other substances. These include **pepsinogens**, precursors of digestive enzymes called **pepsins**. Other gland cells secrete intrinsic factor, a protein required for vitamin B_{12} to be absorbed later on, in the small intestine. Along with water, these substances make up the stomach's strongly acidic **gastric juice**. Combined with the mixing due to stomach contractions, the acidity converts swallowed boluses into a thick mixture called **chyme** (KIME). The acidity kills most microbes in food. It also can cause "heartburn" when gastric fluid sloshes back up into the esophagus.

The digestion of proteins starts when the high acidity denatures proteins and exposes their peptide bonds. The acid also converts pepsinogens to active pepsins, which break the bonds, "chopping" the protein into fragments. Meanwhile, gland cells secrete the hormone gastrin, which stimulates cells that secrete HCl and pepsinogen.

Why don't HCl and pepsin break down the stomach lining? Usually, mucus and bicarbonate protect the lining. These protections form the "gastric mucosal barrier." The barrier is not 100 percent foolproof, however. A bacterium known as *Helicobacter pylori* produces a toxin that inflames the stomach lining. Tight junctions that normally prevent HCl from passing between its cells break down, allowing hydrogen ions and pepsins to diffuse into the lining—and that does further damage. The resulting open sore is called a *peptic ulcer*. Antibiotics can cure peptic ulcers caused by *H. pylori*. They do not help with the 20 percent of ulcers related to factors such as chronic emotional stress, smoking, and overuse of aspirin and alcohol.

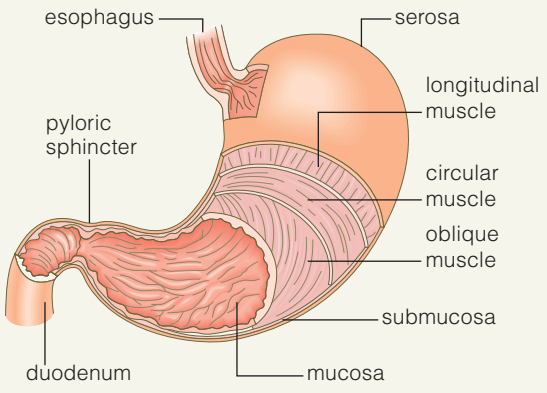
Waves of peristalsis move food out of the stomach. These waves mix chyme and build force as they approach the pyloric sphincter at the stomach's base (Figure 11.7*b*). When a strong contraction arrives, the sphincter closes, squeezing most of the chyme back. Only a small amount moves into the small intestine at a given time. In this way the stomach regulates the rate at which food moves onward, so that food is not passed along faster than it can be processed. Depending mainly on the fat content and acidity of chyme, it can take from two to six hours for a full stomach to empty. When the stomach is empty, its walls crumple into folds called **rugae**.

Water and alcohol are two of a few substances that begin to be absorbed across the stomach wall. Liquids imbibed on an empty stomach pass rapidly to the small intestine, where further absorption occurs. When food is in the stomach, gastric emptying slows. This is why the effects of alcohol are more gradual when drinking accompanies a meal.

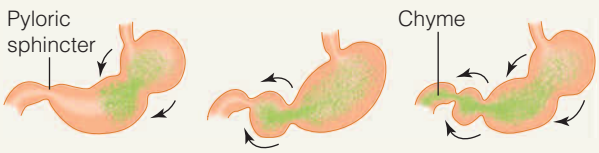
Take-Home Message

What are the main functions of the stomach?

- The stomach's functions are storing food, initial digestion of proteins, and regulating passage of food (in the form of chyme) into the small intestine.



a



1 Circular muscle contracts in a wave, pushing the chyme onward.

2 The longitudinal layer contracts, making space for the contents to advance.

3 Partially processed food (chyme) enters the small intestine.

b

Figure 11.7 Animated! The stomach's structure allows it to store and mix food and move it onward. (**a**) Structure of the stomach. (**b**) How a peristaltic wave moves down the stomach.

11.4 The Small Intestine: A Huge Surface for Digestion and Absorption

- **Your small intestine—about an inch and a half in diameter and 6 meters (20 feet) long—absorbs most nutrients.**

The structure of the small intestine wall is the key to its ability to absorb nutrients. Figure 11.8 shows how densely folded the mucosa is, and how the folds all stick out like ruffles into the lumen. Each fold has even smaller, finger-like projections called **villi** (singular: villus). They in turn are blanketed with epithelial cells that have a brushlike crown of still tinier projections called **microvilli**. All these structures are exposed to the small intestine's lumen.

What is the benefit of so many folds and projections from the intestinal mucosa? Together, they greatly increase the surface area for absorbing nutrients from chyme. Without that huge surface area, absorption would take place too slowly to sustain life.

Figure 11.8*c* shows the structure of a **villus**. Each one is about 1 millimer long, and there are millions of them—so many, in fact, that the mucosa looks velvety. Small blood vessels (an arteriole and a vein) in each villus and a lymph vessel move substances to and from the bloodstream (Figure 11.8*d*).

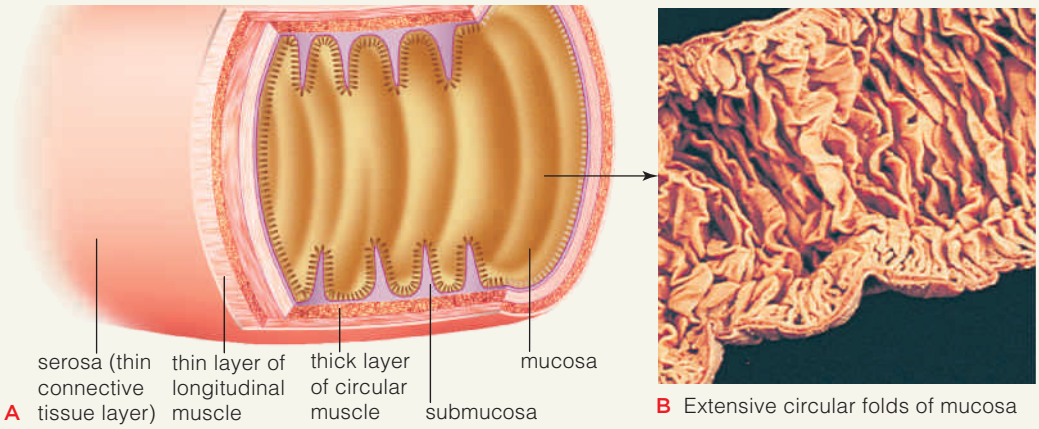
Most cells in the epithelium covering each villus bear microvilli (singular: microvillus). A **microvillus** is a threadlike projection of the epithelial cell's plasma membrane. Each epithelial cell has about 1,700 of them. This dense array gives the epithelium of villi its common name, the "brush border." Gland cells in the lining release digestive enzymes, and defensive cells called phagocytes ("cell eaters") patrol and help protect the lining.

Take-Home Message

How does the small intestine's structure aid the absorption of nutrients?

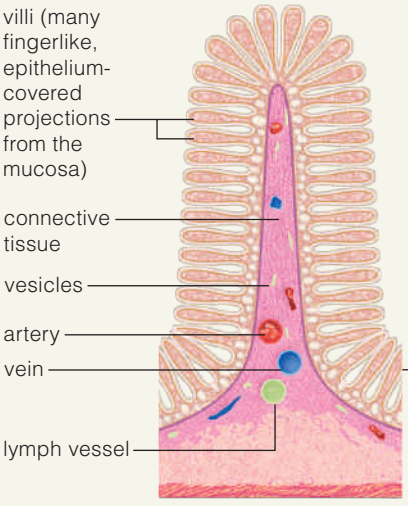
- A folded mucosa, millions of villi, and hundreds of millions of microvilli give the small intestine a vast surface area for absorbing nutrients from food.

Figure 11.8 Animated!
The small intestine has a very large surface area. (**a**,**b**) Notice the circular folds of the intestinal mucosa. (**c**) Each fold is carpeted with villi, which are fingerlike absorptive structures. (**d**) A villus. Simple sugars and most amino acids that cross the intestinal lining enter small blood vessels in a villus. Fats enter lymph vessels. (**e**) The types of epithelial cells at the free surface of a villus. Each villus has a crown of microvilli facing the lumen of the intestine.

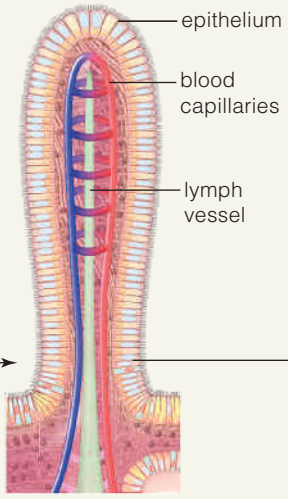


A

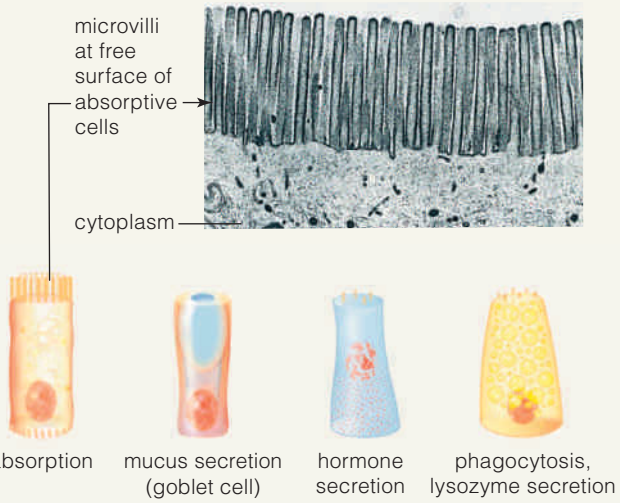
B Extensive circular folds of mucosa



C Villi on one of the folds, longitudinal section



D One villus



E Specialized cells making up the epithelium of a villus

11.5 Accessory Organs: The Pancreas, Gallbladder, and Liver

- **The pancreas, gallbladder, and liver are "accessory" organs because they assist digestion in some way but are outside the digestive tube.**
- **Links to pH and buffers 2.7, Exocrine glands 4.1**

The pancreas produces key digestive enzymes

The **pancreas** nestles behind and below the stomach (Figure 11.9). It contains two kinds of gland cells: exocrine cells that release digestive enzymes into the first section of the small intestine, and endocrine cells that release hormones into the bloodstream. The hormones help regulate blood sugar, a topic of Chapter 15.

The pancreas produces four basic kinds of digestive enzymes, which can chemically dismantle the four major categories of food—complex carbohydrates, proteins, lipids, and nucleic acids. These enzymes are the main ingredients in "pancreatic juice." They work best when the pH is neutral or slightly alkaline, so pancreatic juice also contains bicarbonate (HCO_3^-), which neutralizes the acid in chyme arriving from the stomach. Depending on how often and what type of food you eat, your pancreas may make two quarts of this fluid each day!

The gallbladder stores bile

When the digestive system is processing food, a yellowish fluid called **bile** is released into the upper small intestine. The **liver** makes bile, as described shortly, and bile is stored in the **gallbladder**, a sausage-shaped, green-colored sac tucked behind the liver. As needed, the gallbladder contracts and empties bile into the small intestine where it aids in the digestion and absorption of fats. When there's no food moving through the GI tract, a sphincter closes off the main bile duct, and bile backs up into the gallbladder.

The gallbladder is one of our more "dispensible" organs. If it is surgically removed—usually due to the presence of gallstones, described in a moment—the duct that connects it to the small intestine enlarges and takes on the role of bile storage. This is why millions of people today are walking around minus their gallbladder, with no ill effects.

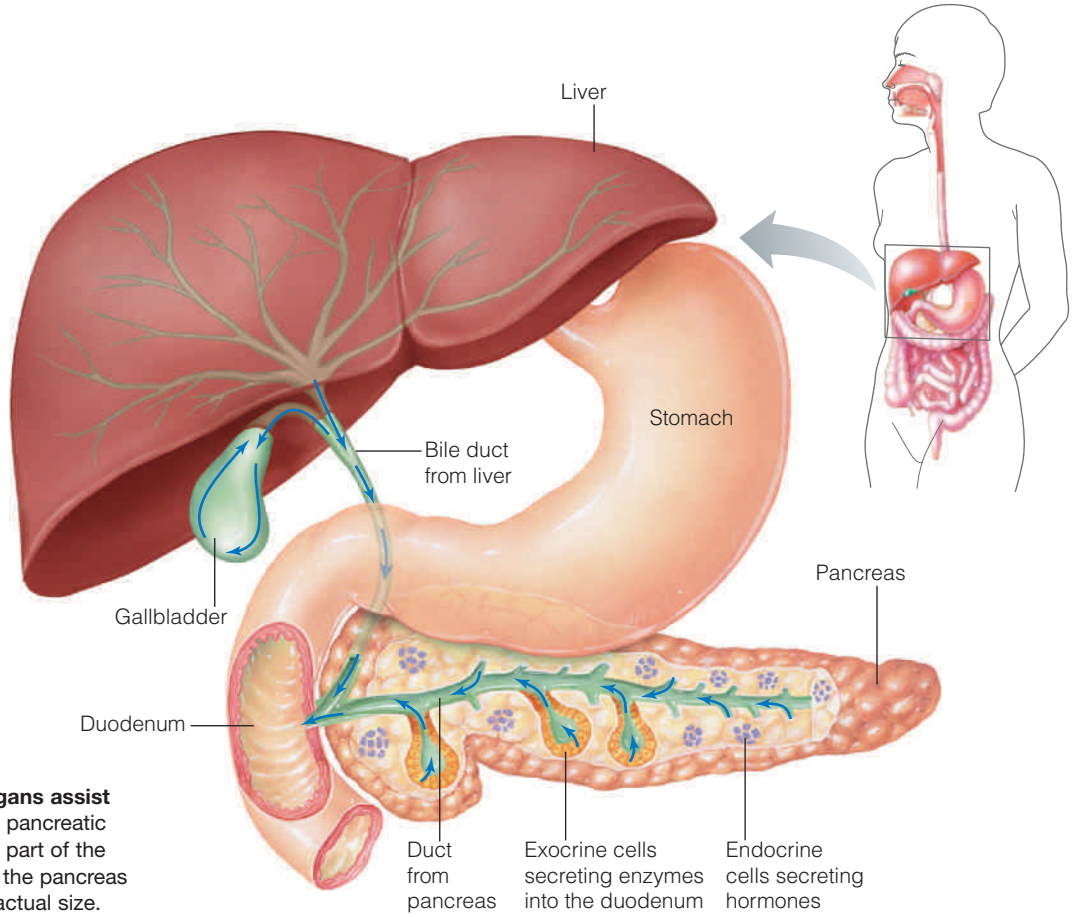


Figure 11.9 Accessory organs assist digestion. Ducts deliver the pancreatic juice and bile into the upper part of the small intestine. The parts of the pancreas are shown here larger than actual size.

Liver Functions

Forms bile (assists fat digestion), rids body of excess cholesterol and blood's respiratory pigments

Controls amino acid levels in the blood; converts potentially toxic ammonia to urea

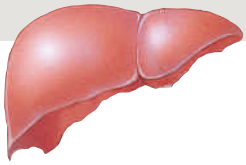
Controls glucose level in blood; major reservoir for glycogen

Removes hormones that served their functions from blood

Removes ingested toxins, such as alcohol, from blood

Breaks down worn-out and dead red blood cells, and stores iron

Stores some vitamins



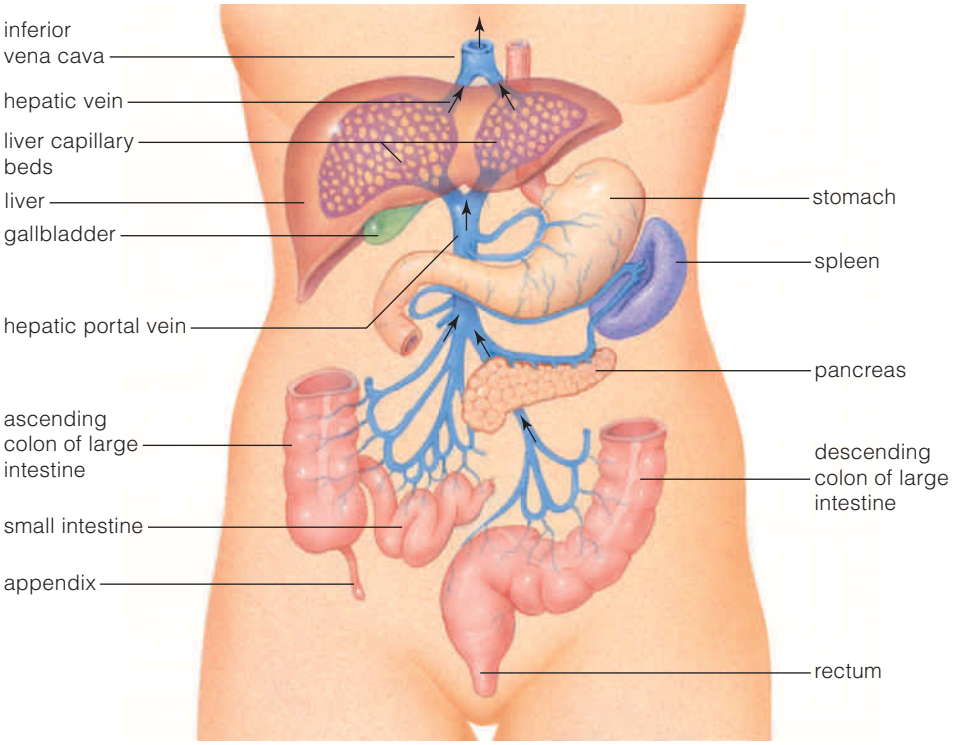


Figure 11.10 The hepatic portal system diverts nutrient-rich blood to the liver. Arrows show the direction of blood flow.

The liver is a multipurpose organ

As you have just read, the liver's role in digestion is to secrete bile—as much as 1,500 ml, or 1.5 quarts, every day. Bile contains bile salts, which the liver synthesizes from cholesterol. Bile salts help to emulsify fats in chyme—that is, to break up large fat globules into smaller bits.

The liver not only uses cholesterol to make bile salts, but also helps manage the level of this lipid in the body. Liver cells secrete cholesterol into bile, which bile salts emulsify along with other lipids in chyme. Some of this cholesterol becomes part of feces and so is excreted. When there is chronically more cholesterol in bile than available bile salts can dissolve, the excess may separate out. Hard gallstones, which are mostly lumps of cholesterol, can develop in the gallbladder. They cause severe pain if they become lodged in bile ducts.

The liver also processes nutrient-bearing blood from the small intestine. This blood flows into the **hepatic portal vein**, which carries the blood through vessels in the liver. In the liver, excess glucose is taken up before a hepatic vein returns the blood to the general circulation (Figure 11.10). The liver converts and stores much of this glucose as glycogen.

Besides its digestive functions, the liver has several other roles in the body. For instance, it processes incoming nutrient molecules into substances the body requires (such as blood plasma proteins) and removes toxins ingested in food or already circulating in the bloodstream. It also inactivates many hormones and sends them to the kidneys for excretion (in urine). Ammonia (NH_3) that is produced when cells break down amino acids can be dangerously toxic to cells, especially in the nervous system. The circulatory system carries ammonia to the liver, where it is converted to a much less toxic waste product, urea, which also is excreted in urine.

Take-Home Message

What roles do accessory organs have in digestion?

- The pancreas, gallbladder, and liver are accessory organs of the digestive system.
- The pancreas produces enzymes that can dismantle complex carbohydrates, protein, lipids, and nucleic acids.
- The gallbladder stores bile, which is produced in the liver.
- The liver also processes nutrient-bearing blood, storing excess glucose as glycogen and removing toxins.

11.6 Digestion and Absorption in the Small Intestine

- **Absorption moves nutrients into the internal environment—tissue fluid and the bloodstream.**
- **Links to Buffers 2.7, Osmosis 3.10**

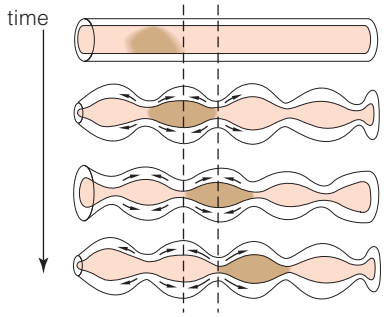
Each day about 9 liters (about 10 quarts) of fluid enters the first section of the small intestine, the **duodenum** (doo-oh-DEE-num). This fluid includes chyme along with digestive juices and other substances from the pancreas, liver, and gallbladder.

Nutrients are released by chemical and mechanical means

Chyme entering the duodenum triggers hormone signals that stimulate a brief flood of digestive enzymes from the pancreas. As part of pancreatic juice, these enzymes act on carbohydrates, fats, proteins, and nucleic acids (Table 11.1). For example, like pepsin in the stomach, the pancreatic enzymes trypsin and chymotrypsin digest the polypeptide chains of proteins into peptide fragments. The fragments are then broken down to amino acids by different peptidases (which are on the surface of the intestinal mucosa). Recall from Section 11.5 that the pancreas also secretes bicarbonate that buffers stomach acid, maintaining a chemical environment in which pancreatic enzymes can function.

Besides enzymes, fat digestion requires the bile salts in bile secreted by the liver and delivered via the gallbladder. You may remember that bile salts speed up fat digestion by breaking up large units of fat into smaller ones. How does this emulsification process work? Most fats in the average diet are triglycerides, which do not dissolve in water. Accordingly, in chyme they tend to clump into big fat globules. When peristalsis mixes chyme, the globules break up into droplets that become coated with bile salts (see Figure 11.11*c*). The salts have a negative charge, so the coated droplets repel each other and stay separated. The droplets give fat-digesting enzymes a much greater surface area to act on. So, because triglycerides are emulsified, they can be broken down much more rapidly to monoglycerides and fatty acids, molecules that are small enough to be absorbed.

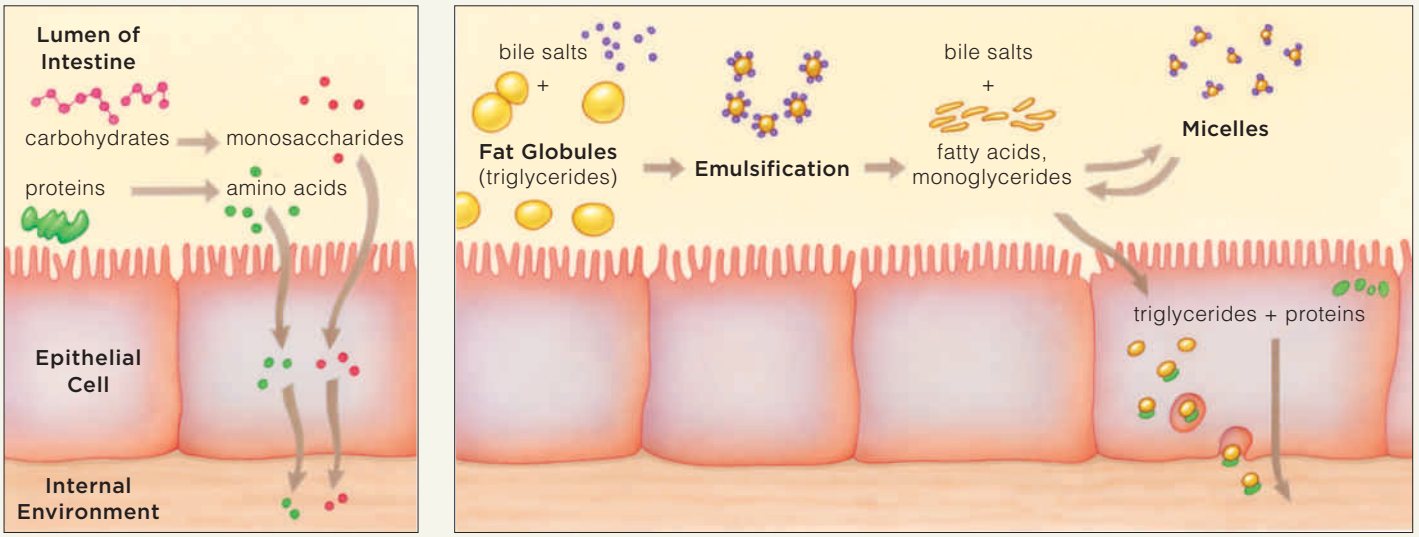
When a nutrient, water, or some other substance is absorbed, it crosses the intestine lining into the bloodstream. Due partly to the vast absorptive surface area of the small intestine, this process is very efficient. **Segmentation** helps, too. In this process, rings of smooth muscle in the wall repeatedly contract and relax. The result is a back-and-forth movement that mixes digested material and forces it against the wall:



Major Enzymes of Digestion and What They Do

Enzyme	Released by:	Active in:	Breaks down:	Resulting Products
DIGESTING CARBOHYDRATES:				
Salivary amylase	Salivary glands	Mouth, stomach	Polysaccharides	Disaccharides, oligosaccharides
Pancreatic amylase	Pancreas	Small intestine	Polysaccharides	Disaccharides, monosaccharides
Disaccharidases	Intestinal lining	Small intestine	Disaccharides	MONOSACCHARIDES* (e.g., glucose)
DIGESTING PROTEINS:				
Pepsins	Stomach lining	Stomach	Proteins	Protein fragments
Trypsin and chymotrypsin	Pancreas	Small intestine	Proteins	Protein fragments
Carboxypeptidase	Pancreas	Small intestine	Peptides	AMINO ACIDS*
Aminopeptidase	Intestinal lining	Small intestine	Peptides	AMINO ACIDS*
DIGESTING FATS:				
Lipase	Pancreas	Small intestine	Triglycerides	FREE FATTY ACIDS, MONOGLYCERIDES*
DIGESTING UCLEIC ACIDS:				
Pancreatic nucleases	Pancreas	Small intestine	DNA, RNA	NUCLEOTIDES*
Intestinal nucleases	Intestinal lining	Small intestine	Nucleotides	NUCLEOTIDE BASES, MONOSACCHARIDES*

*Products small enough to be absorbed into the internal environment.



A Enzymes from the pancreas and from cells of the intestine lining complete the digestion of carbohydrates to monosaccharides and proteins to amino acids.

B Monosaccharides and amino acids are actively transported into epithelial cells, then move out of the cells and into the bloodstream.

C The constant movement of the intestine wall breaks up fat globules into small droplets (emulsification). Bile salts prevent the globules from re-forming. Pancreatic enzymes digest the droplets to fatty acids and monoglycerides.

D Micelles form as bile salts combine with nutrient molecules and phospholipids. Nutrients can easily slip into and out of the micelles.

E Concentrating monoglycerides and fatty acids in micelles creates steeper concentration gradients. Both substances then diffuse into cells of the intestine lining.

F Triglycerides re-form in cells of the intestine lining. They become coated with proteins, then are moved (by exocytosis) into the internal environment. They move into lacteals and then into the blood.

Figure 11.11 Animated! **Different types of nutrients are absorbed by different mechanisms.**

Simple sugars and amino acids are absorbed directly, but fats are absorbed in steps

By the time food is halfway through your small intestine, most of it has been broken apart and digested. Water crosses the intestine lining by osmosis, and cells in the lining also selectively absorb minerals. Figure 11.11 diagrams what happens with other kinds of nutrients.

For instance, transport proteins in the plasma membrane of brush border cells actively move some nutrients, such as the monosaccharide glucose and amino acids, across the lining. After glucose and amino acids are absorbed, they move directly into blood vessels.

By contrast, even after fat globules are emulsified, several more steps are required to move fatty acids and monoglycerides into the bloodstream (Figures 11.11*d*–11.11*f*). Both of these kinds of molecules from digested lipids have hydrophobic regions, so they don't dissolve in watery chyme. Instead, the molecules clump with bile salts, along with cholesterol and other substances, and form tiny droplets. Each droplet is a **micelle** (my-CELL).

The molecules inside micelles don't necessarily stay there. They may move back into the chyme, then back again into a micelle. Eventually, however, the micelles concentrate them next to the intestine lining. When they are concentrated enough, nutrient molecules diffuse out of the micelles and into epithelial cells. There, fatty acids and monoglycerides quickly reunite into triglycerides. Then triglycerides combine with proteins into particles that leave the cells by exocytosis and enter tissue fluid.

Unlike glucose and amino acids, when triglycerides are absorbed they do not move directly into blood vessels. First they cross into lymph vessels called **lacteals**, which drain into the general circulation.

Take-Home Message

How are substances absorbed in the small intestine?

- In the small intestine, most large organic molecules are digested to smaller molecules that can be absorbed.
- Pancreatic enzymes secreted into the small intestine act on carbohydrates, fats, proteins, and nucleic acids in chyme. Bile salts emulsify fats (triglycerides), allowing them to be more easily digested.
- Substances pass through brush border cells that line the surface of each villus by osmosis, active transport, or diffusion across plasma membranes.

11.7 The Large Intestine

- **Anything not absorbed in the small intestine moves into the large intestine.**
- **Link to Osmosis 3.10**

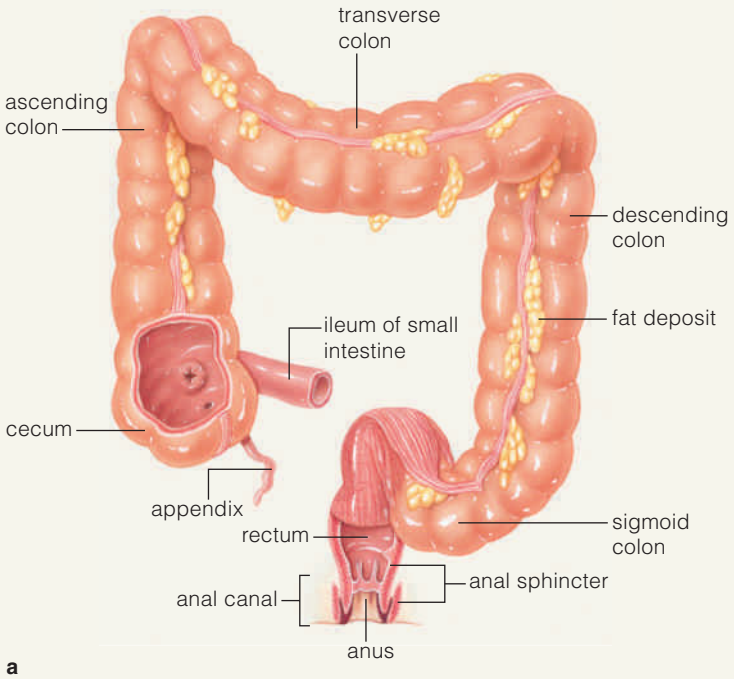
The **large intestine** is about 1.2 meters (5 feet) long (Figure 11.12*a*). It begins as a blind pouch called the cecum. The cecum merges with the **colon**, which is divided into four regions in an inverted U-shape. The ascending colon travels up the right side of the abdomen, the transverse colon continues across to the left side, and the descending colon then turns downward. The sigmoid colon makes an S-curve and connects with the **rectum**.

Cells in the colon's lining actively transport sodium ions out of the tube. When the ion concentration there falls, water moves out by osmosis. As water is removed and returned to the bloodstream, the material left in the colon is gradually concentrated into feces, a mixture of undigested and unabsorbed matter, bacteria, and a little water. It is stored and then eliminated. The typical brown color of feces comes mainly from bile pigments.

Bacteria make up about 30 percent of the dry weight of feces. Such microorganisms, including *Escherichia coli*, normally inhabit our intestines and are nourished by the food residues there. Their metabolism produces useful fatty acids and some vitamins (such as vitamin K), which are absorbed into the bloodstream. Feces of humans and other animals also can contain disease-causing organisms. Health officials use evidence of such "coliform bacteria," including *E. coli*, in water and food supplies as a measure of fecal contamination (Figure 11.12*b*).

Your **appendix** projects from the cecum like the little finger of a glove. No one has ever discovered a digestive function for it, but, like the ileum of the small intestine, the appendix is colonized by defensive cells that combat bacteria you may have consumed in food.

Short, lengthwise bands of smooth muscle in the colon wall are gathered at their ends, like full skirts nipped in at elastic waistbands. As they contract and relax, material in the colon moves back and forth against the wall's absorptive surface. Shortly after you eat, hormone signals and nervous system commands direct large portions of the ascending and transverse colon to contract at the same time. Within a few seconds, residues in the colon may move as much as three-fourths of the colon's length and make way for incoming food. When feces distend the rectal wall, the stretching triggers defecation—elimination of feces from the body. From the rectum feces move into the **anal canal**. The nervous system also controls defecation. It can stimulate or inhibit contractions of sphincter muscles at the **anus**, the terminal opening of the GI tract.



Take-Home Message

What are the main functions of the large intestine?

- In the large intestine, water and salts are reabsorbed from food residues entering from the small intestine. The remaining concentrated residues are stored and later eliminated as feces.

Figure 11.12 Animated! In the large intestine (a), feces form and some substances are reabsorbed. The photograph (**b**) shows Rita Colwell, a microbiologist working to improve drinking water in Bangladesh.

11.8 How Control Systems Regulate Digestion

- **Nerves and hormones regulate food digestion.**
- **Links to Carbohydrates, lipids, and proteins 2.9–2.11, Negative feedback 4.9**

The nervous system and endocrine system jointly control digestion. These controls are sensitive to two factors: the amount of food in the GI tract and the food's chemical makeup.

Food entering the stomach stretches the stomach walls, and then those of the small intestine. This stretching triggers signals from sensory receptors in the walls. Some of the signals give you (by way of processing in your brain) that "full" feeling after you eat. Others can lead to the muscle contractions of peristalsis or the release of digestive enzymes and other substances. Centers in the brain coordinate these activities with factors such as how much blood is flowing to the small intestine, where nutrients are being absorbed.

There are several types of endocrine cells in the GI tract. For example, one type secretes the hormone gastrin into the bloodstream when the stomach contains protein. Gastrin mainly stimulates the release of hydrochloric acid (HCl), which you may recall is a key ingredient in gastric juice. After the stomach has emptied out, the increased acidity there causes another type of endocrine cell to release somatostatin, which shuts down HCl secretion so that conditions in the stomach are less acid. Notice that this is an example of negative feedback.

Hormones also come from endocrine cells in the small intestine. One of them, secretin, signals the pancreas to release bicarbonate when acid enters the duodenum. When fat enters the small intestine, a hormone called CCK (for cholecystokinin) is released. CCK spurs the pancreas to release enzymes and triggers gallbladder contractions that deliver bile into the small intestine. Secretin and CCK also slow the rate at which the stomach empties—the mechanism mentioned in Section 11.3 that prevents food from entering the small intestine faster than it can be processed there. Yet another hormone, GIP (for glucose insulinotropic peptide) is released when fat and glucose are in the small intestine. One of its roles is to stimulate the release of insulin (from the pancreas), which is required for cells to take up glucose. Table 11.2 summarizes the major hormones that regulate digestion.

Main Hormonal Controls of Digestion

Hormone	Source	Effects on Digestive System
Gastrin	Stomach	Increases acid secretion by stomach
Cholecystokinin (CCK)	Small intestine	Increases enzyme secretion by pancreas and causes contraction of gallbladder
Secretin	Small intestine	Increases bicarbonate secretion by pancreas and slows contractions in the small intestine

After nutrients are absorbed, the blood carries them to the liver, as described in Section 11.5. The liver is like a central shipping, storage, and receiving center. When glucose arrives from the small intestine, it is either shipped back out to the brain and other tissues, or stored as glycogen. Arriving fats may be stored, or used to make lipoproteins and other needed molecules. Liver cells also assemble amino acids into various proteins or process and reship them in a form cells can use to make ATP. Figure 11.13 will help you visualize these activities. They are extremely important in maintaining the body's supply of molecules that cells use as fuel, as building blocks, or in other ways.

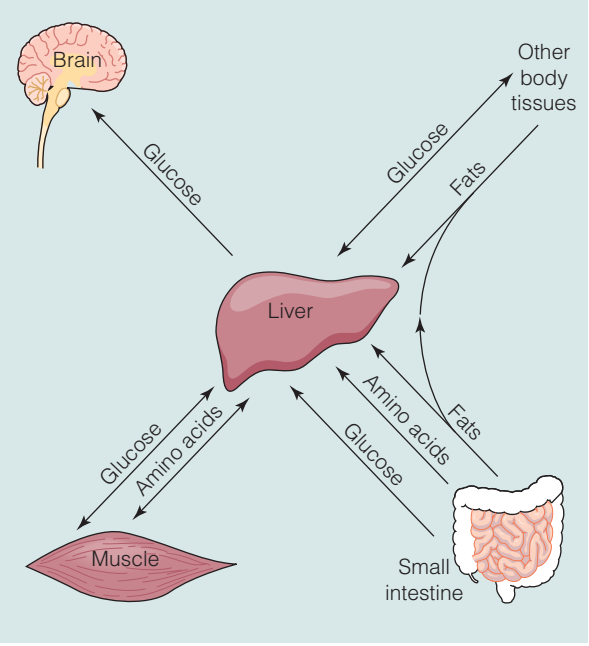


Figure 11.13 **The liver has a central role in managing all types of nutrients.**

Take-Home Message

Which body control systems manage digestion?

- Signals from the nervous system and the endocrine system control activity in the digestive system.
- When absorbed nutrients reach the liver, they are sent on to the general circulation, stored, or converted to other forms for use in body cells.

11.9 Digestive System Disorders

Gastroesophageal reflux is a common upper GI tract disorder

The main symptom of **gastroesophageal reflux disease**, or GERD, is often called "heartburn," but it has nothing to do with the heart. With this common disorder acidic chyme backs up into the esophagus when the lower esophageal sphincter doesn't close properly. The irritation causes burning in the upper center of the chest. Mild cases of GERD often can be controlled by over-the-counter drugs that reduce stomach acid, and by diet adjustments such as limiting intake of acidic foods such as orange juice, coffee, and tomatoes. Severe cases of GERD are worrisome because GERD may lead to a precancerous condition called **Barrett's esophagus**.

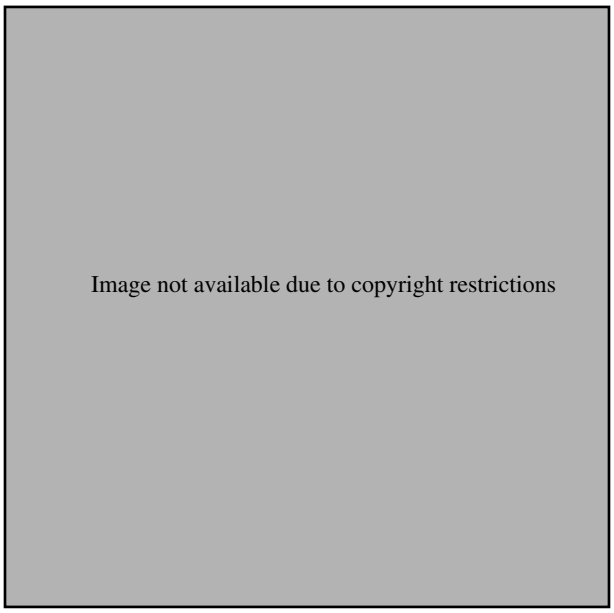
Problems in the colon range from constipation to cancer

It is normal to "move the bowels," or defecate, anywhere from three times a day to once a week. In *constipation*, food residues remain in the colon for too long, too much water is reabsorbed, and the feces become dry, hard, and difficult to eliminate. Constipation is uncomfortable, and it is a common cause of the enlarged rectal blood vessels known as hemorrhoids.

Constipation is often due to a lack of bulk in the diet. Bulk is the volume of fiber (mainly cellulose from plant foods) and other undigested food material that is not decreased by absorption in the colon. Much of it consists of insoluble fiber such as cellulose and other plant compounds that humans cannot digest (we lack the required enzymes) and that does not easily dissolve in water. Wheat bran and the edible skins of fruits such as apples, plums, and grapes are just a few examples (Figure 11.14*a*). (Soluble fiber consists of plant carbohydrates such as fruit pectins that swell or dissolve in water.)

If you chronically eat too little fiber, you are much more likely to be in the 50 percent of the U.S. population in whom the colon has formed *diverticula*—knoblike sacs where the inner colon lining protrudes through the wall of the large intestine. Inflammation of a diverticulum is called **diverticulitis**, and it can have quite serious complications, including peritonitis, if an inflamed diverticulum ruptures. Much more common is **diverticulosis** (Figure 11.14*b*), in which diverticula are there but have not (yet) become inflamed.

Have you ever heard of someone having a "spastic colon"? This problematical condition also is known as **irritable bowel syndrome (IBS)**, and it is the most common intestinal disorder. IBS often begins in early to mid-adulthood, and it affects twice as many women as men.



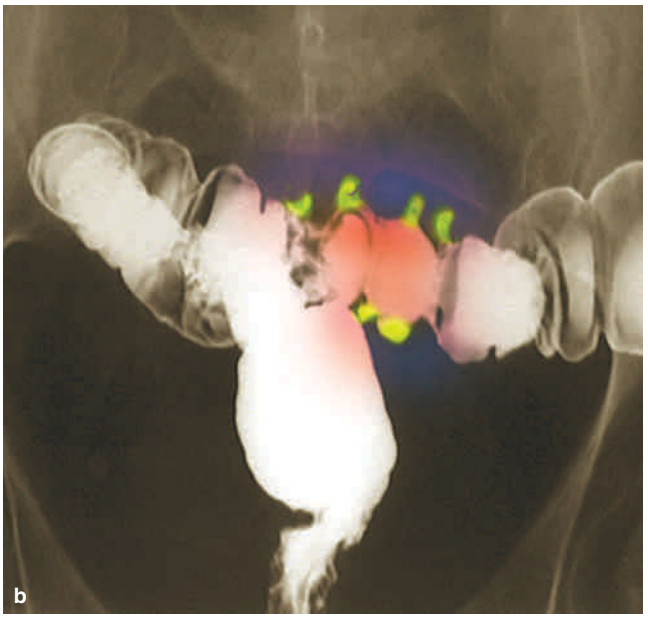


Figure 11.14 Fiber helps keep the colon healthy.

b) X-ray showing a colon in which knoblike diverticula (*green* areas) have developed.

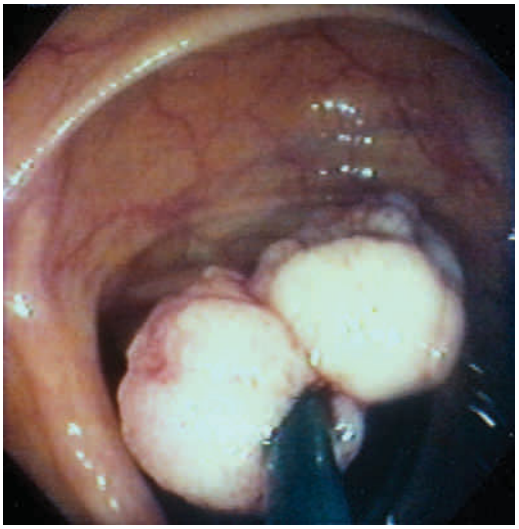


Figure 11.15 A polyp on the colon wall may be a precursor to colorectal cancer. This picture was taken during a colonoscopy. Suspicious polyps can be removed and examined for signs of cancerous cells.

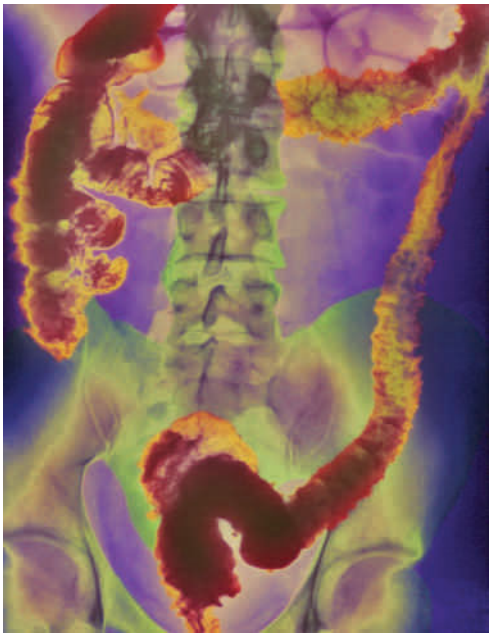


Figure 11.16 Crohn's disease can do severe intestinal harm. The blotchy areas in this X-ray image are ulcers in the wall of the intestine.

Although the symptoms—abdominal pain and alternating diarrhea and constipation—are distressing, a medical examination rarely turns up signs of disease. While the direct cause of IBS symptoms is a disturbance in the smooth muscle contractions that move material through the colon, the reason for the change is not known.

Colon cancer is the number-two cancer diagnosis in the United States, second only to lung cancer, and it accounts for about 20 percent of all cancer deaths. The first internal sign of colon cancer may be a round, depressed area of abnormal cells. Another common early warning sign is a growth called a polyp that develops on the colon wall and becomes malignant (Figure 11.15). Fortunately, many precancerous growths and early cases of colon cancer can be detected by colonoscopy. After the patient is mildly sedated, a physician inserts a viewing tube into the colon and can examine it for polyps and other signs of disease. Although people over age 50 have the highest risk, younger people do develop colon cancer.

The tendency to develop polyps, and colon cancer, can run in families, but usually there is no obvious genetic link. Because colon cancer is much more common in Western societies, some experts have proposed that the typical high-fat, low-fiber Western diet may be a factor, and there is a lot of active research on the issue. Chapter 22 looks in more detail at the causes of cancer.

Malabsorption disorders prevent nutrients from being absorbed

A typical high fat, low fiber dietary choice.

Anything that interferes with the small intestine's ability to take up nutrients can lead to a **malabsorption disorder**. Many adults develop **lactose intolerance**, a mild disorder that results from a deficiency of the enzyme lactase. It prevents normal breakdown and absorption of lactose, the sugar found in milk and many milk products.

More serious malabsorption disorders are associated with some diseases that affect the pancreas, including the genetic condition **cystic fibrosis (CF)**. Patients with CF don't make the necessary pancreatic enzymes for normal digestion and absorption of fats and other nutrients. (CF also affects the lungs, as you will read in later chapters.) **Crohn's disease** is an inflammatory disorder that can so severely damage the intestinal lining that much of the intestine must be removed (Figure 11.16).

11.10 Infectious Diseases of the Digestive System

Bacteria and other types of organisms can infect the GI tract

The GI tract opens to the outside world at both the mouth and the anus, so it is a convenient portal into the body for bacteria, viruses, and other pathogens that contaminate foods, water, and hands.

Diarrhea, or watery feces, is a common effect of an intestinal infection. Diarrhea can develop when an irritant (such as a bacterial toxin) causes the lining of the small intestine to secrete more water and salts than the large intestine can absorb. It can also develop when infections, stress, or other factors speed up peristalsis in the small intestine, so that there isn't time for enough water to be absorbed. Diarrheal diseases are dangerous in part because they dehydrate the body, depleting water and salts that nerve and muscle cells need to function properly. Figure 11.17*a* shows *Giardia intestinalis*, a protozoan that causes **giardiasis**. It forms cysts that enter water or food in contaminated feces. Symptoms include explosive diarrhea and "rotten egg" belches.

Humans also are susceptible to several harmful strains of *E. coli* bacteria (Figure 11.17*b*). One of them, called O157:H7, inhabits the intestines of cattle. If a person eats ground beef or some other food that is contaminated with this microbe, it can cause a dangerous form of diarrhea that is complicated by anemia. A few cases have led to kidney failure and death.

Bacteria that cause tooth decay (dental caries) flourish on food residues in the mouth, especially sugars (Figure 11.18*a*). Daily brushing and flossing are the best way to avoid a bacterial infection of the gums, which can lead to **gingivitis** (jin-juh-VY-tus). This inflammation can spread to the periodontal membrane that helps anchor a tooth in the jaw. Untreated periodontal disease can slowly destroy a tooth's bony socket, which can lead to loss of the tooth and other complications.

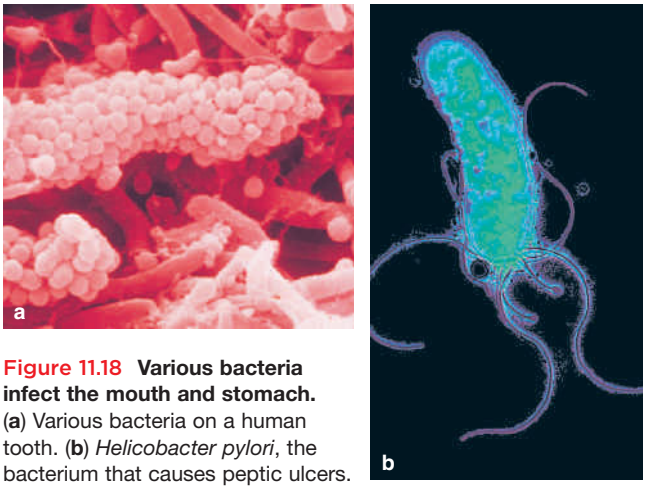


Figure 11.18 Various bacteria infect the mouth and stomach. (**a**) Various bacteria on a human tooth. (**b**) *Helicobacter pylori*, the bacterium that causes peptic ulcers.

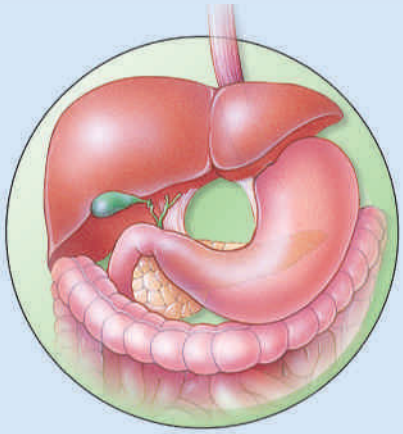
Section 11.3 mentioned *peptic ulcers*, open sores in the wall of the stomach or small intestine (Figure 11.18*b*) that are caused by the bacterium *Helicobacter pylori*. This microbe also is responsible for some cases of **gastritis** (an inflammation of the GI tract), and even **stomach cancer**.

If you have ever had a case of "food poisoning," your stomach or intestines have been colonized by bacteria such as *Salmonella*, which can contaminate meat, poultry, and eggs. An infectious microorganism called *Pseudomonas* may live on sponges and kitchen utensils (Figure 11.19).

Figure 11.17 Intestinal infections can cause diarrhea. Both these organisms, *Giardia intestinalis* (left) and *E. coli* O157:H7 (right), can infect the GI tract.

Figure 11.19 Food and water may also harbor protozoa. Shown here is the protozoan *Pseudomonas* creeping along the surface of a kitchen knife.

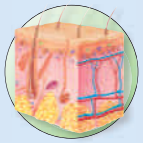
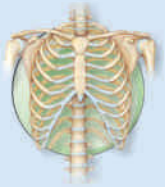
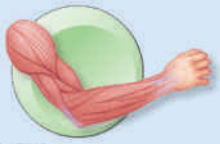
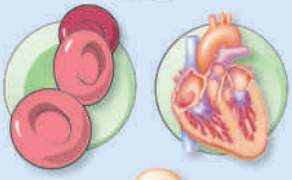
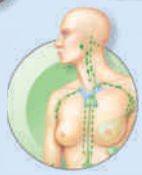
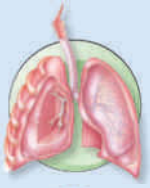
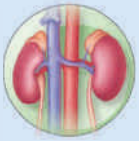
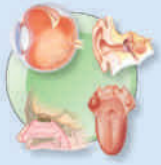
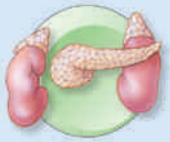
11.11 CONNECTIONS: The Digestive System in Homeostasis



The Digestive System

Body cells require nutrients for energy and for the processes that build new cells and cell parts.

The digestive system contributes to homeostasis by breaking down bulk food to nutrients, vitamins, and minerals that can be absorbed into the bloodstream. It also absorbs water and stores and eliminates solid wastes as feces.

Integumentary system		Excess calories may be stored as insulating fat in the hypodermis; absorbed copper is used in making melanin.
Skeletal system		Absorbed calcium and phosphorus are major components of bone tissue.
Muscular system		Absorbed calcium, potassium, and sodium are needed for muscle contraction; the lactic acid produced by working muscles is converted to glucose in the liver.
Cardiovascular system and blood		Absorbed water maintains blood volume; iron is used in red blood cells to make hemoglobin; vitamin K made in the colon is used in clotting; many plasma proteins are made in the liver.
Immunity and the lymphatic system		Gastric juice and stomach enzymes help destroy microorganisms; diarrrhea helps flush microbes from the intestines.
Respiratory system		Absorbed nutrients nourish lungs and other organs; water provides moisture needed for gas exchange; the stomach and liver provide physical support for the diaphragm.
Urinary system		The kidneys use absorbed water in forming urine; absorbed sodium is essential in adjustments to the body's acid–base balance and the water content of urine.
Nervous system		Glucose from digested carbohydrates or formed in the liver is the basic source of energy for brain cells; absorbed sodium and potassium are requried to generate nerve impulses.
Sensory systems		Absorbed nutrients nourish all sensory organs; vitamin A is used to make pigments used in vision.
Endocrine system		Pancreas, stomach, and intestinal hormones help regulate hunger and digestion; insulin and glucagon from the pancreas regulate blood sugar; the liver deactivates several hormones.
Reproductive system		Absorbed nutirents support development of sperm and eggs and sustain growing offspring during pregnancy.

11.12 The Body's Nutritional Requirements

- **Diet has a major effect on body functions because it supplies major nutrients as well as vitamins and minerals.**
- **Links to Carbohydrates, lipids, and proteins 2.9–2.11**

The nutrients we absorb are burned as fuel to provide energy and used as building blocks to build and replace tissues. In this section we focus on the three main classes of nutrients—carbohydrates, lipids, and proteins—and we take a look at guidelines for what makes up a healthy diet.

Complex carbohydrates are best

There are many views on the definition of a "proper" diet, but just about all nutritionists can agree on this point: The healthiest carbohydrates are "complex" ones such as starch—the type of carbohydrate in fleshy fruits, cereal grains, and legumes, including peas and beans.

Human digestive enzymes easily break down complex carbohydrates to glucose, the body's chief energy source. Foods rich in complex carbohydrates also usually are high in fiber, including the insoluble fiber that adds needed bulk to feces and helps prevent constipation (see Section 11.9). By contrast, simple sugars such as those in sweets don't have much fiber, and they lack the vitamins and minerals of whole foods.

A person who eats lots of packaged food may consume up to two pounds of refined sugars per week. Ingredient labels may list these sugars as corn syrup, corn sweeteners, and dextrose. They represent "empty calories" because they add to our caloric intake, but meet no other nutritional needs. Highly refined carbohydrates also have a high **glycemic index** (GI). This index ranks foods by their effect on blood glucose during the first two hours after a meal. For example, white rice and breads or crackers made with refined white flour have a high GI. They are digested quickly and cause a surge in the blood levels of sugar and insulin.

Circulating insulin makes cells take up glucose quickly, and it also prevents cells from using stored fat as fuel. At the same time, glucose that is not needed as fuel for cells is stored as fat. When blood sugar levels later fall, you feel hungry. So you may eat more, secrete more insulin, and keep storing fat, mainly in the form of triglycerides. Over time, high triglyceride levels increase the risk of heart disease and type 2 diabetes.

Some fats are more healthful than others

The body can't survive without fats and other lipids. The phospholipid lecithin and the sterol cholesterol both are building blocks of cell membranes. Fat stored in adipose tissue serves as an energy reserve, cushions organs such as the eyes and kidneys, and provides insulation beneath the skin. The brain of a young child won't develop properly without a supply of cholesterol and saturated fat. The body also stores fat-soluble vitamins in adipose tissues.

The liver can manufacture most fats the body needs, including cholesterol, from protein and carbohydrates. The ones it cannot produce are **essential fatty acids**, but whole foods and vegetable oils provide plenty of them. Linoleic acid is an example. You can get enough of it by consuming just one teaspoon a day of corn oil, olive oil, or some other polyunsaturated fat.

Animal fats—the fat in butter, cheese, and fatty meat—are rich in saturated fats and cholesterol. Eating too much of these kinds of foods increases the risk for heart disease and stroke, as well as for certain cancers. The trans fatty acids, or "trans fats," are also bad for the cardiovascular system. Food labels are now required to show the amounts of trans fats, saturated fats, and cholesterol per serving. Section 7.8 has more information on "good" and "bad" forms of cholesterol.

Proteins are body-building nutrients

When the digestive system digests and absorbs proteins, their amino acids become available for protein synthesis in cells. Of the twenty common amino acids, eight are **essential amino acids**. Our cells cannot make them, so we must obtain them from food. The eight are isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine (Figure 11.20).

Most animal proteins are complete, meaning their ratios of amino acids match human nutritional needs. Nearly all plant proteins are incomplete, meaning they lack one or more of the essential amino acids. (The proteins of quinoa, pronounced keen-wah, are an exception.) To get required amino acids from a vegetarian diet, one

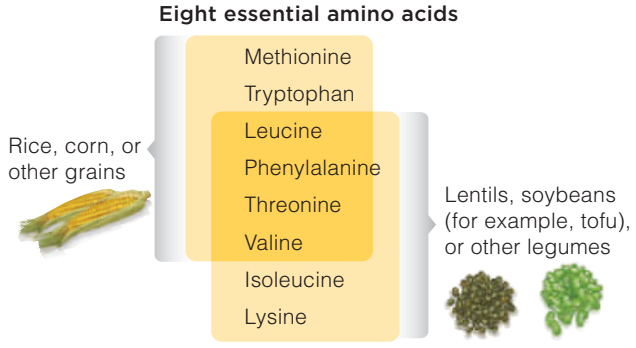


Figure 11.20 **Numerous foods can supply the eight essential amino acids.**

USDA Nutritional Guidelines	
Food Group	**Amount Recommended**
Vegetables	2.5 cups/day
Dark green vegetables	3 cups/week
Orange vegetables	2 cups/week
Legumes	3 cups/week
Starchy vegetables	3 cups/week
Other vegetables	6.5 cups/week
Fruits	2 cups/day
Milk Products	3 cups/day
Grains	6 ounces/day
Whole grains	3 ounces/day
Other grains	3 ounces/day
Fish, poultry, lean meat	5.5 ounces/day
Oils	24 grams/day

must combine plant foods so the amino acids missing from one are present in others. Examples are combining beans with rice, cornbread with chili, tofu with rice, and lentils with wheat bread.

There are several guidelines for healthy eating

Scientists at the Department of Agriculture and other U.S. government agencies study diets that may help prevent health problems such as heart disease, type 2 diabetes, and certain cancers. They perioidically update their nutritional guidelines. Recently they replaced a traditional "food pyramid" with a list that recommends the number of servings for four different food groups (Figure 11.21). Compared to the diet of a typical American, the guidelines call for eating less of foods containing refined grains (such as white flour and white rice), trans fats and saturated fats, and refined sugars. They also suggest eating less meat and more dark green and orange vegetables, fruits, and milk products.

There are respected alternative diets, however. One of them is the Mediterranean diet, which is associated with a lower risk of heart disease, among other chronic ills. It emphasizes grains first, and then fruits and vegetables. Its main fat is olive oil, an excellent antioxidant. The diet also limits weekly intakes of animal protein, eggs, and refined sugars.

Also popular are "low-carb" diets: fewer carbohydrates and more proteins and fats. People often lose weight every rapidly on such diets. However, their long-term effects on organs such as the kidneys are not yet known. High-fat,

Figure 11.21 The USDA formulates nutritional guidelines. The chart shows recommended proportions to add up to a daily 2,000 kilocalorie intake for sedentary females aged 10 to 30. The recommended intake and serving sizes are larger for males and highly active females and less for older females. The USDA recommends a variety of protein sources, including fish, poultry, lean red meats, eggs, beans, nuts, and seeds.

high-protein diets make the kidneys work harder, raising the risk of kidney stones and other kidney problems.

Does a low-carb diet also increase risk of heart disease? You might expect so. Yet studies show that following a low-carb diet for six months does not increase LDLs, the "bad" form of cholesterol. Still, given all the evidence that a diet high in saturated fat increases the risk of heart disease, low-carb dieters are advised to obtain protein from fish, lean meat, or vegetable sources.

Take-Home Message

Which substances are important for a healthy, balanced diet?

- A healthy diet must provide essential nutrients in the proper proportions and amounts.
- Complex carbohydrates provide nutrients and fiber without adding "empty" calories.
- Fats and other lipids are used for building cell membranes, energy stores, and other needs. Food must provide the essential fatty acids, which the body cannot synthesize.
- Proteins are the source of essential amino acids.

11.13 Vitamins and Minerals

- **Vitamins and minerals are essential for normal body functioning.**

Vitamins are organic substances required for growth and survival (Table 11.3). No other substances can play their metabolic roles. In the course of evolution, animal cells have lost the ability to synthesize these substances, so we must obtain vitamins from food.

Each vitamin has specific metabolic functions. Many chemical reactions use several types, and the absence of one affects the functions of others.

Minerals are inorganic substances that also are essential because no other substance can serve their metabolic functions (Table 11.4). As examples, cells need iron for their electron transport chains, red blood cells can't function without iron in hemoglobin (the oxygen-carrying pigment in blood), and neurons require sodium and potassium.

Major Vitamins: Sources, Functions, and Effects of Deficiencies or Excesses*

Vitamin	Common Sources	Main Functions	Effects of Chronic Deficiency	Effects of Extreme Excess
Fat-Soluble Vitamins				
A	Its precursor comes from beta-carotene in yellow fruits, yellow or green leafy vegetables; also in fortified milk, egg yolk, fish liver	Used in synthesis of visual pigments, bone, teeth; maintains epithelia	Dry, scaly skin; lowered resistance to infections; night blindness; permanent blindness	Malformed fetuses; hair loss; changes in skin; liver and bone damage; bone pain
D	Inactive form made in skin, activated in liver, kidneys; in fatty fish, egg yolk, fortified milk products	Promotes bone growth and mineralization; enhances calcium absorption	Bone deformities (rickets) in children; bone softening in adults	Retarded growth; kidney damage; calcium deposits in soft tissues
E	Whole grains, dark green vegetables, vegetable oils	Counters effects of free radicals; helps maintain cell membranes; blocks breakdown of vitamins A and C in gut	Lysis of red blood cells; nerve damage	Muscle weakness; fatigue; headaches; nausea
K	Colon bacteria form most of it; also in green leafy vegetables, cabbage	Blood clotting; ATP formation via electron transport	Abnormal blood clotting; severe bleeding (hemorrhaging)	Anemia; liver damage and jaundice
Water-Soluble Vitamins				
B_1 (thiamin)	Whole grains, green leafy vegetables, legumes, lean meats, eggs	Connective tissue formation; folate utilization; coenzyme action	Water retention in tissues; tingling sensations; heart changes; poor coordination	None reported from food; possible shock reaction from repeated injections
B_2 (riboflavin)	Whole grains, poultry, fish, egg white, milk	Coenzyme action	Skin lesions	None reported
B_3 (niacin)	Green leafy vegetables, potatoes, peanuts, poultry, fish, pork, beef	Coenzyme action	Contributes to pellagra (damage to skin, gut, nervous system, etc.)	Skin flushing; possible liver damage
B_6	Spinach, tomatoes, potatoes, meats	Coenzyme in amino acid metabolism	Skin, muscle, and nerve damage; anemia	Impaired coordination; numbness in feet
Pantothenic acid	In many foods (meats, yeast, egg yolk especially)	Coenzyme in glucose metabolism, fatty acid and steroid synthesis	Fatigue, tingling in hands, headaches, nausea	None reported; may cause diarrhea occasionally
Folate (folic acid)	Dark green vegetables, whole grains, yeast, lean meats; colon bacteria produce some folate	Coenzyme in nucleic acid and amino acid metabolism	A type of anemia; inflamed tongue; diarrhea; impaired growth; mental disorders	Masks vitamin B_{12} deficiency
B_{12}	Poultry, fish, red meat, dairy foods (not butter)	Coenzyme in nucleic acid metabolism	A type of anemia; impaired nerve function	None reported
Biotin	Legumes, egg yolk; colon bacteria produce some	Coenzyme in fat, glycogen formation and in amino acid metabolism	Scaly skin (dermatitis); sore tongue; depression; anemia	None reported
C (ascorbic acid)	Fruits and vegetables, especially citrus, berries, cantaloupe, cabbage, broccoli, green pepper	Collagen synthesis; possibly inhibits effects of free radicals; structural role in bone, cartilage, and teeth; used in carbohydrate metabolism	Scurvy; poor wound healing; impaired immunity	Diarrhea, other digestive upsets; may alter results of some diagnostic tests

*Guidelines for appropriate daily intakes are being worked out by the Food and Drug Administration.

In general, people who are in good health and who eat a balanced diet of whole foods get most of the vitamins and minerals they need. That said, many physicians now recommend that even healthy people can benefit from well-chosen vitamin and mineral supplements, in moderation. For example, vitamins E, C, and A lessen some aging effects and can improve immune function by inactivating free radicals. (A free radical, remember, is an atom or group of atoms that is highly reactive because it has an unpaired electron.) Vitamin K supplements help older women retain calcium and diminish the loss of bone due to osteoporosis.

However, metabolism varies in its details from one person to the next, so no one should take massive doses of any vitamin or mineral supplement except under medical supervision. Also, excessive amounts of many vitamins and minerals can harm anyone. For example, very large doses of the fat-soluble vitamins A and D can accumulate in tissues, especially in the liver, and interfere with normal metabolism. And although sodium has roles in the body's salt–water balance, muscle activity, and nerve function, prolonged, excessive intake of sodium may contribute to high blood pressure in some people.

Take-Home Message

Why are vitamins and minerals required for good nutrition?

- Vitamins and minerals have specific metabolic functions that no other nutrients can serve.
- Severe shortages or self-prescribed, massive excesses of vitamins and minerals can disturb the delicate balances in body function that promote health.

Major Minerals: Sources, Functions, and Effects of Deficiencies or Excesses*

Mineral	Common Sources	Main Functions	Effects of Chronic Deficiency	Effects of Extreme Excess
Calcium	Dairy products, dark green vegetables, dried legumes	Bone, tooth formation; blood clotting; neural and muscle action	Stunted growth; possibly diminished bone mass (osteoporosis)	Impaired absorption of other minerals; kidney stones in susceptible people
Chloride	Table salt (usually too much in diet)	HCl formation in stomach; contributes to body's acid–base balance; neural action	Muscle cramps; impaired growth; poor appetite	Contributes to high blood pressure in certain people
Copper	Nuts, legumes, seafood, drinking water	Used in synthesis of melanin, hemoglobin, and some electron transport chain components	Anemia, changes in bone and blood vessels	Nausea, liver damage
Fluorine	Fluoridated water, tea, seafood	Bone, tooth maintenance	Tooth decay	Digestive upsets; mottled teeth and deformed skeleton in chronic cases
Iodine	Marine fish, shellfish, iodized salt, dairy products	Thyroid hormone formation	Enlarged thyroid (goiter), with metabolic disorders	Goiter
Iron	Whole grains, green leafy vegetables, legumes, nuts, eggs, lean meat, molasses, dried fruit, shellfish	Formation of hemoglobin and cytochrome (electron transport chain component)	Iron-deficiency anemia, impaired immune function	Liver damage, shock, heart failure
Magnesium	Whole grains, legumes, nuts, dairy products	Coenzyme role in ATP/ADP cycle; roles in muscle, nerve function	Weak, sore muscles; impaired neural function	Impaired neural function
Phosphorus	Whole grains, poultry, red meat	Component of bone, teeth, nucleic acids, ATP, phospholipids	Muscular weakness; loss of minerals from bone	Impaired absorption of minerals into bone
Potassium	Diet alone provides ample amounts	Muscle and neural function; roles in protein synthesis and body's acid–base balance	Muscular weakness	Muscular weakness, paralysis, heart failure
Sodium	Table salt; diet provides ample to excessive amounts	Key role in body's salt–water balance; roles in muscle and neural function	Muscle cramps	High blood pressure in susceptible people
Sulfur	Proteins in diet	Component of body proteins	None reported	None likely
Zinc	Whole grains, legumes, nuts, meats, seafood	Component of digestive enzymes; roles in normal growth, wound healing, sperm formation, and taste and smell	Impaired growth, scaly skin, impaired immune function	Nausea, vomiting, diarrhea; impaired immune function and anemia

*Guidelines for appropriate daily intakes are being worked out by the Food and Drug Administration.

11.14 Food Energy and Body Weight

- **Attitudes about body weight often are cultural, but excess weight also raises important health issues.**

The "fat epidemic" described in this chapter's introduction is spreading around the world. In the United States alone, about 300,000 people die each year due to preventable, weight-related conditions. Lifestyles are becoming more sedentary, and many people simply are eating more: Studies show that since the 1970s portion sizes in most restaurants have doubled. This is one reason why the FDA guidelines noted in Section 11.12 don't say "servings" of food but specify amounts instead.

The scientific standard for body weight is based on the ratio of weight to height (Figure 11.22). A person who is overweight has a higher than desirable weight-for-height. **Obesity** is an excess of body fat—more than 20 percent for males and 24 percent for females. The World Health Organization has declared obesity a major global health concern, in part because its harmful effects on health are so serious—increasing not only the risk of type 2 diabetes and heart disease, but also osteoarthritis, high blood pressure, kidney stones, and many other ailments.

One indicator of weight-related health risk is the body mass index (BMI). It is determined by the formula

$$\text{BMI} = \frac{\text{weight (pounds)} \times 700}{\text{height (inches)}^2}$$

If your BMI value is 27 or higher, the health risk rises dramatically. Other risk factors include smoking, a genetic predisposition for heart disease, and fat stored above the waist (having an "apple shape" or "beer belly").

When someone is overweight, the usual culprit is an unbalanced "energy equation" in which too many food calories are taken in while too few calories are burned. We measure food energy in **kilocalories** (kcal). A kilocalorie is 1,000 calories of heat energy. (Calorie, with a capital "C," is shorthand for a kilocalorie.) A value called **basal metabolic rate** (BMR) measures the amount of energy needed to sustain basic body functions. As a general rule, the younger you are, the higher your BMR. But BMR also varies from person to person, and it is influenced by the amount of muscle tissue in the body, emotions, hormones, and differences in physical activity. Adding BMR to the kcal needed for other demands (such as body movements) gives the total amount of food energy you need to fuel your daily life.

To figure out how many kcal you should take in daily to maintain a desired weight, multiply that weight (in pounds) by 10 if you are sedentary, by 15 if you are fairly active, and by 20 if highly active. From the value you get this way, subtract the following amount:

Age	Subtract
20–34	0
35–44	100
45–54	200
55–64	300
Over 65	400

For instance, if you want to weigh 120 pounds and are very active, 120 × 20 = 2,400 kilocalories. If you are 35

Weight Guidelines for Women

Starting with an ideal weight of 100 pounds for a woman who is 5 feet tall, add five additional pounds for each additional inch of height. Examples:

Height (feet)	Weight (pounds)
5′ 2″	110
5′ 3″	115
5′ 4″	120
5′ 5″	125
5′ 6″	130
5′ 7″	135
5′ 8″	140
5′ 9″	145
5′ 10″	150
5′ 11″	155
6′	160

Weight Guidelines for Men

Starting with an ideal weight of 106 pounds for a man who is 5 feet tall, add six additional pounds for each additional inch of height. Examples:

Height (feet)	Weight (pounds)
5′ 2″	118
5′ 3″	124
5′ 4″	130
5′ 5″	136
5′ 6″	142
5′ 7″	148
5′ 8″	154
5′ 9″	160
5′ 10″	166
5′ 11″	172
6′	178

Figure 11.22 Multiple factors determine how much food energy each person needs to maintain a healthy weight. The charts show how to estimate the "ideal" weight for an adult. The values given are consistent with a long-term Harvard study into the link between excessive weight and increased risk of heart disorders. Depending on certain factors, such as having a small, medium, or large skeletal frame, the "ideal" may vary by plus or minus 10 percent.

Calories Expended in Some Common Activities

Activity	Kcal/hour per pound of body weight	Hours needed to lose 1 lb. fat 120 lbs	155 lbs	185 lbs
Basketball	3.78	7.7	6.0	5.0
Cycling (9 mph)	2.70	10.8	8.4	7.0
Hiking	2.52	11.6	8.9	7.5
Jogging	4.15	7.0	5.4	4.5
Mowing lawn (push mower)	3.06	9.5	7.4	6.2
Racquetball	3.90	7.5	5.8	4.8
Running (9-minute mile)	5.28	5.5	4.3	3.6
Snow skiing (cross-country)	4.43	6.6	5.1	4.3
Swimming (slow crawl)	3.48	8.4	6.5	5.4
Tennis	3.00	9.7	7.5	6.3
Walking (moderate pace)	2.16	13.5	10.4	8.7

To calculate these values for your own body weight, first multiply your weight by the kcal/hour expended for an activity to determine total kcal you use during one hour of the activity. Then divide that number into 3,500 (kcal in a pound of fat) to obtain the number of hours you must perform the activity to burn a pound of body fat.

To eat or not to eat?

years old and moderately active, then you should take in a total of 1,800 − 100, or 1,700 kcal a day. Along with this rough estimate, factors such as height and gender also must be considered. Males tend to have more muscle and so burn more calories (they have a higher BMR); hence an active woman needs fewer kilocalories than an active man of the same height and weight. Nor does she need as many as another active woman who weighs the same but is several inches taller.

Genes and activity levels affect weight

You've probably noticed that some people have a lot more trouble keeping off excess weight than others do. Although various factors influence body weight, recent research has shown that genes play a major role. As you will read later in this textbook, there are different chemical versions of many genes, and each version may have a slightly different effect. Scientists have identified several dozen genes that govern hormones, such as leptin and ghrelin, that influence appetite, hunger, how the body stores fat, and other weight-related factors. It may be that differences among genes help explain why some people stay slim no matter what and how often they eat, while others wage a lifelong struggle with extra pounds.

For most people, maintaining a healthy weight over the years requires balancing their "energy budget" so that energy in—calories in food—equals energy used by body cells. Losing a pound of fat requires expending about 3,500 kcal. Weight-loss diets may accomplish this deficit temporarily, but over the long haul keeping off excess weight means pairing a moderate reduction in caloric intake with an increase in physical activity (Table 11.5). Exercise also increases the mass of skeletal muscles, and even at rest muscle burns more calories than other types of tissues.

Emotions can influence weight gain and loss, sometimes to extremes. People who suffer from *anorexia nervosa* see themselves as fat no matter how thin they become. An anorexic purposely starves and may overexercise as well. Most common among younger women, anorexia can be fatal. Another extreme is the binge–purge disorder called *bulimia*. The term means "having an oxlike appetite." A bulimic might consume as much as 50,000 calories at one sitting and then purposely vomit, take a laxative, or both. Chronic vomiting can erode away the enamel from a person's teeth (due to stomach acid) and rupture the stomach. In severe cases it also can cause chemical imbalances that lead to heart and kidney failure.

Take-Home Message

What is the relationship between food energy consumed and body weight?

- To maintain an acceptable body weight, energy input (caloric intake) must be balanced with energy used in metabolic activity and exercise.
- Basal metabolic rate, physical activity, age, hormones, and emotions all influence the body's energy use.
- Genes govern the hormones that influence appetite, hunger, and how the body stores and uses energy.

IMPACTS, ISSUES

Food for Thought

MANY health care organizations are mounting education campaigns to inform people about the health risks associated with obesity. New research shows that genetic factors make it difficult for some people to reach and maintain a healthy weight, and that hormones affect appetite, hunger, and metabolic rate.

How Would You Vote?

Fast food is contributing to the obesity crisis. Should fast-food items be required to carry health warnings? See CengageNOW for details, then vote online.

Summary

Section 11.1 The digestive system breaks food down into molecules that are small enough to be absorbed into the bloodstream. It also stores and eliminates unabsorbed materials and promotes homeostasis by its interactions with other organ systems.

The gastrointestinal tract includes the mouth, pharynx, esophagus, stomach, small intestine, and large intestine. Its associated accessory organs include salivary glands, the liver, the gallbladder, and the pancreas (Table 11.6).

The GI tract is lined with mucous membrane. From the esophagus onward its wall consists of four layers: an innermost mucosa, then the submucosa, then smooth muscle, then the serosa. Sphincters at either end of the stomach and at other locations within the GI tract control the forward movement of ingested material.

- Use the animation and interaction on CengageNOW to tour the human digestive system.

Section 11.2 Starch digestion begins in the mouth or oral cavity, where the salivary glands secrete saliva, which contains salivary amylase. Chewed food mixes with saliva to form a bolus that is swallowed. Waves of peristalsis move each bolus down the esophagus to the stomach.

Section 11.3 Protein digestion begins in the stomach, where gastric fluid containing pepsins and other substances is secreted. The stomach contents are reduced to a watery chyme that passes through a sphincter into the small intestine.

Section 11.4 Digestion is completed and most nutrients are absorbed in the small intestine, which has a large surface area for absorption due to its many villi and microvilli.

- Use the animation and interaction on CengageNOW to learn about the small intestine's structure and how it absorbs nutrients.

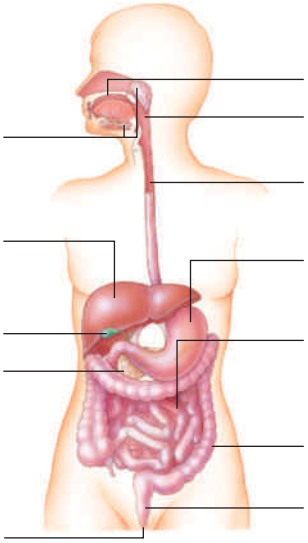
Section 11.5 Enzymes and some other substances secreted by the pancreas, the liver, and the gallbladder aid digestion. Bile (secreted by the liver and then stored and released into the small intestine by the gallbladder) contains bile salts that speed up the digestion of fats. Micelles aid the absorption of fatty acids and triglycerides. A hepatic portal vein carries nutrient-laden blood to the liver for processing.

Section 11.6 In the small intestine, segmentation mixes material and forces it close to the absorptive surface. Absorbed glucose and amino acids move into blood vessels in intestinal villi. Triglycerides enter lacteals, then move into blood vessels.

Section 11.7 Peristalsis moves wastes into the large intestine. Water is reabsorbed in the colon; wastes (feces) move on to the rectum and into the anal canal and are eliminated via the anus. The appendix projects from the upper part of the large intestine. It may have a role in immunity.

Summary of the Digestive System

Mouth (oral cavity)	Start of digestive system, where food is chewed, moistened, polysaccharide digestion begins
Pharynx	Entrance to tubular parts of digestive and respiratory systems
Esophagus	Muscular tube, moistened by saliva, that moves food from pharynx to stomach
Stomach	Sac where food mixes with gastric fluid and protein digestion begins; stretches to store food taken in faster than can be processed; gastric fluid destroys many microbes
Small Intestine	The first part (duodenum) receives secretions from the liver, gallbladder, and pancreas
	Most nutrients are digested, absorbed in second part (jejunum)
	Some nutrients absorbed in last part (ileum), which delivers unabsorbed material to colon
Colon (large intestine)	Concentrates and stores undigested matter (by absorbing mineral ions and water)
Rectum	Distension triggers expulsion of feces
Anus	Terminal opening of digestive system
Accessory Organs:	
Salivary Glands	Glands (three main pairs, many minor ones) that secrete saliva, a fluid with polysaccharide-digesting enzymes, buffers, and mucus (which moistens and lubricates ingested food)
Pancreas	Secretes enzymes that digest all major food molecules and buffers against HCl from stomach
Liver	Secretes bile (used in fat emulsification); role in carbohydrate, fat, and protein metabolism
Gallbladder	Stores and concentrates bile from the liver



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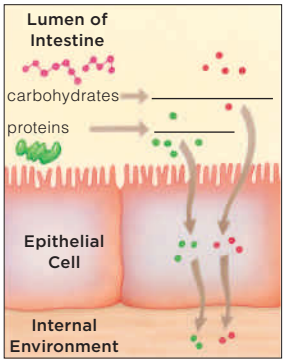

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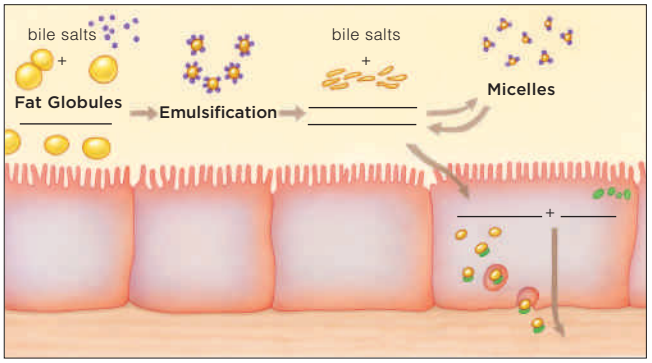


Figure 11.23 In part **a**, list the organs and accessory organs of the digestive system. In part **b**, fill in the blanks for substances that cross the lining of the small intestine

Section 11.8 The nervous and endocrine systems govern the digestive system. Many controls operate in response to the volume and composition of food in the gut. They cause changes in muscle activity and in the secretion rates of hormones or enzymes.

Section 11.12 Complex carbohydrates are the body's preferred energy source. The diet also must provide eight essential amino acids, some essential fatty acids, vitamins, and minerals.

Section 11.13 Vitamins and minerals both are essential for normal body growth and functioning. Vitamins are organic substances; minerals are inorganic.

Section 11.14 Food energy is measured in kilocalories. The basal metabolic rate is the amount of kilocalories needed to sustain the body when a person is awake and resting. To maintain a healthy weight a person's total energy output must balance caloric intake. Obesity is a health-threatening condition that increases the risk of type 2 diabetes, heart trouble, and other diseases and disorders.

- Use the animation and interaction on CengageNOW to calculate your body mass index.

Review Questions

1. What are the main functions of the stomach? What roles do enzymes and hormones play?
2. Explain the differences between the digestion roles of the small and large intestines. Does the appendix also have a digestive function?
3. Using the sketch above (Figure 11.23*a*), list the organs and accessory organs of the digestive system. On a separate piece of paper, list the main functions of each organ.
4. Define peristalsis, and list the regions of the GI tract where it occurs. Be sure to mention segmentation in your answer.
5. Using the black lines shown in Figure 11.23*b*, name the types of molecules small enough to be absorbed across the small intestine's lining.

Self-Quiz *Answers in Appendix V*

1. Different regions of the digestive system specialize in and food and in _____ unabsorbed food residues.
2. Maintaining normal body weight requires that intake be balanced by _____ output.
3. The preferred energy sources for the body are _____.
4. The human body cannot produce its own vitamins or minerals, nor can it produce certain _____ and _____.
5. Which of the following is not associated with digestion?
   a. salivary glands
   b. thymus gland
   c. liver
   d. gallbladder
   e. pancreas
6. Digestion is completed and products are absorbed in the _____.
   a. mouth
   b. stomach
   c. small intestine
   d. large intestine
7. After triglycerides, fatty acids, and monoglycerides are absorbed, they leave the cell and move into the _____.
   a. bloodstream
   b. intestinal cells
   c. liver
   d. lacteals
8. Excess carbohydrates and proteins are stored as _____.
   a. amino acids
   b. starches
   c. fats
   d. monosaccharides
9. Basal metabolic rate is a measure of:
   a. the total amount of calories you burn in 24 hours.
   b. the amount of food energy needed to sustain basic body operations.
   c. the amount of energy burned by skeletal muscle in a given period.
   d. weight-related health risk.
   e. Both a and d are correct.

10. Match the digestive system parts and functions.

____ liver	a. secrete substances that moisten food, start polysaccharide breakdown
____ small intestine	b. where protein digestion begins
____ salivary glands	c. where water is reabsorbed
____ stomach	d. where most digestion is completed
____ large intestine	e. receives blood carrying absorbed nutrients

Critical Thinking

1. A glass of whole milk contains lactose, protein, triglycerides (in butterfat), vitamins, and minerals. Explain what happens to each component when it passes through your digestive tract.

2. Some nutritionists claim that the secret to long life is to be slightly underweight as an adult. If a person's weight is related partly to diet, partly to activity level, and partly to genetics, what underlying factors could be at work to generate statistics that support this claim?

3. As a person ages, the number of body cells steadily decreases and energy needs decline. If you were planning an older person's diet, what kind(s) of nutrients would you emphasize, and why? Which ones would you recommend an aging person eat less of?

4. Along the lines of question 3, formulate a healthy diet for an actively growing seven-year-old.

5. Raw poultry can carry *Salmonella* or *Campylobacter* bacteria, both of which produce toxins that can cause serious diarrhea, among other symptoms. Aside from the discomfort, why does such an infection require immediate medical attention?

Figure 11.24 **Dutch cyclist Leontien Zijlaard recovered from anorexia and went on to win Olympic gold.**

6. Dutch cyclist Leontien Zijlaard, the young woman shown in Figure 11.24, won three Olympic gold medals. Four years earlier, she was suffering from anorexia and too weak and malnourished to compete. Many recovered anorexics lead normal—even extraordinary—lives, and researchers are uncovering a wealth of new information about the disorder. Do some research yourself and find answers to the following questions:

Are eating disorders common or rare?

How many people die each year from anorexia and bulemia?

Is there evidence that genes influence these conditions?

EXPLORE ON YOUR OWN

This is an exercise you can eat when you're done. All you need is a food item like a hamburger or a salad and paper for jotting notes.

To begin, analyze your meal, noting the various kinds of biological molecules it includes. (For this exercise, ignore nucleic acids.) Then, beginning with your mouth and teeth, write what happens to your meal as it moves through your digestive system. Key questions to consider include: What kinds of enzymes act on the different components of the meal (such as lettuce or meat), and where do they act, as it is digested? What mechanical processes aid digestion? Which ones can you consciously control? Using the tables in Section 11.13, list the vitamins and minerals that your meal likely contains. Finally, analyze your meal in terms of its contribution (or lack of one) to a balanced diet.

The Urinary System

12

IMPACTS, ISSUES

Truth in a Test Tube

LIGHT or dark? Clear or cloudy? A lot or a little? Today physicians routinely check the chemical composition of our urine. Acidic urine can signal metabolic problems, while alkaline urine may be a sign of a bacterial infection. Too much protein in urine might mean the kidneys are not functioning properly. Specialized urine tests can detect chemicals produced by cancers of the kidney, bladder, and prostate gland.

Do-it-yourself urine tests are popular for monitoring a woman's fertile period or early signs she may be pregnant. A test for older women may reveal declining hormone levels that signal the onset of menopause.

Not everyone is anxious to have their urine tested. Athletes can be stripped of honors or medals when mandatory urine tests reveal they use prohibited drugs. If you use marijuana, cocaine, Ecstasy, or other kinds of illegal drugs, urine also tells the tale. For example, after the active ingredient of marijuana enters the blood, the liver converts it to another compound. The kidneys filter the blood and they add this telltale compound to the newly forming urine. It can take up to ten days for all of it to be metabolized and removed from the body. Until then, urine tests can detect it.

That our urine can be such a trusty indicator of health, the presence of hormones, and drug use is a tribute to the urinary system. As you will read in this chapter, each day, your kidneys filter all of the blood in your body—not once, but thirty times. This constant processing is extremely important for homeostasis because it rids the body of excess water and excess or harmful substances in the blood and other body fluids.

LINKS TO EARLIER CONCEPTS

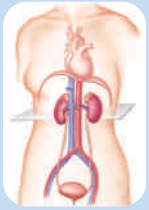
- As you learn how the urinary system helps maintain homeostasis in the extracellular fluid (blood and tissue fluid), you will tap your knowledge of pH and buffer systems (2.7) and of osmosis and transport mechanisms (3.10, 3.11).
- You will also use what you have learned about the functions of blood and blood circulation by the cardiovascular system (7.1, 7.7), and the movement of substances into and out of blood capillaries (7.7).

KEY CONCEPTS

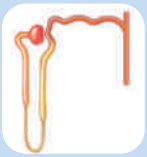
Maintaining the Extracellular Fluid

The body must eliminate chemical wastes from extracellular fluid, including the blood, and manage the levels of water and solutes in it. The urinary system performs this task. Section 12.1

The Urinary System



The urinary system consists of the kidneys, ureters, bladder, and urethra. In the kidneys, structures called nephrons filter substances from the blood, eliminating unneeded ones in urine. Section 12.2



How the Kidneys Form Urine

The kidneys form urine in steps called filtration, reabsorption, and secretion. Hormones and a thirst mechanism adjust the chemical makeup of urine. Sections 12.3–12.5

Disorders of the Urinary System and Homeostasis

Sections 12.6–12.8

How Would You Vote?

Many companies use urine testing to screen prospective employees for drug and alcohol use. Some people say this is an invasion of privacy. Do you think employers should be allowed to require a person to undergo urine testing before being hired? See CengageNOW for details, then vote online.

12.1 The Challenge: Shifts in Extracellular Fluid

- **The chemical makeup of body fluid changes constantly as water and solutes enter and leave it.**
- **Links to Water and life 2.5, Condensation reactions 2.8, Metabolism 3.13, Blood 8.1, Nutrient absorption 11.4**

If you are an adult female in good health, by weight your body is about 50 percent fluid. If you are an adult male, the ratio is about 60 percent. Fluid is extremely important both in the composition of body structures and in nearly all body functions. A simple way to start thinking about the many roles of fluid in the body is to divide things up into two "fluid compartments"—one that is inside cells, and a second that is outside cells (Figure 12.1).

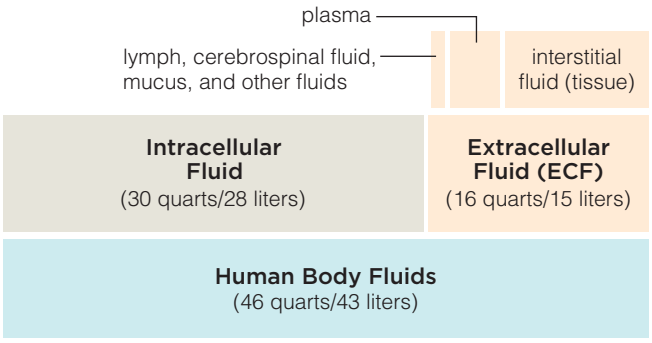


Figure 12.1 Body fluid occurs intwo compartments—one inside cells and the other outside cells.

The urinary system adjusts fluid that is outside cells

Recall that tissue fluid fills the spaces between cells and other components of our body tissues. Blood, which is mostly the watery fluid called plasma, circulates in blood vessels. Together, tissue fluid, blood plasma, and the relatively small amounts of other fluids (such as in lymph) outside cells are the body's **extracellular fluid**, or ECF.

The fluid *inside* our cells is **intracellular fluid**. From previous chapters you know that a variety of gases and other substances move constantly between intracellular and extracellular fluid. Those exchanges are crucial for keeping cells functioning smoothly. They cannot occur properly unless the volume and composition of the ECF are stable.

Yet the ECF is always changing, because gases, cell products, ions, and other materials enter or leave it. To maintain stable conditions in the ECF, especially the concentrations of water and vital ions such as sodium (Na^+) and potassium (K^+), there must be mechanisms that remove substances as they enter the extracellular fluid or add needed ones as they leave it. The **urinary system** performs this task. Before examining how it operates, however, let's take a general look at the traffic of substances into and out of extracellular fluid.

The body gains water from food and metabolic processes

Ordinarily, each day you take in about as much water as your body loses (Table 12.1). Some of the water is absorbed from foods and liquids you consume. The rest is produced during metabolic reactions, including cellular respiration and condensation reactions.

Thirst influences how much water we take in. When there is a water deficit in body tissues, the brain "urges" us to seek out water—for example, from a water fountain or a cold drink from the refrigerator. We will be looking at the thirst mechanism later in the chapter.

TABLE 12.1 Normal Daily Balance between Water Gain and Water Loss in Adult Humans

Water Gain (milliliters)		Water Loss (milliliters)	
Ingested in solids:	850	Urine:	1,500
Ingested as liquids:	1,400	Feces:	200
Metabolically derived:	350	Evaporation:	900
	2,600		2,600

The body loses water in urine, sweat, feces, and by evaporation

Water leaves the body in four ways: Excretion in urine, evaporation from the lungs and skin, sweating, and in feces. Of these four routes, **urinary excretion** is the form of water loss over which the body has the most control. Urinary excretion eliminates excess water, as well as excess or harmful solutes, in the form of **urine**. Some water also evaporates from our skin and from the respiratory surfaces of the lungs. These are sometimes called "insensible" water losses, because a person is not always aware they are taking place. As noted in Chapter 11, normally very little water that enters the GI tract is lost; most is absorbed and only a little is eliminated in feces.

Solutes enter extracellular fluid from food, respiration, and metabolism

Three main sources add solutes to the body's extracellular fluid. Food supplies nutrients (including glucose) and mineral ions (such as potassium and sodium ions) that are absorbed from the GI tract. We also consume many drugs and food additives. The respiratory system brings oxygen into the blood (Figure 12.2). Last but not least, living cells continually secrete substances, including carbon dioxide, into tissue fluid and circulating blood.

Solutes leave the ECF by urinary excretion, in sweat, and during breathing

Metabolic wastes, mineral ions, and other solutes leave extracellular fluid in several ways. Metabolism produces more than 200 waste substances. Carbon dioxide is the most abundant one, and we get rid of it by exhaling it from our lungs. All other major wastes leave in urine.

Important metabolic wastes include by-products of processes that break down nucleic acids and proteins. Dismantling nucleic acids produces one of these wastes, uric acid. Another one, ammonia, forms in "deamination" reactions, which remove the nitrogen-containing amino groups from amino acids. Ammonia is highly toxic if it accumulates in the body. Reactions in the liver combine ammonia with carbon dioxide, producing the much less toxic **urea**. Accordingly, urea is the main waste product when cells break down proteins. About half of the urea filtered from blood in the kidneys is reabsorbed. The rest is excreted. Protein breakdown also produces creatine, phosphoric acid, sulfuric acid, and small amounts of other, nitrogen-containing compounds, some of which are toxic. These also are excreted.

Although sweat carries away a small percentage of urea, by far the most nitrogen-containing wastes are removed by our kidneys while they filter other substances from the blood. In addition to removing wastes and excess water, the kidneys also help maintain the balance of important ions such as sodium, potassium, and calcium. These ions are sometimes called **electrolytes** because a solution in which they are dissolved will carry an electric current. Chapter 13 describes the crucial roles electrolytes have in the functioning of the nervous system.

Normally only a little of the water and solutes that enter the kidneys leaves as urine. In fact, except when you drink lots of fluid (without exercise), all but about 1 percent of the water is returned to the blood. However, the chemical composition of the fluid that is returned has been adjusted in vital ways. Just how this happens will be our focus as we turn our attention to the urinary system.

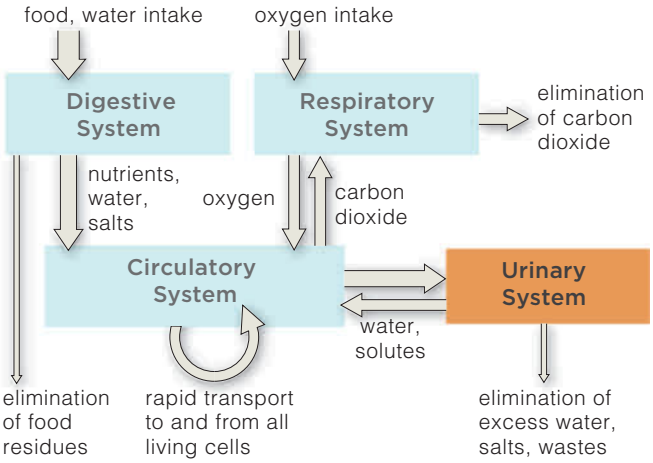


Figure 12.2 The activities of the urinary system coordinate with those of other organ systems.

Take-Home Message

How does the body deal with shifts in extra-cellular fluid?

- Each day the body gains water consumed in liquids and solid foods and from metabolism. It loses an approximately equal amount of water through urinary excretion, evaporation, sweating, and elimination in feces.
- The body gains solutes from digested food, respiration, secretion by cells, and metabolism. Excess or harmful solutes are removed by urinary excretion, respiration, and sweating.
- The kidneys adjust the volume and chemical composition of the blood. In this way they help maintain homeostasis in the extracellular fluid.

12.2 The Urinary System: Built for Filtering and Waste Disposal

- **The urinary system consists of filtering organs—the kidneys—and structures that carry and store urine.**
- **Links to Metabolism 3.13, Blood exchanges with tissues 7.7, Red blood cell production 8.3**

Each **kidney** is a bean-shaped organ about the size of a rolled-up pair of socks (Figure 12.3). It has several internal lobes. In each lobe, an outer **cortex** wraps around a central region, the *medulla*, as you can see sketched in Figure 12.3*c*. The whole kidney is wrapped in a tough coat of connective tissue, the *renal capsule* (from the Latin *renes*, meaning kidneys). The kidney's central cavity is called the *renal pelvis*.

Our kidneys have several functions. They produce the hormone erythropoietin, which stimulates the production of red blood cells (Section 8.3). They also convert vitamin D to a form that stimulates the small intestine to absorb calcium in food. In addition, kidneys make the enzyme renin, which helps regulate blood pressure, as you will read later in this chapter. The main function of kidneys, however, is to remove metabolic wastes from the blood and adjust fluid balance in the body.

In addition to the two kidneys, the urinary system includes "plumbing" that transports or stores urine. Once urine has formed in a kidney, it flows into a tube-like **ureter**, then on into the **urinary bladder**, where it is stored until you urinate. It leaves the bladder through the **urethra**, a muscular tube that opens at the body surface.

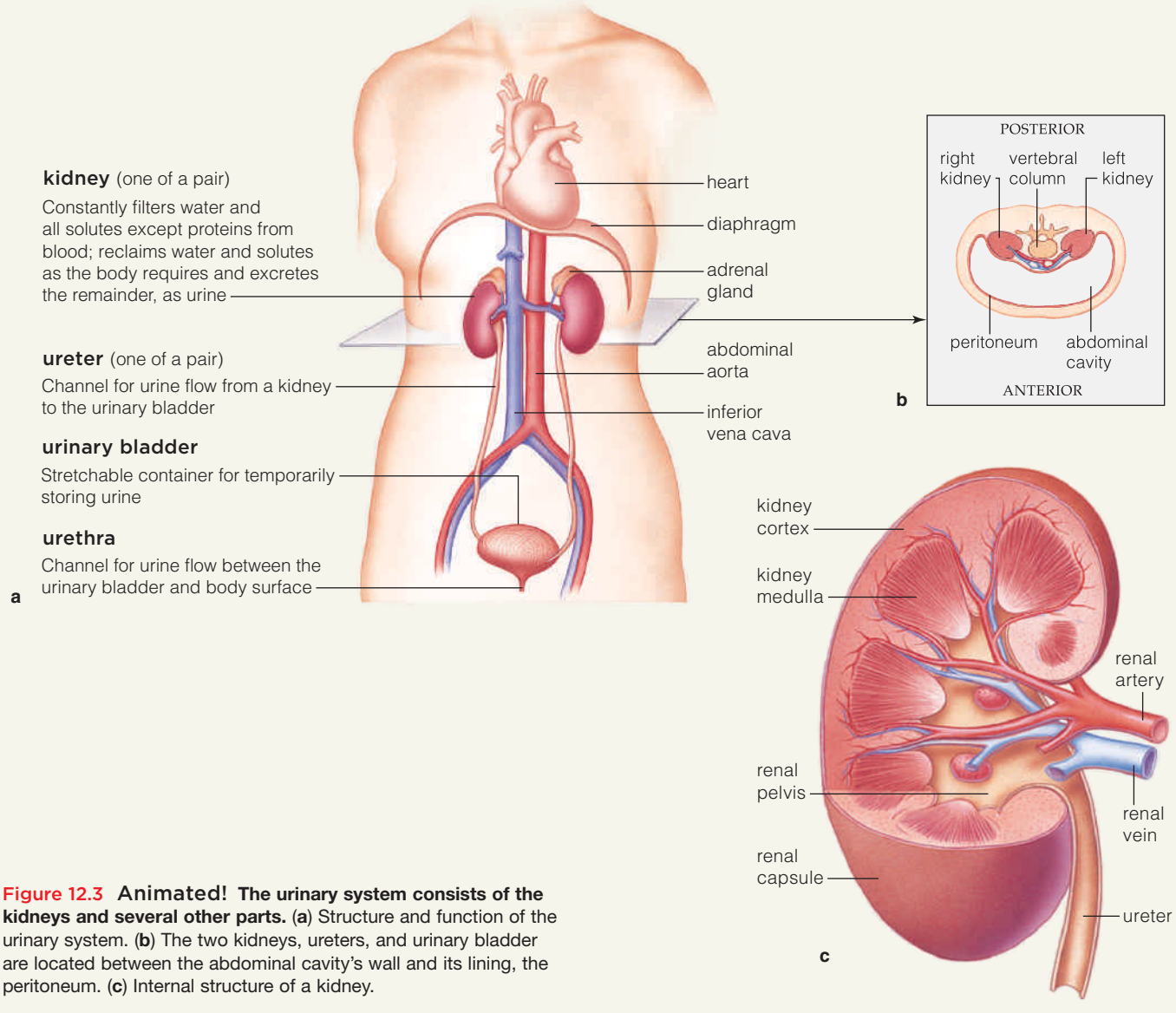
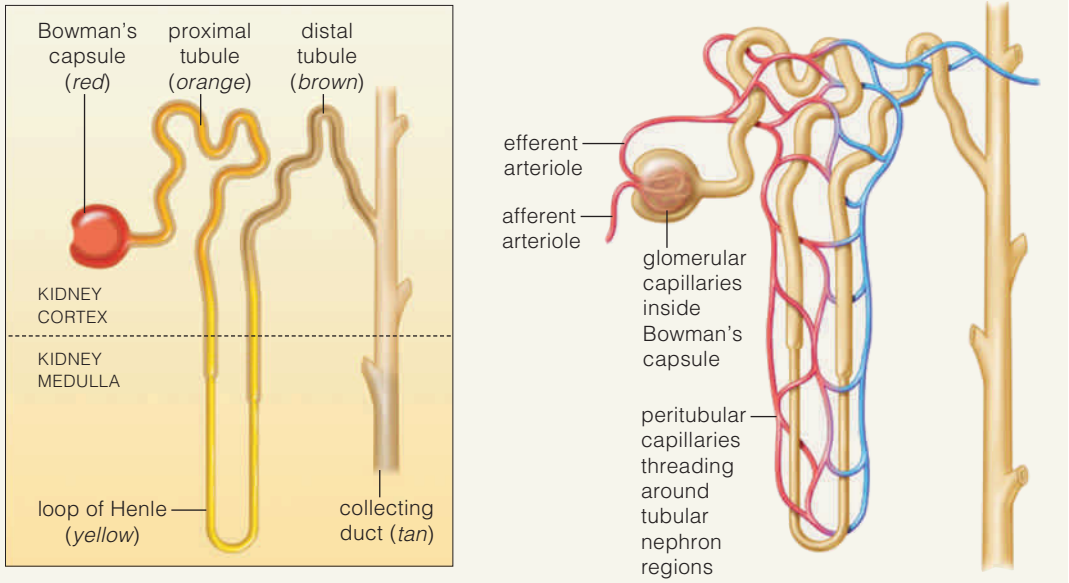


Figure 12.3 Animated! The urinary system consists of the kidneys and several other parts. (**a**) Structure and function of the urinary system. (**b**) The two kidneys, ureters, and urinary bladder are located between the abdominal cavity's wall and its lining, the peritoneum. (**c**) Internal structure of a kidney.



a Bowman's capsule and tubular regions of one nephron, cutaway view.

b Blood vessels associated with the nephron.

Figure 12.4 Animated! **Interacting with two sets of capillaries, nephrons are a kidney's blood-filtering units.** (**a**) Diagram of a nephron. (**b**) The arterioles and capillaries associated with a nephron.

Nephrons are the kidney filters

Each kidney lobe contains blood vessels and more than a million slender tubes called **nephrons**. Nephrons are the structures that filter water and solutes from blood.

A nephron is shaped a bit like the piping under a sink (Figure 12.4*a*). Its wall is a single layer of epithelial cells, but the cells and junctions between them vary in different parts of the tube. Water and solutes pass easily through some parts, but other parts block solutes unless they are moved across by active transport (Section 3.11).

As sketched in Figure 12.4*b*, the nephron wall balloons around a tiny cluster of blood capillaries called the **glomerulus** (plural: glomeruli). The cuplike wall region, called the **Bowman's** (glomerular) **capsule**, receives the substances that are filtered from blood. The rest of the nephron is a winding tubule ("little tube"). Filtrate flows from the cup into the **proximal tubule** (proximal means "next to"), then through a hairpin-shaped **loop of Henle** and into the **distal tubule** ("most distant" from the glomerular capsule). This part of the nephron tubule empties into a collecting duct.

Special vessels transport blood to, in, and away from nephrons

Each hour, about 75 gallons of blood course through your kidneys, delivered by the renal artery. An **afferent arteriole** brings blood to each nephron (afferent means "carrying toward"). The blood flows into the glomerular capillaries inside Bowman's capsule. These capillaries are not like capillaries in other parts of the body, however. Slitlike pores between the cells of their walls make them much more permeable than other capillaries. Thus it is much easier for water and solutes to move across the wall.

The glomerular capillaries also do not channel blood to venules, as other capillaries do (Section 7.7). Instead, the glomerular capillaries merge to form an **efferent** ("carrying away from") **arteriole**. This arteriole branches into yet another set of capillaries, called **peritubular** ("around the tubule") **capillaries**. As you can see in Figure 12.4*b*, the peritubular capillaries weave around a nephron's tubules. They merge into venules, which carry filtered blood out of the kidneys.

As we see next, the network of capillaries that feed and drain blood from nephrons is a key factor in the kidneys' ability to fine-tune the chemical makeup of the blood.

Take-Home Message

What are the parts and functions of the urinary system?

- The urinary system consists of two kidneys, two ureters, the urinary bladder, and the urethra.
- Kidney nephrons filter water and solutes from blood. A tiny cluster of capillaries called a glomerulus is the nephron's blood-filtering unit.
- The capillaries in a glomerulus have pores in their walls that make the vessels much more permeable than usual.
- Afferent arterioles deliver blood to nephrons and efferent arterioles carry it away. Peritubular capillaries weave around nephron tubules and deliver filtered blood back to the general circulation.

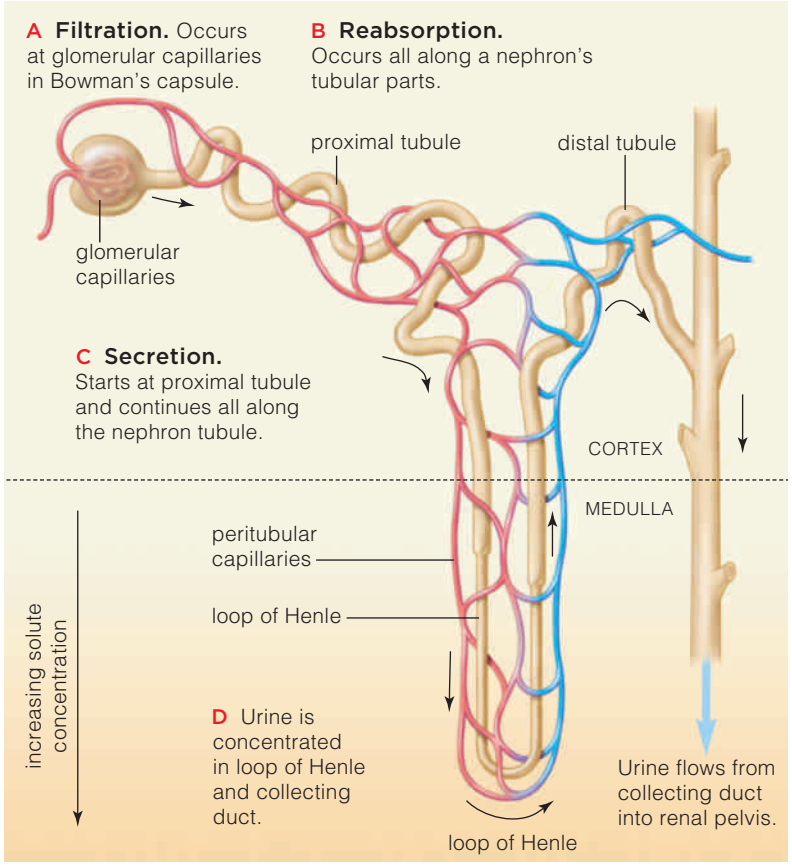
12.3 How Urine Forms: Filtration, Reabsorption, and Secretion

- **The processes that form urine normally ensure that only unneeded substances are excreted from the body.**
- **Links to Diffusion and osmosis 3.10, Other ways substances cross membranes 3.11, Liver functions 11.5**

The fluid we call urine forms in a sequence of three steps called filtration, reabsorption, and secretion. Figure 12.5 gives you an overview of these steps.

Filtration removes a large amount of fluid and solutes from the blood

Blood pressure is the driving force for **filtration**, the first step in forming urine. Efferent arterioles are narrow, so they deliver blood to the glomerulus under high pressure. This pressure forces about 20 percent of the blood plasma into Bowman's capsule. Blood cells, platelets, proteins, and other large solutes stay in the blood. Everything else—water and small solutes such as glucose, amino acids, sodium, urea, and vitamins—can filter out of the glomerular capillaries and into Bowman's capsule. From there the filtrate flows into the proximal tubule (Figure 12.6*a*), where reabsorption can begin.



Next, reabsorption returns useful substances to the blood

The body cannot afford to lose the huge amounts of water and valuable solutes such as glucose, amino acids, and electrolytes that are filtered from the blood by the kidneys. Fortunately, most of the filtrate is recovered by **reabsorption**. In this process, substances leak or are pumped out of the nephron tubule and then enter peritubular capillaries and so return to the bloodstream.

Most reabsorption takes place across the walls of proximal tubules. As in all parts of the tubule, the walls in this area are only one cell thick. Figure 12.6*b* shows what happens with water, glucose, and salt (ions of sodium, NA^+, and chloride, Cl^-). All these substances can diffuse from the filtrate in a tubule into and through the cells of the tubule wall. On the outer side of the cells, active transport (through proteins in the cells' plasma membranes) moves glucose and Na^+ into the tissue fluid. Sodium ions (Na^+) are positively charged, and negatively charged ions, including chloride (Cl^-), follow the sodium.

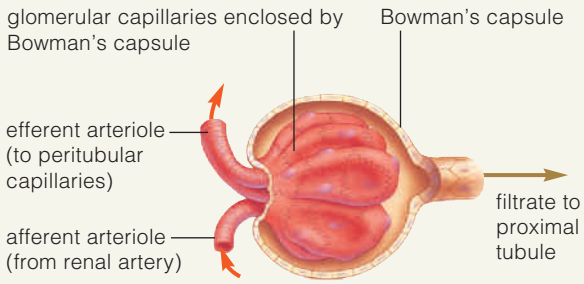
As the concentration of solutes rises in the fluid, water moves out of the tubule cells by osmosis. In a final step, solutes are actively transported into peritubular capillaries and water again follows by osmosis. These substances now have been reabsorbed. The solutes and water that remain in the tubule become part of urine.

Reabsorption usually returns almost 99 percent of the filtrate's water, all of the glucose and most amino acids, all but about 0.5 percent of the salt (sodium and chloride ions), and 50 percent of the urea to the blood (Table 12.2).

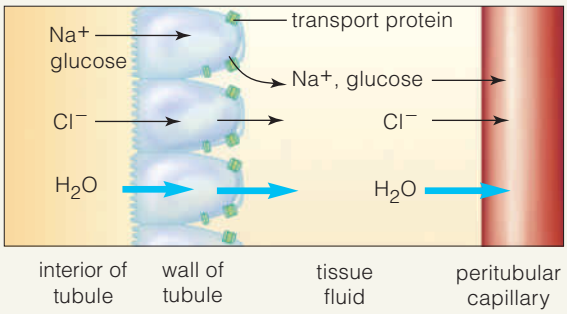
Average Daily Reabsorption Values for a Few Substances

	Amount Filtered	Percentage Excreted	Percentage Reabsorbed
Water	180 liters	1	99
Glucose	180 grams	0	100
Amino acids	2 grams	5	95
Sodium ions	630 grams	0.5	99.5
Urea	54 grams	50	50

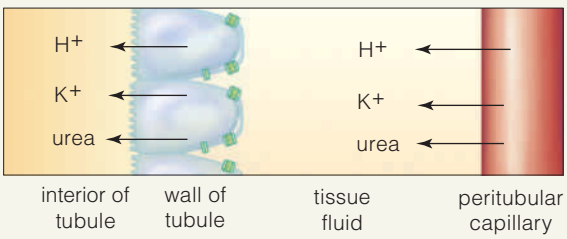
Figure 12.5 Animated! Urine forms in a sequence of three steps (a, b, and c). Before flowing on, urine is concentrated in (d) the loop of Henle.



A Filtration. Water and solutes forced out across the glomerular capillary wall collect in Bowman's capsule, which drains into the proximal tubule.



B Reabsorption. As filtrate flows through the proximal tubule, ions and some nutrients are actively and passively transported outward, into tissue fluid. Water follows, by osmosis. Cells of peritubular capillaries transport them into blood. Water again follows by osmosis.



C Secretion. Transport proteins move H^+, K^+, urea, and wastes out of peritubular capillaries. Transporters in the nephron tubule move them into the filtrate.

Figure 12.6 Animated! The urine-forming steps are filtration, reabsorption, and secretion.

Secretion rids the body of excess hydrogen ions and some other substances

Secretion takes up unwanted substances that have been transported out of peritubular capillaries and adds them to the urine that is forming in nephron tubules (Figure 12.6*c*). Among other functions, this highly controlled process rids the body of urea and of excess hydrogen ions (H^+) and potassium ions (K^+).

Secretion is crucial to maintaining the body's acid–base balance, which you will read about in a later section. It also helps ensure that some wastes (such as uric acid and some breakdown products of hemoglobin) and foreign substances (such as antibiotics and some pesticides) do not build up in the blood. The drug testing noted in the chapter introduction relies on the use of urinalysis to detect drug residues that have been secreted into urine.

Homeostasis requires that the total volume of fluid in the blood and tissues stay fairly stable. Blood and tissue fluid are mostly water, and while your kidneys are removing impurities from your blood they are also adjusting the amount of water that is excreted in urine or returned to the bloodstream.

Urination is a controllable reflex

Urination is urine flow from the body. It is a reflex response. As the bladder fills, tension increases in the smooth muscle of its strong walls. Where the bladder joins the urethra, an *internal urethral sphincter* built of smooth muscle helps prevent urine from flowing into the urethra. As tension in the bladder wall increases, though, the sphincter relaxes; at the same time, the bladder walls contract and force urine through the urethra.

Skeletal muscle forms an *external urethral sphincter* closer to the urethral opening. Learning to control it is the basis of urinary "toilet training" in young children.

Take-Home Message

How does urine form?

- Urine consists of water and solutes that are not needed to maintain the chemical balance of extracellular fluid, as well as water-soluble wastes.
- Urine forms through the steps called filtration, reabsorption, and secretion.
- In filtration, water and other small molecules are filtered from the blood and into the nephron.
- Reabsorption recaptures needed water and solutes.
- Secretion adds unwanted substances into urine, including hydrogen ions and foreign substances such as antibiotics.

12.4 How Kidneys Help Manage Fluid Balance and Blood Pressure

- **In addition to removing wastes from blood, the kidneys concentrate urine. The concentration mechanisms also help regulate blood volume and blood pressure.**
- **Links to Chemical bonds 2.3, Liver functions 11.5**

Overall, the total volume of your body fluids, including blood plasma, doesn't vary much. This is because during reabsorption, the kidneys adjust how much water and salt (sodium + chloride ions) the body conserves or excretes in urine. As you know, blood and tissue fluid are mostly water. In general, when the volume of blood increases or decreases, so does blood pressure. The kidneys help ensure that the volume of extracellular fluid, and blood in particular, stays within a normal range.

Water follows salt as urine forms

Although about two-thirds of filtered salt and water is reabsorbed in the proximal tubule, the filtrate usually still contains more of both than the body can afford to lose in urine. This situation is addressed as the filtrate enters the loop of Henle, which descends into the kidney medulla (Figure 12.7). There the loop is surrounded by extremely salty tissue fluid. Water can pass through the thin wall of the loop's descending limb, so more water moves out by osmosis and is reabsorbed. As the water leaves, the salt concentration in the fluid still inside the descending limb increases until it matches that in the fluid outside.

Now the filtrate "rounds the turn" of the loop and enters the ascending limb. The wall of this part of the nephron tubule does not allow water to pass through. This is an important variation in the tubule's structure, because here sodium is actively transported out of the ascending limb—but water cannot move with it.

The filtrate now moves into the distal tubule. Its cells continue to remove salt, but also do not let water escape. Hence, a dilute urine moves on into the collecting duct.

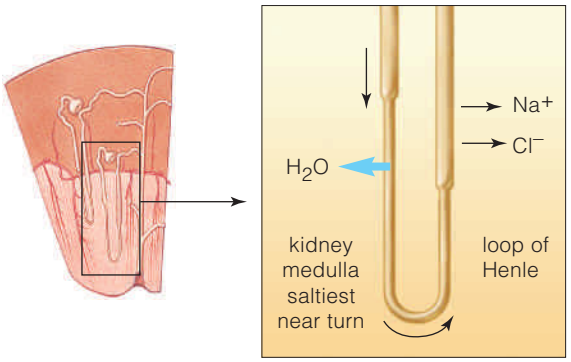


Figure 12.7 Water and salt are reabsorbed in the loop of Henle.

Naturally, as salt leaves the filtrate moving through a nephron tubule, the concentration of solutes rises outside the tubule and falls inside it. This steep gradient helps drive the reabsorption of valuable solutes, which move into peritubular capillaries. It also draws water out of the descending limb by osmosis.

Urea boosts the gradient. As water is reabsorbed, the urea left behind in the filtrate becomes concentrated. Some of it will be excreted in urine, but when filtrate enters the final portion of the collecting duct, some urea also will diffuse out—so the concentration of solutes in the inner medulla rises even more.

Drink a large glass of water and the next time you "go" your urine may be pale and dilute. If you sleep eight hours without a break, your urine will be concentrated and darker yellow. As described next, hormones control how much water the kidneys add to urine. These controls also adjust blood pressure.

Hormones control whether kidneys make urine that is concentrated or dilute

When you do not take in as much water as your body loses, the salt concentration in your blood rises. In the brain, receptors sense this change and trigger the release of antidiuretic hormone, or **ADH**. It acts on the cells in distal tubules and collecting ducts so that more water moves out of them and is reabsorbed into the blood (Figure 12.8). As a result, the urine becomes more concentrated. Gradually the additional water in blood reduces the salt concentration there. It also increases the blood volume and blood pressure. Then a negative feedback loop inhibits the release of ADH (Figure 12.9).

Reduced blood volume also affects cells in the efferent arterioles that bring blood to nephrons. These cells release the enzyme renin. They are part of the **juxtaglomerular apparatus** (Figure 12.10*a*). *Juxta-* means "next to," and this "apparatus" is an area where arterioles of the glomerulus come into contact with a nephron's distal tubule.

Renin triggers reactions that produce a protein called angiotensin I and then convert it to angiotensin II. Among other effects, angiotensin II stimulates cells of the adrenal cortex, the outer portion of a gland perched on top of each kidney, to secrete the hormone **aldosterone** (Figures 12.8 and 12.10*b*). Aldosterone causes cells of the distal tubules and collecting ducts to reabsorb sodium faster, so less of it and less water are excreted. By limiting the loss of water, this process also influences blood pressure.

What must the kidneys do to make dilute urine? Not much. Urine is automatically dilute as long as ADH levels are low, so little of the hormone acts on the distal tubules and collecting ducts.

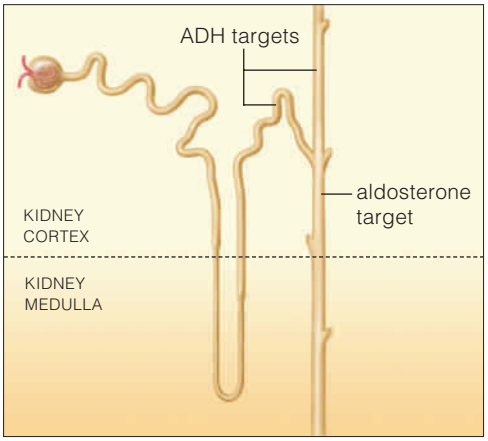


Figure 12.8 ADH and aldosterone act in different parts of kidney nephrons.

A *diuretic* is any substance that promotes the loss of water in urine. For example, caffeine reduces the reabsorption of sodium along nephron tubules, so more water is excreted.

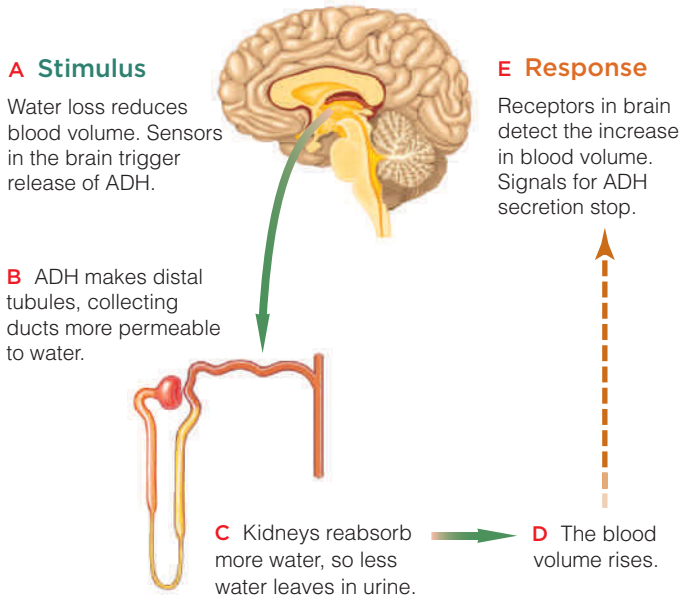


Figure 12.9 A negative feedback loop from the kidneys to the brain helps adjust the fluid volume of the blood.

A thirst center monitors sodium

When you don't drink enough, after a while you realize you're thirsty. Why? The concentration of salt in your blood has risen, and this change reduces the amount of saliva your salivary glands produce. A drier mouth stimulates nerve endings that signal a **thirst center** in the brain. The center also receives signals from the same sensors that stimulate the release of ADH. In this case the signals are relayed to a part of the brain that "tells" you to find and drink fluid.

Take-Home Message

How do the kidneys help maintain fluid balance?

- In a nephron tubule, water and salt can be reabsorbed or excreted as required to maintain the volume of the extracellular fluid, including blood.
- ADH stimulates the kidneys to conserve water. It acts on distal tubules and collecting ducts. Aldosterone promotes the reabsorption of sodium, which indirectly increases the amount of water the body retains.

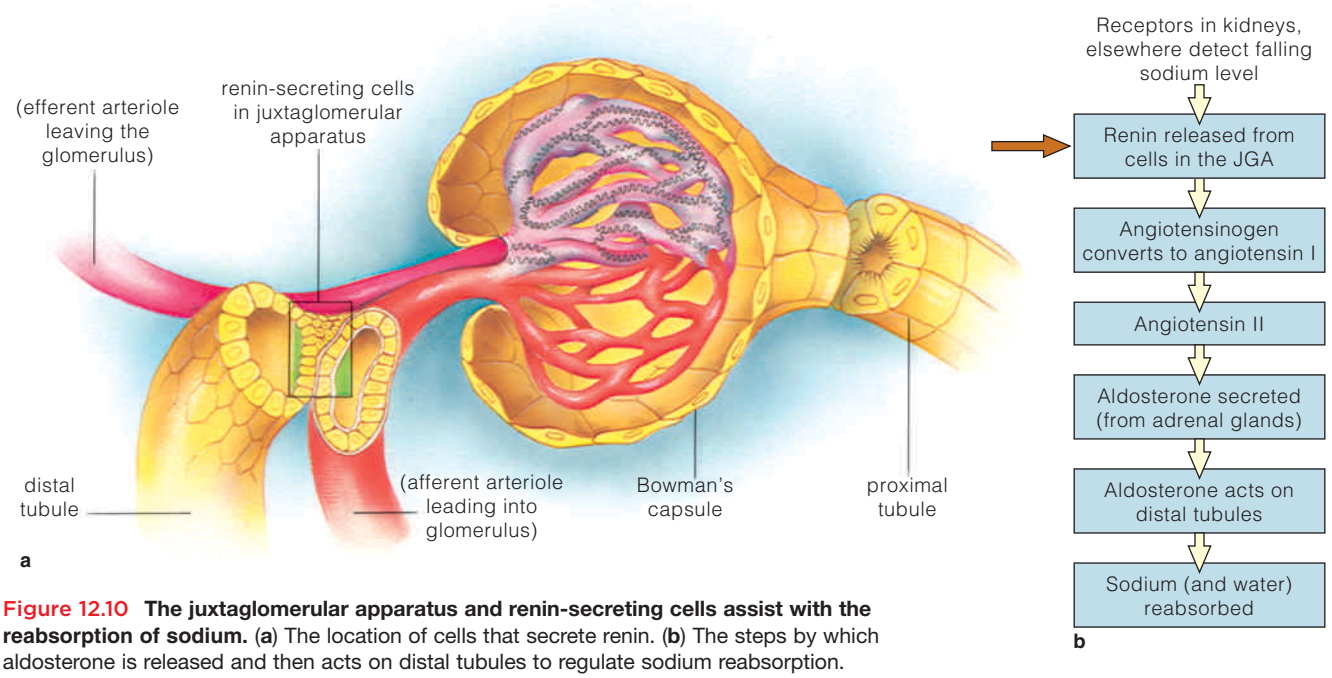


Figure 12.10 The juxtaglomerular apparatus and renin-secreting cells assist with the reabsorption of sodium. (**a**) The location of cells that secrete renin. (**b**) The steps by which aldosterone is released and then acts on distal tubules to regulate sodium reabsorption.

12.5 Removing Excess Acids and Other Substances in Urine

- **As urine forms, nephrons make adjustments that help keep the extracellular fluid from becoming too acidic or too basic.**
- **Links to The pH scale 2.7, Breathing controls 11.5**

The kidneys play a key role in maintaining the balance of acids and bases in the blood

You may recall from Chapter 2 that normal pH in the blood and other body fluids is between 7.37 and 7.43. Because acids lower pH and bases raise it, pH reflects the body's **acid–base balance**—the relative amounts of acidic and basic substances in extracellular fluid. Remember also that a buffer system involves substances that reversibly bind and release H^+ and OH^- ions. Buffers minimize pH changes as acidic or basic molecules enter or leave body fluids.

Chapter 10 described how bicarbonate (HCO_3^-) serves as a buffer in the lungs. It forms when carbon dioxide combines with water. The bicarbonate then reacts with H^+ to form carbonic acid, and enzyme action converts carbonic acid into water and carbon dioxide. The CO_2 is exhaled, while the hydrogen ions are now a part of water molecules. H^+ is not eliminated permanently, however. Only the kidneys can do that. They also restore the buffer bicarbonate.

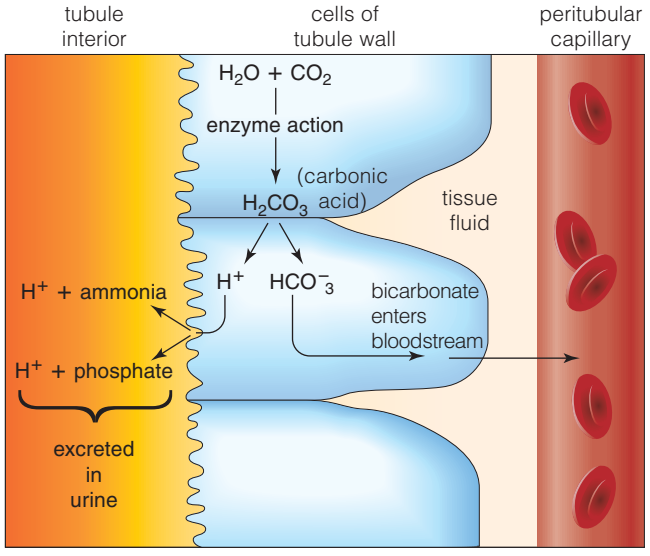


Figure 12.11 The kidneys remove H^+ from the body, preventing the blood from becoming too acidic.

Depending on changes in the acid–base balance of the blood that enters nephrons, the kidneys can either excrete bicarbonate or form new bicarbonate and add it to the blood. The necessary chemical reactions go on in the cells of nephron tubule walls. For example, when the blood is too acid (a too high concentration of H^+), water and carbon dioxide combine with the help of an enzyme. They form carbonic acid that then can be broken into bicarbonate and H^+. Figure 12.11 summarizes these steps.

As you can see, bicarbonate produced in the reactions moves into peritubular capillaries. It ends up circulating in the blood, where it buffers excess H^+. When the blood is too basic (alkaline), chemical adjustments in the kidneys normally ensure that less bicarbonate is reabsorbed into the bloodstream.

The H^+ that is formed in the tubule cells is secreted into the filtrate in the tubule. There the excess H^+ may combine with phosphate ions, ammonia (NH_3), or even bicarbonate. In this way the excess H^+ is excreted.

Various factors may cause serious acid–base imbalances

If the pH of blood falls outside the normal range for long, the most serious impact occurs in the central nervous system (brain and spinal cord). When severe diarrhea, kidney disease, or some other problem prevents kidneys from excreting enough acid (*metabolic acidosis*), nerve cells cannot communicate properly and an affected person may fall into a fatal coma.

Severe vomiting or dehydration, hormonal disorders, and overuse of antacids are common causes of *metabolic alkalosis*, or blood that is too basic. Then nerve cells are overstimulated, so a person may suffer muscle spasms, nervousness, or convulsions. In the next two sections you will find information about other major disorders that prevent the urinary system from functioning normally.

Take-Home Message

How do the kidneys help adjust the body's acid–base balance?

- Along with buffering systems and the respiratory system, the kidneys help keep the extracellular fluid from becoming too acidic or too basic.
- The urinary system eliminates excess hydrogen ions and also replenishes bicarbonate used in buffering reactions.

12.6 Kidney Disorders

Many people don't realize how much good health depends on normal kidney function. Disorders or injuries that interfere with it may cause only mild distress, but often the impact is quite serious.

Kidney stones are deposits of uric acid, calcium salts, and other substances that have settled out of urine and collected in the renal pelvis. Smaller kidney stones usually are eliminated naturally during urination. Larger ones can become lodged in the renal pelvis or ureter or even in the bladder or urethra. The blockage can partially dam urine flow and cause intense pain and kidney damage. Large kidney stones must be removed medically or surgically. A procedure called *lithotripsy* uses high-energy sound waves to break up the stone into fragments that are small enough to pass out in the urine.

Glomerulonephritis is an umbrella term for several disorders that can lead to kidney failure. Two major ones are chronic high blood pressure and diabetes, both of which damage kidney capillaries. Sometimes the flow of blood through the glomeruli all but stops.

At any given time, roughly 1 million people in the United States have kidneys so impaired that they can only minimally filter the blood and form urine. This loss of kidney function means that toxic by-products of protein breakdown can accumulate in the bloodstream. Patients can suffer nausea, fatigue, and memory loss. In advanced cases, death may result. A kidney dialysis machine can restore the proper solute balances (Figure 12.12*a*). Like the kidneys, the machine helps maintain healthy volume and composition of extracellular fluid by selectively removing and adding solutes to the patient's bloodstream.

In a dialysis process, substances in one solution can be exchanged with those in a chemically different solution by crossing a permeable membrane. In *hemodialysis*, a dialysis machine is connected to an artery or a vein, and then blood is pumped through tubes made of a material similar to cellophane. The tubes are submerged in warm water that contains a precise mix of salts, glucose, and other substances. As blood flows through the tubes, the wastes dissolved in it diffuse out, so solute concentrates return to a normal range. The cleansed blood then returns to the patient's body.

Patients usually receive hemodialysis three times a week, although for some it is a daily need. Patients with reversible kidney disorders may receive dialysis until they recover. In chronic cases, the procedure must be used for the rest of the patient's life or until a healthy kidney can be transplanted.

Polycystic kidney disease is an inherited disorder in which cysts (semisolid masses) form in the kidneys and in many cases gradually destroy normal kidney tissue. Frequent urinary tract infections are a common early symptom; in severe cases, dialysis or a kidney transplant are the only real options for treatment. With treatment and the proper diet, many people with chronic kidney disease are able to pursue a surprisingly active, close-to-normal lifestyle (Figure 12.12*b*).

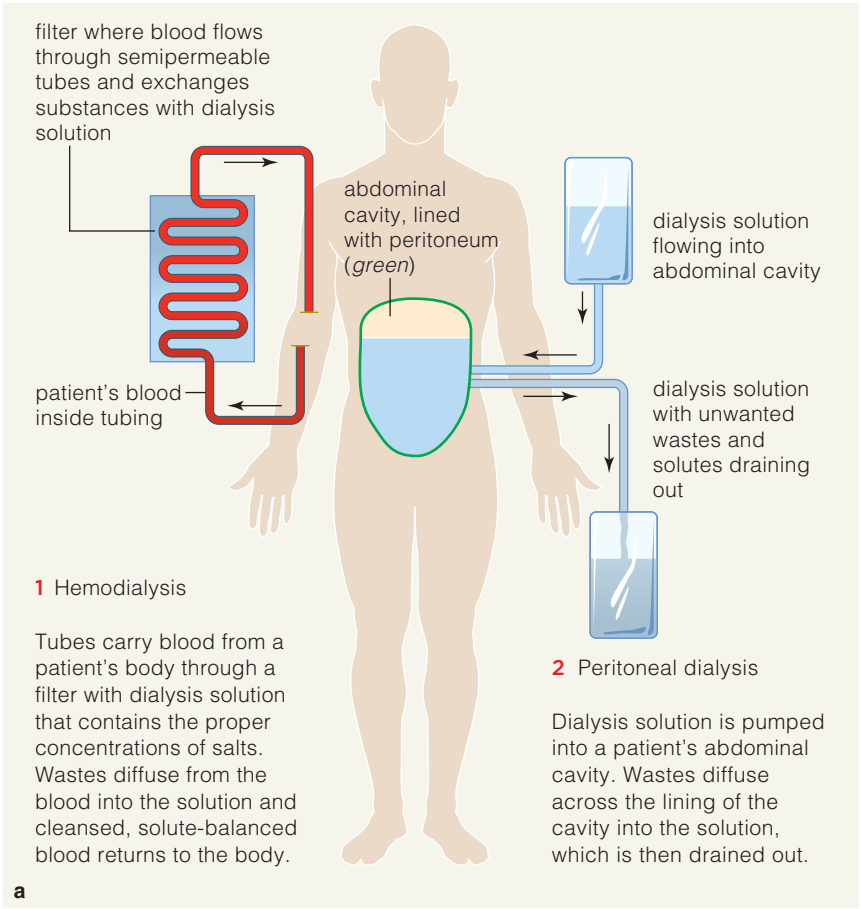


Figure 12.12 Animated! Kidney dialysis cleanses the blood of patients with kidney failure. (**a**) Two options for dialysis: hemodialysis and peritoneal dialysis. (**b**) Karole Hurtley, who lives with kidney failure. Despite severe kidney disease requiring daily peritoneal dialysis, Karole became a national champion in karate at age 13.

12.7 Cancer, Infections, and Drugs in the Urinary System

Urinary system cancer is on the rise

Carcinomas of the bladder and kidney (Figure 12.13) account for about 100,000 new cancer cases each year, a number that is increasing. The incidence is higher in males, and smoking and exposure to certain industrial chemicals are major risk factors. Kidney cancer easily metastasizes via the bloodstream to the lungs, bone, and liver. An inherited type, called Wilms tumor, is one of the most common of all childhood cancers.

Urinary tract infections are common

Urinary tract infections plague millions of people. Women especially are susceptible to bladder infections because of their urinary anatomy: The female urethra is short, just a little over 1 inch long. (An adult male's urethra is about 9 inches long.) The outer opening of a female's urethra also is close to the anus, so it is fairly easy for bacteria from outside the body to make their way to a female's bladder and trigger an inflammation called **cystitis**—or even all the way to the kidneys to cause **pyelonephritis**.

In both sexes, urinary tract infections sometimes result from sexually transmitted microbes, including the microorganisms that cause *chlamydia*. Chapter 16 gives more information on this topic.

Nephritis is an inflammation of the kidneys. It can be caused by various factors, including bacterial infections. As you may remember from Chapter 9, inflamed tissue tends to swell as fluid accumulates in it. However, because a kidney is "trapped" inside the tough renal capsule, it can't increase in size. As a result, pressure builds up in or around the capillaries that service the glomerulus, hampering or preventing the flow of blood. Then blood filtering becomes difficult or impossible.

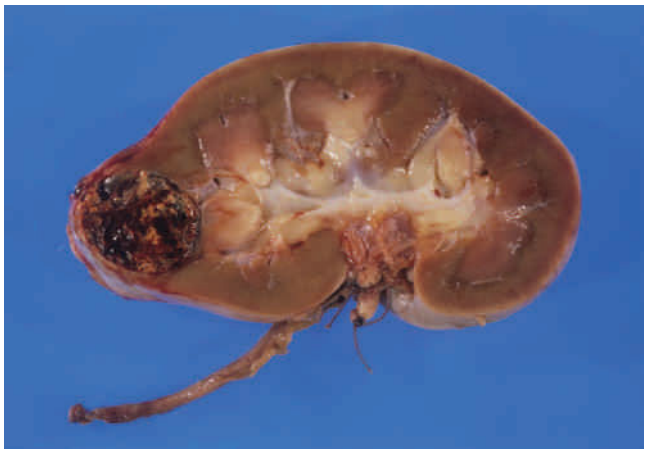


Figure 12.13 More than 50,000 cases of kidney cancer are diagnosed each year in the United States. This photograph shows a tumor in a kidney, which has been cut open to reveal the cancer's location (the circular area on the left).

Painkillers and other drugs may harm the kidneys

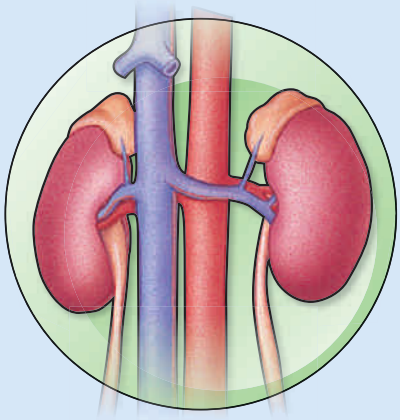
Over-the-counter painkillers such as aspirin, acetaminophen, and NSAIDS (nonsteroidal anti-inflammatory drugs such as ibuprofen) come with consumer warnings about possible kidney damage. These drugs usually are safe when used according to directions. According to the National Kidney Foundation, however, millions of Americans have unwittingly destroyed their kidneys by excessive use of these substances. Experts recommend that people who must take large amounts of such painkillers drink 6 to 8 glasses of water a day to help flush harmful residues from the kidneys.

Heavy alcohol use also is hard on the kidneys, and some illegal street drugs—including amphetamines, cocaine, and heroin—can cause major kidney damage.

Urinalysis provides a chemical snapshot of conditions in the body

When the kidneys have finished processing fluid and solutes from the blood, the result is urine that contains a wide variety of substances. In addition to revealing traces of drugs, urinalysis provides a chemical snapshot of many physiological processes in the body, and it can be quite helpful in diagnosing illness or disease. For example, glucose in urine may be a sign of diabetes. White blood cells (pus) frequently indicate a urinary tract infection. Red blood cells in urine can reveal bleeding due to an infection, cancer, or an injury. Abnormally high levels of albumin or other proteins in urine may indicate kidney disease, severe hypertension, or other disorders.

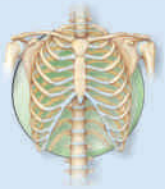
12.8 CONNECTIONS: The Urinary System in Homeostasis



The Urinary System

The kidneys adjust the chemical composition of the extracellular fluid, including blood, in ways that are essential to the survival of the body as a whole. They remove toxic nitrogenous wastes from the breakdown of proteins. They also maintain the balance of water, electrolytes, and acids and bases in the blood. The bladder, ureters, and urethra provide for the storage and elimination of wastes in urine.

Skeletal system

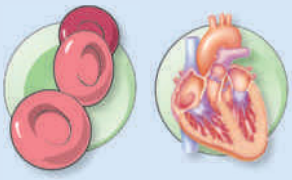


The kidneys adjust blood levels of calcium and phosphate used in building bone.

Muscular system

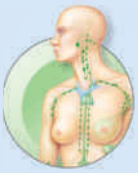
Adjustments in elimination of CO_2 help manage hydrogen ions (H^+) in blood and so help maintain blood pH (acid–base balance).

Cardiovascular system and blood



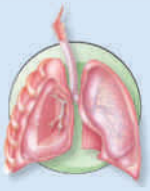
Kidney adjustments to water content of urine help main blood volume. The kidney hormone erythropoietin stimulates the production of red blood cells.

Immunity and the lymphatic system



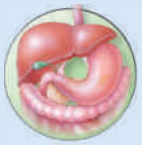
Urine washes pathogens out of the urethra. Adjustments to water and solutes in blood plasma help assure adequate volume and chemical composition of lymph.

Respiratory system



Kidney adjustments in acid–base balance complement shifts in the depth and rate of breathing that help maintain pH of blood and tissue fluid.

Digestive system

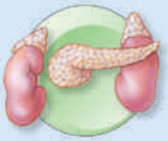


Kidneys convert vitamin D to a form that aids absorption of calcium from food.

Nervous system

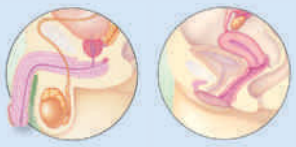
Kidney management of acid–base balance helps ensure that nerve cells can function properly.

Endocrine system



Kidney hormone erythropoietin is part of overall hormonal controls in the body. Adjustments that help maintain blood volume assist with hormone transport in the bloodstream.

Reproductive system



The male urethra also serves as a channel for sperm ejaculated during intercourse.

IMPACTS, ISSUES

Truth in a Test Tube

MANY employers ask potential new hires to undergo urine testing for drug and alcohol use. Some people say this is an invasion of privacy. Also, some foods, such as poppy seeds used on bagels and in pastries, may trigger a false "positive" result for opiates.

How Would You Vote?

Do you think employers should be allowed to require a person to have a urine test as a condition of employment? See CengageNOW for details, then vote online.

Summary

Section 12.1 The fluid inside cells is intracellular fluid. The fluid outside cells is extracellular fluid (ECF). It contains various types and amounts of substances dissolved in water. The ECF fills tissue spaces and (in the form of blood plasma) fills blood vessels. The following processes maintain a healthy balance in the volume and chemical composition of ECF:

a. The body takes in water by absorbing it from the GI tract and by metabolism. Water is lost by urinary excretion, evaporation from the lungs and skin, sweating, and elimination in feces.

b. Solutes are gained by absorption from the GI tract, secretion, respiration, and metabolism. They are lost by excretion, respiration, and sweating. The solutes include important electrolytes such as ions of sodium, potassium, and calcium.

c. Losses of water and solutes are controlled mainly by the kidneys, which adjust the volume and chemical makeup of urine.

Section 12.2 The urinary system consists of two kidneys, two ureters, a urinary bladder, and a urethra. In the kidneys, blood is filtered and urine forms in nephrons.

a. A nephron starts as a cup-shaped capsule that is followed by three tubelike regions: the proximal tubule, loop of Henle, and distal tubule, which empties into a collecting duct.

b. The Bowman's (glomerular) capsule surrounds a set of highly permeable capillaries. Together, they are a blood-filtering unit, the glomerulus.

- Use the animation and interaction on CengageNOW to explore the anatomy of the urinary system and kidneys.

Section 12.3 Urine forms through a sequence of steps: filtration, reabsorption, and secretion (Table 12.3).

a. Filtration of blood at the glomerulus of a nephron transfers water and small solutes into the nephron.

b. In reabsorption needed water and solutes leave the nephron tubule and enter the peritubular capillaries that thread around the tubule. Many solutes are reabsorbed when they diffuse down their concentration gradients back into the bloodstream. Others, such as sodium, are reabsorbed by active transport. The reabsorption of water is always passive, by osmosis. A small amount of water and solutes remains in the nephron.

Processes of Urine Formation

Process	Characteristics
Filtration	Pressure generated by heartbeats drives water and small solutes (not proteins) out of glomerulus capillaries and into Bowman's capsule, the entrance to the nephron.
Reabsorption	Most water and solutes in the filtrate move from a nephron's tubule into interstitial fluid around the nephron, then into blood inside the peritubular capillaries.
Secretion	Urea, H^+, and some other solutes move out of peritubular capillaries, into interstitial fluid, then into the filtrate inside the nephron for excretion in urine.

c. In secretion some ions and a few other substances leave the peritubular capillaries and enter the nephron for disposal in urine.

- Use the animation and interaction on CengageNOW to learn more about how urine forms.

Section 12.4 During reabsorption in kidney nephrons, water and salt are reabsorbed or excreted as required to conserve or eliminate water. The mechanisms that concentrate urine also help regulate blood volume and blood pressure.

Urine becomes more or less concentrated by the action of two hormones, ADH and aldosterone, on cells of distal tubules and collecting ducts.

a. ADH is secreted when the body must conserve water; it increases reabsorption from the distal nephron tubule and collecting ducts. Inhibition of ADH allows more water to be excreted.

b. Aldosterone conserves sodium by increasing its reabsorption in the distal tubule. It is secreted when cells in the juxtaglomerular apparatus (next to the distal tubule) secrete renin, an enzyme that triggers reactions that lead to aldosterone secretion. More sodium is excreted when aldosterone is inhibited. Because "water follows salt," aldosterone influences how much water is reabsorbed into the bloodstream.

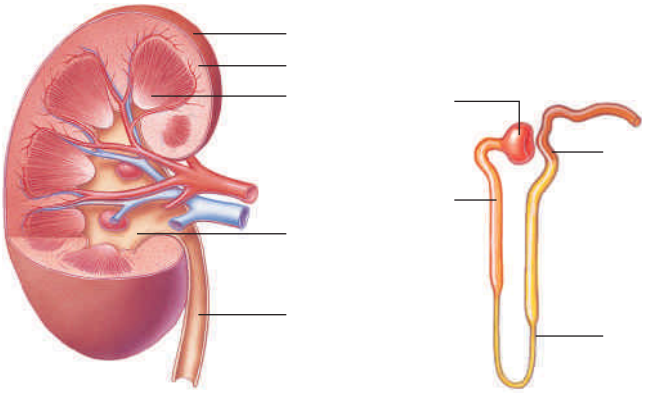
Section 12.5 Together with the respiratory system and other mechanisms, the kidneys also help maintain the

body's overall acid–base balance. They help regulate pH by eliminating excess hydrogen ions and replenishing the supply of bicarbonate, which acts as a buffer elsewhere in the body.

Section 12.6 Urinary tract infections can develop when bacteria enter through the urethra. Disorders and diseases that damage kidney tissues can interfere seriously with the excretion of wastes in urine and with the kidneys' ability to help regulate blood volume and pressure.

Review Questions

1. Label the parts of this kidney and nephron:



2. How does the formation of urine help maintain the body's internal environment?
3. Explain what is meant when we talk about filtration, reabsorption, and secretion in the kidneys.
4. Which hormone or hormones promote (*a*) water conservation, (*b*) sodium conservation, and (*c*) thirst behavior?
5. Explain how the kidneys help to maintain the balance of acids and bases in extracellular fluid.

Self-Quiz *Answers in Appendix V*

1. The body gains water by _____.
   a. absorption in the gut
   b. metabolism
   c. responding to thirst
   d. all of the above
2. The body loses water by way of the _____.
   a. skin
   b. lungs
   c. digestive system
   d. urinary system
   e. c and d
   f. a through d
3. Water and small solutes enter nephrons during _____.
   a. filtration
   b. reabsorption
   c. secretion
   d. both a and b
4. Kidneys return water and small solutes to blood by _____.
   a. filtration
   b. reabsorption
   c. secretion
   d. both a and c
5. Some substances move out of the peritubular capillaries and are moved into the nephron during _____.
   a. filtration
   b. reabsorption
   c. secretion
   d. both a and c
6. Reabsorption depends on _____.
   a. osmosis across the nephron wall
   b. active transport of sodium across the nephron wall
   c. a steep solute concentration gradient
   d. all of the above
7. _____ directly promotes water conservation.
   a. ADH
   b. Renin
   c. Aldosterone
   d. both b and c
8. _____ enhances sodium reabsorption.
   a. ADH
   b. Renin
   c. Aldosterone
   d. both b and c
9. Match the following salt–water balance concepts:
   ____ aldosterone — a. blood filter of a nephron
   ____ nephron — b. controls sodium reabsorption
   ____ thirst mechanism — c. occurs at nephron tubules
   ____ reabsorption — d. site of urine formation
   ____ glomerulus — e. controls water gain

Critical Thinking

1. A urinalysis reveals that the patient's urine contains glucose, hemoglobin, and white blood cells (pus). Are any of these substances abnormal in urine? Explain.
2. As a person ages, nephron tubules lose some of their ability to concentrate urine. What is the effect of this change?
3. Fatty tissue holds the kidneys in place. Extremely rapid weight loss may cause this tissue to shrink so that the kidneys slip from their normal position. On rare occasions, the slippage can put a kink in one or both ureters and block urine flow. Suggest what might then happen to the kidneys.
4. Licorice is used as a remedy in Chinese traditional medicine and also is a flavoring for candy. When licorice is eaten, one of its components triggers the formation of a compound that mimics aldosterone and binds to receptors for it. Based on this information, explain why people who have high blood pressure are advised to avoid eating much licorice.
5. Drinking too much water can be a bad thing. If someone sweats heavily and drinks lots of water, their sodium levels drop. The resulting "water intoxication" can be fatal. Why is the sodium balance so important?
6. As the text noted, two-thirds of the water and solutes that the body reclaims by reabsorption in nephrons occurs in the proximal tubule. Proximal tubule cells have large numbers of mitochondria and demand a great deal of oxygen. Explain why.

EXPLORE ON YOUR OWN

The rider and horse shown at the right are living examples of the mammalian body's ability to cool itself by producing sweat. Since sweat is mostly water, how is heavy sweating likely to affect the concentration of urine, especially if the athlete—in this case, a polo player—doesn't remember to drink fluid during the match? (You may well have observed this effect in your own body after exercise.)

Drink one quart of water in one hour. What changes might you expect (and can you observe) in your kidney function and the nature of your urine?

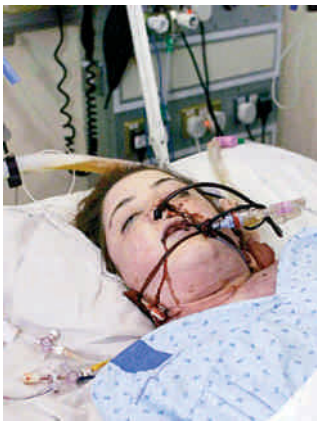
The Nervous System

13

IMPACTS, ISSUES

In Pursuit of Ecstasy

"ECSTASY" is an illegal but popular drug that sharpens the senses, relieves anxiety, and produces a mild high. An overdose also may leave you dying in a hospital, foaming at the mouth, and bleeding from every orifice as your temperature skyrockets. When Lorna Spinks was nineteen years old, her life ended that way.



Lorna's parents released the photographs at left, the lower one taken a few minutes after her death. They wanted others to know that Ecstasy can kill. Ecstasy's active ingredient, MDMA, is related to amphetamine, or "speed." MDMA causes brain neurons to release too much of the signaling molecule serotonin. And instead of being cleared away as usual, serotonin saturates receptors for it on other, target neurons. The unending overstimulation leads to waves of panic and seizures. Then the person's heart rate and blood pressure soar, and body temperature rises so high that organ systems shut down one by one.

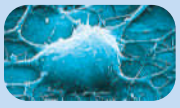
An MDMA overdose is only sometimes lethal, but other problems are common. For example, when the brain's serotonin stores eventually are depleted, the brain can't rebound very quickly. Below-normal levels of serotonin can contribute to loss of concentration, depression, and memory problems. Studies of Ecstasy users reveal that more often you use it, the worse memory loss becomes. If you stop using the drug, it can be many months before your brain functions normally.

In this chapter we look at how the nervous system manages a wide range of body functions. We start by considering how neurons are built and operate. Then we'll examine how neurons interact in the nervous system and how the brain serves as the body's master control center.

LINKS TO EARLIER CONCEPTS

- This chapter expands on Chapter 4's introduction to neurons and other cells that make up the body's nervous tissue (4.4).
- Your knowledge of the structure of plasma membranes (3.4), and how substances move across them (3.10–3.11) will help you understand how neurons produce nerve impulses.
- You will also see in more detail how nervous system signals produce muscle contractions (6.4).

KEY CONCEPTS



How Neurons Work

The operation of the nervous system depends on the capacity of neurons to produce electrical signals and transmit them to other cells. Sections 13.1–13.5

The Nervous System

Different parts of the nervous system detect information, process it, and then select or control muscles and glands that carry out responses. Sections 13.6, 13.7

The Brain

The brain is a master controller that receives, processes, stores, and retrieves information. It also orders and coordinates responses by adjusting body activities. Sections 13.8–13.11

Disorders of the Nervous System and Homeostasis

Sections 13.12–13.14

How Would You Vote?

Should people caught using illegal drugs enter mandatory drug rehabilitation programs as an alternative to jail? Or does the threat of jail make some think twice before experimenting with possibly dangerous drugs? See CengageNOW for details, then vote online.

13.1 Neurons: The Communication Specialists

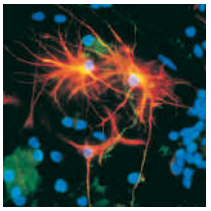
- **Three types of neurons are the nervous system's communication cells.**
- **Link to Nervous tissue 4.4**

The **nervous system** detects and integrates information about external and internal conditions. It then selects or controls muscles and glands that carry out responses. Three basic types of **neurons** allow the nervous system to perform these functions:

- **Sensory neurons** collect information about stimuli (such as light) and relay it to the spinal cord and brain.
- **Interneurons** in the spinal cord and brain receive and process sensory input, and send signals to other neurons.
- **Motor neurons** relay signals from interneurons to muscles and glands that carry out responses. Because muscles and glands produce the "desired" effect, they are called effectors.

A neuron has a **cell body**, where its nucleus and organelles are. The cell body and slim extensions called **dendrites** are input zones for information. Near the cell body is a trigger zone. In motor neurons and interneurons the trigger zone is called the axon hillock ("little hill"). At this patch of the neuron's plasma membrane, information travels along a slender and often long extension called an **axon**, the neuron's conducting zone. As you can see in the diagram of a motor neuron in Figure 13.1, dendrites tend to be shorter than axons. Their number and length vary, depending on the type of neuron. The axon's endings are output zones where messages are sent to other cells.

About 90 percent of your nervous system consists of **neuroglia**, or simply "glia." One type is star-shaped (*right*). Glia help maintain the proper concentrations of vital ions in the fluid around neurons, and some physically support and protect neurons. Others provide insulation that allows signals to move along sensory and motor neurons with lightning speed. Still others do "clean-up" duty in the central nervous system.

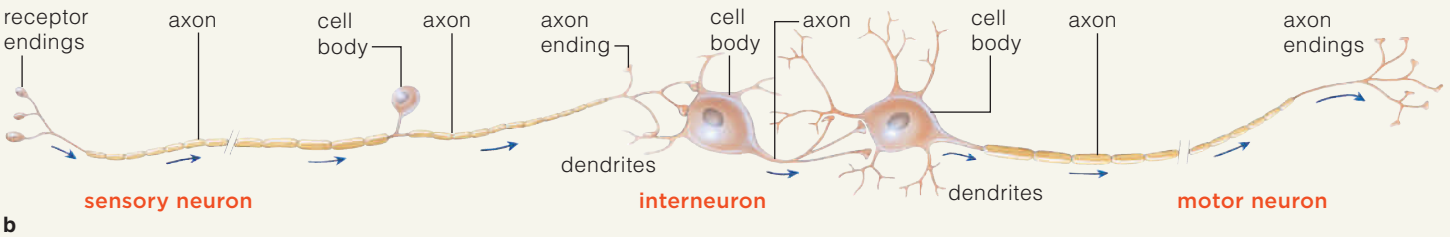


Star-shaped glia, called astrocytes

Take-Home Message

What are the three types of neurons?

- The communication lines of the nervous system consist of sensory neurons, interneurons, and motor neurons.



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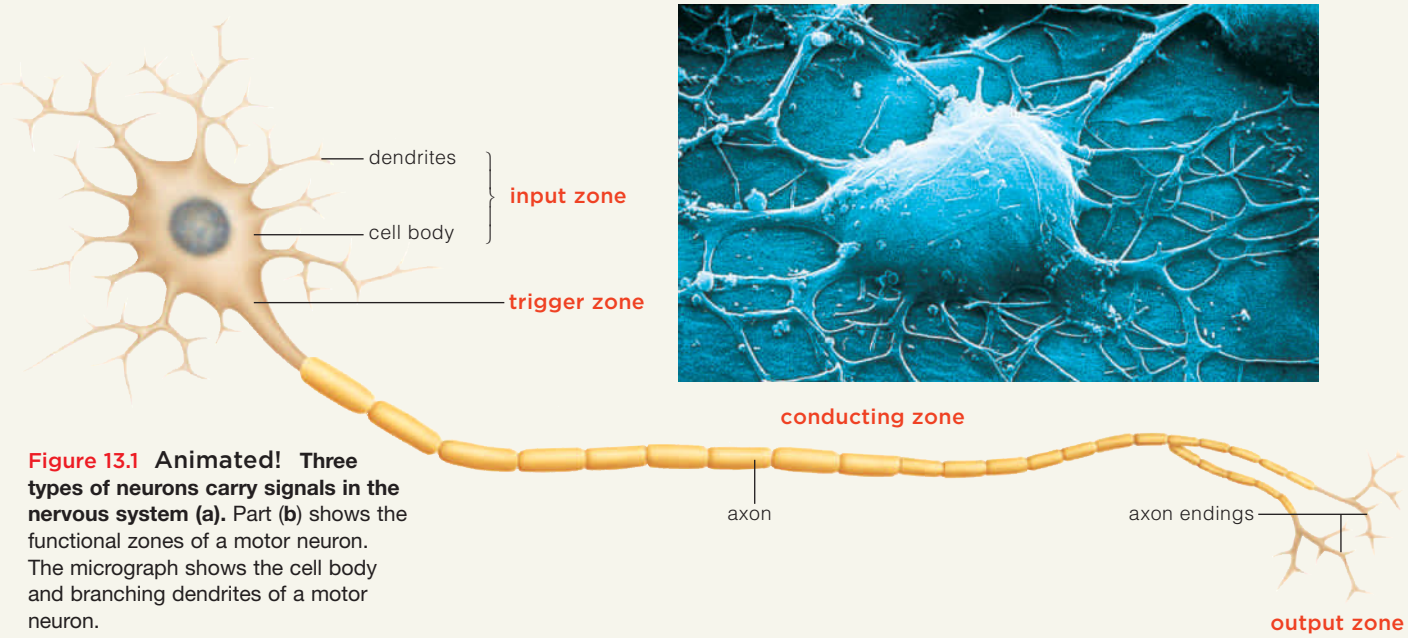


a

Figure 13.1 Animated! Three types of neurons carry signals in the nervous system (a). Part (**b**) shows the functional zones of a motor neuron. The micrograph shows the cell body and branching dendrites of a motor neuron.

13.2 Why Can Neurons Carry Signals?

- **Properties of a neuron's plasma membrane allow it to carry signals.**
- **Link to the Cell plasma membrane 3.4**

Neurons are suited for communication partly because they are excitable—that is, a neuron can respond to certain stimuli by producing an electrical signal.

You may remember from Chapter 3 that the plasma membrane's lipid bilayer prevents charged substances—such as ions of potassium (K^+) and sodium (Na^+)—from freely crossing it. Even so, ions can cross the membrane through channel proteins that span the bilayer (Figure 13.2). Some channels are always open, so that ions can steadily "leak"—by diffusion—in or out. Other channels open like gates under the proper circumstances. These controls mean that the concentrations of an ion can be different on either side of the plasma membrane.

For example, in a resting neuron, the gated sodium channels are closed and the plasma membrane allows only a little sodium to leak inward. The membrane is more permeable to K^+. As a result, each ion has its own concentration gradient across the membrane (Figure 13.2*a*). Following the rules of diffusion, sodium tends to move in and potassium tends to move out.

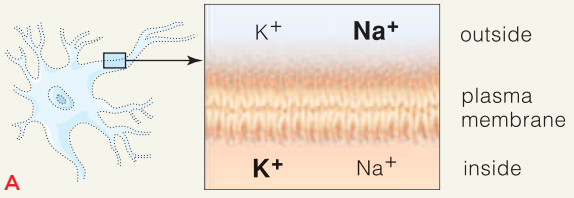
For several reasons, on balance the cytoplasm next to the membrane is more negative than the fluid just outside the membrane. Electrical charges may be measured in millivolts, and for many neurons, the steady charge difference across the plasma membrane is about −70 millivolts. (The minus indicates that the cytoplasm side of the membrane is more negative.) The difference is called the **resting membrane potential**. The term means that the charge difference has the potential to do physiological work in the body. This "work" is the launching of a nerve impulse.

Various kinds of signals occur in the nervous system, but not all of them spark nerve impulses. Only a signal that is strong enough when it reaches a resting neuron's input zone may spread to a trigger zone. When a strong enough signal does arrive, however, it can cause the voltage difference across the plasma membrane to reverse, just for an instant. In the following section, we see how these reversals produce nervous system signals.

Take-Home Message

What is a neuron's resting potential?

- In a resting neuron, differences in the concentrations of Na^+ and K^+ across the plasma membrane produce a resting membrane potential—a difference in electrical charge across the plasma membrane. The difference has the potential to do physiological work in the body.



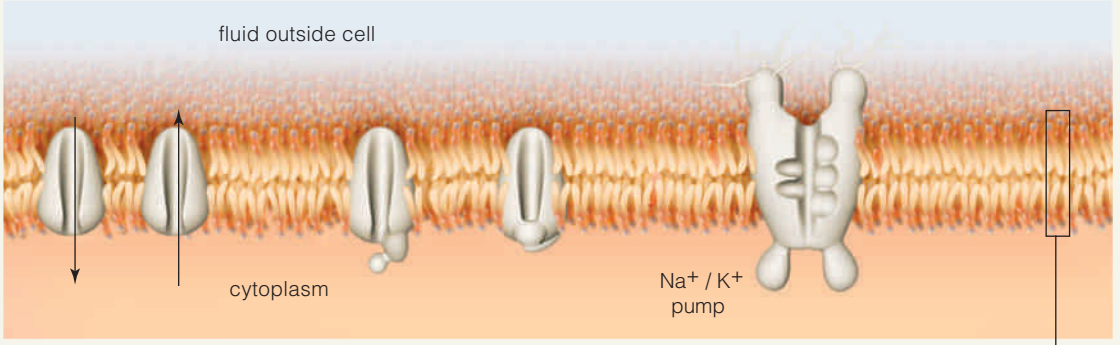


Figure 13.2 Animated! Ions produce an electrical gradient across a neuron's plasma membrane. (**a**) Gradients of sodium (Na^+) and potassium (K^+) ions across a neuron's plasma membrane. (**b**) How ions cross the plasma membrane of a neuron. They are selectively allowed to cross at protein channels and pumps that span the membrane.

Passive transporters with open channels let ions steadily leak across the membrane.

Other passive transporters have voltage-sensitive gated channels that open and shut. They assist diffusion of Na^+ and K^+ across the membrane as the ions follow concentration gradients.

Active transporters pump Na^+ and K^+ across the membrane, against their concentration gradients. They counter ion leaks and restore resting membrane conditions.

B

13.3 Nerve Impulses = Action Potentials

- **A nerve impulse fires when a signal causes the resting membrane potential of a neuron to briefly reverse.**
- **Link to Concentration and electric gradients 3.10**

When an adequate signal reaches a resting neuron's input zone, a change occurs in the membrane. Sodium gates in it open and Na^+ rushes into the neuron. As the positively charged sodium flows inward, the cytoplasm next to the plasma membrane becomes less negative (Figure 13.3*a* and 13.3*b*). Then, more gates open, more sodium enters, and so on (an example of positive feedback). When the voltage difference across the neuron plasma membrane shifts by a certain minimum amount called the **threshold** level, the result is an **action potential** or **nerve impulse**.

The threshold for an action potential can be reached at any part of a neuron's plasma membrane where there are voltage-sensitive gated channels for sodium ions. Because of the positive feedback just described, when the threshold level is reached, the opening of more sodium gates doesn't depend any longer on the strength of the stimulus. The gates open on their own.

It's important to remember that an action potential occurs only if the stimulus to a neuron is strong enough. A weak stimulus—say, pressure from a tiny insect walking on your skin—that arrives at an input zone may not upset the ion balance enough to cause an action potential. This is because input zones don't have gated sodium channels, so sodium can't flood in there. On the other hand, a neuron's trigger zone is packed with sodium channels. If a stimulus that reaches an input zone is strong enough to spread to the trigger zone, an action potential may "fire."

Action potentials travel away from their starting point

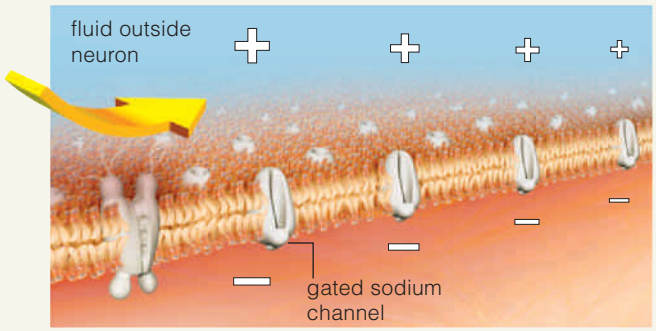
To transmit messages within the body, action potentials must spread to other neurons or to cells in muscles or glands. Each action potential propagates itself, moving away from its starting point. This self-propagation occurs in part because the changes in membrane potential leading up to an action potential don't lose strength. When the change spreads from one patch of a neuron's plasma membrane to another patch, approximately the same number of gated channels open (Figure 13.3*c* and 13.3*d*). Action potentials always propagate *away* from the trigger zone, for reasons described next.

A neuron can't "fire" again until ion pumps restore its resting potential

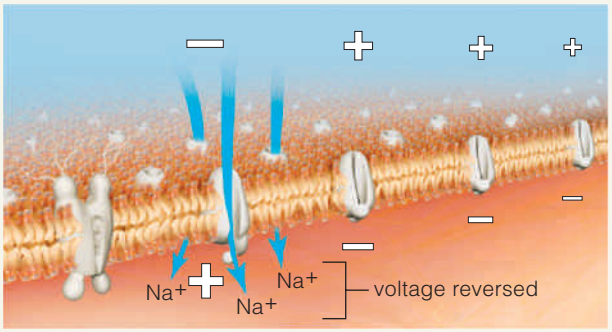
When a signal causes an action potential in a neuron's trigger zone, that area of the cell's plasma membrane can't receive another signal until its resting membrane potential is restored.

To understand how the resting potential is restored, remember that a neuron's resting membrane potential is due in part to the different concentrations of Na^+ and K^+ on either side of the plasma membrane. Remember also that the inside of the cell is a bit more negative than the outside. Negatively charged proteins in the cytoplasm help create this *electric gradient*. Together these factors mean that sodium is always leaking into the neuron (down an electrochemical gradient), and potassium is always leaking out (down its concentration gradient).

Figure 13.3 Animated! An inward flood of sodium ions triggers an action potential. (**a**,**b**) Steps leading to an action potential. (**c**,**d**) How an action potential propagates, or travels, along a neuron.



A In a membrane at rest, the inside of the neuron is negative relative to the outside. An electrical disturbance (yellow arrow) spreads from an input zone to an adjacent trigger zone of the membrane, which has a large number of gated sodium channels.



B A strong disturbance initiates an action potential. Sodium gates open. Sodium flows in, reducing the negativity inside the neuron. The change causes more gates to open, and so on until threshold is reached and the voltage difference across the membrane reverses.

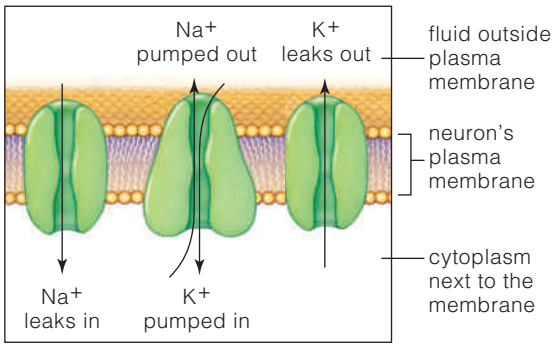


Figure 13.4 **Pumping and leaking processes maintain the proper balance of ions across a resting neuron's plasma membrane.**

A neuron can't respond to an incoming signal unless the proper concentration and electric gradients across its plasma membrane are in place. Yet the Na^+ and K^+ leaks never stop, opening the possibility that an imbalance might develop in the necessary gradients. This imbalance doesn't develop, however, because a resting neuron uses energy to power a pumping mechanism that maintains the gradients. Carrier proteins called **sodium–potassium pumps** span the neuron's membrane (Figure 13.4). With energy from ATP, they actively transport potassium *into* the neuron and transport sodium *out*.

Action potentials are "all-or-nothing"

There is no such thing as a "small" or "large" action potential. Every action potential in a neuron spikes to the same level above threshold as an all-or-nothing event. That is, once the positive-feedback cycle of opening sodium gates starts, nothing will stop the full spiking. If threshold is not reached, the disturbance to the plasma membrane will fade away as soon as the stimulus is removed. Figure 13.5 shows a recording of the voltage difference across a neuron's plasma membrane before, during, and after an action potential.

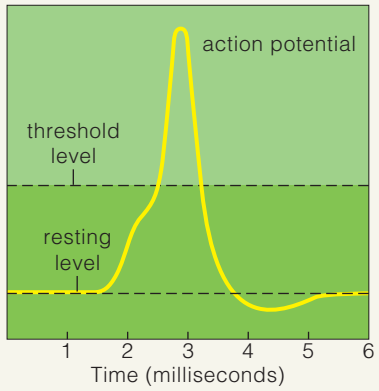


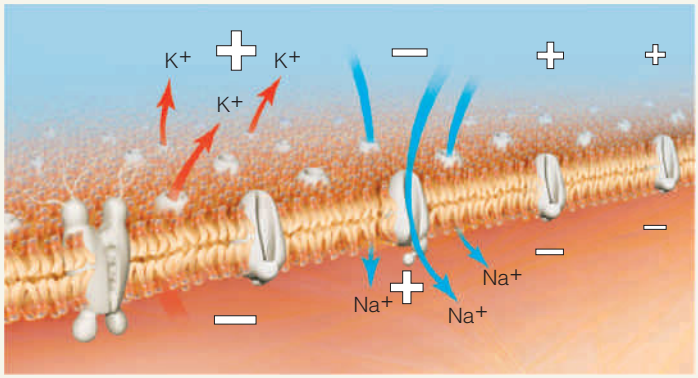
Figure 13.5 **Animated!** **The action potential spikes when threshold is reached.**

Each spike lasts for about a millisecond. At the place on the membrane where the charge reversed, the gated sodium channels close and the influx of sodium stops. About halfway through the action potential, potassium channels open, so potassium ions flow out and restore the original voltage difference across the membrane. And sodium–potassium pumps restore ion gradients, as you've read. Later, after the resting membrane potential has been restored, most potassium gates are closed and sodium gates are in their initial state, ready to be opened again when a suitable stimulus arrives.

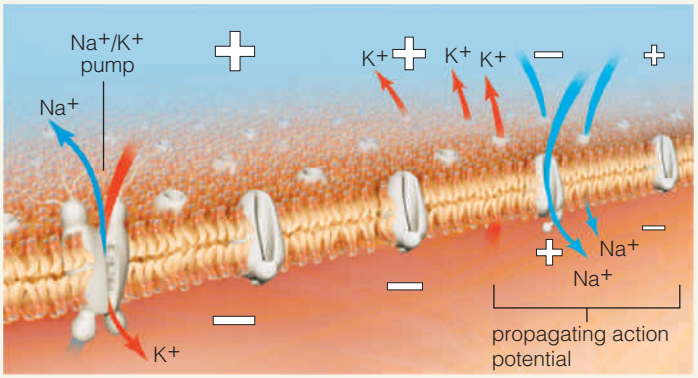
Take-Home Message

What happens during an action potential?

- An action potential occurs when a neuron's resting membrane potential briefly reverses. Action potentials self-propagate and always move away from the trigger zone.
- After an action potential, sodium–potassium pumps restore the neuron's resting potential.
- An action potential is all-or-nothing. Once the spiking starts, nothing can stop it.



C At the next patch of membrane, another group of gated sodium channels open. In the previous patch, some K^+ moves out through other gated channels. That region becomes negative again.



D After each action potential, the sodium and potassium concentration gradients in a patch of membrane are not yet fully restored. Active transport at sodium–potassium pumps restores them.

13.4 How Neurons Communicate

- **Action potentials may cause a neuron to release neurotransmitters, signaling molecules that diffuse to a receiving cell. This is one way that information flows from cell to cell.**
- **Link to Neuromuscular junctions 6.6**

Action potentials can stimulate neurons to release the chemical signals called **neurotransmitters**. These molecules diffuse across a **chemical synapse**, a narrow gap between a neuron's output zone and the input zone of a neighboring cell. Some chemical synapses occur between neurons, others between a neuron and a muscle cell or gland cell.

At a chemical synapse, one of the two cells stores neurotransmitter molecules in synaptic vesicles in its cytoplasm. This is the *pre*synaptic cell. The cell's plasma membrane has gated channels for calcium ions, and they open when an action potential arrives. There are more calcium ions outside the cell, and when they flow in (down their gradient), synaptic vesicles fuse with the plasma membrane, discharging their content. Neurotransmitter molecules now pour into the synapse, diffuse across it, and bind with receptor proteins on the plasma membrane of the *post*synaptic, or receiving, cell. Binding changes the shape of these proteins, so that a channel opens up through them. Ions then diffuse through the channels and enter the receiving cell.

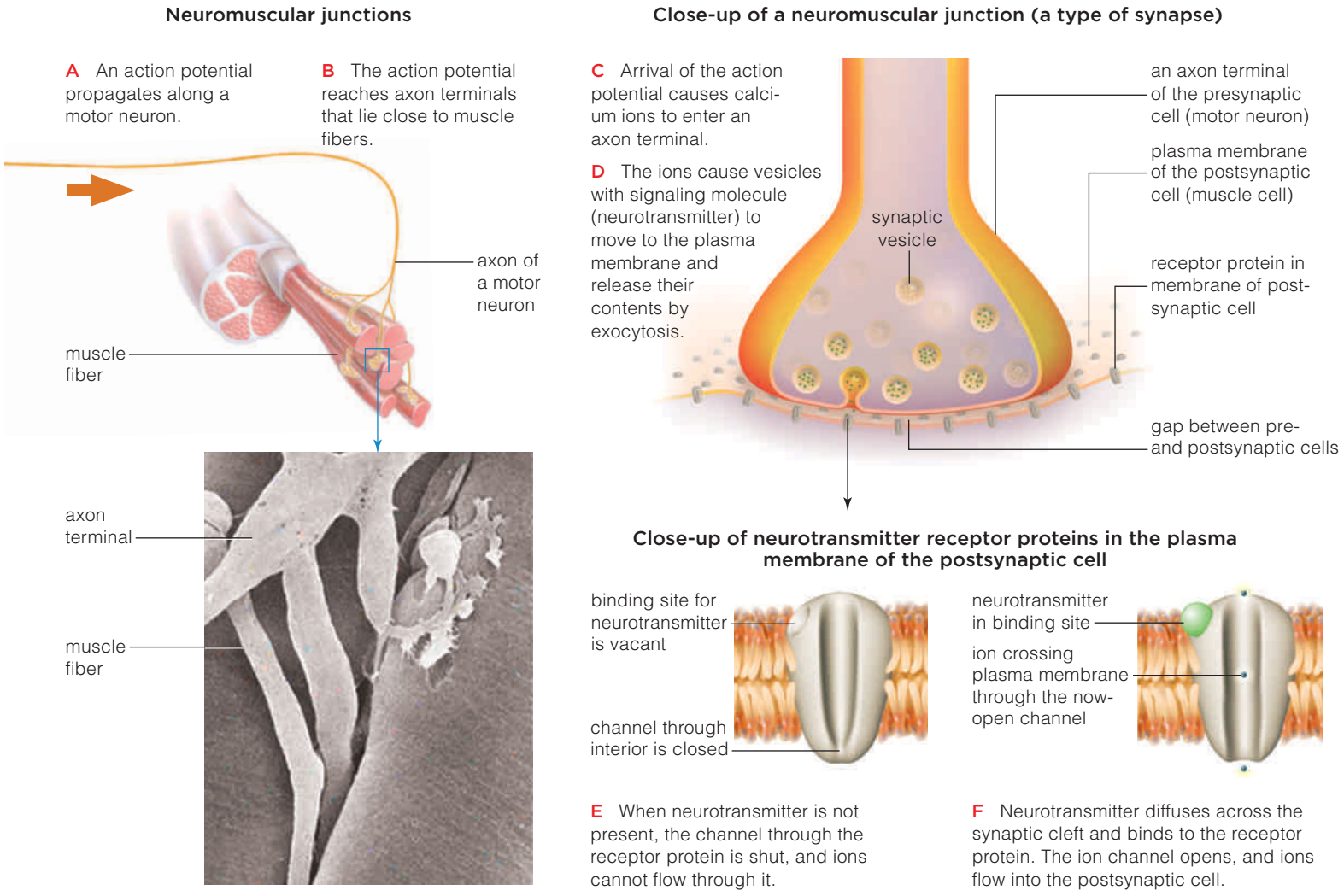


Figure 13.6 A neuromuscular junction forms between axon endings of motor neurons and skeletal muscle fibers. The micrograph shows several of these junctions.

Neurotransmitters can excite or inhibit a receiving cell

How a receiving cell responds to a neurotransmitter depends on the type and amount of a neurotransmitter, the kinds of receptors the cell has, and some other factors. *Exciting* signals help drive the membrane toward an action potential. *Inhibiting* signals have the opposite effect. Table 13.1 lists some common neurotransmitters and their effects in the body.

One neurotransmitter, **acetylcholine (ACh)**, can excite *or* inhibit different target cells in the brain, spinal cord, glands, and muscles. Figure 13.6 shows a neuromuscular junction chemical synapse between a motor neuron and a muscle cell. ACh released from the neuron diffuses across the gap and binds to receptors on the muscle cell membrane. It excites this kind of cell, triggering the action potentials that cause skeletal muscle contractions.

Epinephrine and *norepinephrine* prepare the body to respond to stress or excitement. *Dopamine* acts in fine motor control and influences some type of learning. *GABA* inhibits the release of other neurotransmitters.

Serotonin acts on brain cells that govern emotional states, sleeping, sensory perception, and regulation of body temperature. Some neurons secrete *nitric oxide* (NO), a gas that controls blood vessel dilation. It is not stored in synaptic vesicles but instead is manufactured as needed. As an example, a sexually aroused male has an erection when NO calls on blood vessels in his penis to dilate, allowing blood to rush in.

Neuromodulators can magnify or dampen the effects of a neurotransmitter. These substances include natural painkillers called *endorphins*. Endorphins inhibit nerves from releasing substance P, which conveys information about pain. In athletes who exercise beyond normal fatigue, endorphins can produce a euphoric "high."

Competing signals are "summed up"

At any moment, many signals are washing over the input zones of a receiving neuron. All of them are graded potentials (their magnitude can be large or small), and they compete for control of the membrane potential at the trigger zone. The ones called EPSPs (for excitatory postsynaptic potentials) *depolarize* the membrane—they bring it closer to threshold. On the other hand, IPSPs (inhibitory postsynaptic potentials) may *hyperpolarize* the membrane (drive it away from threshold) or help keep the membrane at its resting level.

Synaptic integration tallies up the competing signals that reach an input zone of a neuron at the same time—a little like adding up the pros and cons of a certain course of action. This process, called *summation*, is how signals arriving at a neuron are suppressed, reinforced, or sent onward to other cells in the body.

Integration occurs when neurotransmitter molecules from more than one presynaptic cell reach a neuron's input zone at the same time. Signals also are integrated after a neurotransmitter is released repeatedly, over a short time period, from a neuron that is responding to a rapid series of action potentials.

Some Neurotransmitters and Their Effects

Neurotransmitter	Examples of Effects
Acetylcholine (ACh)	Causes skeletal muscle contraction, affects mood and memory
Epinephrine and norepinephrine	Speed heart rate; dilate the pupils and airways to lungs; slow GI tract contractions; increase anxiety
Dopamine	Reduces excitatory effects of other neurotransmitters; roles in memory, learning, fine motor control
Serotonin	Elevates mood; role in memory
GABA	Inhibits release of other neurotransmitters

Neurotransmitter molecules must be removed from the synapse

The flow of signals through the nervous system depends on the rapid, controlled removal of neurotransmitter molecules from synapses. Some of the neurotransmitter molecules diffuse out of the gap. Enzymes cleave others in the synapse, as when acetylcholinesterase breaks down ACh. Also, membrane transport proteins actively pump the neurotransmitter molecules back into presynaptic cells or into neighboring neuroglia.

Some drugs can block the reuptake of certain neurotransmitters. For example, the antidepressant drug Prozac (fluoxetine) elevates a depressed person's mood by blocking the reuptake of serotonin.

Take-Home Message

How does information pass between cells at a synapse?

- A synapse is a narrow gap between two neurons or between a neuron and a muscle cell or gland cell.
- Neurotransmitters carry signals between the cells at a synapse. They may excite or inhibit the activity of different kinds of target cells.
- In synaptic integration, incoming signals that excite or inhibit the same postsynaptic cell are summed. In this way nervous system messages can be reinforced or downplayed, sent onward or suppressed.

13.5 Information Pathways

- **Once a message is "sent" in the nervous system, where it goes depends on how neurons are organized in the body.**

Nerves are long-distance lines

Nerves are communication lines between the brain or spinal cord and the rest of the body. A **nerve** consists of nerve fibers, which are the long axons of sensory neurons, motor neurons, or both. Connective tissue encloses most of the axons like electrical cords inside a tube (Table 13.2 and Figure 13.7*a*). In the central nervous system (the brain and spinal cord) nerves are called **nerve tracts**.

Each axon has an insulating **myelin sheath**, which allows action potentials to propagate faster than they would otherwise. The sheath consists of glial cells that wrap around the long axons like jelly rolls. As you can see in Figure 13.7*b*, an exposed node, or gap, separates each cell from the next one. There, voltage-sensitive, gated sodium channels pepper the plasma membrane. In a manner of speaking, action potentials jump from node to node (a phenomenon that sometimes is called saltatory conduction, after a Latin word meaning "to jump"). The sheathed areas between nodes hamper the movement of ions across the plasma membrane, so stimulation tends to travel along the membrane until the next node in line. At each node, however, the flow of ions can produce a new action potential. In large sheathed axons, action potentials propagate at a remarkable 120 meters (nearly 400 feet) per second!

In the central nervous system glial cells called oligodendrocytes form the myelin sheath. In the rest of the nervous system glial cells called **Schwann cells** form the sheath.

Basic Components of the Nervous System

Neuron	Nervous system cell specialized for communication
Nerve fiber	Long axon of one neuron
Nerves	Long axons of several neurons enclosed by connective tissue

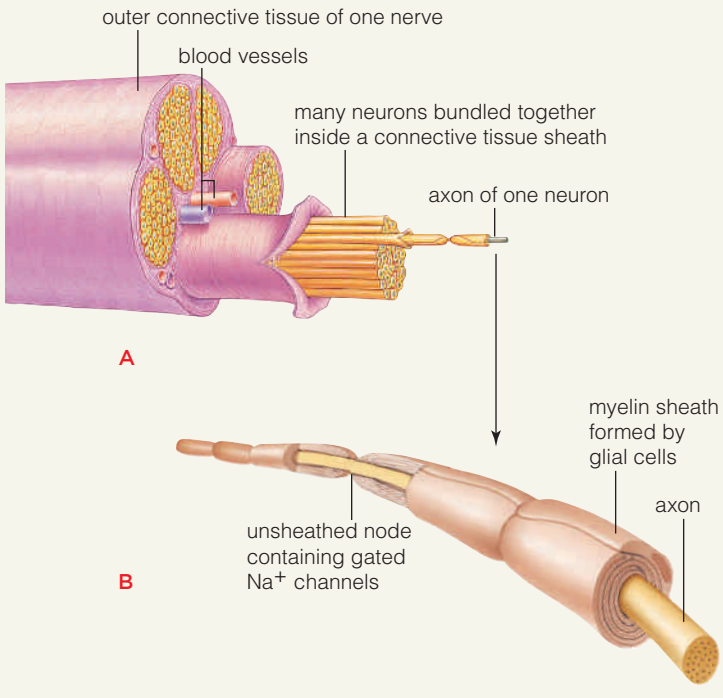


Figure 13.7 Animated! Nerves are bundled long axons of neurons. (**a**) Structure of a nerve. (**b**) Structure of a sheathed axon. A myelin sheath blocks the flow of ions except at nodes between Schwann cells.

Reflex arcs are the simplest nerve pathways

Sensory and motor neurons of certain nerves take part in automatic responses called reflexes. A **reflex** is a simple, stereotyped movement (it is always the same) in response to a stimulus. In the simplest **reflex arcs**, sensory neurons synapse directly on motor neurons.

The *stretch reflex* contracts a muscle after gravity or some other load has stretched the muscle. Suppose you hold out a bowl and keep it stationary as someone loads peaches into it, adding weight to the bowl. When your hand starts to drop, a muscle in your arm (the biceps) is stretched.

In the muscle, stretching activates receptor endings that are a part of muscle spindles. These are sensory organs in which specialized cells are enclosed in a sheath that runs parallel with the muscle. The receptor endings are the input zones of sensory neurons whose axons synapse with motor neurons in the spinal cord (Figure 13.8). Axons of the motor neurons lead back to the stretched muscle. Action potentials that reach the axon endings trigger the release of ACh, which triggers contraction. As long as receptors continue to send messages, the motor neurons are excited. This allows them to maintain your hand's position.

In most reflex pathways, the sensory neurons also interact with several interneurons. These excite or inhibit motor neurons as needed for a coordinated response.

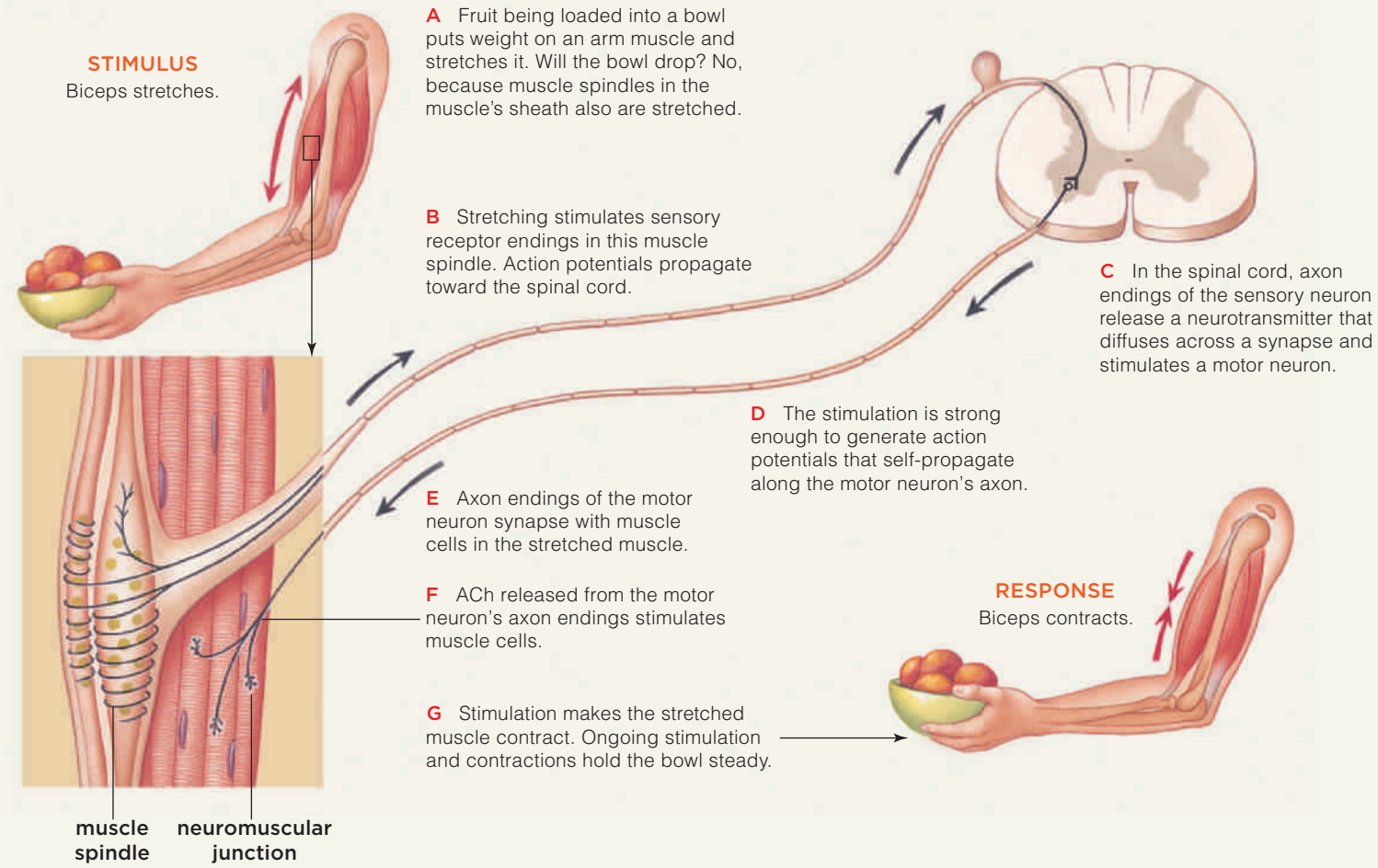


Figure 13.8 Animated! **Reflex arcs are simple but important neural pathways.** This diagram shows how nerves are organized in a reflex arc that operates when skeletal muscle stretches. Stretch-sensitive receptors of a sensory neuron are located in muscle spindles. The stretching generates action potentials, which reach axon endings in the spinal cord. These synapse with a motor neuron that carries contraction signals from the spinal cord back to the stretching muscle.

In the brain and spinal cord, neurons interact in circuits

In your nervous system, sensory nerves relay information into the spinal cord, where they form chemical synapses with interneurons. The spinal cord and brain contain only interneurons, which integrate the signals. Many interneurons synapse with motor neurons, which carry signals away from the spinal cord and brain.

In the brain and spinal cord, interneurons are grouped into blocks of hundreds or thousands. The blocks in turn are parts of circuits. Each block receives signals—some that excite, others that inhibit—and then integrates the messages and responds with new ones. For example, in some brain regions the circuits diverge—the processes of neurons in one block fan out to form connections with other blocks. Elsewhere signals from many neurons are funneled to just a few. And in still other places in the brain, neurons synapse back on themselves, repeating signals among themselves. These "reverberating" circuits include the ones that make your eye muscles twitch as you sleep.

Take-Home Message

How are neurons organized in the nervous system?

- Nerves containing the long axons of sensory neurons, motor neurons, or both, connect the brain and spinal cord with the rest of the body.
- In the simplest reflex arc, sensory neurons synapse directly on motor neurons.
- Interneurons in the brain and spinal cord are organized in information-processing blocks.

13.6 Overview of the Nervous System

- **The nervous system consists of two parts—the central nervous system and the peripheral nervous system.**
- **Link to Nervous tissue 4.4**

Humans have the most intricately wired nervous system in the animal world (Figure 13.9). The brain alone contains at least 100 billion neurons, and many more form part of the nerves that branch throughout the rest of the body. We can simplify this complexity by dividing the nervous system into the central nervous system and the peripheral nervous system. The brain and spinal cord make up the **central nervous system** (CNS). It contains all of the nervous system's interneurons. The **peripheral nervous system** (PNS) consists mainly of nerves that thread through the rest of the body and carry signals into and out of the central nervous system. Figure 13.10 gives an overview of how the two parts interconnect.

The peripheral nervous system consists of thirty-one pairs of spinal nerves that carry signals to and from the spinal cord and twelve pairs of cranial nerves that carry signals to and from the brain (Figure 13.11). At some places in the PNS, cell bodies of several neurons occur in clusters called **ganglia** (singular: ganglion). The central and peripheral nervous systems both also have glia, such as the oligodendrocytes (CNS) and Schwann cells (PNS) described in Sections 13.1 and 13.5.

As Figure 13.10 shows, the peripheral nervous system is organized into *somatic* and *autonomic* subdivisions, and the autonomic nerves are subdivided yet again. We'll consider the roles of those nerves in Section 13.7.

Nerves that carry sensory information to the central nervous system sometimes are called *afferent* ("bringing to") nerves. Nerves that carry motor messages away from the central nervous system to muscles and glands may be termed *efferent* ("carrying outward") nerves.

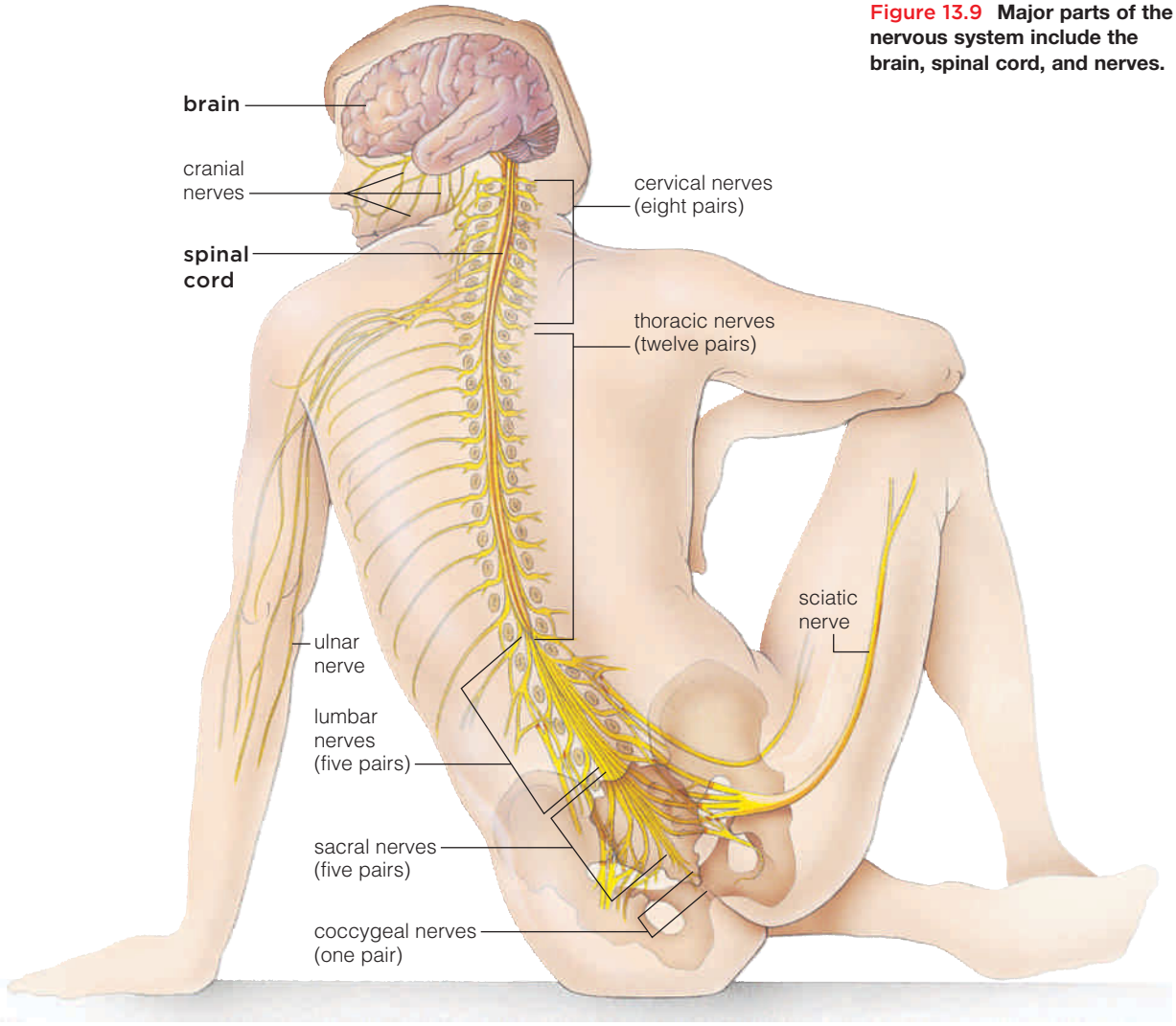


Figure 13.9 **Major parts of the nervous system include the brain, spinal cord, and nerves.**

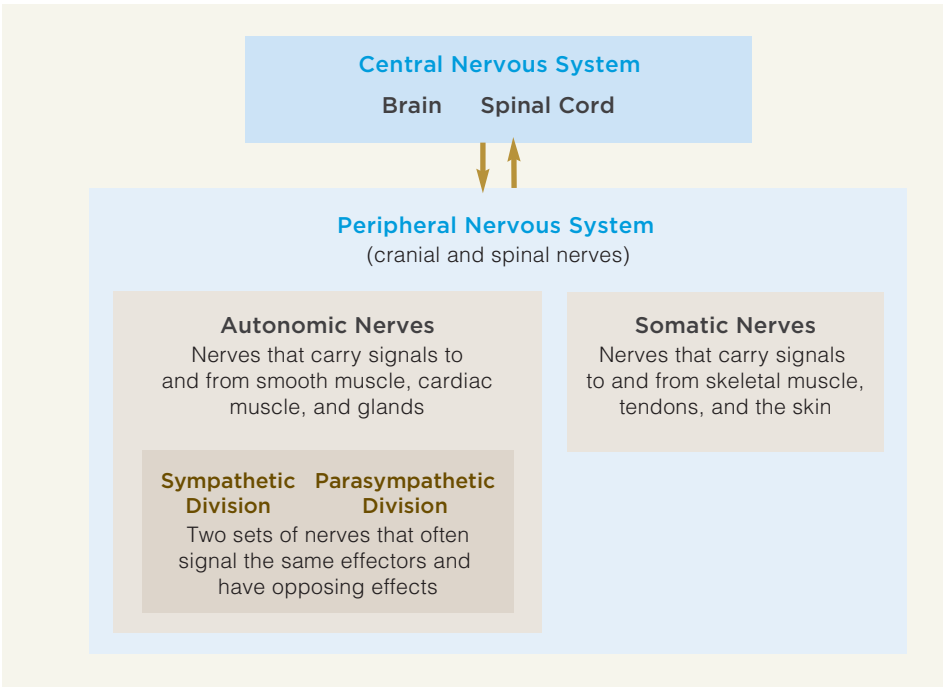


Figure 13.10 Animated! **The nervous system is subdivided into central and peripheral portions.** The brain and spinal cord form the central nervous system (CNS). The peripheral nervous system (PNS) consists of the spinal nerves, cranial nerves, and their branches, which extend through the rest of the body.

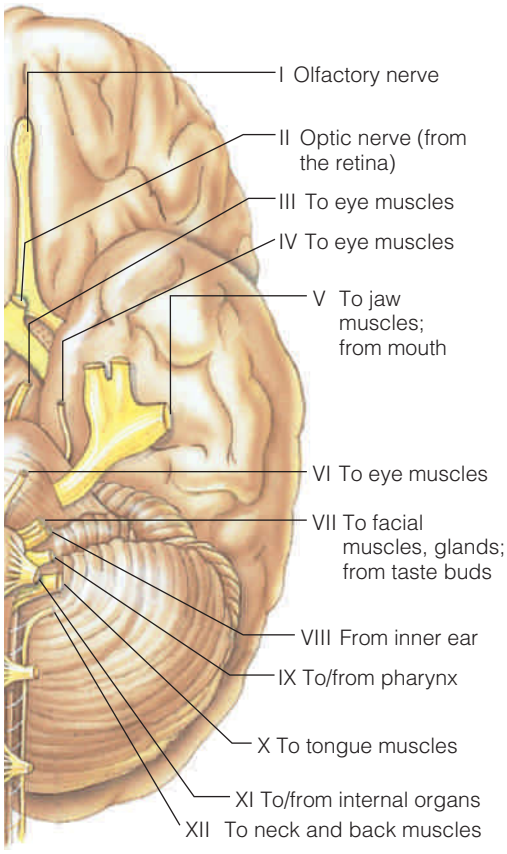


Figure 13.11 **Twelve pairs of cranial nerves extend from different regions of the brain stem.** Roman numerals traditionally are used to designate cranial nerves.

Throughout our lives, our remarkable nervous system integrates the array of body functions in ways that help maintain homeostasis. Operations of the CNS also give us much of our "humanness," including the ability to appreciate the vast number of other organisms with which we share the living world. With this introduction, we now turn to a closer look at the two major parts of the nervous system.

Take-Home Message

What are the subdivisions of the nervous system?

- The nervous system is divided into the central nervous system (CNS) and the peripheral nervous system (PNS).
- The central nervous system consists of the brain and spinal cord. The peripheral nervous system consists of branching spinal and cranial nerves that carry signals to and from the CNS.

13.7 Major Expressways: Peripheral Nerves and the Spinal Cord

- **Peripheral nerves and the spinal cord carry signals to and from the brain.**

The peripheral nervous system consists of somatic and autonomic nerves

Nerves of the PNS are grouped by function. To begin with, cranial and spinal nerves are subdivided into two groups. **Somatic nerves** carry signals related to movements of the head, trunk, and limbs. **Autonomic nerves** carry signals beween internal organs and other structures.

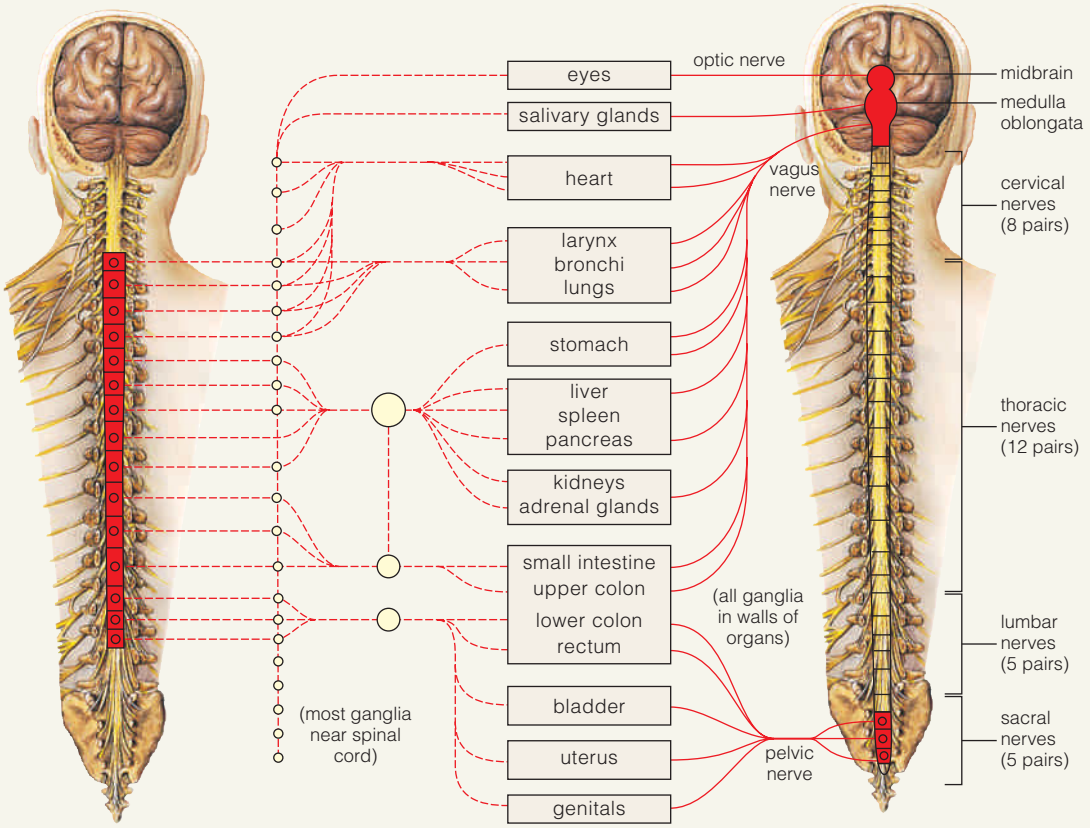
In somatic nerves, sensory axons carry information from receptors in skin, skeletal muscles, and tendons to the central nervous system. Their motor axons deliver commands from the brain and spinal cord to skeletal muscles. In the autonomic category, motor axons of spinal and cranial nerves carry messages to smooth muscle, cardiac (heart) muscle, and glands (Figure 13.12).

Unlike somatic neurons, single autonomic neurons do not extend the entire distance between muscles or glands and the central nervous system. Instead, preganglionic ("before a ganglion") neurons have cell bodies inside the spinal cord or brain stem, but their axons travel through nerves to autonomic system ganglia *outside* the CNS. There, the axons synapse with postganglionic ("after a ganglion") neurons, which make the actual connection with effectors—the body's muscles and glands.

Autonomic nerves are divided into parasympathetic and sympathetic groups

Autonomic nerves are divided into *parasympathetic* and *sympathetic* nerves. Normally these two sets of nerves work antagonistically—the signals from one oppose those of the other. However, both these groups of nerves carry exciting and inhibiting signals to internal organs. Often their signals arrive at the same time at muscle or gland cells and compete for control. When that situation arises, synaptic integration leads to minor adjustments in an organ's activity.

Figure 13.12 Animated!
Autonomic nerves serve internal organs. This is a diagram of the major sympathetic and parasympathetic nerves leading out from the central nervous system to some major organs. There are *pairs* of both kinds of nerves, servicing the right and left halves of the body. The ganglia are clusters of cell bodies of the neurons that are bundled together in nerves.



A sympathetic outflow from the spinal cord

Examples of Responses
Heart rate increases
Pupils of eyes dilate (widen, let in more light)
Salivary gland secretions thicken
Stomach and intestinal movements slow down
Sphincters (rings of muscle) contract

Examples of Responses
Heart rate decreases
Pupils of eyes constrict (keep more light out)
Salivary gland secretions become dilute
Stomach and intestinal movements increase
Sphincters (rings of muscle) relax

B parasympathetic outflow from the spinal cord and brain

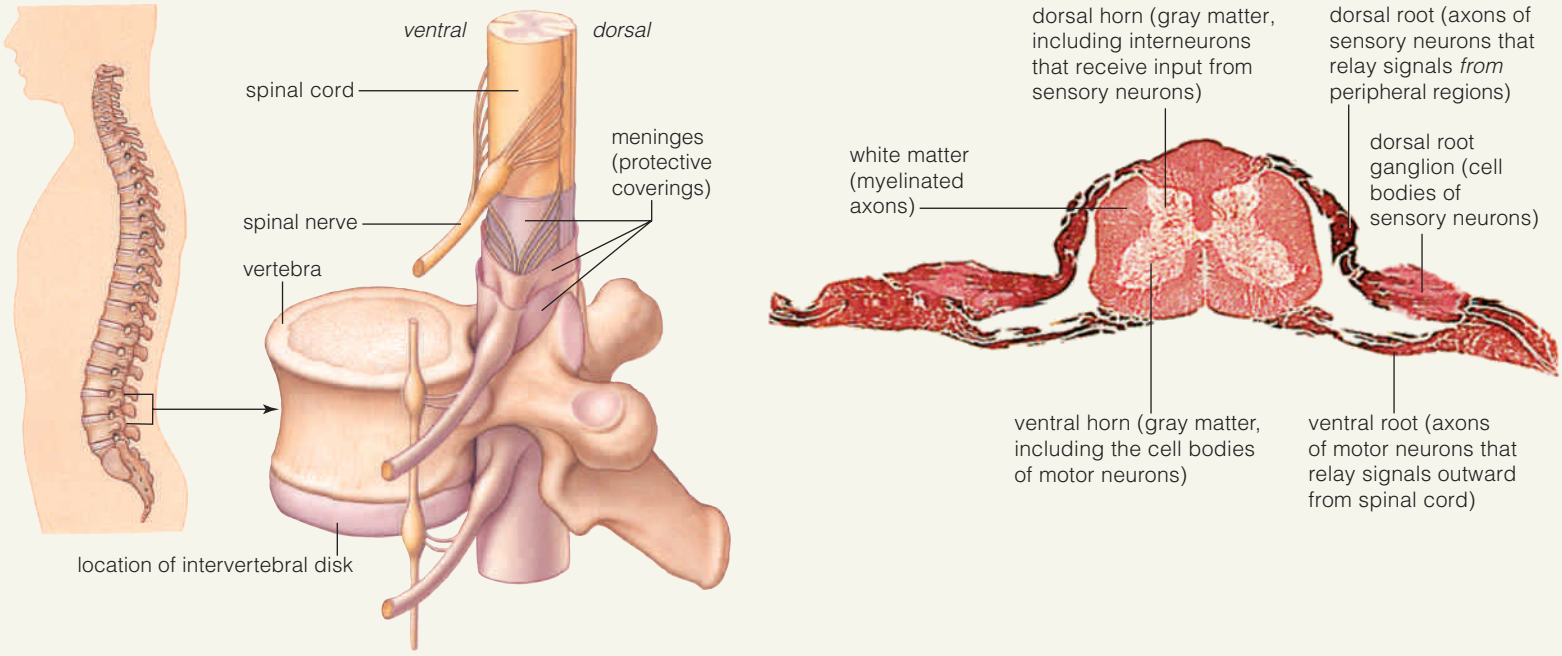


Figure 13.13 Animated! **The spinal cord connects the brain with the peripheral nervous system.**

Parasympathetic nerves dominate when the body is not receiving much outside stimulation. They tend to slow down the body overall and divert energy to basic bodily housekeeping tasks, such as digestion.

Sympathetic nerves dominate when a person is in a state of heightened awareness, as when you are excited or sense danger. Their signals tend to shift activity away from housekeeping tasks. For example, as you read this, some of your sympathetic nerves are prompting your heart to beat a bit faster, and parasympathetic nerves are commanding it to beat a little slower. Integration of these opposing signals influences your heart rate. If something scares or excites you, parasympathetic input to your heart drops. At the same time, sympathetic nerves release the neurotransmitter norepinephrine, which makes your heart beat faster and makes you breathe faster and sweat. In this **fight–flight response**, you are primed to fight hard or to get away fast.

When the stimulus for the fight–flight response stops, sympathetic activity may fall and parasympathetic activity may rise. This "rebound effect" can occur after someone has been mobilized, say, to rush onto a street to save a child from an oncoming car. The person may well collapse as soon as the child has been swept out of danger.

The spinal cord links the PNS and the brain

The **spinal cord** serves as an information highway for signals between the peripheral nervous system and the brain. It threads through a canal made of bones of the vertebral column (Figure 13.13). Most of the cord consists of nerve tracts (bundles of myelinated axons). Because the myelin sheaths of these axons are white, the tracts are called **white matter**. The cord also contains **gray matter** that consists of dendrites, cell bodies of neurons, interneurons, and neuroglial cells. A cross section of the cord's gray matter looks a little bit like a butterfly. The cord lies inside a closed channel formed by the bones of the vertebral column. Those bones, and ligaments attached to them, protect the soft nervous tissue of the cord. So do protective coverings called *meninges*. They are discussed in Section 13.8.

In addition to carrying signals between the peripheral nervous system and the brain, the spinal cord is a control center for reflexes. Sensory and motor neurons involved in many reflex movements of skeletal muscle make direct connections in the cord. These *spinal reflexes* do not involve the brain. When you jerk your hand away from a hot stove burner, you are experiencing a spinal reflex in action. Information about the sensory stimulus does reach higher brain centers, however, so you become aware of "hot burner!" even as your hand is moving away from it. The spinal cord also contributes to *autonomic reflexes* that deal with internal functions such as bladder emptying.

Take-Home Message

What is the peripheral nervous system?

- The peripheral nervous system consists of the nerves to and from the brain and spinal cord.
- PNS somatic nerves deal with skeletal muscle movements. Its autonomic nerves deal with internal organs and glands. Autonomic nerves are divided into parasympathetic nerves (for housekeeping functions) and sympathetic nerves (for aroused states).
- The spinal cord carries signals between peripheral nerves and the brain. It also is a control center for some reflexes.

13.8 The Brain: Command Central

- **The brain is divided into three main regions, each one containing centers that manage specific biological tasks.**

The spinal cord merges with the **brain**, which weighs about 3 pounds (1,300 grams) in an adult. Like the spinal cord, the brain is protected by bones (of the cranium) and by the three **meninges** (meh-NIN-jeez). These are membranes of connective tissue layered between the skull and the brain (Figure 13.14). Meninges cover and protect the fragile CNS neurons and blood vessels that service the tissue. The leathery, outer membrane, the *dura mater*, is folded double around the brain. Its upper surface attaches to the skull. The lower surface is the outer covering of the brain and separates its right and left hemispheres. A second membrane is called the *arachnoid*, and the even more delicate *pia mater* wraps the brain and spinal cord. The meninges also enclose fluid-filled spaces that cushion and nourish the brain.

The brain is divided into a hindbrain, midbrain, and forebrain

The brain's three divisions are the *hindbrain*, *midbrain*, and *forebrain* (Figure 13.15). In the hindbrain and midbrain are centers that control many simple, basic reflexes; this tissue is the **brain stem**. As the ancestors of humans evolved, expanded layers of gray matter developed over the brain stem. These changes in brain structure probably correlate with our species' growing reliance on three major sensory organs: the nose, ears, and eyes. They are topics in Chapter 14.

Hindbrain The medulla oblongata, cerebellum, and pons are all components of the hindbrain. The **medulla oblongata** contains reflex centers for a number of vital tasks, such as respiration and blood circulation. It also coordinates motor responses with certain complex reflexes, such as coughing. In addition, the medulla influences brain centers that help you sleep or wake up.

The **cerebellum** integrates sensory signals from the eyes, inner ears, and muscles with motor signals from the forebrain to coordinate movement and balance. It helps control dexterity. Some of its activities may also be crucial in language and other forms of mental agility.

Bands of many axons extend from the cerebellum into the **pons** ("bridge") in the brain stem. The pons directs the

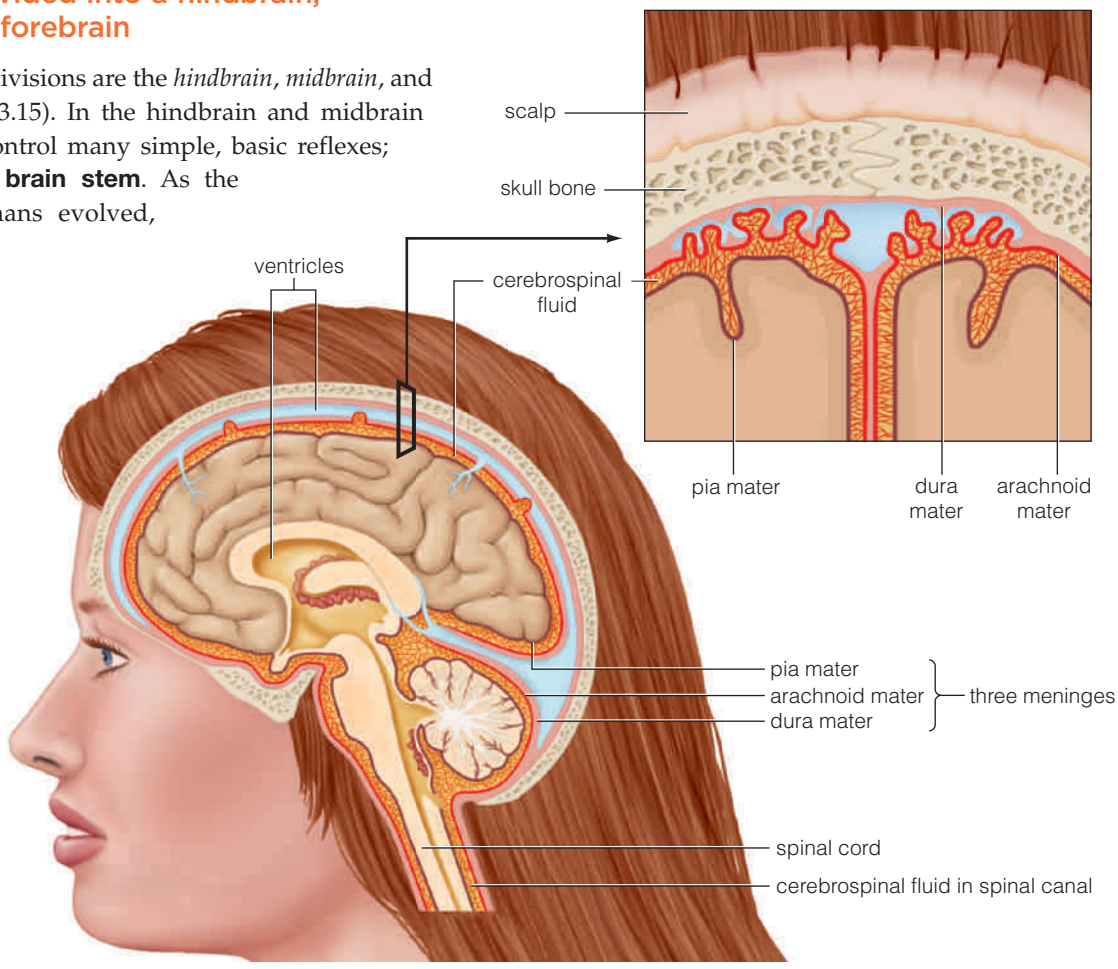
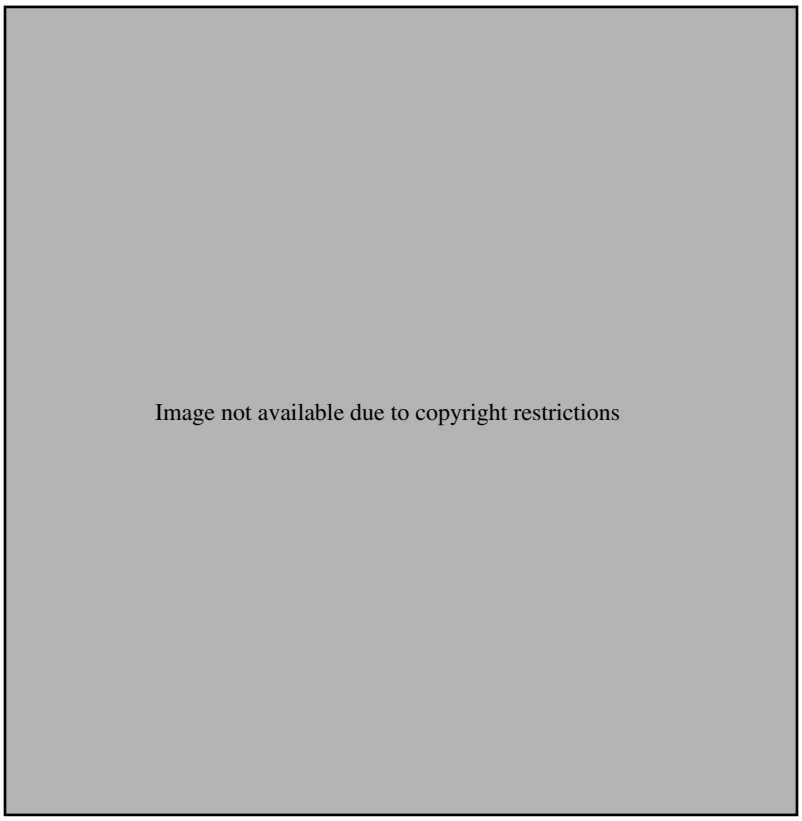


Figure 13.14 The three meninges help protect the brain and spinal cord. Cerebrospinal fluid fills the space between the arachnoid and the pia mater.



signal traffic between the cerebellum and the higher integrating centers of the forebrain.

Midbrain The midbrain coordinates reflex responses to sights and sounds. It has a roof of gray matter, the *tectum* (Latin for "roof"), where visual and auditory sensory input converges before being sent on to higher brain centers.

Forebrain The forebrain is the most highly developed brain region. It includes the cerebrum, olfactory bulbs, and the thalamus and hypothalamus. In the **cerebrum**, information is processed and sensory input and motor responses are integrated. A pair of *olfactory bulbs* deal with sensory information about smell. The **thalamus** is mainly a sensory relay switchboard. In it, incoming signals in sensory nerve tracts are relayed to clusters of neuron cell bodies (called *nuclei*), then relayed onward. The nuclei also process some outgoing motor information. As you will read in Section 13.12, Parkinson's disease results when functioning of *basal nuclei* in the thalamus is disrupted.

Located below the thalamus, the **hypothalamus** has evolved into the body's "supercenter" for controlling homeostatic adjustments in the activities of internal organs. As noted in previous chapters, for example, it helps govern states such as thirst and hunger. The hypothalamus also has roles in sexual behavior and emotional expression, such as when fear causes a person to break into a sweat.

Cerebrospinal fluid fills cavities and canals in the brain

Our brain and spinal cord would both be extremely vulnerable to damage if they were not protected by bones and meninges. In addition, as you can see in Figure 13.14, both of them contain **cerebrospinal fluid**, or CSF. This transparent fluid forms from blood plasma and is chemically similar to it. It is secreted from specialized capillaries inside a system of fluid-filled cavities and canals in the brain. The cavities in the brain are called ventricles. They connect with each other and with the central canal of the spinal cord and are filled with cerebrospinal fluid. The fluid also fills the space between the innermost layer of the meninges and the brain itself. Because the enclosed cerebrospinal fluid can't be compressed, it helps cushion the brain and spinal cord from jarring movements. Some diseases, such as **meningitis** (inflammation of the meninges), can be diagnosed by analyzing a sample of the CSF.

Maintaining homeostasis in the fluid that bathes brain neurons is vital. Yet as you know, the chemical makeup of extracellular fluid, including levels of ions and other substances, is constantly changing. In the brain this problem is solved by the unusual structure of brain capillaries. Their walls are much less permeable than the walls of capillaries elsewhere in the body, so substances must pass *through* the wall cells, rather than between them, to reach the brain. This **blood–brain barrier** helps control which blood-borne substances reach the brain's neurons.

Transport proteins embedded in the plasma membrane of the cells in brain capillary walls allow glucose and other water-soluble substances to cross the barrier. However, lipid-soluble substances are another matter. They quickly diffuse through the lipid bilayer of the plasma membrane. This "lipid loophole" in the blood–brain barrier is one reason why lipid-soluble chemicals such as caffeine, nicotine, alcohol, barbiturates, heroin, and anesthetics can rapidly affect brain function.

Take-Home Message

What are the main regions of the brain?

- The brain's main divisions are the hindbrain, midbrain, and forebrain. Their roles range from reflex controls over basic body functions to the integration of sensory information and motor responses.
- Cerebrospinal fluid fills a system of cavities and canals in the brain and spinal cord to provide a protective cushion.

13.9 A Closer Look at the Cerebrum

- **Our capacity for conscious thought and language arises from the activity of the cerebral cortex.**
- **The cortex interacts with other brain regions to shape our emotional responses and memories.**

The cerebrum is divided into two **cerebral hemispheres** (Figure 13.16*a*). Each hemisphere has a deeply folded, outer layer of gray matter, the **cerebral cortex**. Below the cortex are the white matter (axons) and the basal nuclei—patches of gray matter in the thalamus.

Each cerebral hemisphere receives and processes signals mainly from the opposite side of the body. For example, "cold" signals from an ice cube in your left hand travel to your right cerebral hemisphere. The left hemisphere deals mainly with speech, analytical skills, and mathematics. In most people it dominates the right hemisphere, which deals more with visual–spatial relationships, music, and other creative activities. A band of nerve tracts, the corpus callosum, carries signals between the hemispheres.

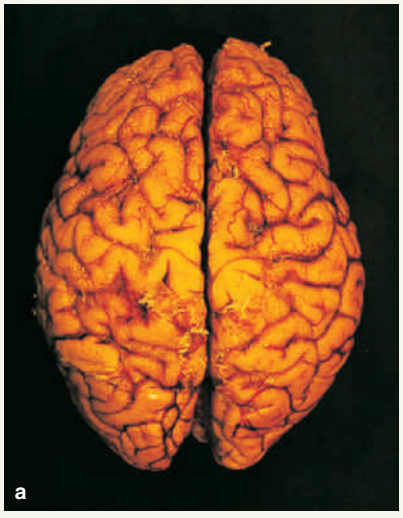
Each hemisphere is divided into lobes that process different signals. The lobes are the frontal, occipital, temporal, and parietal lobes (Figure 13.16*b*). EEGs and PET scans (Figure 13.16*c*) can reveal activity in each lobe. EEG, short for electroencephalogram, is a recording of electrical activity in some part of the brain.

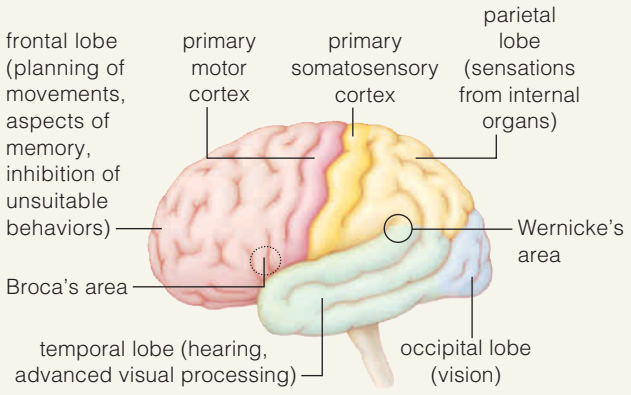
The cerebral cortex controls consciousness

Thoughts, memories, the ability to understand, and voluntary acts all begin in the cerebral cortex. The cortex is divided into three main parts. *Motor* areas control voluntary movements. *Sensory* areas govern the ability to grasp the meaning of sensations (information from sensory organs). *Association* areas process information as needed to produce a conscious action.

Motor areas In the frontal lobe of each hemisphere, the whole body is spatially mapped out in the primary motor cortex. This area controls coordinated movements of skeletal muscles. Thumb, finger, and tongue muscles get much of the area's attention, indicating how much control is required for voluntary hand movements and verbal expression (Figure 13.17).

Also in the frontal lobe are the premotor cortex, Broca's area, and the frontal eye field. The premotor cortex deals with learned patterns or motor skills. Repetitive motor





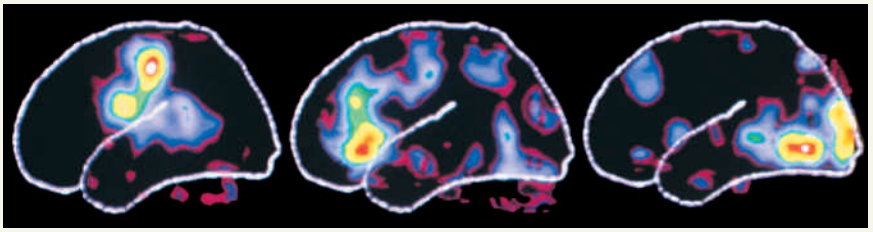


Figure 13.16 Animated! The cerebrum is divided into hemispheres and lobes.

(**a**) A top-down view of the brain's two cerebral hemispheres.

(**b**) Lobes of the brain, showing the primary receiving and integrating centers of the cerebral cortex.

(**c**) PET scans show brain regions that are active when a person performed three specific language tasks: speaking, writing words, and reading.

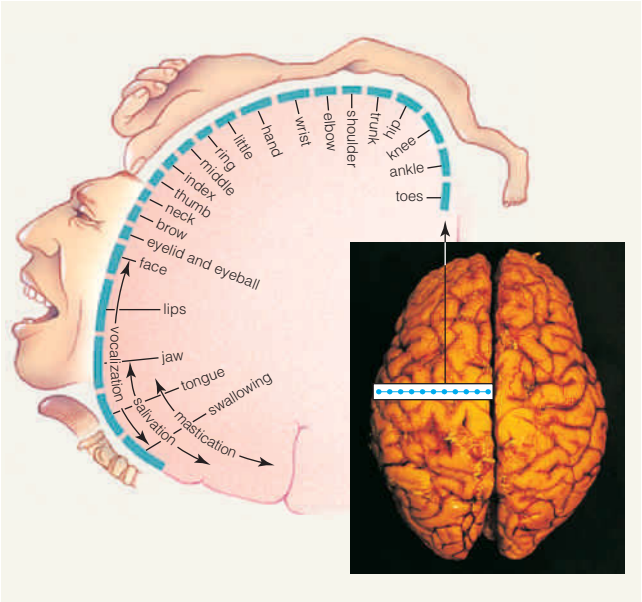


Figure 13.17 Animated! **The body is "mapped" in the primary motor cortex.** This diagram depicts a slice through the primary motor cortex of the left cerebral hemisphere. The distortions to the body draped over the diagram indicate which body parts are controlled with the greatest precision.

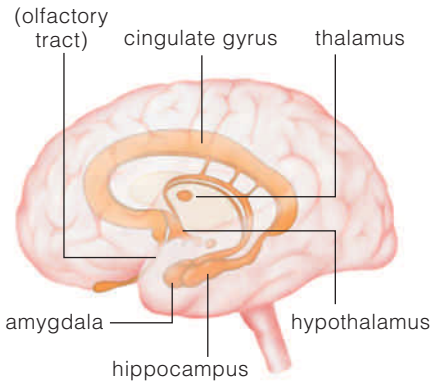


Figure 13.18 **The limbic system operates in emotions, memory, and some other mental activities.** The limbic system encircles the upper brain stem. The amygdala and the cingulate gyrus are especially important in emotions. The hypothalamus is a clearinghouse for emotions and visceral activity. Both the hippocampus and the amygdala help convert stimuli into long-term memory (Section 13.10).

actions, such as bouncing a ball, are evidence that your motor cortex is coordinating the movements of several muscle groups. Broca's area (usually in the left hemisphere) and a corresponding area in the right hemisphere control the tongue, throat, and lip muscles used in speech. It kicks in when we are about to speak and even when we plan voluntary motor activities other than speaking (so you can talk on the phone and write down a message at the same time). Above Broca's area is the frontal eye field. It controls voluntary eye movements.

Sensory areas Sensory areas occur in different parts of the cortex. In the parietal lobe, the body is spatially mapped out in the primary somatosensory cortex. This area is the main receiving center for sensory input from the skin and joints. The parietal lobe also has a primary cortical area dealing with perception of taste. At the back of the occipital lobe is the primary visual cortex, which receives sensory inputs from your eyes. Perception of sounds and of odors arises in primary cortical areas in each temporal lobe.

Association areas Association areas occupy all parts of the cortex except the primary motor and sensory regions. Each integrates, analyzes, and responds to many inputs. For instance, the visual association area surrounds the primary visual cortex. It helps us recognize something we see by comparing it with visual memories. Neural activity in the most complex association area—the prefrontal cortex—is the basis for complex learning, intellect, and personality. Without it, we would be incapable of abstract thought, judgment, planning, and concern for others.

The limbic system governs emotions and more

The **limbic system** governs our emotions and has roles in memory. Brain imaging studies show that it also is active during some kinds of decision-making processes. In all these activities the limbic system interacts closely with the prefrontal cortex. The system includes parts of the thalamus along with the hypothalamus, the amygdala, and the hippocampus (Figure 13.18). It is called the "emotional–visceral brain" because it produces "gut" reactions such as rage. The system's links with other brain centers also allow it to correlate self-gratifying behavior, such as eating and sex, with the activities of associated organs. Responses of the limbic system also are part of the reason you may feel "warm and fuzzy" when you recall the cologne of a special person who wore it.

Take-Home Message

What are the main parts and roles of the cerebrum?

- Each cerebral hemisphere receives and processes responses to sensory input mainly from the opposite side of the body. The corpus callosum carries signals between the hemispheres.
- The left hemisphere deals mainly with speech, analytical skills, and mathematics. It usually dominates the right hemisphere, which deals more with creative activity.
- The cerebral cortex has motor, sensory, and association areas. Communication among these areas governs conscious behavior. The cerebral cortex interacts with the limbic system, which governs emotions and memory.

13.10 Memory

■ **Memory is how the brain stores and retrieves facts and other types of information.**

Learning and modifications of our behavior would be impossible without **memory**. The brain stores information in stages. The first is *short-term* storage of bits of sensory information—numbers, words of a sentence, and so on—for a few minutes or hours. In *long-term* storage, seemingly unlimited amounts of information get tucked away more or less permanently (Figure 13.19).

Only some of the sensory information reaching the cerebral cortex is transfered to short-term memory. Information is processed for relevance, so to speak. If irrelevant, it is forgotten; otherwise it is consolidated with the banks of information in long-term storage structures.

The brain processes facts separately from skills. Dates, names, faces, words, odors, and other bits of explicit information are facts that are stored together with the circumstance in which they were learned. Hence you might associate the smell of bread baking, say, with your grandmother's kitchen. This "fact" recall may be brief or long-term and is called *declarative* memory. By contrast, *skill memory* is gained by practicing specific motor activities. How to maneuver a snowboard or play a piano concerto is best recalled by actually performing it, rather than by remembering the circumstances in which the skill was first learned.

Separate memory circuits handle different kinds of input. A circuit leading to declarative memory (Figure 13.20*a*) starts with inputs at the sensory cortex that flow to the amygdala and hippocampus in the limbic system. The amygdala is the gatekeeper, connecting the sensory cortex

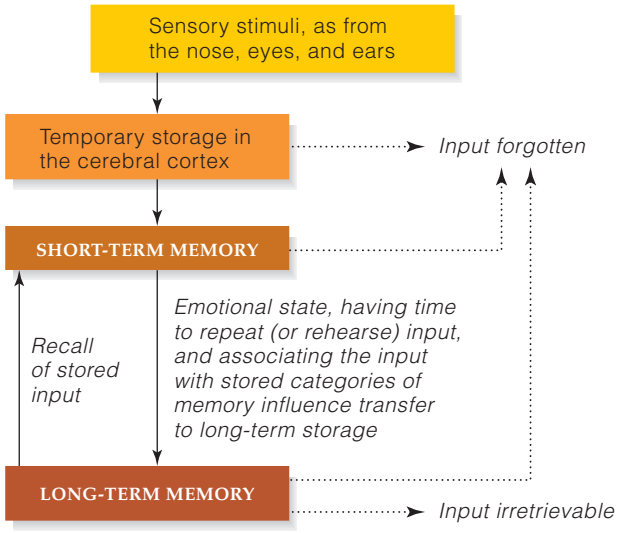


Figure 13.19 Memories are processed in two stages. Short-term memory is temporary. Long-term memories may be stored in the cerebral cortex for years.

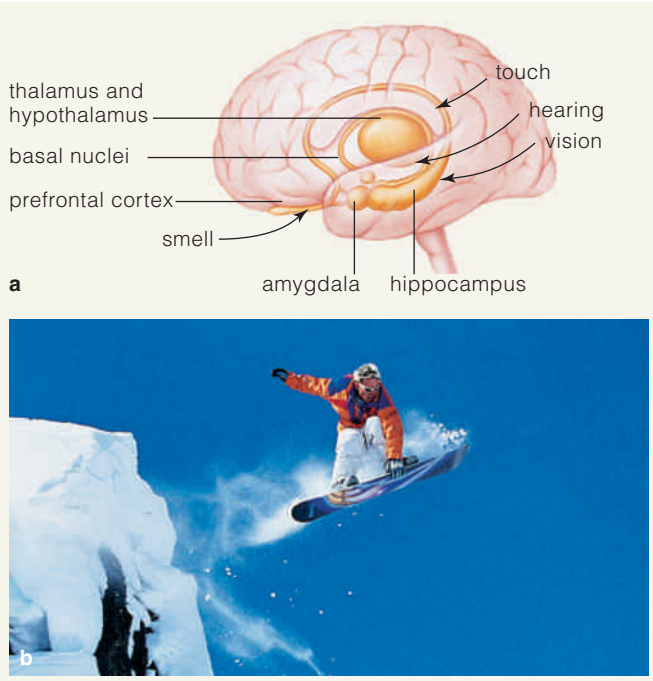


Figure 13.20 Animated! Memories of facts and skills are stored differently. (**a**) Possible circuits involved in declarative memory. (**b**) A snowboarder provides a dramatic demonstration of skill memory.

with parts of the thalamus and with parts of the hippocampus that govern emotional states. Information flows on to the prefrontal cortex, where multiple banks of fact memories are retrieved and used to stimulate or inhibit other parts of the brain. The new input also flows to basal nuclei, which send it back to the cortex in a feedback loop that reinforces the input until it can be consolidated in long-term storage.

Skill memory also starts at the sensory cortex, but this circuit routes sensory input to a region deeper in the brain that promotes motor responses (Figure 13.20*b*). Motor skills entail muscle conditioning. The skill memory circuit extends to the cerebellum, the brain region that coordinates motor activity.

Amnesia is a loss of fact memory. How severe the loss is depends on whether the hippocampus, amygdala, or both are damaged, as by a head blow. Amnesia does not affect a person's capacity to learn new skills.

Take-Home Message

How do memories form?

- Circuits between the cerebral cortex and parts of the limbic system, thalamus, and hypothalamus produce memories when sensory messages are processed through short-term and long-term storage.

13.11 Consciousness

- **Consciousness is a spectrum of brain states such as alertness and stages of sleep.**

The spectrum of consciousness ranges from being wide awake and fully alert to drowsiness, sleep, and coma. When you are awake and alert, the neural chattering in your brain shows up as wavelike patterns in an EEG. As mentioned earlier, EEGs are recordings of the electrical activity of brain neurons. Imaging methods like the PET scans in Figure 13.16c (Section 13.9) can show the exact location of brain activity as it takes place.

A network of neurons in the brain called the **reticular formation** (Figure 13.21*a*) helps govern skeletal muscle activity that helps maintain balance, posture, and muscle tone. It also promotes chemical changes that influence whether you stay awake or fall asleep. A network sleep center releases the neurotransmitter serotonin. Its effects include inhibiting neurons that arouse the brain and maintaining wakefulness. High serotonin levels trigger drowsiness and sleep. You wake up when substances released from another brain center inhibit serotonin's effects.

EEGs from electrodes placed on the scalp show up as tracings like those in Figure 13.21. Figure 13.21*b* shows the patterns for full alertness and for the two major sleep stages: slow-wave, "normal" sleep and REM (*rapid eye movement*) sleep.

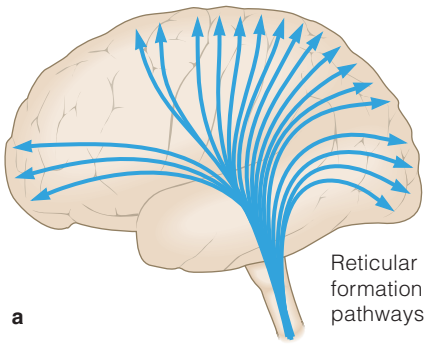
Most of the time you spend sleeping is slow-wave sleep. During this stage, your heart rate, breathing, and muscle tone change very little and you can be easily roused. Approximately every 90 minutes, however, a sleeper normally enters a period of REM sleep, in which the eyelids flicker and the eyeballs move rapidly back and forth. Dreaming occurs during REM sleep, and it is much harder to wake up during this time. The heart rate and breathing become more erratic, and muscle tone decreases dramatically.

You probably know from personal experience that people who are sleep-deprived feel tired and cranky and have difficulty concentrating. Sleep is important for the brain, but researchers do not know exactly why. Although neural activity changes during sleep, the brain clearly is not resting. Sleep may be a time when the brain does tasks such as consolidating memories and firming up connections involved in learning.

Take-Home Message

What is consciousness?

- The spectrum of consciousness includes sleeping and states of arousal. It is influenced by the reticular formation.
- Sleep has two stages, slow-wave sleep and REM sleep, in which the brain's activity is altered. Sleep may be important in memory and learning.



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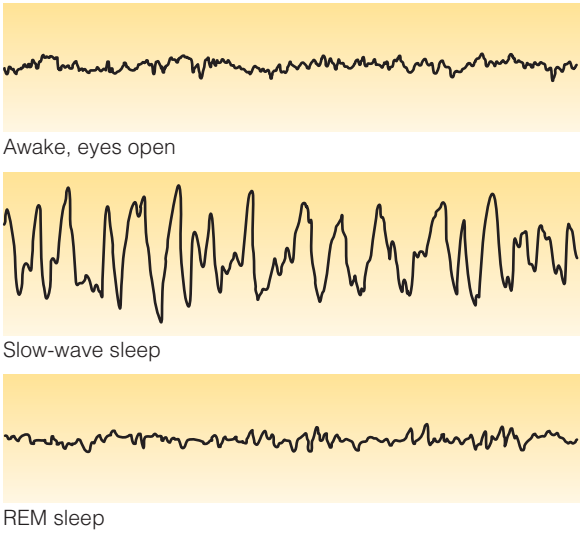


b

Figure 13.21 Several states of consciousness occur in the brain. (**a**) Communication pathways of the reticular formation, which influence sleeping and waking. (**b**) EEG patterns for alertness, slow-wave sleep, and REM (rapid eye movement) sleep. The brain waves of the student pictured below would resemble the pattern in (**a**).

13.12 Disorders of the Nervous System

Physical injury is a common cause of nervous system damage

A blow to the head or neck can cause a **concussion**, one of the most common brain injuries. Blurred vision and a brief loss of consciousness result when the blow temporarily upsets the electrical activity of brain neurons.

Damage to the spinal cord can lead to lost sensation and muscle weakness or **paralysis** below the site of the injury (Figure 13.22). Immediate treatment is crucial to limit swelling. Although cord injuries usually have severe consequences, intensive therapy during the first year after an injury can improve the patient's long-term prognosis. Using nerve growth factors or stem cells to repair spinal cord injuries is a major area of medical research.

Brain injury, birth trauma, or other assaults can cause various forms of *epilepsy*, or **seizure disorders**. In some cases the trigger may be an inherited predisposition. Each seizure results when the brain's normal electrical activity suddenly becomes chaotic. Worldwide, many thousands of people develop recurrent seizures either as children or later in life. All but the most intractable cases usually respond well to modern anticonvulsant drugs.

In some disorders, brain neurons break down

In 1817, physician James Parkinson observed troubling symptoms in certain people navigating the streets of London. They walked slowly, taking short, shuffling steps. And their limbs trembled, sometimes violently. Today we know that the culprit is a degenerative brain disorder that now is called **Parkinson's disease**, or PD (Figure 13.23*a*). In PD, neurons in the basal nuclei of the thalamus (Section 13.8) begin to die. Those neurons make neurotransmitters (dopamine and norepinephrine) that are needed for normal muscle function, so PD symptoms include muscle tremors and balance problems, among others. Treatments include drugs that help replace absent neurotransmitters or surgical treatments that may relieve some symptoms. There is no cure.

Like PD, **Alzheimer's disease** involves the progressive degeneration of brain neurons. At the same time, there is an abnormal buildup of amyloid protein, leading to the loss of memory and intellectual functions. Alzheimer's disease is associated with advancing age and we consider it again in our discussion of aging and the nervous system in Chapter 17.

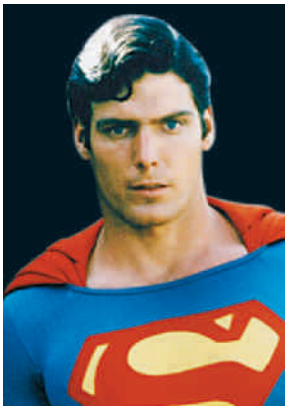


Figure 13.22 The brain and spinal cord are vulnerable to physical injuries. Actor Christopher Reeve, who played Superman, suffered a fall from a horse that fractured cervical vertebrae and left him paralyzed. Until his death in 2004 he was a strong supporter of stem cell research.

Infections and cancer inflame or destroy brain tissue

Meningitis is an often fatal disease caused by a bacterial or viral infection. Symptoms include headache, a stiff neck, and vomiting. They develop when the meninges covering the brain and/or spinal cord become inflamed. **Encephalitis** is inflammation of the brain. It is usually caused by a viral infection, such as by the West Nile virus or a herpes virus. Like meningitis, encephalitis can be extremely dangerous. Early symptoms include fever, confusion, and seizures. A form of **Creuzfeldt-Jakob disease** has occurred in people who ate beef from animals infected by a *prion*—a small infectious protein—that causes "mad cow disease," or *bovine spongiform encephalitis* (BSE). A BSE outbreak in Britain in the late 1990s raised public awareness of the potential danger of eating meat from infected animals. The infection causes holes in an affected person's brain tissue (Figure 13.23*d*). The disease is always fatal.

In cancer, cells divide much more often than normal. Neurons generally do not divide, so cancer does not develop in them. Glial cells (Figure 13.23*e*) do divide, however, and glial cancers, called gliomas, can have extremely destructive effects in the nervous system. An aggressive form called glioblastoma multiforme usually strikes males and kills within a year of the diagnosis. Most cases of spinal cancer are metastases, meaning that the cancer has spread to the spine from a primary cancer somewhere else.

In young adults, the most common disease of the nervous system is **multiple sclerosis (MS)**. It is an autoimmune disease that may be triggered by a viral infection in susceptible people. MS involves progressive

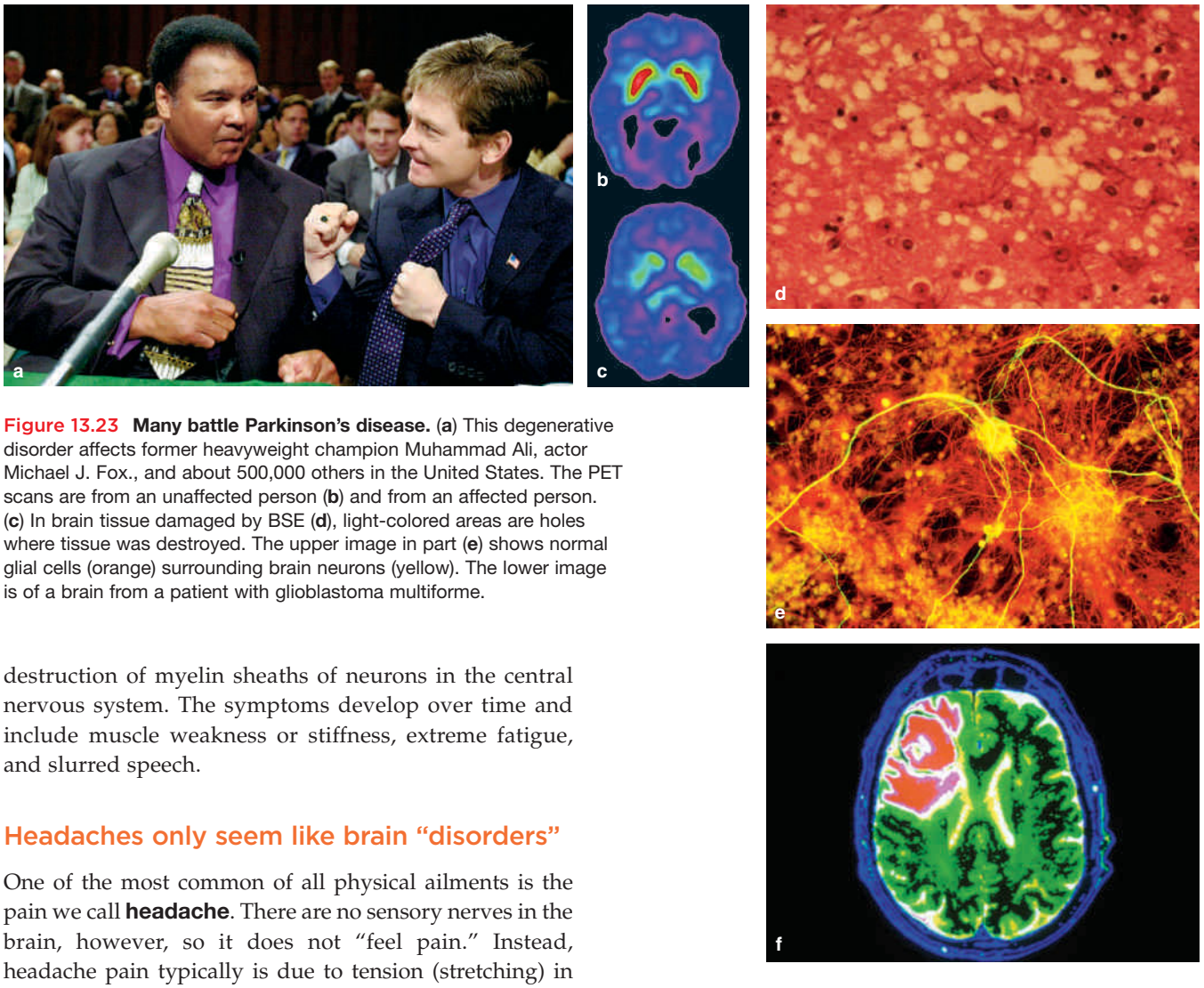


Figure 13.23 Many battle Parkinson's disease. (**a**) This degenerative disorder affects former heavyweight champion Muhammad Ali, actor Michael J. Fox., and about 500,000 others in the United States. The PET scans are from an unaffected person (**b**) and from an affected person. (**c**) In brain tissue damaged by BSE (**d**), light-colored areas are holes where tissue was destroyed. The upper image in part (**e**) shows normal glial cells (orange) surrounding brain neurons (yellow). The lower image is of a brain from a patient with glioblastoma multiforme.

destruction of myelin sheaths of neurons in the central nervous system. The symptoms develop over time and include muscle weakness or stiffness, extreme fatigue, and slurred speech.

Headaches only seem like brain "disorders"

One of the most common of all physical ailments is the pain we call **headache**. There are no sensory nerves in the brain, however, so it does not "feel pain." Instead, headache pain typically is due to tension (stretching) in muscles or blood vessels of the face, neck, and scalp.

Throbbing *migraine* headaches are infamous for being extremely painful and lasting for up to three days. In the United States alone, 28 million people, mainly female, suffer from migraines, which can be triggered by hormonal changes, fluorescent lights, certain foods (such as chocolate)—even changes in the weather. Often, a migraine is accompanied by nausea, vomiting, or sensitivity to light.

Nowadays tension headaches and migraines are thought to be part of a continuum, and both are treated with drugs ranging from aspirin to prescription painkillers and drugs that act as neuromodulators (Section 13.4) to reduce the sensitivity of affected brain neurons to stimuli that trigger the headache in the first place.

Cluster headaches develop more often in men and are in a class by themselves. This type of headache produces a piercing pressure in one eye and may recur several times a day for weeks or months. Some sufferers have found the pain so unbearable that they have been driven to suicide.

Thinking is disrupted in autism and schizophrenia

Autism and related conditions such as *Asperger's syndrome* are forms of persistent developmental disorders (PDDs) that usually show up in childhood. Affected youngsters experience mild to severe problems in thinking, language skills, and the capacity to relate to other people. Research suggests that a family of "autism genes" may underlie PDDs. In some cases, affected children show major improvement with intensive behavioral therapy.

Disrupted thinking is the hallmark of *schizophrenia*, which usually develops in young adulthood. People with schizophrenia experience paranoid delusions and often "hear voices" (auditory hallucinations). Holding a job or having normal social relationships often are impossible. Therapeutic drugs can help control symptoms, but there is no cure. Many researchers suspect that multiple factors, including physical changes in the brain, trigger this devastating mental disorder.

13.13 The Brain on "Mind-Altering" Drugs

Psychoactive drugs bind to neuron receptors in the brain. As a result, the neurons send or receive altered messages. The drugs typically affect parts of the brain that govern consciousness and behavior. Some also alter heart rate, respiration, sensory processing, and muscle coordination. Many affect a pleasure center in the hypothalamus and artificially fan the sense of pleasure we associate with eating, sex, or other activities.

Stimulants include caffeine, nicotine, cocaine, and amphetamines—including Ecstasy (MDMA). Nicotine mimics ACh, directly stimulating certain sensory receptors. It also increases the heart rate and blood pressure. At first amphetamines cause a flood of the neurotransmitters norepinephrine and dopamine, which stimulate the brain's pleasure center. Over time, however, the brain slows its production of those substances and depends more on the amphetamine. Chronic users may become psychotic, depressed, and malnourished. They may also develop heart problems.

Cocaine stimulates the pleasure center by *blocking* the reabsorption of dopamine and other neurotransmitters. It also weakens the cardiovascular and immune systems.

Alcohol is a *depressant*, even though it produces a high at first. Drinking only an ounce or two diminishes judgment and can lead to disorientation and uncoordinated movements. *Blood alcohol concentration* (BAC) measures the percentage of alcohol in the blood. In most states, someone with a BAC of 0.08 per milliliter is considered legally drunk. When the BAC reaches 0.15 to 0.4, a drinker is visibly intoxicated and can't function normally. A BAC greater than 0.4 can kill.

Morphine, an *analgesic* (painkiller), is derived from the seed pods of the opium poppy. Like its cousin heroin, it blocks pain signals by binding with certain receptors on neurons in the central nervous system. Both morphine and the synthetic version OxyContin produce euphoria. Thousands of people who obtained OxyContin illegally or by subterfuge have overdosed and died.

TABLE 13.3 Warning Signs of Drug Addiction*

1. Tolerance—it takes increasing amounts of the drug to produce the same effect.
2. Habituation—it takes continued drug use over time to maintain self-perception of functioning normally.
3. Inability to stop or curtail use of the drug, even if there is persistent desire to do so.
4. Concealment—not wanting others to know of the drug use.
5. Extreme or dangerous behavior to get and use a drug, as by stealing, asking more than one doctor for prescriptions, or jeopardizing employment by drug use at work.
6. Deteriorating professional and personal relationships.
7. Anger and defensive behavior when someone suggests there may be a problem.
8. Preferring drug use over previous activities.

*Having three or more of these signs may be cause for concern.

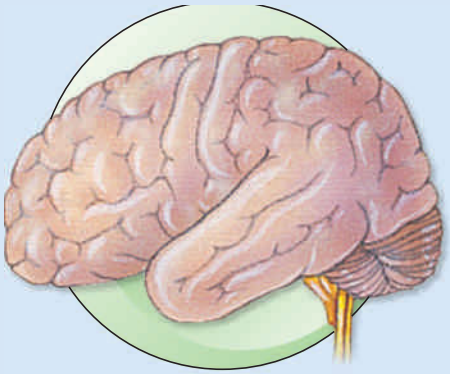
Marijuana is a *hallucinogen*. In low doses it slows but doesn't impair motor activity and causes mild euphoria. It can also cause visual hallucinations. Like alcohol, it skews the performance of complex tasks, such as driving.

The body eventually may develop drug *tolerance*, meaning that it takes larger or more frequent doses to produce the same effect. Tolerance reflects physical drug dependence. The liver produces enzymes that detoxify drugs in the blood. Tolerance develops when the level of those enzymes rises in response to the ongoing presence of the drug in the bloodstream. In effect, a drug user must increase his or her intake to stay ahead of the liver's growing ability (up to a point) to break down the drug.

In psychological drug dependence, or *habituation*, a user begins to crave the feelings associated with a particular drug. Without a steady supply of it the person can't "feel good" or function normally. Table 13.3 lists warning signs of potentially serious drug dependence. Habituation and tolerance both are evidence of addiction.

When different psychoactive drugs are used together, they can interact dangerously. For example, alcohol and barbiturates (such as Seconal and Nembutal) both depress the central nervous system. Used at the same time, they can lethally depress respiratory centers in the brain.

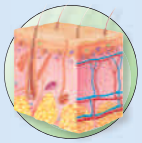
13.14 CONNECTIONS: The Nervous System in Homeostasis



The Nervous System

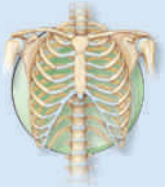
The nervous system produces signals that flow between the brain and spinal cord and other parts of the body. Together with chemical signals from the endocrine system, these nerve impulses (action potentials) provide the communication required to monitor, adjust, and regulate all body functions.

Integumentary system



Sweat glands and skeletal muscles that move hair follicles receive signals from sympathetic nerves (autonomic division of the PNS). Sensory nerve endings detect pain, pressure, temperature.

Skeletal system

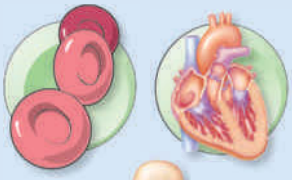


Sensory nerves that service bone tissue signal damage due to breaks or other physical harm.

Muscular system

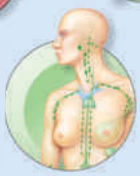
Signals from motor areas stimulate skeletal muscle contractions required for movement; signals from the cerebellum coordinate motor activity and maintain posture; spinal cord governs reflex movements.

Cardiovascular system and blood



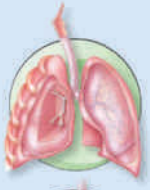
Centers in the brain stem help control the heart rate and help maintain proper blood pressure by adjusting the diameter of arterioles.

Immunity and the lymphatic system



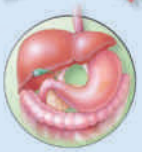
Positive/negative mental states may strengthen/weaken some immune responses.

Respiratory system



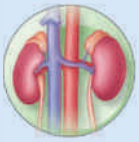
Centers in the brain stem adjust the rate and depth of breathing.

Digestive system



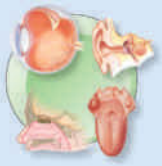
Parasympathetic nerves (ANS) regulate various aspects of digestion. Sensory signals trigger release of saliva, feelings of hunger/fullness, and regulate peristalsis.

Urinary system



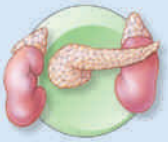
Reflexes govern urination (bladder emptying); parasympathetic nerves (ANS) adjust blood flow to the kidneys.

Sensory systems



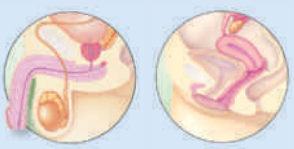
Sensory association areas manage perception of sensory information, including injury to sense organs.

Endocrine system



Signals from the hypothalamus trigger the secretion of hormones from the pituitary gland. Signals from parasympathetic nerves (ANS) regulate the release of hormones from the pancreas and adrenals.

Reproductive system



The hypothalamus governs the release of sex hormones and functioning of ovaries and testes. Sexual arousal and behavior depends on signals from the hypothalamus and the limbic system.

IMPACTS, ISSUES

In Pursuit of Ecstasy

MDMA, the active ingredient in Ecstasy harms and may kill brain neurons that produce the neurotransmitter serotonin. Damaged neurons are not replaced. MDMA also impairs the blood–brain barrier, so it allows larger than normal molecules to pass into the brain for as long as 10 weeks after use.

How Would You Vote?

Should people who are caught using illegal drugs be offeredtreatment as an alternative to jail time? See CengageNOW for details, then vote online.

Summary

Section 13.1 The nervous system detects, processes, and responds to stimuli. Sensory neurons respond directly to external or internal stimuli. Interneurons in the brain and spinal cord receive sensory signals, process them, and then send outgoing signals that influence other neurons. Motor neurons relay messages away from the brain and spinal cord to muscles or glands. Neuroglia provide various forms of physical or chemical support for neurons.

Neurons have extensions called axons and dendrites. Axons carry outgoing signals, and dendrites receive them.

Section 13.2 A resting neuron has a steady voltage difference across its plasma membrane. This difference is called the resting membrane potential. A neuron maintains concentration gradients of various ions, notably sodium and potassium, across the membrane. Changes in this difference allow a neuron to send signals (nerve impulses).

- Use the animation and interaction on CengageNOW to review the structure and properties of neurons.

Section 13.3 When the voltage difference across the membrane exceeds a threshold level, gated sodium channels in the membrane open and close rapidly and suddenly reverse the voltage difference. This reversal is a nerve impulse, or action potential. A sodium–potassium pump restores ion gradients after an action potential fires. Action potentials propagate away from the point of stimulation.

- Use the animation and interaction on CengageNOW to view the steps of an action potential.

Section 13.4 Action potentials self-propagate along the neuron membrane until they reach a synapse with another neuron, a muscle, or gland. The presynaptic cell releases a neurotransmitter into the synapse. The neurotransmitter excites or inhibits the receiving (postsynaptic) cell. Synaptic integration sums up the various signals acting on a neuron. Neuromodulators boost or reduce the effects of neurotransmitters.

- Use the animation and interaction on CengageNOW to see what happens at a synapse between a motor neuron and a muscle cell.

Section 13.5 Nerves consist of the long axons of motor neurons, sensory neurons, or both. A myelin sheath formed by Schwann cells insulates each axon, so that action potentials propagate along it much more rapidly. Nerve pathways extend from neurons in one body region to neurons or effectors in different regions.

A reflex is a simple, stereotyped movement. Reflex arcs, in which sensory neurons directly signal motor neurons that act on muscle cells, are the simplest nerve pathways. In more complex reflexes, interneurons coordinate and refine the responses.

- Use the animation and interaction on CengageNOW to observe what happens during a stretch reflex.

Section 13.6 The brain and spinal cord make up the central nervous system. The peripheral nervous system consists of nerves and ganglia in other body regions.

Section 13.7 The peripheral nervous system's somatic nerves deal with skeletal muscles involved in voluntary body movements and sensations arising from skin, muscles, and joints. Its autonomic nerves deal with the functions of internal organs.

Autonomic nerves are subdivided into sympathetic and parasympathetic groups. Parasympathetic nerves govern basic tasks such as digestion and tend to slow the pace of other body functions. Signals from sympathetic nerves produce the fight–flight response, a state of intense arousal in situations that may demand increased activity.

Spinal cord nerve tracts carry signals between the brain and the PNS. The cord also is a center for many reflexes.

- Use the animation and interaction on CengageNOW to explore the structure of the spinal cord and compare sympathetic and parasympathetic responses.

Section 13.8 The brain is divided into two cerebral hemispheres and has three main divisions (Table 13.4). It and the spinal cord are protected by bones (skull and vertebrae) and by the three meninges. Both are cushioned by cerebrospinal fluid. Specialized capillaries create a blood–brain barrier that prevents some blood-borne substances from reaching brain neurons.

In the forebrain the thalamus relays sensory information and helps coordinate motor responses. The hypothalamus monitors internal organs and influences behaviors related to their functions (such as thirst). The limbic system has roles in learning, memory, and emotional behavior.

Midbrain centers coordinate and relay sensory information from the eyes and ears. The midbrain, medulla oblongata, and pons make up the brain stem.

The hindbrain includes the medulla oblongata, pons, and cerebellum. It contains reflex centers for vital functions and muscle coordination.

Section 13.9 The cerebral cortex is devoted to receiving and integrating information from sense organs and coordinating motor responses in muscles and glands.

- Use the animation and interaction on CengageNOW to review the brain's structure and function.

Section 13.10 Memory occurs in short-term and long-term stages. Long-term storage depends on chemical or structural changes in the brain. States of consciousness vary between total alertness and deep coma. The levels are governed by the brain's reticular activating system.

TABLE 13.4 Summary of the Central Nervous System*

Forebrain	Cerebrum	Processes sensory inputs; initiates, controls skeletal muscle activity. Governs thought, memory, emotions.
	Olfactory lobe	Relays sensory input from nose to olfactor centers of cerebrum
	Thalamus	Relays sensory signals to and from cerebral cortex; has role in memory
	Hypothalamus	With pituitary gland, a homeostatic control center; adjusts volume, composition, temperature of internal environment. Governs organ-related behaviors (e.g., sex, thirst, hunger) and expression of emotions
	Limbic system	Governs emotions; has roles in memory
	Pituitary gland	With hypothalamus, provides endocrine control of metabolism, growth, development
	Pineal gland	Helps control some circadian rhythms; also has role in reproductive physiology
Midbrain	Roof of midbrain (tectum)	In humans and other mammals, its reflex centers relay visual and auditory sensory input to the forebrain
Hindbrain	Pons	Some tracts bridge the cerebrum and cerebellum; others connect spinal cord with forebrain. With the medulla oblongata, controls rate and depth of respiration
	Cerebellum	Coordinates motor activity for moving limbs and maintaining posture, and for spatial orientation
	Medulla oblongata	Its tracts relay signals between spinal cord and pons; its reflex centers help control heart rate, adjustments in blood vessel diameter, respiratory rate, coughing, other vital functions
Spinal Cord		Makes reflex connections for limb movements. Its tracts connect brain, peripheral nervous system

*The reticular formation extends from the spinal cord to the cerebral cortex.

Review Questions

1. Explain the difference between a sensory neuron, an interneuron, and a motor neuron.
2. What are the functional zones of a motor neuron?
3. Define an action potential.
4. What is a synapse? Explain the difference between an excitatory and an inhibitory synapse.
5. Explain what happens during synaptic integration.
6. What is a reflex? Describe what happens during a stretch reflex.
7. Distinguish between the following:
   a. neurons and nerves
   b. somatic system and autonomic system
   c. parasympathetic and sympathetic nerves

Self-Quiz *Answers in Appendix V*

1. The nervous system senses, interprets, and issues commands for responses to _____.
2. A neuron responds to adequate stimulation with _____, a type of self-propagating signal.
3. When action potentials arrive at a synapse between a neuron and another cell, they stimulate the release of molecules of a _____ that diffuse over to that cell.
4. In the simplest kind of reflex, _____ directly signal _____, which act on muscle cells.
   a. sensory neurons; interneurons
   b. interneurons; motor neurons
   c. sensory neurons; motor neurons
   d. motor neurons; sensory neurons
5. The accelerating flow of _____ ions through gated channels across the membrane triggers an action potential.
   a. potassium
   b. sodium
   c. hydrogen
   d. a and b are correct
6. _____ nerves slow down the body overall and divert energy to housekeeping tasks; _____ nerves slow down housekeeping tasks and increase overall activity during times of heightened awareness, excitement, or danger.
   a. Autonomic; somatic
   b. Sympathetic; parasympathetic
   c. Parasympathetic; sympathetic
7. Match each of the following central nervous system regions with some of its functions.

____ spinal cord	a. receives sensory input, integrates it with stored information, coordinates motor responses
____ medulla oblongata	b. monitors internal organs and related behavior (e.g., hunger)
____ hypothalamus	c. governs emotions
____ limbic system	d. coordinates reflexes
____ cerebral cortex	e. makes reflex connections for limb movements, internal organ activity

Critical Thinking

1. In some cases of ADD (attention deficit disorder) the impulsive, erratic behavior can be normalized with drugs that *stimulate* the central nervous system. Explain this finding in terms of neurotransmitter activity in the brain.
2. Meningitis is an inflammation of the membranes that cover the brain and spinal cord. Diagnosis involves making a "spinal tap" (lumbar puncture) and analyzing a sample of cerebrospinal fluid for signs of infection. Why analyze this fluid and not blood?
3. In newborns and premature babies, the blood–brain barrier is not fully developed. Explain why this might be reason enough to pay careful attention to their diet.
4. In PET scans, red areas are brain regions that are most active, while blue, yellow, and green areas are least active. Figure 13.24 shows PET scans of normal brain activity (left) and (right) of the brain of a person while using cocaine. The frontal lobes of the brain hemispheres are toward the top of the scans. Their neurons play major roles in reasoning and other intellectual functions. Looking at these scan images, how do you suppose cocaine may affect mental functioning?
5. Research now demonstrates that new neurons can form in the adult brain, although slowly. Based on your reading in this chapter, name some diseases for which the ability to grow new brain neurons might be helpful.

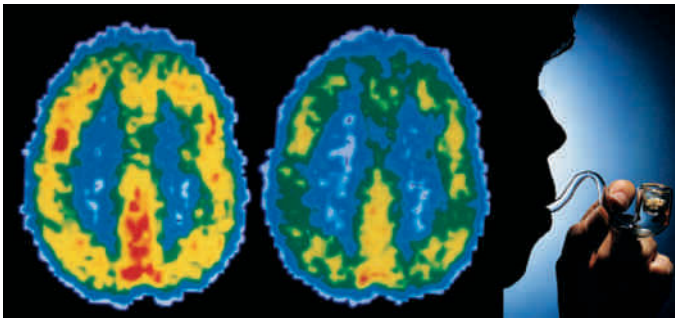


Figure 13.24 **Crack cocaine has major effects on the brain.**

EXPLORE ON YOUR OWN

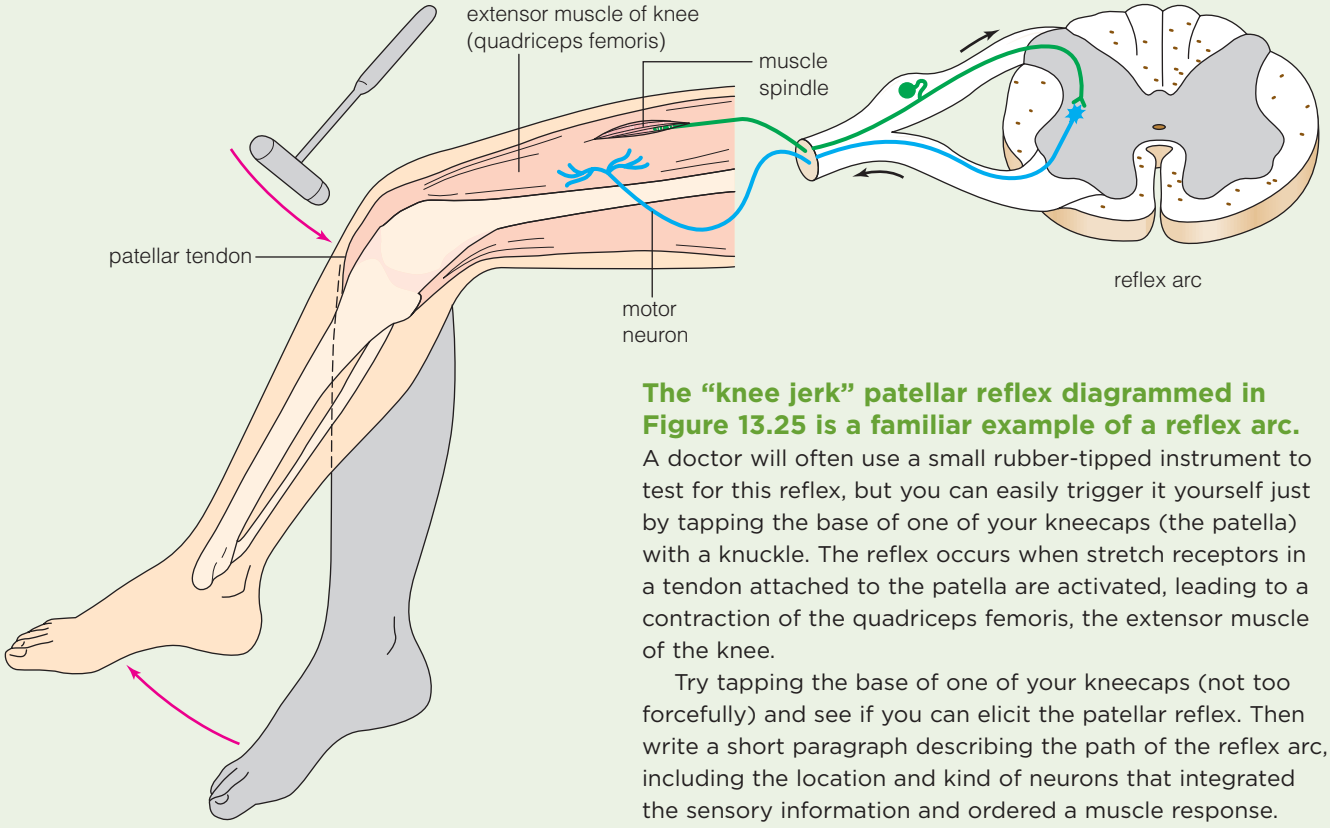


Figure 13.25 **The patellar reflex is an example of a reflex arc.**

The "knee jerk" patellar reflex diagrammed in Figure 13.25 is a familiar example of a reflex arc. A doctor will often use a small rubber-tipped instrument to test for this reflex, but you can easily trigger it yourself just by tapping the base of one of your kneecaps (the patella) with a knuckle. The reflex occurs when stretch receptors in a tendon attached to the patella are activated, leading to a contraction of the quadriceps femoris, the extensor muscle of the knee.

Try tapping the base of one of your kneecaps (not too forcefully) and see if you can elicit the patellar reflex. Then write a short paragraph describing the path of the reflex arc, including the location and kind of neurons that integrated the sensory information and ordered a muscle response.

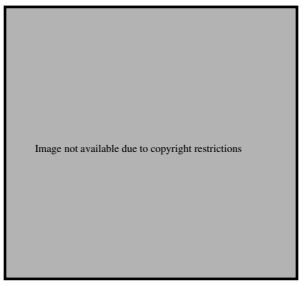
Sensory Systems

14

IMPACTS, ISSUES

Private Eyes

DETERMINED terrorists. Cagey identity thieves hoping to get your social security number or a bank PIN. Is there any kind of "foolproof" security against these threats? Governmental agencies, many businesses, some airports, and even schools and hospitals are hoping that biometric identification technology will come close.



Biometrics measures data about some aspect of human physical makeup, such as digital fingerprints or individual patterns in the retina or iris of the eyes. One of the most reliable methods, iris scanning, relies on the spokelike arrangement of smooth muscle fibers in the iris, the colored surface part of the eyes. Like fingerprints, each person's iris pattern is different from that of every other human on Earth.

For iris scanning to be a solid identity check, each person's iris pattern must first be recorded digitally and entered into an electronic database. Someone who later wants to gain entry to a secure location—or maybe just withdraw money from an ATM—looks into a scanning device that can instantly compare their eyes' iris pattern with the patterns stored in the database. Advocates and manufacturers of iris scanners say that the technology is 99 percent foolproof.

Where might an iris database come from? A number of governments are considering requiring travelers to provide an "iris print" when applying for a passport or visa, or even when buying a ticket for travel. Your bank could iris-print you when you open an account. Employers might require potential employees to allow an iris print as part of the job application process. Some already do.

Iris scanning is a technological means for obtaining identity information. It takes advantage of one feature of a powerful natural information gathering device, the human eye. In this chapter we look at the biological role of the eyes, ears, and other structures that form our sensory systems. These systems are a major means by which the brain obtains information from both inside and outside the body—information that it may use to help manage the body's biological affairs.

LINKS TO EARLIER CONCEPTS

- Building on our discussion of the nervous system in Chapter 13, we now explore how sensory receptors and nerves detect and convey information to the brain.
- You will draw on what you have learned about action potentials, neurotransmitters, synapses between neurons and other cells, and nerves (13.2–13.6).
- You will also learn more about how the brain processes sensory input of all kinds (13.9).

KEY CONCEPTS

Sensory Receptors and Pathways

Different kinds of sensory receptors detect different types of stimuli. When signals from sensory systems are decoded in the brain, we become aware of sights, sounds, odors, painful stimuli, and other sensations. Section 14.1

Somatic Senses

Receptors found at more than one location in the body produce somatic (body) sensations such as touch, pressure, temperature, and pain. Section 14.2

Special Senses

Receptors for the special senses detect chemicals (taste and smell), light (vision), sound waves (hearing), and changes in the body's position (balance). Sections 14.3–4.9

Disorders of the Ears and Eyes

Sections 14.7, 14.10

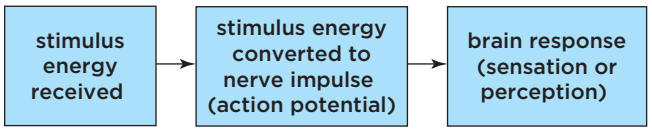
How Would You Vote?

Iris scanning and other biometric identification systems are coming into wider use. Some people are concerned that the technologies may be abused. As one example, they worry that biometric data could be used to discriminate against non-citizens. Do you favor laws that allow employers and others to collect the information required for iris scanning—and to be protected from liability if the scans were misused? See CengageNOW for details, then vote online.

14.1 Sensory Receptors and Pathways

- **Sensory systems notify the brain and spinal cord of specific changes inside and outside the body.**
- **Links to Action potentials 13.2, Information pathways 13.5, Sensory areas of the brain 13.9**

In a **sensory system**, a stimulus activates receptors, which convert the stimulus to a nerve impulse—an action potential—that travels to the brain. There it may trigger a sensation or perception:



Technically, a **stimulus** (plural: stimuli) is a form of energy that activates receptor endings of a sensory neuron. That energy is converted to the electrochemical energy of action potentials—the nerve impulses by which the brain receives information and sends out commands in response. The brain's basic response is a **sensation**, which is conscious awareness of a stimulus. Higher-level processing results in a **perception**—an understanding of what the sensation means.

A

There are six main categories of sensory receptors. They reflect the type of stimulus that each kind of receptor detects. **Mechanoreceptors** detect changes in pressure, position, or acceleration. **Thermoreceptors** respond to heat or cold. **Nociceptors** (pain receptors) detect damage to tissues. **Chemoreceptors** detect chemicals dissolved in the fluid around them. **Osmoreceptors** detect changes in water volume (solute concentration) in a body fluid. **Photoreceptors** detect visible light (Table 14.1).

TABLE 14.1 Major Categories of Sensory Receptors

Category	Examples	Stimulus
Mechanoreceptors		
Touch, pressure	Certain free nerve endings and Merkel discs in skin	Mechanical pressure against body surface
Baroreceptors	Carotid sinus (artery)	Pressure changes in fluid (blood) that bathes them
Stretch	Muscle spindle in skeletal muscle	Stretching of muscle
Auditory	Hair cells in organ inside ear	Vibrations (sound waves)
Balance	Hair cells in organ inside ear	Fluid movement
Thermoreceptors	Certain free nerve endings	Change in temperature (heating, cooling)
Nociceptors (pain receptors)*	Certain free nerve endings	Tissue damage (e.g., distortions, burns)
Chemoreceptors		
Internal chemical sense	Carotid bodies in blood vessel wall	Substances (O_2, CO_2, etc.) dissolved in extracellular fluid
Taste	Taste receptors of tongue	Substances dissolved in saliva, etc.
Smell	Olfactory receptors of nose	Odors in air, water
Osmoreceptors	Hypothalamic osmoreceptors	Change in water volume (solute concentration) of fluid they are in contact with
Photoreceptors		
Visual	Rods, cones of eye	Wavelengths of light

*Extremely intense stimulation of any sensory receptor also may be perceived as pain.

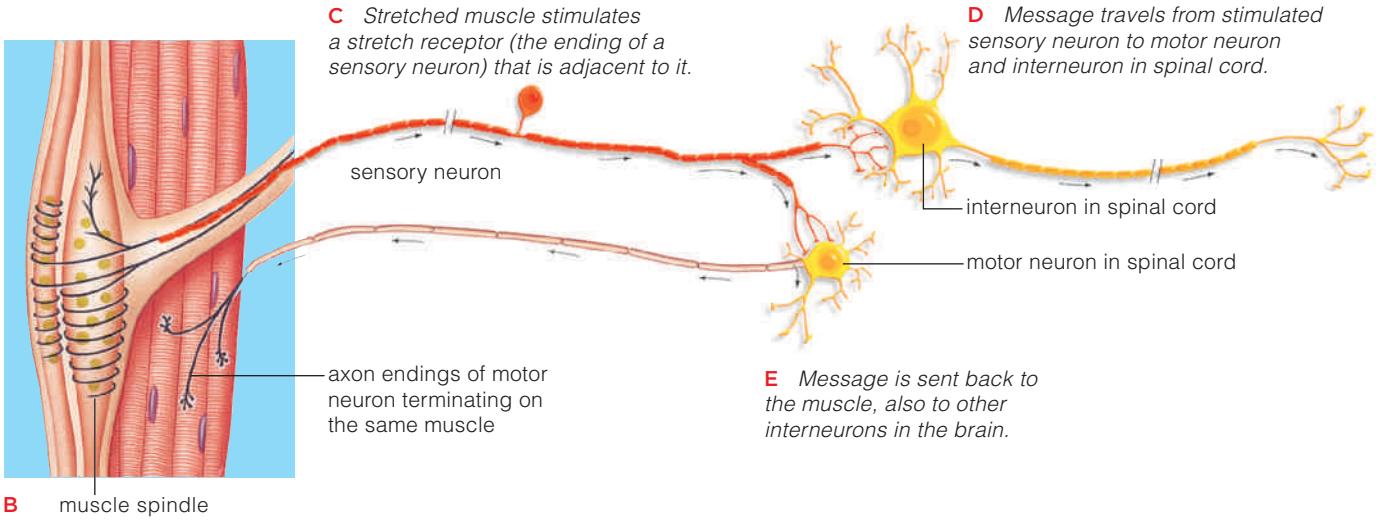


Figure 14.1 Signals from stretch receptors in muscles provide an example of a sensory pathway. This diagram depicts the path of impulses from receptors called muscle spindles to the spinal cord and brain.

Regardless of their differences, all sensory receptors convert the stimulus to nerve impulses (action potentials).

Nerve impulses that move along sensory neurons are all the same. So how does the brain know what sort of sensory event has occurred? It assesses *which* nerves are carrying nerve impulses, the *frequency* of the nerve impulses on each axon in the nerve, and the *number* of axons that responded to the stimulus. Let's consider the steps involved in this processing.

First, specific sensory areas of the brain can interpret action potentials only in certain ways. That is why you "see stars" when your eye is poked, even in the dark. The mechanical pressure on photoreceptors in the eye triggers signals that travel along the optic nerve. The brain always interprets signals from an optic nerve as "light." In fact, as you will read in Section 14.2, the brain has a detailed map of the sources of different sensory stimuli.

Second, a strong signal makes receptors fire nerve impulses more often and longer than a weak one does. So, while the same receptor in your ear can detect the sounds of a whisper and a screech, the brain senses the difference through variations in the signals each sound produces.

Third, the stronger a stimulus, the more sensory receptors respond. Gently tap a spot of skin on your arm and you activate only a few touch receptors. Press hard on the same spot and you activate more. The increase translates into nerve impulses in many sensory neurons at once. Your brain interprets the combined activity as an increase in the intensity of the stimulus.

In some cases the frequency of nerve impulses (how often they occur in a given period of time) slows or stops even when the stimulus continues at constant strength. For instance, after you put on a T-shirt, you quickly become only dimly aware of its pressure against your skin. This diminishing response to an ongoing stimulus is called **sensory adaptation**.

Some mechanoreceptors adapt rapidly to a sustained stimulus and only signal when it starts and stops. Other receptors adapt slowly or not at all; they help the brain monitor particular stimuli all the time.

The gymnast in Figure 14.1*a* is holding his position in response to signals from his skin, skeletal muscles, joints, tendons, and ligaments. For example, how fast and how far a muscle stretches depends on activation of stretch receptors in muscle spindles (Figure 14.1*b* and Section 13.5). By responding to changes in the length of muscles, his brain helps him maintain his balance and posture.

In the rest of this chapter we explore examples of the body's sensory receptors. Receptors that are found at more than one location in the body contribute to somatic ("of the body") sensations. Other receptors are restricted to sense organs, such as the eyes or ears, and contribute to what are called the "special senses."

Take-Home Message

What are the basic features of sensory systems and sensory pathways?

- A sensory system has sensory receptors for specific stimuli. It also has nerve pathways that conduct information from receptors to the brain, and brain regions that receive and process the information.
- The brain senses a stimulus based on which nerves carry the incoming signals, the frequency of nerve impulses traveling along each axon in the nerve, and the number of axons that have been recruited.

14.2 Somatic Sensations

- **Somatic sensations start with receptors near the body surface, in skeletal muscles, and in the walls of soft internal organs.**
- **Links to Skin structure 4.9, Inflammation 9.4, Somatosensory cortex 13.9**

Receptors for somatic senses are located in different parts of the body. **Somatic sensations** come about when signals from receptors reach the **somatosensory cortex** in the cerebrum There, interneurons are organized like maps of individual parts of the body surface, just as they are for the motor cortex. The largest areas of the map correspond to body parts where sensory receptors are the most dense. These body parts, including the fingers, thumbs, and lips, have the sharpest sensory acuity and require the most intricate control (Figure 14.2).

Receptors near the body surface sense touch, pressure, and more

There are thousands of sensory receptors in your skin, providing information about touch, pressure, cold, warmth, and pain (Figure 14.3). Places with the most sensory receptors, such as the fingertips and the tip of the tongue, are the most sensitive. Less sensitive areas, such as the back of the hand, have many fewer receptors.

Several types of **free nerve endings** in the epidermis and many connective tissues detect touch, pressure, heat, cold, or pain. These nerve endings are simple structures. Basically, they are thinly myelinated or unmyelinated ("naked") dendrites of sensory neurons. One type coils around hair follicles and detects the movement of the hair inside. That might be how, for instance, you become aware that a spider is gingerly making its way across your arm. Free nerve endings sensitive to chemicals such as histamine may be responsible for the sensation of itching.

Encapsulated receptors are enclosed in a capsule of epithelial or connective tissue and are named for the biologist who discovered them. One type, Merkel's discs, adapt slowly and are the most important receptors for steady touch. In the lips, fingertips, eyelids, nipples, and genitals there are many Meissner's corpuscles, which are sensitive to light touching. Deep in the dermis and in joint capsules are Ruffini endings, which respond to steady touching and pressure.

The Pacinian corpuscles widely scattered in the skin's dermis are sensitive to deep pressure and vibrations. They also are located near freely movable joints (like shoulder and hip joints) and in some soft internal organs.

Sensing limb motions and changes in body position relies on mechanoreceptors in skin, skeletal muscles, joints, tendons, and ligaments. Examples include the stretch receptors of muscle spindles described in Section 14.1.

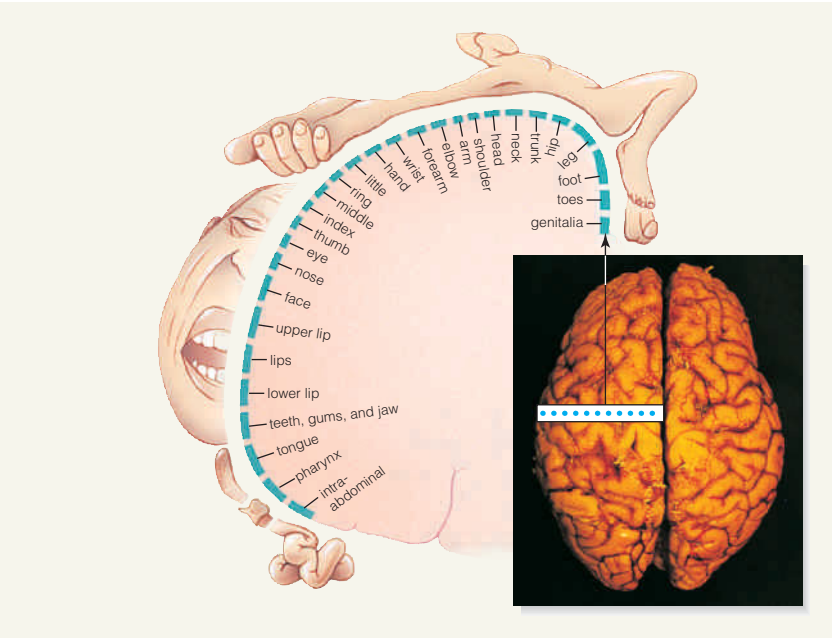


Figure 14.2 Animated! The somatosensory cortex "maps" body parts. This strip of cerebral cortex is a little wider than an inch (2.5 centimeters), from the top of the head to just above the ear.

Pain is the perception of bodily injury

Pain is perceived injury to some body region. The most important pain receptors are free nerve endings called **nociceptors** (from the Latin word *nocere*, "to do harm"). Several million of them are distributed throughout the skin and in internal tissues, except for the brain.

Somatic pain starts with nociceptors in skin, skeletal muscles, joints, and tendons. One group is the source of prickling pain, like the jab of a pin when you stick your finger. Another contributes to itching or the feeling of warmth caused by chemicals such as histamine. Sensations of *visceral pain*, which is associated with internal organs, are related to muscle spasms, muscle fatigue, too little blood flow to organs, and other abnormal conditions.

When cells are damaged, they release chemicals that activate neighboring pain receptors. The most potent are bradykinins. They open the floodgates for histamine, prostaglandins, and other substances associated with inflammation (Section 9.4).

When signals from pain receptors reach interneurons in the spinal cord, the interneurons release a chemical called substance P. One result is that the hypothalamus and midbrain send signals that call for the release of endorphins and enkephalins. These are natural opiates (morphinelike substances) that, like morphine derived

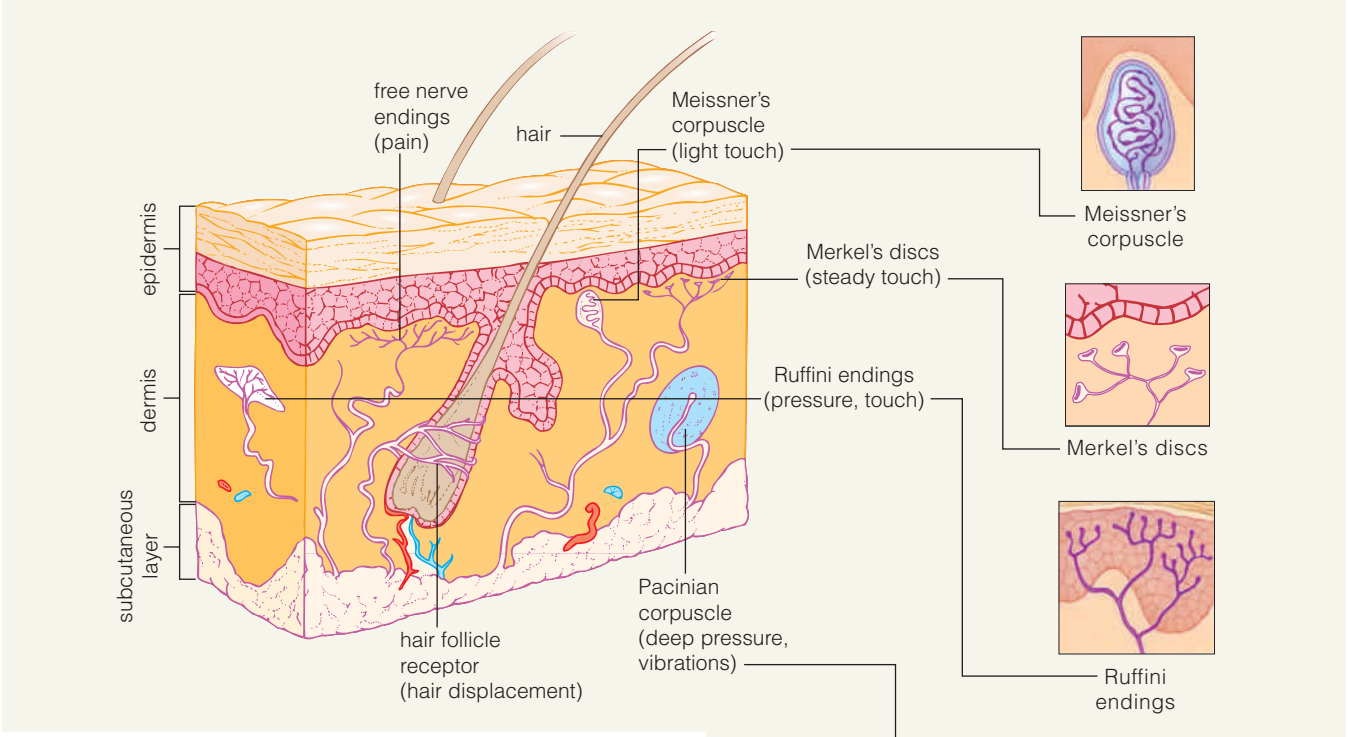


Figure 14.3 Animated! **The skin contains a variety of sensory receptors.**

from opium poppies, reduce our ability to perceive pain. Morphine, hypnosis, and natural childbirth techniques may also stimulate the release of these natural opiates.

Referred pain is a matter of perception

A person's perception of pain often depends on the brain's ability to identify the affected tissue. Get hit in the face with a snowball and you "feel" the contact on facial skin. However, sensations of pain from some internal organs may be wrongly projected to part of the skin surface. This response, called *referred pain*, is related to the way the nervous system is built. Sensory information from the skin and from certain internal organs may enter the spinal cord along the same nerve pathways, so the brain can't accurately identify their source. For example, as shown in Figure 14.4, a heart attack can be felt as pain in skin above the heart and along the left shoulder and arm.

Referred pain is not the same as the *phantom pain* reported by amputees. Often they sense the presence of a missing body part, as if it were still there. In some undetermined way, sensory nerves that were severed during the amputation continue to respond to the trauma. The brain projects the pain back to the missing part, past the healed region.

Take-Home Message

Which sensors detect somatic sensations?

- Free nerve endings and encapsulated receptors detect somatic sensations—touch, pressure, heat and cold, pain, limb motions, and changes in body position.

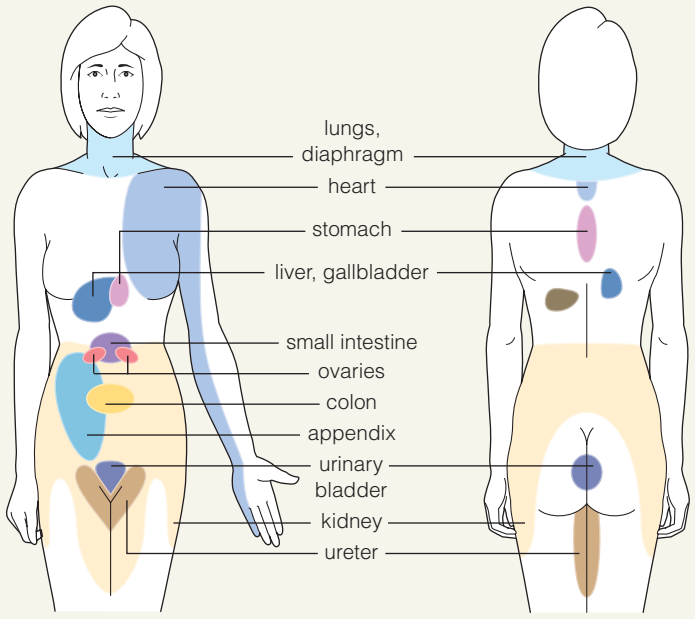


Figure 14.4 Animated! **In referred pain, the brain projects a sensation from an internal organ to an area of the skin.**

14.3 Taste and Smell: Chemical Senses

- **Sensory receptors sensitive to chemicals are responsible for the special senses of taste and smell.**
- **Links to Facial bones 5.3, Sensory centers in the forebrain 13.8, Sensory areas of the parietal lobe 13.9**

Taste and smell are *chemical* senses. They begin at chemoreceptors, which are activated when they bind a chemical that is dissolved in fluid around them. Although these receptors wear out, new ones replace them. In both cases, sensory information travels from the receptors through the thalamus and on to the cerebral cortex, where perceptions of the stimulus form. The input also travels to the limbic system, which can integrate it with emotional states and stored memories.

Gustation is the sense of taste

The technical term for taste is *gustation* (as in gusto!). Sensory organs called taste buds hold our **taste receptors** (Figure 14.5). You have about 10,000 taste buds scattered over your tongue, the roof of your mouth (the palate), and your throat.

A taste bud has a pore through which saliva and other fluids in the mouth contact the surface of receptors. The stimulated receptor in turn stimulates a sensory neuron, which conveys the message to centers in the brain where the stimulus is interpreted. Every perceived taste is some combination of five primary tastes: sweet, sour, salty, bitter, and *umami* (the brothy or savory taste we associate with aged cheese or meats).

The flavors of most foods are some combination of the five basic tastes, plus information from olfactory receptors in the nose. Simple as this sounds, scientists now know that our taste sense involves complex genetic mechanisms. *Science Comes to Life* on the facing page examines some of these findings.

The olfactory element of taste is extremely important. In addition to odor molecules in inhaled air, molecules of volatile chemicals are released as you chew food. These waft up into the nasal passages. There, the "smell" inputs contribute to the perception of a smorgasbord of complex flavors. This is why anything that dulls your sense of smell—such as a head cold—also seems to diminish food's flavor.

Olfaction is the sense of smell

Olfactory receptors (Figure 14.6) detect water-soluble or easily vaporized substances. When odor molecules bind to receptors on olfactory neurons in cells of the nose's olfactory epithelium, the resulting nerve impulse travels directly to olfactory bulbs in the frontal area of the brain. There, other neurons forward the message to a center in the cerebral cortex, which interprets it as "fresh bread," "pine tree," or some other substance.

From an evolutionary perspective, olfaction is an ancient sense—and for good reason. Food, potential mates, and predators give off substances that can diffuse through air (or water) and so give clues or warnings of their whereabouts. Even with our rather insensitive sense of smell, we humans have about 10 million olfactory receptors in patches of olfactory epithelium in the upper nasal passages.

Just inside your nose, next to the vomer bone (Section 5.3), is a *vomeronasal organ*, or "sexual nose." (Some other mammals also have one.) Its receptors detect pheromones, which are signaling chemicals that influence social interactions in many animal species. Pheromones can affect the behavior—and maybe the physiology—of other individuals. For instance, one or more pheromones in the sweat of females may account for

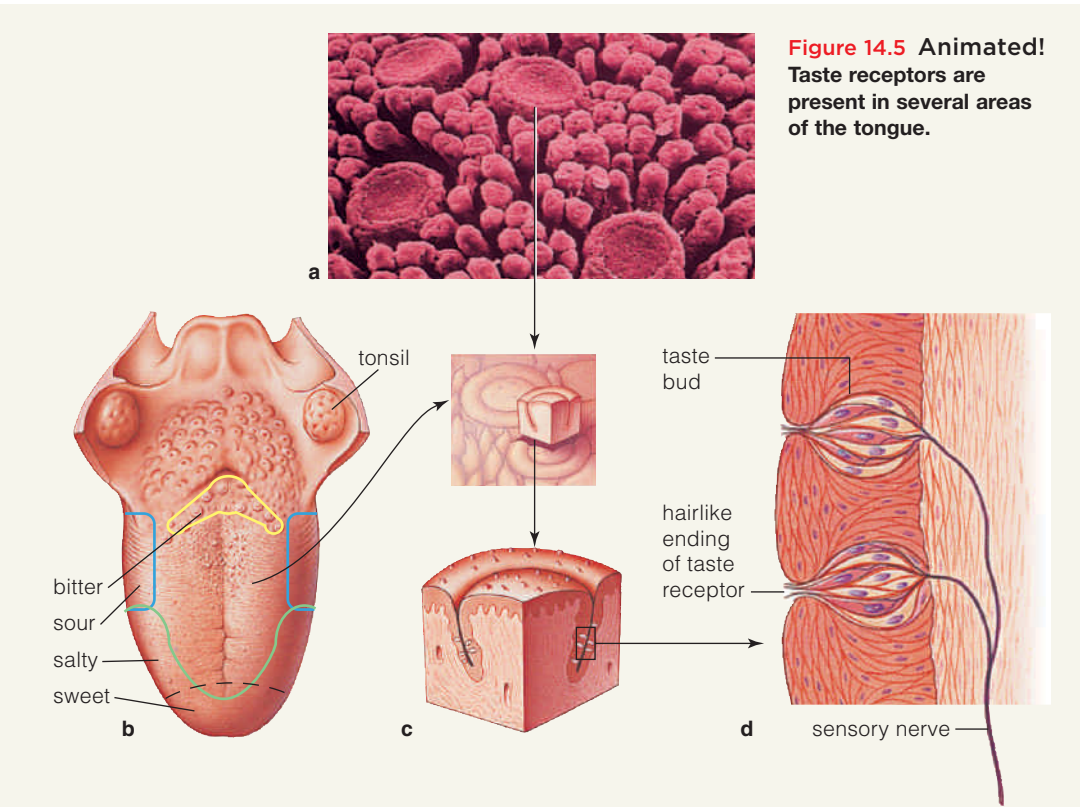


Figure 14.5 Animated! **Taste receptors are present in several areas of the tongue.**

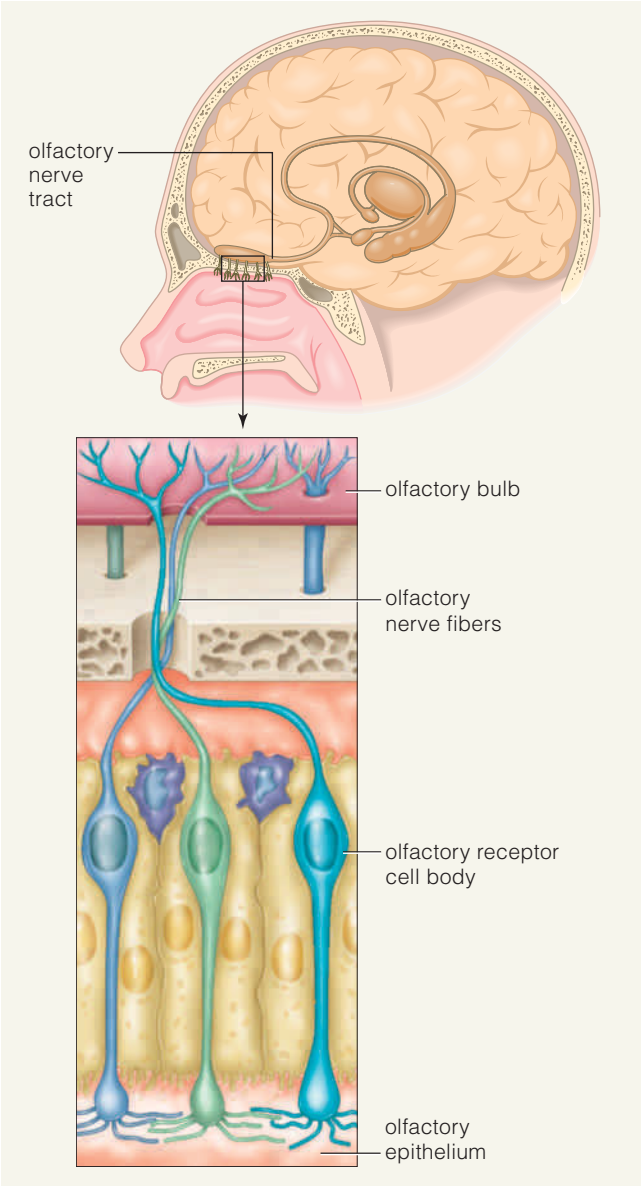


Figure 14.6 **Animated! A sensory pathway leads from olfactory receptors in the nose to primary receiving centers in the brain.**

the common observation that women of reproductive age who are in regular, close contact with one another often come to have their menstrual periods on a similar schedule. Many scientists are not convinced that pheromones operate in humans, however, and debate on the topic is always lively!

Take-Home Message

How do humans sense tastes and odors?

- Taste depends on receptors in taste buds in the tongue. The receptors bind molecules dissolved in fluid. The five primary tastes are sweet, sour, salty, bitter, and *umami*.
- Olfaction (smell) relies on receptors in patches of epithelium in the upper nasal passages. Neural signals along olfactory neurons travel directly to the olfactory bulbs in the brain.

14.4 Tasty Science

Taste buds help make eating one of life's pleasures. So how do the sensory receptors in taste buds distinguish different tastes?

Each taste category such as sweet or sour is associated with particular "tastant" molecules. When you eat food, however, which taste category (or combination of them) you ultimately perceive depends on the nature of the triggering chemical and on how it is processed by the receptor. In each case, some event causes the receptor cell to release a neurotransmitter that triggers nerve impulses in a nearby sensory neuron.

For example, when you taste "salt," the receptor cell's response is due to the flow of Na^+ through sodium ion channels in its plasma membrane. Acidic tastant molecules release hydrogen ions that block certain ion channels. The blockage causes a receptor to respond with a "sour" message.

Cells that detect bitter substances may have receptors sensitive to as many as 100 different trigger tastants. This diversity probably is a survival tool. Many toxic chemicals (including plant alkaloids such as nicotine and morphine) taste bitter, an adaptation that may help protect us from ingesting dangerous substances. Familiar bitter-tasting alkaloids are caffeine and quinine, the mouth-puckering tastant in tonic water. And while many "sweet" tastants are sugars, others are amino acids or alcohols. Both bitter and sweet tastes are detected by specific proteins inside the receptor. The taste category called *umami* also is triggered by amino acids, notably glutamate. Its name was bestowed by the Japanese researcher who identified it.

Each taste bud has receptors that can respond to tastants in at least two—and in some cases all five—of the taste classes. Various tastants commingle (together with odors) into our perceptions of countless flavors.

Not all taste receptors are equally sensitive. "Bitter" ones tend to be extremely sensitive and so can detect tiny amounts of bitter tastants—and thus potential poisons. Sour tastants are needed in higher concentrations before the stimulus registers. Even higher levels of sweet and salty substances must be present for the stimulus to register. So why can relatively small amounts of artificial sweeteners so readily sweeten foods? Their molecular characteristics make them 150 times (aspartame) to more than 600 times (saccharin) as potent as plain sucrose.

14.5 Hearing: Detecting Sound Waves

- **The sense of hearing depends on structures in the ear that trap and process sounds traveling through air.**

Sounds are waves of compressed air. They are a form of mechanical energy. If you clap your hands, you force out air molecules, creating a low-pressure state in the area they vacated. The pressure variations can be depicted as a wave form, and the *amplitude* of its peaks corresponds to loudness. The *frequency* of a sound is the number of wave cycles per second. Each cycle extends from the start of one wave to the start of the next (Figure 14.7).

The sense of hearing starts with vibration-sensitive mechanoreceptors deep in the ear. When sound waves travel down the ear's auditory canal, they reach a membrane and make it vibrate. The vibrations cause a fluid inside the ear to move, the way water in a waterbed sloshes. In your ear, the moving fluid bends the tips of hairs on mechanoreceptors. With enough bending, the end result will be action potentials sent to the brain, where they are interpreted as sound.

The ear gathers and sends "sound signals" to the brain

Each of your ears consists of three regions (Figure 14.8*a*), each with its own role in hearing. The *outer ear* provides a pathway for sound waves to enter the ear, setting up vibrations. The vibrations are amplified in the *middle ear*. In the *inner ear*, vibrations of different sound frequencies are "sorted out" as they stimulate different patches of receptors. Inner ear structures include *semicircular canals*, which are involved in balance—the topic of Section 14.6. It also contains the coiled **cochlea** (KAHK-lee-uh), where key events in hearing take place. As you'll now read, a coordinated sequence of events in the ear's various regions provides the brain with the auditory input it can interpret to give us a hearing sense.

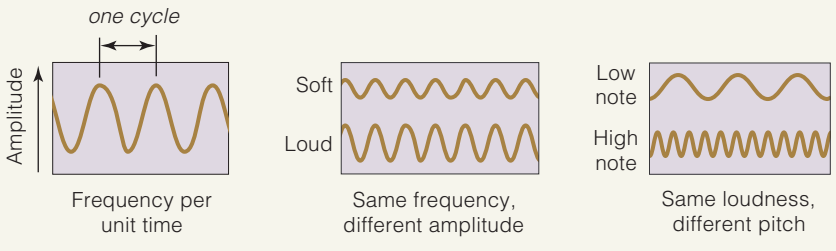


Figure 14.7 Animated! Sound travels in the form of a wave.

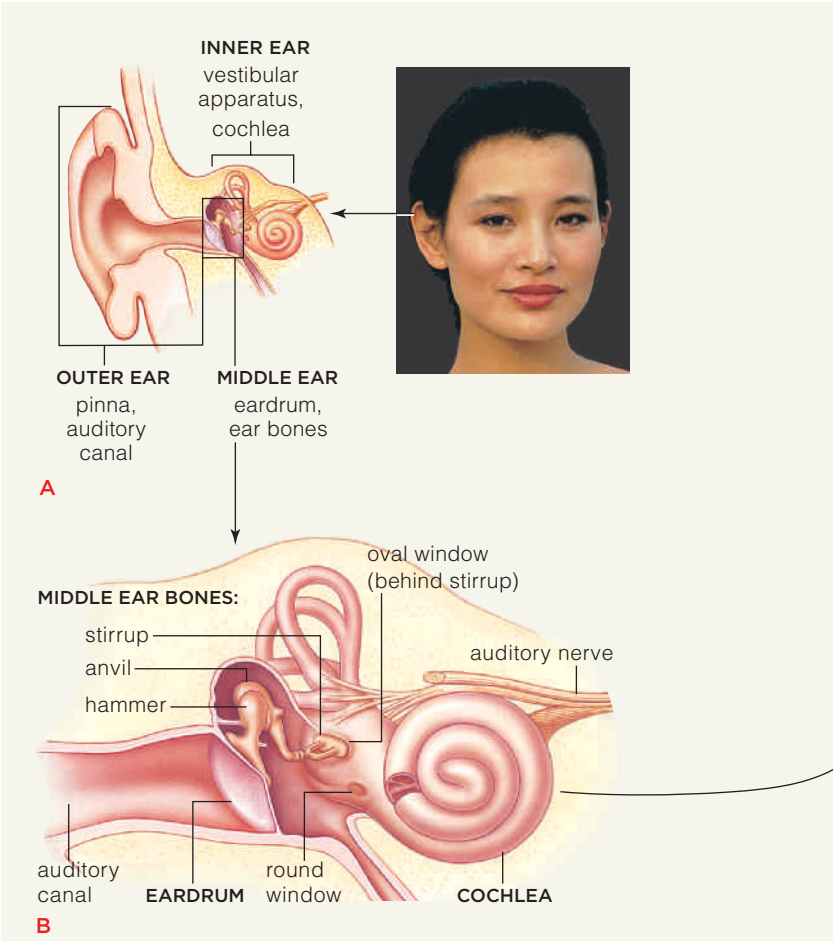
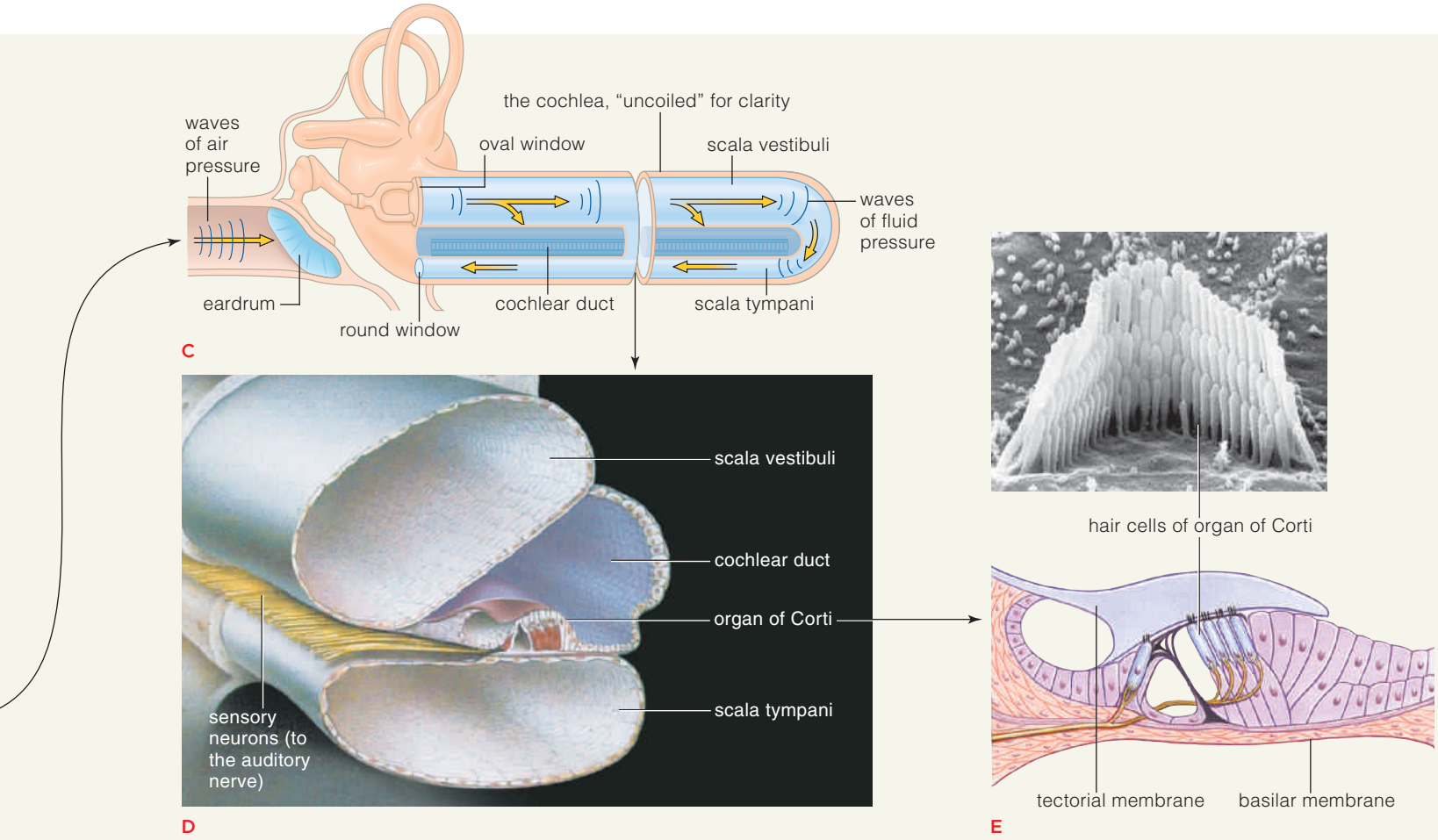


Figure 14.8 Animated! The ear gathers sound waves and converts them to nerve impulses.

Sensory hair cells are the key to hearing

Hearing begins when the outer ear's fleshy flaps collect and channel sound waves through the auditory canal to the **tympanic membrane** (the eardrum). Sound waves cause the membrane to vibrate, which in turn causes vibrations in a leverlike array of three tiny bones of the middle ear: the *malleus* ("hammer"), *incus* ("anvil"), and stirrup-shaped *stapes*. The vibrating bones transmit their motion to the *oval window*, an elastic membrane over the entrance to the cochlea. The oval window is much smaller than the tympanic membrane. So, as the middle-ear bones vibrate against its small surface with the full energy that struck the tympanic membrane, the force of the original vibrations is amplified.

Now the action shifts to the cochlea. If we could uncoil the cochlea, we would see that a fluid-filled chamber folds around an inner *cochlear duct* (Figure 14.8*c*). Each "arm" of the outer chamber functions as a separate compartment (the *scala vestibuli* and



scala tympani, respectively). The amplified vibrations of the oval window create pressure waves in the fluid within the chambers. In turn, these waves are transmitted to the fluid in the cochlear duct. On the floor of the cochlear duct is a *basilar membrane*, and resting on the basilar membrane is a specialized **organ of Corti**, which includes sensory **hair cells**.

Slender projections at the cell tips rest against an overhanging **tectorial** ("rooflike") **membrane**, which is not a membrane at all but a jellylike structure. When pressure waves in the cochlear fluid vibrate the basilar membrane, its movements can press hair cell projections against the tectorial membrane so that the projections bend like brush bristles. Affected hair cells release a neurotransmitter, triggering action potentials in neurons of the auditory nerve, which carries them to the brain.

Different sound frequencies cause different parts of the basilar membrane to vibrate—and, accordingly, to bend different groups of hair cells. Apparently, the total number of hair cells stimulated in a given region determines the loudness of a sound. The perceived tone or "pitch" of a sound depends on the frequency of the vibrations that excite different groups of hair cells. The higher the frequency, the higher the pitch.

Eventually, pressure waves moving through the cochlea push against the *round window*, a membrane at the far end of the cochlea. As the round window bulges outward toward the air-filled middle ear, it serves as a "release valve" for the force of the waves. Air also moves through an opening in the middle ear into the *eustachian tube*. This tube runs from the middle ear to the throat (pharynx), permitting air pressure in the middle ear to be equalized with the pressure of outside air. When you change altitude (say, during a plane trip), this equalizing process makes your ears pop.

Sounds such as amplified music and the thundering of jet engines are so intense that long-term exposure to them can permanently damage the inner ear (Section 14.7). Evolution has not equipped hair cells of the human ear to cope with such extremely loud, modern-day sounds.

Take-Home Message

How does the sense of hearing work?

- Hearing relies on mechanoreceptors called hair cells, which are attached to membranes inside the cochlea of the inner ear.
- Pressure waves generated by sound cause membrane vibrations that bend hair cells. The bending produces nerve impulses in neurons of the auditory nerve.

14.6 Balance: Sensing the Body's Natural Position

- **A balance sense helps the brain assess changes from the body's natural or "equilibrium" position.**

Our sense of balance relies partly on messages from receptors in our eyes, skin, and joints. In addition, there are organs of equilibrium located in a part of the inner ear called the **vestibular apparatus**. This "apparatus" is a closed system of sacs and three fluid-filled **semicircular canals** (Figure 14.9). The canals are positioned at right angles to one another, corresponding to the three planes of space. Inside them, some sensory receptors monitor dynamic equilibrium—that is, rotating head movements. Elsewhere in the vestibular apparatus are the receptors that monitor the straight-line movements of acceleration and deceleration.

The receptors attuned to rotation are on a ridge of the swollen base of each semicircular canal (Figure 14.10). As in the cochlea, these receptors are sensory hair cells; their delicate hairs project up into a jellylike *cupula* ("little cap"). When your head rotates horizontally or vertically or tilts diagonally, fluid in a canal corresponding to that direction moves in the opposite direction. As the fluid presses against the cupula, the hairs bend. This bending is the first step leading to nerve impulses that travel to the brain—in this case, along the vestibular nerve.

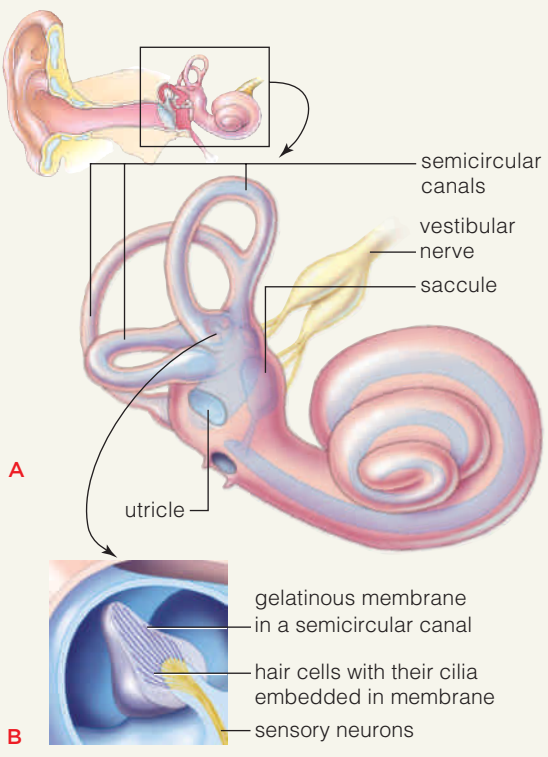


Figure 14.9 Animated! The vestibular apparatus is an organ of equilibrium.

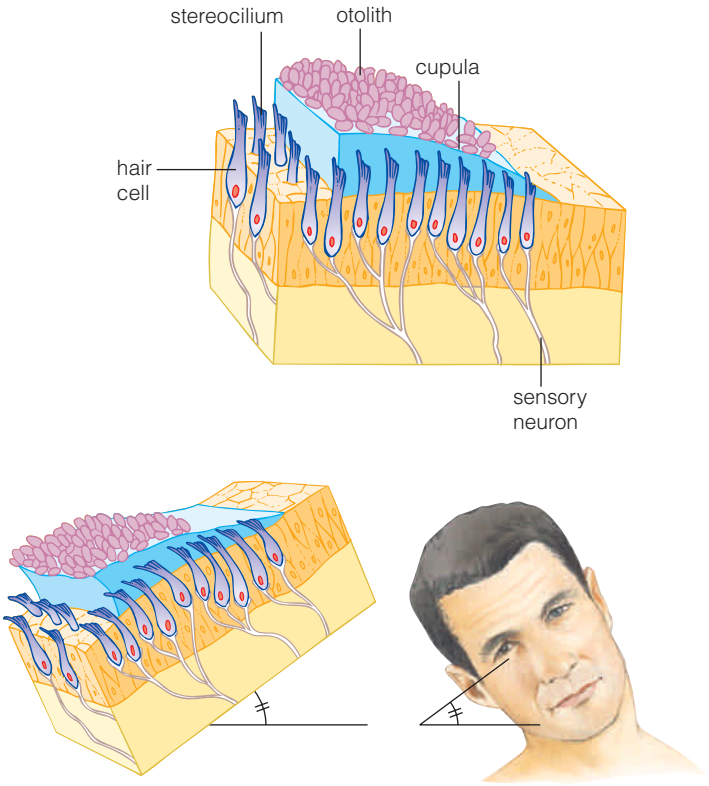


Figure 14.10 Otoliths move in response to gravity when the head tilts.

The head's position in space tracks *static* equilibrium. The receptors attuned to it are located in two fluid-filled sacs in the vestibular apparatus, the utricle and saccule shown in Figure 14.9. Each sac contains an *otolith* organ, which has hair cells embedded in a jellylike "membrane." The material also contains hard bits of calcium carbonate called *otoliths* ("ear stones"). Movements of the membrane and otoliths signal changes in the head's orientation relative to gravity, as well as straight-line acceleration and deceleration. For example, if you tilt your head, the otoliths slide in that direction, the membrane mass shifts, and tips of the hair cells bend (Figure 14.10). The otoliths also press on hair cells if your head accelerates, as when you start running or are riding in an accelerating vehicle.

Nerve impulses from the vestibular apparatus travel to reflex centers in the brain stem. As the signals are processed along with information from your muscles and eyes, the brain orders compensating movements that help you keep your balance when you stand, walk, dance, or move your body in other ways (Figure 14.11).

Figure 14.11 Champion skater Sarah Hughes demonstrates her brain's ability to monitor inputs from her eyes and muscles. Her brain orders adjustments that help her keep her balance while executing a difficult maneuver on the ice.

Motion sickness can result when extreme or continuous motion overstimulates hair cells in the balance organs. It can also be caused by conflicting signals from the ears and eyes about motion or the head's position. If you are prone to motion sickness, you know all too well that nerve impulses triggered by the sensory input can reach a brain center that governs the vomiting reflex.

Take-Home Message

What is the sense of balance?

- Balance is a sense of the natural position for the body or its parts. This sense relies mainly on signals from the vestibular apparatus, a system of fluid-filled canals and sacs in the inner ear.
- The semicircular canals lie at angles that correspond to the three planes of space. Sensory receptors inside them detect rotation, acceleration, and deceleration of the head.
- Otolith organs contain sensory hair cells embedded in a jellylike membrane. Movements of the membrane and otoliths signal changes in the head's orientation relative to gravity, as well as straight-line acceleration and deceleration.

14.7 Disorders of the Ear

Although the hearing apparatus of our ears is remarkably sturdy, a variety of illnesses and injuries can damage it.

Children have short eustachian tubes, so they especially are susceptible to **otitis media**—a painful inflammation of the middle ear that usually is caused by the spread of a respiratory infection such as a cold. An antibiotic is the usual treatment, although resistant infections are now common. In some cases pus and fluid can build up and cause the eardrum to tear. The rupture usually will heal on its own.

Ear infections, taking lots of aspirin, and genetic factors can cause the ringing, whirring, or buzzing in the ears known as **tinnitus**. While the condition is not a serious health threat, it can be extremely annoying.

Deafness is the partial or complete inability to hear. Some people suffer from congenital (inborn) deafness, and in other cases aging, disease, or environmentally caused damage is the culprit. About one-third of adults in the United States will suffer significant hearing loss by the time they are 65. Researchers believe that most cases of this progressive deafness are due to the long-term effects of living in a noisy world.

The loudness of a sound is measured in decibels. A quiet conversation occurs at about 50 decibels. Rustling papers make noise at a mere 20 decibels. The delicate sensory hair cells in the inner ear (Figure 14.12) begin to be damaged when a person is exposed to sounds louder than about 75–85 decibels over long periods. Some MP3 players can crank out sound at well over 100 decibels. At 130 decibels—typical of a rock concert or shotgun blast—permanent damage can occur much more quickly. Protective earwear is a must for anyone who regularly operates noisy equipment or who works around noisy machinery such as aircraft.

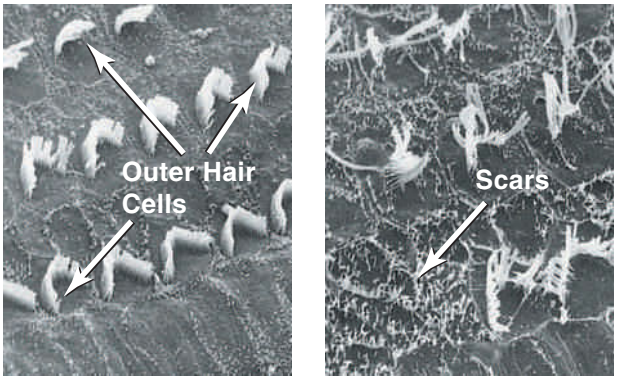


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Figure 14.12 Noise is a danger to the ear's hair cells. (**a**) Healthy sensory hair cells of the inner ear. (**b**) Hair cells damaged by exposure to loud noise.

14.8 Vision: An Overview

- **Vision requires a system of photoreceptors and brain centers that can receive and interpret the patterns of nerve impulses from different parts of the system.**

The sense of **vision** is an awareness of the position, shape, brightness, distance, and movement of visual stimuli. Our **eyes** are sensory organs that contain tissue with a dense array of photoreceptors.

The eye is built to detect light

The eye has three layers (Table 14.2), sometimes called "tunics." The outer layer consists of a sclera and a transparent **cornea**. The middle layer consists mainly of a choroid, ciliary body, and iris. The key feature of the inner layer is the retina (Figure 14.13).

The *sclera* is the dense, fibrous "white" of the eye. It protects most of the eyeball, except for the region formed by the cornea. Moving inward, the thin, darkly pigmented *choroid* lies under the sclera. It prevents light from scattering inside the eyeball and contains most of the eye's blood vessels.

Behind the transparent cornea is the round, pigmented **iris** (after *irid*, which means "colored circle"). The iris has more than 250 measurable features (such as pigments and fibrous tissues). This is why, as you read in the chapter introduction, the iris can be used for identification. Look closely at someone's eye, and you will see a "hole" in the center of the iris. This *pupil* is the entrance for light. When bright light hits the eye, circular muscles in the iris contract and shrink the pupil. In dim light, radial muscles contract and enlarge the pupil.

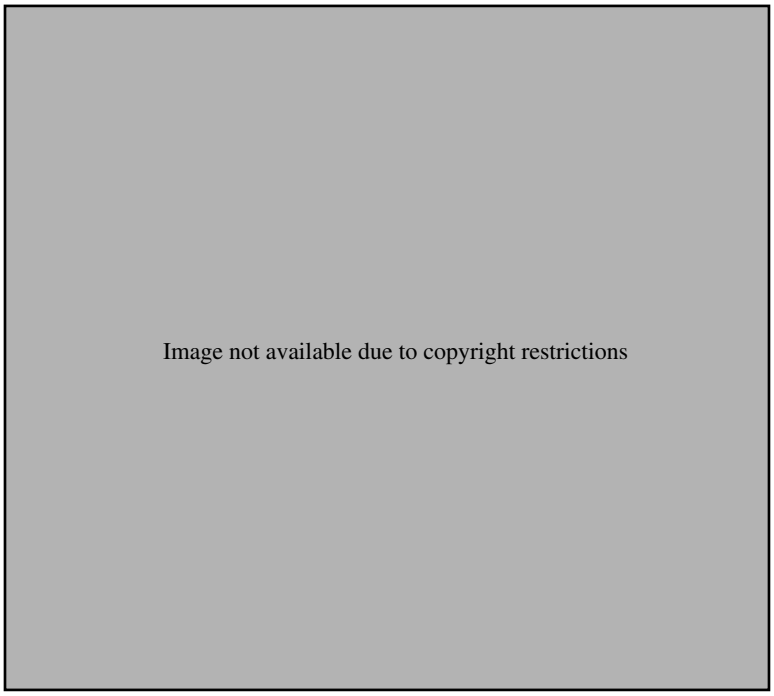


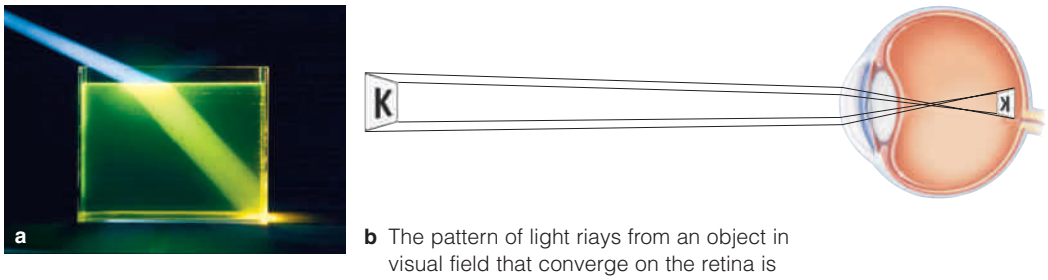
TABLE 14.2 Parts of the Eye

Wall of eyeball	(three layers)
Sensory Tunic (inner layer)	*Retina.* Absorbs, transduces light energy
	Fovea. Increases visual acuity
Vascular Tunic (middle layer)	*Choroid.* Blood vessels nutritionally support wall cells; pigments prevent light scattering
	Ciliary body. Its muscles control lens shape; its fine fibers hold lens upright
	Iris. Adjusting iris controls incoming light
	Pupil. Serves as entrance for light
	Start of optic nerve. Carries signals to brain
Fibrous Tunic (outer layer)	*Sclera.* Protects eyeball
	Cornea. Focuses light
Interior of eyeball	
Lens	Focuses light on photoreceptors
Aqueous humor	Transmits light, maintains pressure
Vitreous body	Transmits light, supports lens and eyeball

Behind the iris is a saucer-shaped **lens**, with onionlike layers of transparent proteins. Ligaments attach the lens to smooth muscle of the *ciliary body*; this muscle functions in focusing light, as we will see shortly. The lens focuses incoming light onto a dense layer of photoreceptor cells behind it, in the retina. A clear fluid, *aqueous humor* (body fluids were once called "humors"), bathes both sides of the lens. A jellylike substance (*vitreous humor*) fills the chamber behind the lens.

The **retina** is a thin layer of neural tissue at the back of the eyeball. It has a pigmented basement layer that covers the choroid. Resting on the basement layer are densely packed photoreceptors that are linked with a variety of neurons. Axons from some of these neurons converge to form the optic nerve at the back of the eyeball. The optic nerve is the trunk line to the thalamus—which sends signals on to the **visual cortex**. The place where the optic nerve exits the eye is a "blind spot" because there are no photoreceptors there.

The surface of the cornea is curved. This means that incoming light rays hit it at different angles and, as they



b The pattern of light riays from an object in visual field that converge on the retina is upside-down and inverted left to right.

Figure 14.14 Light entering the eye bends as it travels toward the retina. (**a**) How light can bend. (**b**) How light rays reverse as they travel toward the retina. The pattern of light rays that converge on the retina is upside-down and reversed left to right.

pass through the cornea, their trajectories (paths) bend (Figure 14.14*a*). There, because of the way the rays were bent at the curved cornea, the rays converge at the back of the eyeball. They stimulate the retina in a pattern that is upside-down and reversed left to right relative to the source of the light rays. Figure 14.14*b* gives a simplified diagram of this process. The brain corrects the "upside-down and backwards" orientation.

Eye muscle movements fine-tune the focus

Light rays from sources at different distances from the eye strike the cornea at different angles. As a result, they will be focused at different distances behind it, and adjustments must be made so that the light will be focused precisely on the retina. Normally, the lens can be adjusted so that the focal point coincides exactly with the retina. A ciliary muscle adjusts the shape of the lens. As you can see in Figure 14.13, the muscle encircles the lens and attaches to it by ligaments. When the muscle contracts, the lens bulges, so the focal point moves closer. When the muscle relaxes, the lens flattens, so the focal point moves farther back (Figure 14.15). Adjustments like these are called **accommodation**. If they are not made, rays from distant objects will be in focus at a point just in front of the retina, and rays from very close objects will be focused behind it.

Sometimes the lens can't be adjusted enough to place the focal point on the retina. Sometimes also, the eyeball is not shaped quite right. The lens is too close to or too far away from the retina, so accommodation alone cannot produce a precise match. Eyeglasses or contact lenses can correct these problems, which we will consider more fully in Section 14.10.

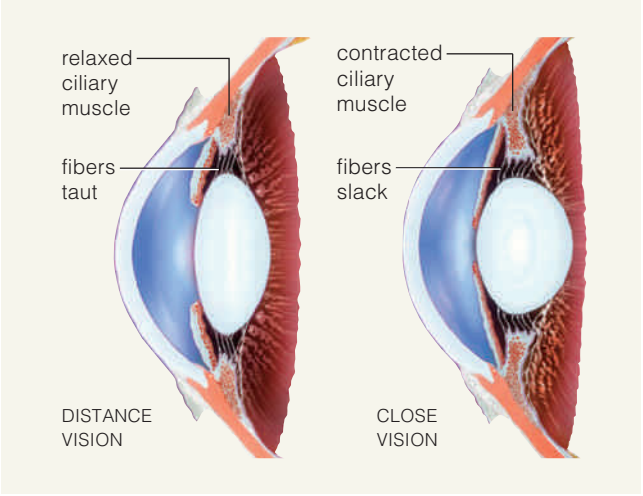


Figure 14.15 Animated! Adjusting the lens focuses light on the retina. Adjustments of the ciliary muscle focus light from near or distant sources on the retina by changing the tension of fibers that ring the lens.

Take-Home Message

What are eyes and how do they manage light?

- Eyes are sensory organs specialized for photoreception. In the outer eye layer, the sclera protects the eyeball and the cornea focuses light.
- In the middle layer, the choroid prevents light scattering, the iris controls incoming light, and the ciliary body and lens aid in focusing light on photoreceptors.
- Photoreception occurs in the retina of the inner layer. Adjustments in the position or shape of the lens focus incoming visual stimuli onto the retina.

14.9 From Visual Signals to "Sight"

- **Our vision sense is based on the sensory pathway from the retina to the brain.**
- **Links to Nerve impulses 13.3, Chemical synapses 13.4, Nerves 13.5, Visual processing in the brain 13.9**

"Seeing" something is a multistep process that begins when your eyes receive raw visual information. The information then is transmitted to the brain and processed. The end result is conscious awareness of light and shadows, of colors, and of near and distant objects in the world around us.

Rods and cones are the photoreceptors

Vision begins when light reaches the retina, at the back of the eyeball. Between the retina and the choroid is a layer of epithelium where visual pigments form. Millions of photoreceptors called **rod cells** and **cone cells** rest on this layer (Figure 14.16 and Table 14.3) and have visual pigments embedded in them. Rod cells are sensitive to dim light. They detect changes in light intensity across the visual field. Their signals are the start of coarse perception of motion. Cone cells detect bright light. Their signals are the start of sharp daytime vision and color perception.

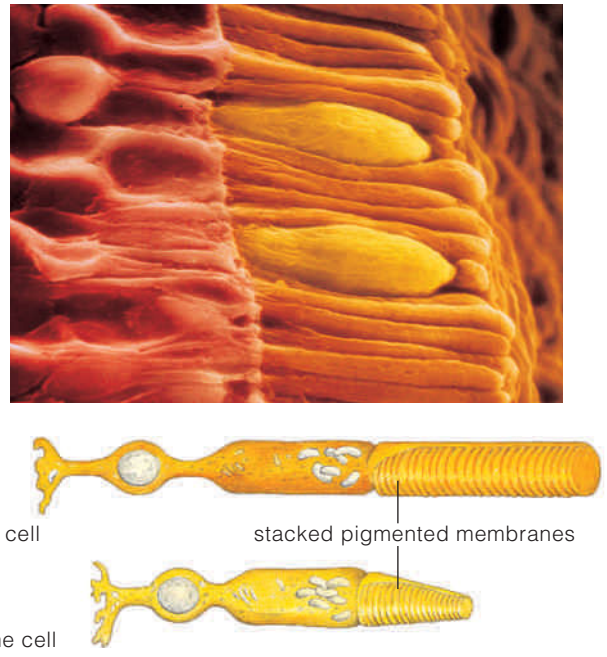


Figure 14.16 **Rods and cones contain visual pigments.**

Visual pigments intercept light energy

Like sound, light energy travels in waves, and different light wavelengths correspond to different colors. As you can see in the lower part of Figure 14.16, there are stacks of membrane disks in the light-sensitive part of rods and cones. These disks are where visual pigments are found.

Visual pigments are proteins that change shape when they absorb certain wavelengths, or colors, of light. They consist of different versions of a protein called opsin together with retinal, a light-absorbing substance that is derived from vitamin A. Rods contain a single type of visual pigment, called rhodopsin. It absorbs mainly blue to green light. By contrast, depending on the type of opsin in its pigment, a cone may be sensitive to red, green, or blue light. Thus we say there there are three types of cones—red, green, or blue.

Changes in visual pigments are key to our vision sense. When light stimulates a visual pigment, its opsin changes shape. The change begins a process that converts light energy to nerve impulses. In this process, a series of chemical reactions slow the release of a neurotransmitter that inhibits neurons next to the photoreceptor. When they are no longer inhibited, the neurons start sending signals about the visual stimulus on toward the brain.

Near the center of the retina is a tiny depression called the **fovea** (Figure 14.17). It is packed with cones. As a result, visual acuity, the ability to discriminate between two objects, is greatest there. For example, the fovea's dense cluster of cones enables you to distinguish between neighboring points in space—like the *e* and the period at the end of this sentence.

TABLE 14.3 Rods and Cones Compared

Cell Type	Sensitive To	Related Perception
Rod	Dim light	Coarse perception of movement
Cone	Bright light	Daytime vision and perception of color

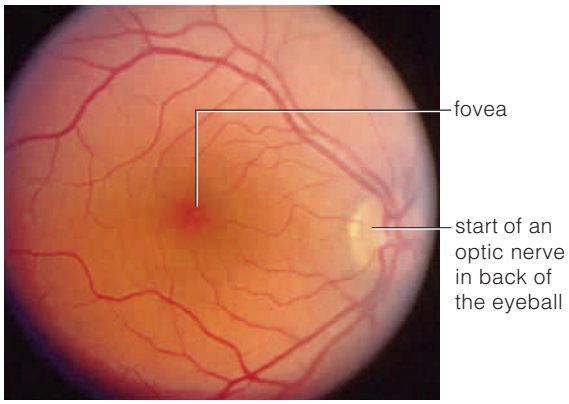


Figure 14.17 The fovea contains densely packed rods and cones. This image shows the location of the fovea and the start of the optic nerve.

The retina begins processing visual signals

In an early embryo, its retinas arise from its developing brain. As a result, anatomically speaking, the retina is an extension of the brain. Perhaps it is not surprising, then, that cells in the retina process visual signals before they are sent on to the brain's vision centers.

Neurons in the eye are organized in layers above the rods and cones. As you can see in Figure 14.18, signals flow from rods and cones to *bipolar* interneurons, then to interneurons called *ganglion cells*. Signals also travel to *horizontal* cells and *amacrine* cells. These neurons jointly strengthen or weaken the signals before they reach ganglion cells. The axons of ganglion cells form the two optic nerves to the brain.

Signals move on to the visual cortex

The part of the outside world you actually see is called the "visual field." The right side of each retina intercepts light from the left half of the visual field and the left side intercepts light from the right half. As you can see in Figure 14.19, signals from each eye "criss-cross." The optic nerve leading out of each eye delivers signals from the left visual field to the right cerebral hemisphere, and signals from the right go to the left hemisphere.

Axons of the optic nerves end in an island of gray matter in the cerebrum (the lateral geniculate nucleus). Its layers each have a map corresponding to receptive fields of the retina. Each map's interneurons deal with one aspect of a visual stimulus—its form, movement, depth, color, texture, and so on. After initial processing all the visual signals travel rapidly, at the same time, to different parts of the visual cortex. There, final processing produces the sensation of sight.

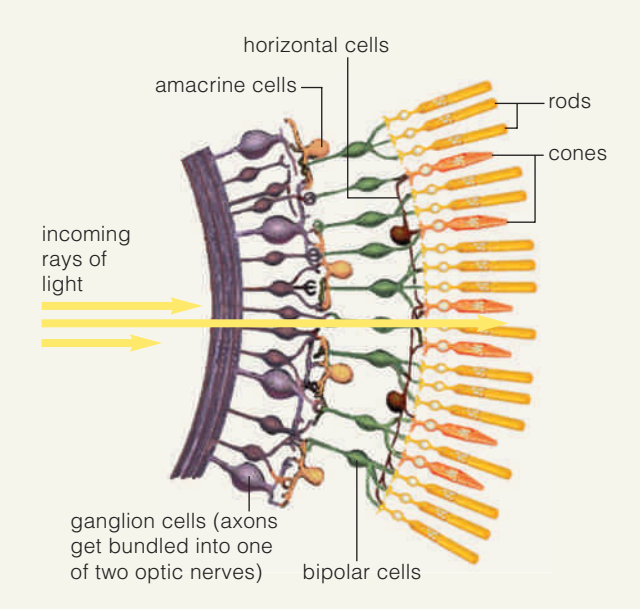


Figure 14.18 Animated! Photoreceptors connect with sensory neurons in the retina.

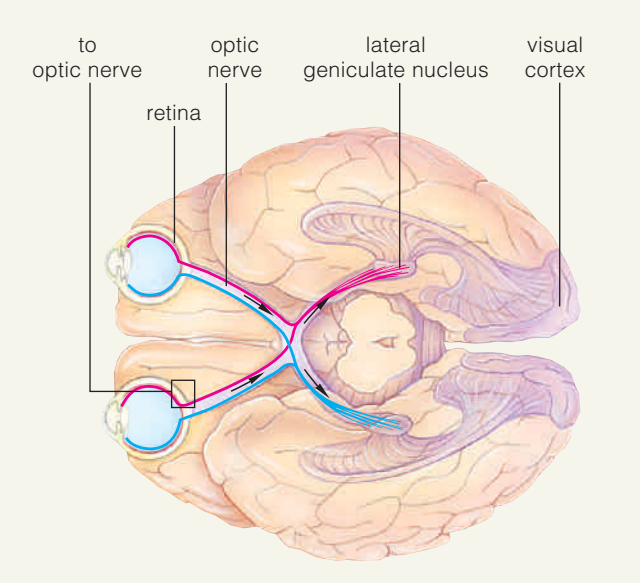


Figure 14.19 Animated! Sensory signals criss-cross as they travel from the retina to the brain.

Take-Home Message

How does the eye convert light energy to vision?

- Rods and cones are the eye's photoreceptors. Rods detect dim light. Cones detect bright light and provide our sense of color.
- The eye analyzes information on the distance, shape, brightness, position, and movement of a visual stimulus.
- Visual signals move through layers of neurons in the retina before moving on to the brain.

14.10 Disorders of the Eye

Problems that disrupt normal eye functions range from injuries and diseases to inherited abnormalities and natural changes associated with aging. The outcomes range from some relatively harmless conditions, such as nearsightedness, to total blindness.

Missing cone cells cause color blindness

Occasionally, some or all of the cone cells that selectively respond to light of red, green, or blue are missing. The rare people who have only one of the three kinds of cones are totally color-blind. They see the world only in shades of gray.

Consider a common inherited abnormality, **red-green color blindness**. It shows up most often in males, for reasons you can read about in Chapter 20. The retina lacks some or all of the cone cells with pigments that normally respond to light of red or green wavelengths. Most of the time, color-blind people have trouble distinguishing red from green only in dim light. However, some cannot distinguish between the two even in bright light.

So-called "**night blindness**" results when a person's diet is deficient in vitamin A, which you may recall is required to form the retinal in visual pigments. The effect is most severe in rods, which detect dim light.

Malformed eye parts cause common focusing problems

Some inherited vision problems are due to misshapen eye structures that affect the eye's ability to focus light. In **astigmatism**, for example, one or both corneas have an uneven curvature; they cannot bend incoming light rays to the same focal point.

In **myopia**, or nearsightedness, the eyeball is wider than it is high, or the ciliary muscle responsible for adjusting the lens contracts too strongly. Then, images of distant objects are focused in front of the retina instead of on it (Figure 14.20*a*). **Hyperopia**, farsightedness, is the opposite problem. The eyeball is "taller" than it is wide (or the lens is "lazy"), so close images are focused behind the retina (Figure 14.20*b*).

The eyes also are vulnerable to infections and cancer

The eyes are vulnerable to pathogens including viruses, bacteria, and fungi. Health authorities estimate that in the U.S., about 1 in every 50 visits to a doctor's office is for **conjunctivitis**, inflammation of the transparent membrane (the conjunctiva) that lines the inside of the eyelids

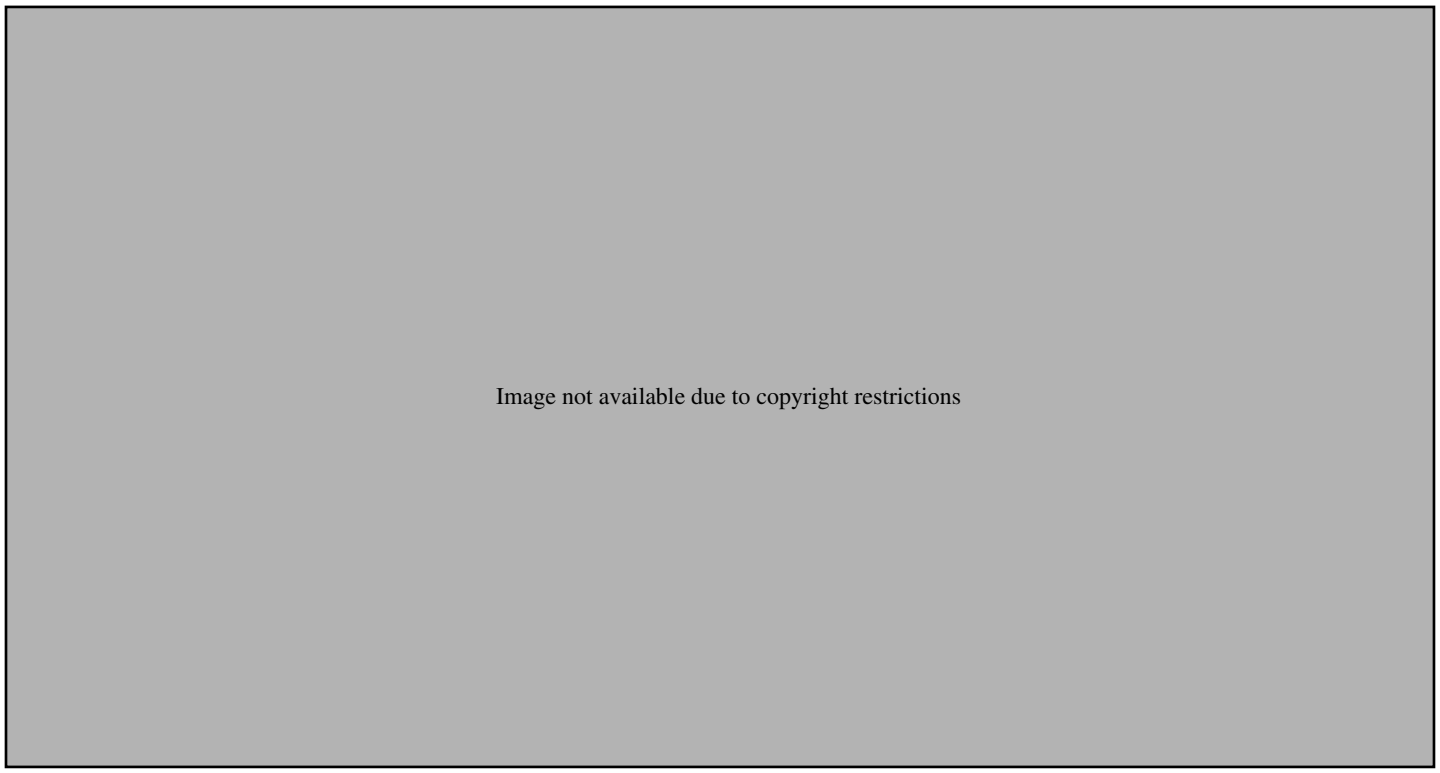


Figure 14.21 **Conjunctivitis may be due to a bacterial infection or an allergy.**

and covers the sclera (the white of the eye). Symptoms include redness, discomfort, and a discharge. In children, conjunctivitis usually is caused by bacteria; in adults it more often is triggered by allergy (Figure 14.21). Most cases of bacterial conjunctivitis are easily treated with antibiotics.

Trachoma is a highly contagious disease that has blinded millions, mostly in North Africa and the Middle East. The culprit is a bacterium that also is responsible for the sexually transmitted disease chlamydia (Chapter 16). Trachoma damages both the eyeball and the conjunctiva. Then, other bacteria can enter the damaged tissues and cause secondary infections. In time the cornea can become so scarred that blindness follows.

Herpes simplex, a virus that causes cold sores and genital herpes, also can infect the cornea. Because blindness can result from a **herpes infection** in the eyes, a pregnant woman who has a history of genital herpes likely will be delivered by Caesarian section to avoid any chance of exposing her newborn to the virus.

Malignant melanoma is the most common eye cancer. It typically develops in the choroid (the eye's middle layer) and may not trigger noticeable vision problems until it has spread to other parts of the body. About 1 in 20,000 babies is born with **retinoblastoma**, a cancer of the retina. Because it can readily spread along the optic nerve to the brain, the affected eye often is removed surgically. If both eyes are involved, radiation therapy may be used to try to save one of them.

Aging increases the risk of cataracts and some other eye disorders

Clouding of the eye's lens, or **cataracts**, is associated with aging, although an injury or diabetes can also cause them to develop. The underlying change may be an alteration in the structure of transparent proteins that make up the lens. This change in turn may skew the trajectory of incoming light rays. If the lens becomes totally opaque, no light can enter the eye.

Even a normal lens loses some of its natural flexibility as we grow older. This normal stiffening is why people over 40 years old often must start wearing eyeglasses.

Elderly people can suffer **macular degeneration**, in which a portion of the retina breaks down and is replaced by scar tissue. As a result, a "blind spot" develops. Often both eyes are affected. Treatment is difficult unless the problem is detected early.

Glaucoma results when too much aqueous humor builds up inside the eyeball. Blood vessels that service the retina collapse under the increased fluid pressure. An affected person's vision deteriorates as neurons of the retina and optic nerve die. Although chronic glaucoma often is associated with advanced age, the problem really starts in a person's middle years. If detected early, the fluid pressure can be relieved by drugs or surgery before the damage becomes severe.

Medical technologies can remedy some vision problems and treat eye injuries

Today many different procedures are used to correct eye disorders. In *corneal transplant surgery*, the defective cornea is removed; then an artificial cornea (made of clear plastic) or a natural cornea from a donor is stitched in place. Within a year, the patient is fitted with eyeglasses or contact lenses. Similarly, cataracts often can be surgically corrected by removing the lens and replacing it with an artificial one.

Severely nearsighted people may opt for procedures that eliminate the need for corrective lenses. So-called "lasik" (for laser-assisted in situ keratomilieusis) and "lasek" (for laser-assisted subepithelial keratectomy) use a laser to reshape the cornea. All or part of the surface of the cornea is peeled back and then replaced into position after the defect being treated is corrected. *Conductive keratoplasty* (CK) uses radio waves to reshape the cornea and bring near vision back into focus.

Retinal detachment is the eye injury we read about most often. It may follow a physical blow to the head or an illness that tears the retina. As the jellylike vitreous body oozes through the torn region, the retina is lifted from the underlying choroid. In time it may peel away entirely, leaving its blood supply behind. Early symptoms of the damage include blurred vision, flashes of light that occur in the absence of outside stimulation, and loss of peripheral vision. Without medical help, the person may become totally blind in the damaged eye.

A detached retina may be treatable with *laser coagulation*, a painless technique in which a laser beam seals off leaky blood vessels and "spot welds" the retina to the underlying choroid.

IMPACTS, ISSUES

Private Eyes

THE use of biometric identification systems is spreading. Critics are concerned that widespread use of such measures, even highly reliable ones such as iris scanning, may lead to discrimination and other abuses, including intrusions into the privacy of ordinary citizens.

How Would You Vote?

Do you favor laws that allow biometric data such as iris scans to be collected for security purposes—and that protect users from liability? See CengageNOW for details, then vote online.

Summary

Section 14.1 A stimulus is a form of energy that the body detects by means of sensory receptors. A sensation is a conscious awareness that stimulation has occurred. Perception is understanding what the sensation means.

Sensory receptors are endings of sensory neurons or specialized cells next to them. They respond to stimuli, which are specific forms of energy, such as mechanical pressure and light.

a. Mechanoreceptors detect mechanical energy that is associated with changes in pressure (e.g., sound waves), changes in position, or acceleration.

b. Thermoreceptors detect the presence of or changes in radiant energy from heat sources.

c. Nociceptors (pain receptors) detect tissue damage. Their signals are perceived as pain.

d. Chemoreceptors detect chemical substances that are dissolved in the body fluids around them.

e. Osmoreceptors detect changes in water volume (hence solute concentrations) in the surrounding fluid.

f. Photoreceptors detect light.

A sensory system has receptors for specific stimuli and nerve pathways from those receptors to processing centers in the brain. The brain assesses each stimulus based on which nerve pathway is delivering the signals, how often signals are traveling along each axon of the pathway, and the number of axons that were recruited into action. In sensory adaptation, the response to a stimulus decreases.

The special senses include taste, smell, hearing, balance, and vision. The receptors associated with these senses are in sense organs or another specific body region.

- Use the animation and interaction on CengageNOW to see how the intensity of a sensory stimulus affects the frequency of nerve impulses to the brain.

Section 14.2 Somatic sensations include touch, pressure, pain, temperature, and muscle sense. Receptors associated with these sensations occur in various parts of the body. Their signals are processed in the somatosensory cortex of the brain. The simplest receptors, including those for temperature and pain, are free nerve endings in the skin or internal tissues. Some somatic sensations arise when encapsulated receptors respond to stimuli.

- Use the animation and interaction on CengageNOW to learn about many of the sensory receptors in skin.

Section 14.3 Taste and smell are chemical senses. Their sensory pathways travel from chemoreceptors to processing regions in the cerebral cortex and limbic system. Taste buds in the tongue and mouth contain the taste receptors. The sense of smell relies on olfactory receptors in patches of epithelium in the upper nasal passages.

Section 14.5 The sense of hearing requires parts of the outer, middle, and inner ear that collect, amplify, or respond to sound waves that vibrate the tympanic membrane (eardrum). The vibrations are transferred to fluid in the cochlea of the inner ear, where they in turn vibrate the tectorial membrane. The moving fluid bends sensory hair cells in the organ of Corti. The bending triggers nerve impulses that travel to the brain via the auditory nerve.

- Use the animation and interaction on CengageNOW to explore the structure and function of the ear.

Section 14.6 Balance organs are located in the vestibular apparatus of the inner ear. Sensory receptors in these semicircular canals (including hair cells) respond to gravity, velocity, acceleration, and other factors that affect body positions and movements.

Section 14.8 Eyes are the sensory organs associated with the sense of vision. Key eye structures include the cornea and lens, which focus light; the iris, which adjusts incoming light; and the retina, which contains photoreceptors (rods and cones). The optic nerve at the back of the eyeball transmits visual signals to the visual cortex in the brain.

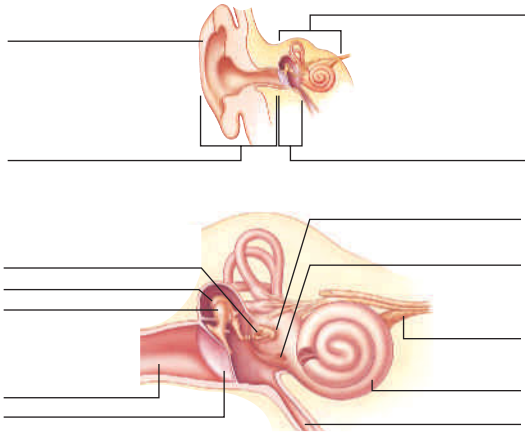
- Use the animation and interaction on CengageNOW to investigate the structure and function of the eye.

Section 14.9 The rod cells and cone cells detect dim and bright light, respectively. Light detection in rods depends on changes in the shape of the visual pigment rhodopsin. The visual pigments in cones respond to colors. Visual signals are processed in the retina before being sent on to the brain. In the retina, abundant receptors in the fovea provide sharp visual acuity.

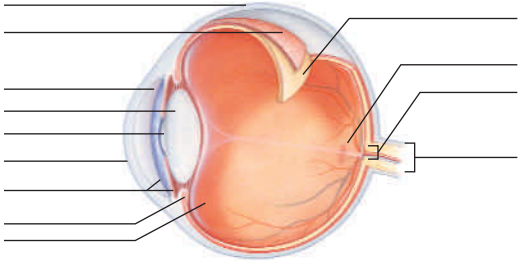
- Use the animation and interaction on CengageNOW to learn about the organization of the retina and how visual stimuli are processed.

Review Questions

1. When a receptor cell detects a specific kind of stimulus, what happens to the stimulus energy?
2. Name six categories of sensory receptors and the type of stimulus that each type detects.
3. How do somatic sensations differ from special senses?
4. Explain where free nerve endings are located in the body and note some functions of the various kinds.
5. What is pain? Describe one type of pain receptor.
6. What are the stimuli for taste receptors?
7. How do "smell" signals arise and reach the brain?
8. Label the parts of the ear:



9. In the ear, sound waves cause the tympanic membrane to vibrate. What happens next in the middle ear? In the inner ear?
10. Label the parts of the eye:



11. How does the eye focus the light rays of an image? What do nearsighted and farsighted mean?

Self-Quiz *Answers in Appendix V*

1. A _____ is a specific form of energy that can elicit a response from a sensory receptor.
2. Awareness of a stimulus is called a _____.
3. _____ is understanding what particular sensations mean.
4. A sensory system is composed of _____.
   a. nerve pathways from specific receptors to the brain
   b. sensory receptors
   c. brain regions that deal with sensory information
   d. all of the above
5. _____ detect energy associated with changes in pressure, body position, or acceleration.
   a. Chemoreceptors
   b. Mechanoreceptors
   c. Photoreceptors
   d. Thermoreceptors
6. Detecting substances present in the body fluids that bathe them is the function of _____.
   a. thermoreceptors
   b. photoreceptors
   c. mechanoreceptors
   d. chemoreceptors
7. Which of the special senses is based on the following events? Membrane vibrations cause fluid movements, which lead to bending of mechanoreceptors and firing of action potentials.
   a. taste
   b. smell
   c. hearing
   d. vision
8. Rods differ from cones in the following ways:
   a. They detect dim light, not bright light.
   b. They have a different visual pigment.
   c. They are not located in the retina.
   d. all of the above
   e. a and b only
9. The outer layer of the eye includes the _____.
   a. lens and choroid
   b. sclera and cornea
   c. retina
   d. both a and c are correct
10. The inner layer of the eye includes the _____.
    a. lens and choroid
    b. sclera and cornea
    c. retina
    d. start of optic nerve
11. Your visual field is _____.
    a. a specific, small area of the retina
    b. what you actually "see"
    c. the area where color vision occurs
    d. where the optic nerve starts
12. Match each of the following terms with the appropriate description.

____ somatic senses (general senses)	a. produced by strong stimulation
____ special senses	b. endings of sensory neurons or specialized cells next to them
____ variations in stimulus intensity	c. taste, smell, hearing, balance, and vision
____ action potential	d. frequency and number of action potentials
____ sensory receptor	e. touch, pressure, temperature, pain, and muscle sense

Critical Thinking

1. In a roller coaster like the one shown in Figure 14.22 at right, are organs of dynamic equilibrium, static equilibrium, or both activated?
2. Juanita started having bouts of dizziness. Her doctor asked her whether "dizziness" meant she felt lightheaded as if she were going to faint, or whether it meant she had sensations of *vertigo*—that is, a feeling that she herself or objects near her were spinning around. Why was this clarification important for the diagnosis?
3. Michael, a 3-year-old, experiences chronic middle-ear infection, which is common among youngsters, in part due to an increase in antibiotic-resistant bacteria. This year, despite antibiotic treatment, an infection became so advanced that he had trouble hearing. Then his left eardrum ruptured and a jellylike substance dribbled out. The pediatrician told Michael's parents not to worry, that if the eardrum had not ruptured on its own she would have had to drain it. Suggest a reason why the physician concluded that this procedure would have been necessary to cure Michael's problem.
4. Jill is diagnosed with sensorineural deafness, a disorder in which sound waves are transmitted normally to the inner ear but they are not translated into neural signals that travel to the brain. Sometimes the cause is a problem with the auditory nerve, but in Jill's case it has to do with a problem in the inner ear itself. Where in the inner ear is the disruption most likely to be located?
5. Larry goes to the doctor complaining that he can't see the right side of the visual field with either eye. Where in the visual signal-processing pathway is the problem?

Figure 14.22 **A rollercoaster gives the vestibular apparatus a workout.**

EXPLORE ON YOUR OWN

As Section 14.10 described, there are various forms of color blindness. Figure 14.23 shows simple tests, called Ishihara plates, which are standardized tests for different forms of color blindness. For instance, you may have one form of red-green color blindness if you see the numeral "7" instead of "29" in the circle in part *a*. You may have another form if you see a "3" instead of an "8" in the circle in part *b*.

If you do this exercise and have questions about your color vision, visit your doctor to determine whether additional testing is in order.

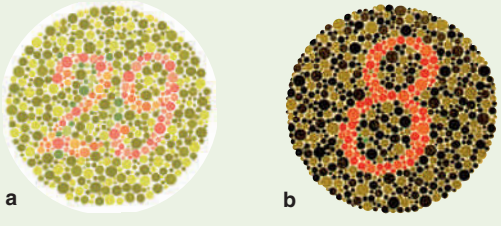


Figure 14.23 **Color blindness tests.**

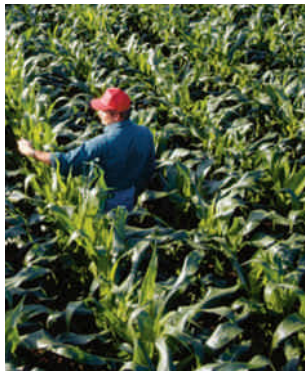
The Endocrine System

15

IMPACTS, ISSUES

Hormones in the Balance

IN 2001, researchers at Dartmouth College discovered what may be another harmful role for the poison arsenic. Arsenic appears to be an endocrine disrupter, a chemical that interferes with normal hormone activity. Like some other chemical pollutants, arsenic blocks hormones or mimics them. Unlike natural hormones, a mimic can't be turned off. As a result, the body loses control of the affected function. The Dartmouth team discovered that arsenic disrupts the action of glucocorticoids, hormones that help regulate blood sugar and that are "on" switches for genes that may protect against cancer.



Arsenic is present in water supplies in many areas. Long-term exposure to it in drinking water is associated with bladder, lung, and skin cancers; birth defects; and other problems. In 2001 the Environmental Protection Agency cited the risks and lowered the allowable arsenic levels in water supplies. Later, some factions lobbied to get the levels increased again.

There are other possible endocrine disrupters. One is atrazine, a widely used weedkiller on golf courses and farm fields. Atrazine now is found in groundwater throughout the American Midwest.

Other suspects are PCBs, chemicals that were long used as fluid insulation in electrical transformers. Now banned, PCBs stay in the environment for years. They now contaminate soil, groundwater, and even the tissues of deep sea fishes.

Some researchers suspect that hormone disrupters are contributing to two puzzling trends: an earlier onset of puberty in pre-teens and reduced sperm counts in men. Other scientists dismiss the hypotheses as junk science. With luck, additional studies will shed more light on the effects of hormone-disrupting chemicals.

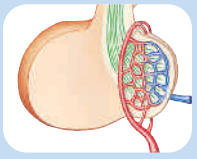
Together with the nervous system, hormones regulate many body functions. Your study of their sources and activities in this chapter will help you better understand how your own body works. It may also help you better understand some important environmental concerns.

KEY CONCEPTS

How Hormones Work

Hormones control many body functions and influence behavior. Hormones bind to and activate receptors on target cells. Their signals are converted into forms that work inside target cells to bring about a response. Sections 15.1, 15.2

The Endocrine System



Glands and tissues of the endocrine system release most hormones. The hypothalamus and pituitary glands control much of this activity. Chemical changes in certain tissues trigger the release of other hormones. Sections 15.3–15.10

Disorders of the Endocrine System and Homeostasis

Sections 15.5, 15.6, 15.9, 15.11

LINKS TO EARLIER CONCEPTS

- This chapter builds on your understanding of the roles of several cell structures (3.2, 3.4). It also expands on what you have learned about the functions of the hypothalamus and the pituitary gland (13.8).
- You will see more examples of how homeostatic feedback loops help regulate body functions (4.10).
- You will also see how certain proteins in cell plasma membranes function in physiological processes (3.4)—in this case, by serving as receptors for hormone molecules.

How Would You Vote?

Some widely used agricultural chemicals may disrupt hormone action in humans. Should these potentially harmful chemicals stay on the market while researchers study their safety? See CengageNOW for details, then vote online.

15.1 The Endocrine System: Hormones

- **Hormones are signaling molecules that have a major role in coordinating and managing the activities of the billions of body cells.**
- **Links to Receptor proteins in cell membranes 3.4, Neurotransmitters 13.4, Pheromones 14.3**

Hormones are signaling molecules carried in the bloodstream

You have already read about several types of signaling molecules, including neurotransmitters that carry nervous system messages. The body's chemical messengers are all alike in one key way: They act on target cells. A **target cell** is any cell that has receptors for the signaling molecule and that may change its activities in response. A target may or may not be next to the cell that sends the signal.

Hormones, our main topic here, are secreted by the body's endocrine glands, endocrine cells, and some neurons. They travel the bloodstream to target cells some distance away. Many types of cells also release "local" signaling molecules that change conditions in nearby tissues (Table 15.1). Prostaglandins are an example. Their targets include smooth muscle cells in the walls of bronchioles, which then close up or dilate and so change air flow in the lungs (Section 10.5). Prostaglandins that affect smooth muscle in the uterus cause menstrual cramps.

Examples of Chemical Signals in the Body

Type	Route to Target Cells
Hormones	Carried by blood to distant targets
Neurotransmitters	Released at synapses between neurons and target cells
Prostaglandins	Released in tissues and diffuse to target cells
Pheromones	Possibly reach target cells in other individuals

The endocrine system is the hormone source

The word hormone—from the Greek *hormon*, "to set in motion"—was coined in 1900 by scientists studying food digestion in dogs. They discovered that a substance released by gland cells in the canine gastrointestinal tract could stimulate the pancreas. Later researchers identified other hormones and their sources (Figure 15.1).

These hormone-producing glands, organs, and cells became known as the **endocrine system**. The name is misleading, hoever, because it implies that there is an independent hormone-based control system for the body. (*Endon* means "within"; *krinein* means "separate.") However, we now know that the functioning of hormone sources and the nervous system are closely connected, as you will soon see.

Hormones are produced in small amounts and often interact

In general, endocrine glands usually release small amounts of hormones in short bursts. Controls usually prevent hormones from being either overproduced or underproduced. Negative feedback is the most common control mechanism. As you will read later in this chapter, if something interferes with the controls, the body's form and functioning may be altered in abnormal ways.

It is quite common for two or more hormones to affect the same process. There are three common kinds of these hormone "partnerships":

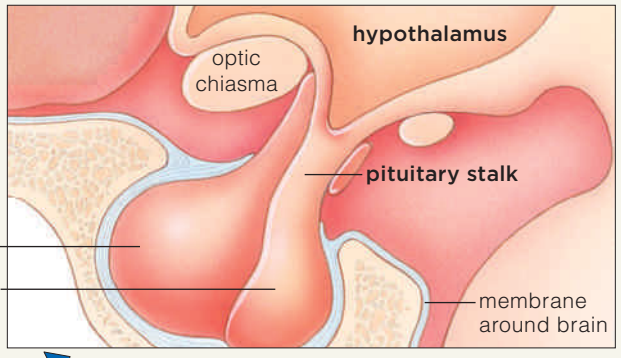
1. **Opposing interaction.** The effect of one hormone may oppose the effect of another. Insulin, for example, reduces the level of glucose in the blood, and glucagon increases it.
2. **Synergistic interaction.** The combined action of two or more "cooperating" hormones may be required to trigger a certain effect on target cells. For instance, a woman's mammary glands can't produce and secrete milk without the synergistic interaction of three other hormones: prolactin, oxytocin, and estrogen.
3. **Permissive interaction.** One hormone can exert its effect on a target cell only when a different hormone first "primes" the target cell. For example, even if one of a woman's eggs is fertilized, she can become pregnant only if the lining of her uterus has been exposed to estrogens, then to progesterone.

Take-Home Message

What are hormones?

- Hormones are signaling molecules secreted in small amounts by endocrine glands, endocrine cells, and some neurons. The bloodstream carries hormones to distant target cells.
- Together, the glands and cells that secrete hormones make up the endocrine system. Their activity usually is regulated by negative feedback.
- Hormones may interact in opposition, in cooperation (synergistically), or permissively. That is, a target cell must be primed by exposure to one hormone in order to respond to a second one.

Figure 15.1 Animated! **This diagram gives an overview of major hormone secreting organs and their primary endocrine functions.**



hypothalamus (part of the brain)

Produces, secretes six releasing and inhibiting hormones (act on different endocrine cells in the anterior lobe of pituitary).

Produces ADH (conserves water) and oxytocin (roles in childbirth, milk secretion). The pituitary's posterior lobe stores and secretes both.

pituitary gland, anterior lobe

Four hormones (ACTH, TSH, FSH, LH) stimulate other glands. Two (prolactin, somatotropin) stimulate overall growth and development.

pituitary gland, posterior lobe

Stores, secretes two hypothalamic hormones: ADH and oxytocin

adrenal gland (one pair)

cortex Cortisol (affects glucose metabolism) and aldosterone (conserves sodium)

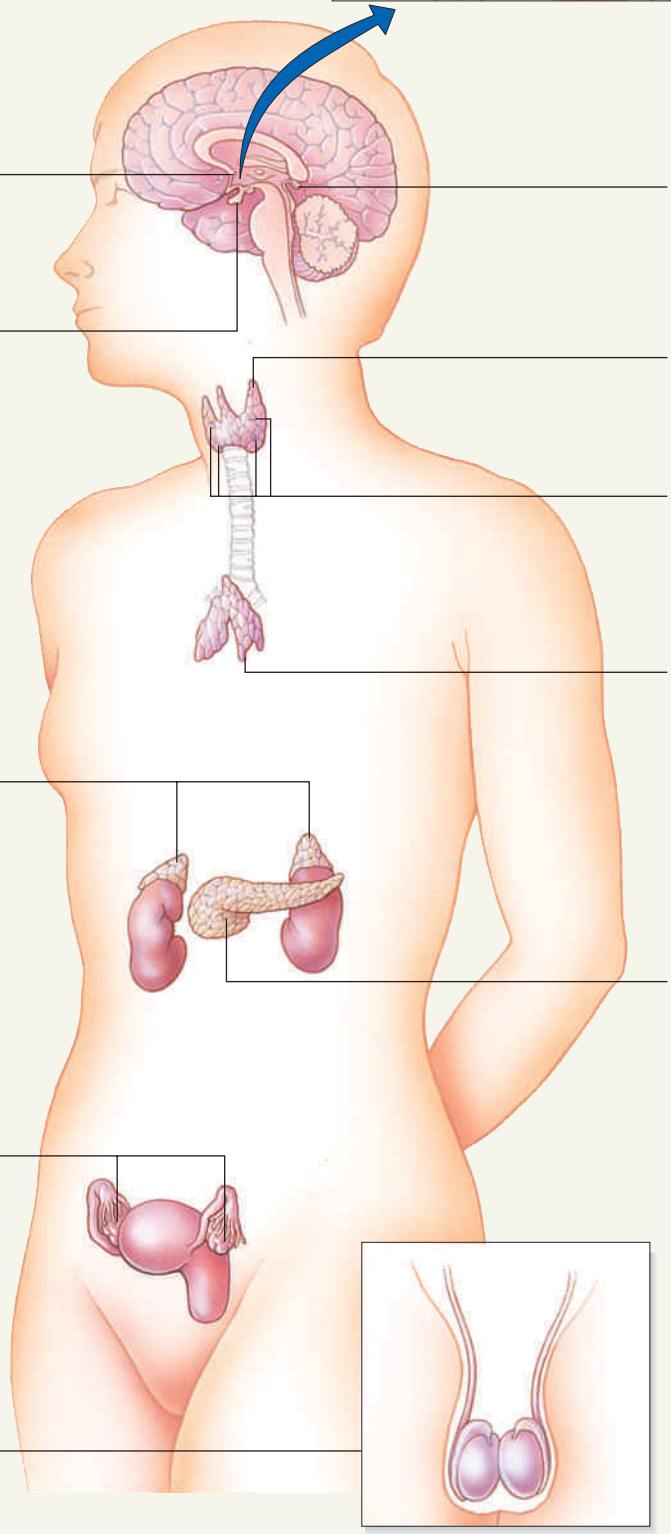
medulla Epinephrine and norepinephrine (these hormones interact, in concert with the sympathetic nervous system, to help adjust organ activities, especially during times of excitement or stress)

ovaries (one pair of female gonads)

Estrogens and progesterone (maintain primary sex organs, influence secondary sexual traits)

testes (one pair of male gonads)

Testosterone (develops and maintains primary sex organs, influences secondary sexual traits)



pineal gland

Melatonin (affects biological clocks, overall level of activity, reproductive cycles)

thyroid gland

Thyroxine and triiodothyronine (roles in growth, development, metabolic control)

parathyroid glands (four)

Parathyroid hormone (increases blood level of calcium)

thymus gland

Thymosins (roles in white blood cell functioning)

pancreatic islets

Insulin (lowers blood level of glucose), glucagon (raises blood level of glucose)

15.2 Types of Hormones and Their Signals

- **Like other signaling molecules, hormones bind with receptors of target cells. What happens next depends on whether a hormone is a steroid or a peptide hormone.**
- **Links to Steroids 2.10, Amino acids 2.11, Proteins of the plasma membrane 3.4**

Hormones come in several chemical forms

Hormones vary in their chemical structure, which affects how they function. **Steroid hormones** are lipids derived from cholesterol. **Amine hormones** are modified amino acids. **Peptide hormones** consist of a few amino acids. **Protein hormones** are longer amino acid chains. Table 15.2 lists some examples of each.

Regardless of their chemical makeup, hormones affect cell activities by binding to protein receptors of target cells. The signal is then converted into a form that can work in the cell. Then the cell's activity changes:

Some hormones cause a target cell to take in more of a substance, such as glucose. Other hormones stimulate or inhibit the target cell in ways that alter the rate at which it makes new proteins or modifies existing proteins or other structures in the cytoplasm. Sometimes a hormone may even change a cell's shape.

Two factors have a strong influence on how a target cell responds to hormone signals. To begin with, different hormones activate different kinds of mechanisms in target cells. Secondly, not all types of cells can respond to a given signal. For example, many types of cells have receptors for the hormone cortisol, so it has widespread effects in the body. If only a few types of cells have receptors for a given hormone, its effects in the body will be limited to tissues and organs where those types of cells are present.

Categories of Hormones and a Few Examples	
Steroid hormones	Estrogens, progesterone, testosterone, aldosterone, cortisol
Amines	Melatonin, epinephrine, norepinephrine, thyroid hormone (thyroxine, triiodothyronine)
Peptides	Oxytocin, antidiuretic hormone, calcitonin, parathyroid hormone
Proteins	Growth hormone (somatotropin), insulin, prolactin, follicle-stimulating hormone, luteinizing hormone

Steroid hormones interact with cell DNA

Steroid hormones are produced by cells in the adrenal glands and in the primary reproductive organs—ovaries and testes. Estrogen made in the ovaries and testosterone made in the testes are good examples.

Figure 15.2*a* illustrates how a steroid hormone may act. Being lipid-soluble, it may diffuse directly across the lipid bilayer of a target cell's plasma membrane. Once inside the cytoplasm, the hormone molecule usually moves into the nucleus and binds to a receptor. In some cases it binds to a receptor in the cytoplasm, and then the hormone–receptor complex enters the nucleus. There the complex interacts with a particular gene—a segment of the cell's DNA. Genes carry the instructions for making proteins. By turning genes on or off, steroid hormones turn protein-making machinery on or off. This change in a target cell's activity is the response to the hormone signal.

Some steroid hormones act in another way. They bind receptors on cell membranes and change the membrane properties in ways that affect the target cell's function.

Thyroid hormones and vitamin D are not chemically the same as steroid hormones, but they behave like steroids so we can consider them as part of this group.

Nonsteroid hormones act indirectly, by way of second messengers

Nonsteroid hormones—the amine, peptide, and protein hormones—do not enter a target cell. Their chemical makeup makes them water-soluble, and this property means they can't cross a target cell's lipid-rich plasma membrane. Instead, when this type of hormone binds to receptors in the plasma membrane, the binding sets in motion a series of reactions that activate enzymes. These reactions lead to the target cell's response.

For instance, consider a liver cell that has receptors for glucagon, a peptide hormone. As sketched in Figure 15.2*b*, this type of receptor spans the plasma membrane and extends into the cytoplasm. When a receptor binds glucagon, the cell produces a **second messenger**, a small molecule in the cytoplasm that relays signals from hormone–receptor complexes into the cell. A molecule called **cyclic AMP** (cyclic adenosine monophosphate) is this messenger. (The hormone itself is the "first messenger.")

An activated enzyme (adenylate cyclase) launches a cascade of reactions by converting ATP to cyclic AMP. Molecules of cyclic AMP are signals for the cell to activate molecules of another enzyme called a protein kinase. These act on other enzymes, and so forth, until a final reaction converts stored glycogen in the cell to glucose.

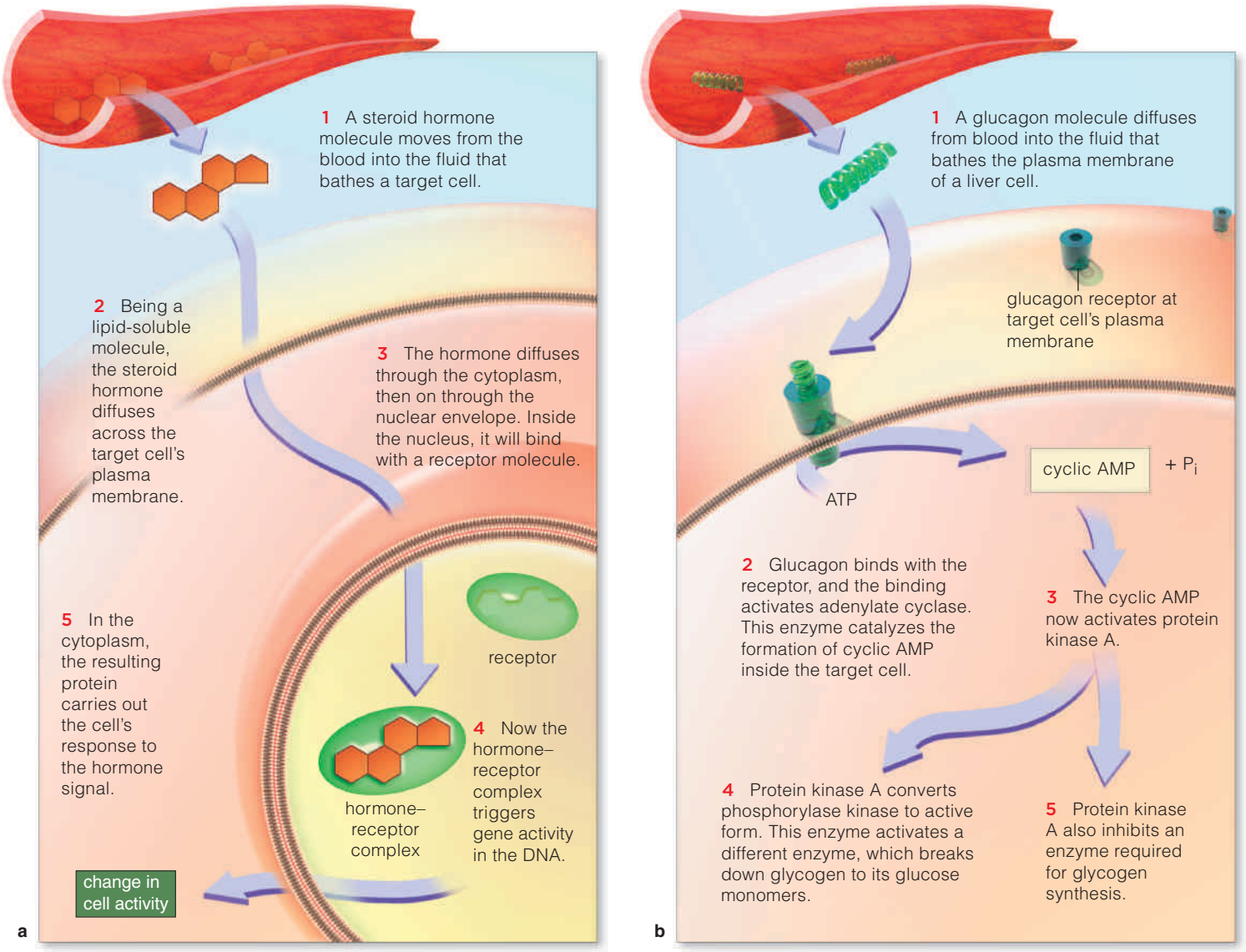


Figure 15.2 Different types of hormones cause change in a target cell by different mechanisms. Part (**a**) shows an example of a mechanism by which a steroid hormone triggers changes in a target cell's activities. Part (**b**) is an example of how a peptide hormone triggers changes in the activity of a target cell. In this example, glucagon binds to a receptor and triggers reactions inside the cell. Cyclic AMP, a type of second messenger, relays the signal inside the cell.

Soon a huge number of molecules are taking part in the final response to the glucagon–receptor complex.

Epinephrine is another amine hormone. Like glucagon, it combines with specific receptors at the surface of the target cell. Binding triggers the release of cyclic AMP as a second messenger that assists in the target cell response.

A slightly different example is a muscle cell that has receptors for insulin, a protein hormone. Among other things, when insulin binds to the receptor, the complex stimulates transporter proteins to insert themselves into the plasma membrane so that the cell can take up glucose faster. The signal also activates enzymes that catalyze reactions allowing the cell to store glucose.

Take-Home Message

How do hormones exert an effect on target cells?

- Hormones interact with receptors at the plasma membrane or in the cytoplasm of target cells. Ultimately, the hormone influences protein synthesis in a target cell.
- Most steroid hormones interact with a target cell's DNA after they enter the nucleus or bind a receptor in the cell's cytoplasm. Some steroid hormones alter properties of the plasma membrane.
- Nonsteroid hormones bind to plasma membrane receptors. This activates an enzyme system. Often a second messenger relays the signal to the cell's interior, where the full response unfolds.

15.3 The Hypothalamus and Pituitary Gland

- **The hypothalamus and pituitary gland interact as a major brain center that controls activities of other organs. Many of these organs also have endocrine functions.**
- **Links to Management of water balance by the kidneys 12.4, Hypothalamus 13.8**

Recall from Chapter 13 that the **hypothalamus** in the forebrain monitors internal organs and states related to their functioning, such as eating, among other roles. It has secretory neurons that extend down into the slender stalk to its base, then into the lobed, pea-sized **pituitary gland**.

In addition to its nervous system functions, the hypothalamus makes hormones. Two of these are later secreted from the pituitary's *posterior* lobe. Others have targets in the *anterior* lobe of the pituitary, which makes and secretes its own hormones. Most of these govern the activity of other endocrine glands (Table 15.3).

The posterior pituitary lobe releases ADH and oxytocin

Figure 15.3 gives you an idea of how axons of certain neurons in the hypothalamus extend downward into the posterior lobe, ending next to a capillary bed. The neurons make antidiuretic hormone (ADH) and oxytocin, which are stored in the axon endings. When one of these hormones is released, it diffuses through tissue fluid and into capillaries, then travels the bloodstream to its targets.

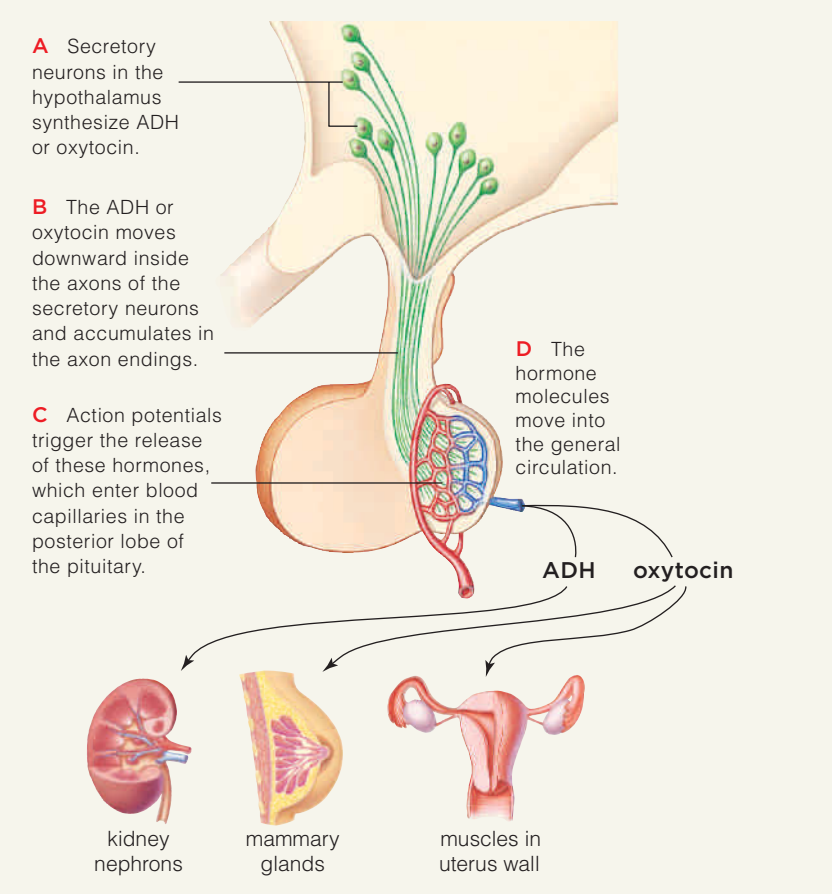


Figure 15.3 Animated! The posterior pituitary lobe stores and releases hormones from the hypothalamus. The diagram also shows main targets of the posterior lobe's hormones.

TABLE 15.3 Primary Actions of Hormones Released from the Human Pituitary Gland

Pituitary Lobe	Secretions	Designation	Main Targets	Primary Actions
Posterior Nervous tissue (extension of hypothalamus)	Antidiuretic hormone (vasopressin)	ADH	Kidneys	Causes water conservation as required to maintain extracellular fluid volume and solute concentrations
	Oxytocin	OT	Mammary glands Uterus	Causes milk to move into secretory ducts Causes uterine contractions during childbirth
Anterior Glandular tissue, mostly	Adrenocorticotropic hormone	ACTH	Adrenal glands	Stimulates release of cortisol, an adrenal steroid hormone
	Thyroid-stimulating hormone	TSH	Thyroid gland	Stimulates release of thyroid hormones
	Follicle-stimulating hormone	FSH	Ovaries, testes	In females, stimulates estrogen secretion, egg maturation; in males, helps stimulate sperm formation
	Luteinizing hormone	LH	Ovaries, testes	In females, stimulates progesterone secretion, ovulation, corpus luteum formation; in males, stimulates testosterone secretion, sperm release
	Prolactin	PRL	Mammary glands	Stimulates and sustains milk production
	Growth hormone (somatotropin)	GH	Most cells	Promotes growth in young; causes protein synthesis, cell division; roles in glucose, protein metabolism in adults

ADH acts on cells of kidney nephrons and collecting ducts. As Chapter 12 described, ADH promotes water reabsorption when the body must conserve water.

Various events—such as water lost in sweat or severe blood loss from an injury—may cause a drop in blood pressure. The hypothalamus monitors these shifts and releases ADH into the bloodstream when blood pressure falls below a set point. ADH causes the arterioles in some tissues to narrow, so blood pressure rises. For this reason, ADH is sometimes called vasopressin.

Oxytocin affects reproduction. In a pregnant woman, for example, it triggers muscle contractions in the uterus during labor and causes milk to be released when a mother nurses her infant. In sexually active people, both male and female, it apparently is a chemical trigger for feelings of satisfaction after sexual contact. Studies suggest that oxytocin is a "cuddle hormone" that helps stimulate affectionate behavior.

The anterior pituitary lobe makes hormones

Unlike the posterior pituitary lobe, the anterior pituitary lobe produces and secretes six hormones:

Corticotropin	ACTH
Thyrotropin	TSH
Follicle-stimulating hormone	FSH
Luteinizing hormone	LH
Prolactin	PRL
Growth hormone (somatotropin)	GH (or STH)

Anterior pituitary hormones have widespread effects. As described shortly, ACTH and TSH regulate the secretion of hormones from the adrenal glands and thyroid gland, respectively. FSH and LH both influence reproduction, as you'll read in Chapter 16. Prolactin is best known for its role in stimulating and sustaining the production of breast milk, after other hormones have primed the tissues. There also is evidence that it promotes the synthesis of the male sex hormone testosterone.

Growth hormone (GH) affects most body tissues. It stimulates the processes by which cells divide and make new proteins, and so has a major influence on growth. GH is also important as a "metabolic hormone." It stimulates cells to take up amino acids and promotes the breakdown and release of fat stored in adipose tissues when cells require more fatty acids. GH also adjusts the rate at which cells take up glucose. In this way it helps to maintain proper blood sugar levels.

The hypothalamus regulates the anterior lobe by secreting hormones that move into blood capillaries in the pituitary stalk. The blood carries those hormones to another capillary bed in the anterior lobe. There the hormones leave the bloodstream and act on their target cells (Figure 15.4). Most of these hormones are **releasers** that spur target cells to secrete their own hormones. For example, GnRH (gonadotropin-releasing hormone) triggers the secretion of FSH and LH. They are gonadotropins, which affect the functioning of cells in the gonads, or reproductive organs. TRH (for thyrotropin-releasing hormone) stimulates the secretion of TSH. Other hypothalamic hormones are **inhibitors**. They *block* secretions from cells in the anterior pituitary. One of them, called somatostatin, inhibits the secretion of growth hormone and thyrotropin.

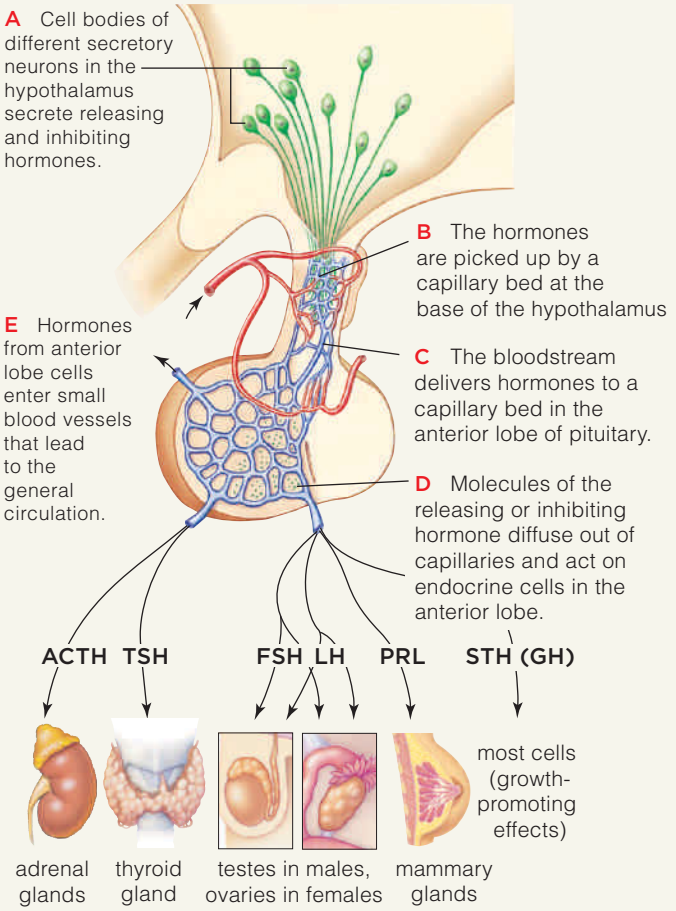


Figure 15.4 Animated! The anterior pituitary lobe both makes and releases hormones. Hormones from the hypothalamus control this activity.

Take-Home Message

What are the endocrine functions of the hypothalamus and the pituitary gland?

- The hypothalamus produces hormones that are stored and released by the posterior pituitary (ADH and oxytocin), or that regulate the activity of the anterior pituitary.
- The anterior lobe of the pituitary produces and secretes ACTH, TSH, FSH, LH, PRL, and GH. These hormones trigger the release of other hormones from other endocrine glands.

15.4 Hormones as Long-Term Controllers

- **Hormones typically regulate actvities that occur over an extended period.**

As you know, nervous system signals control rapid-fire reflexes and speedy responses to changing conditions inside or outside the body. By contrast, the endocrine system specializes in slower, often long-term bodily changes such as growth, sexual maturation, production of red blood cells, and the like. Some of these functions involve hormones from the hypothalamus and pituitary, while others depend on other sources (Table 15.4).

We have now completed our overview of hormones and general information about how they function. The rest of the chapter looks at how some major hormones operate in the body and how disorders arise when those key substances do not function properly.

Take-Home Message

What is the overall role of hormones in the body?

- Hormones generally regulate slower, often long-term changes in the growth or functioning of body parts.

TABLE 15.4 Hormone Sources Other Than the Hypothalamus and Pituitary

Source	Secretion(s)	Main Targets	Primary Actions
Pancreatic islets	Insulin	Muscle, adipose tissue	Lowers blood-sugar level
	Glucagon	Liver	Raises blood-sugar level
	Somatostatin	Insulin-secreting cells	Influences carbohydrate metabolism
Adrenal cortex	Glucocorticoids (including cortisol)	Most cells	Promote protein breakdown and conversion to glucose
	Mineralocorticoids (including aldosterone)	Kidney	Promote sodium reabsorption; control salt–water balance
Adrenal medulla	Epinephrine (adrenalin)	Liver, muscle, adipose tissue	Raises blood level of sugar, fatty acids; increases heart rate, force of contraction
	Norepinephrine	Smooth muscle of blood vessels	Promotes constriction or dilation of blood vessel diameter
Thyroid	Triiodothyronine, thyroxine	Most cells	Regulate metabolism; have roles in growth, development
	Calcitonin	Bone	Lowers calcium levels in blood
Parathyroids	Parathyroid hormone	Bone, kidney	Elevates levels of calcium and phosphate ions in blood
Thymus	Thymosins, etc.	Lymphocytes	Have roles in immune responses
Gonads:			
Testes (in males)	Androgens (including testosterone)	General	Required in sperm formation, development of genitals, maintenance of sexual traits; influence growth, development
Ovaries (in females)	Estrogens	General	Required in egg maturation and release; prepare uterine lining for pregnancy; required in development of genitals, maintenance of sexual traits; influence growth, development
	Progesterone	Uterus, breasts	Prepares, maintains uterine lining for pregnancy; stimulates breast development
Pineal	Melatonin	Hypothalamus	Influences daily biorhythms
Endocrine cells of stomach, gut	Gastrin, secretin, etc.	Stomach, pancreas, gallbladder	Stimulate activity of stomach, pancreas, liver, gallbladder
Liver	IGFs (Insulin-like growth factors)	Most cells	Stimulate cell growth and development
Kidneys	Erythropoietin	Bone marrow	Stimulates red blood cell production
	Angiotensin*	Adrenal cortex, arterioles	Helps control blood pressure, aldosterone secretion
	Vitamin D3*	Bone, gut	Enhances calcium resorption and uptake
Heart	Atrial natriuretic hormone	Kidney, blood vessels	Increases sodium excretion; lowers blood pressure

*These hormones are not produced in the kidneys but are formed when enzymes produced in kidneys activate specific substances in the blood.

15.5 Growth Hormone Functions and Disorders

- **Growth hormone (GH) is so important to normal bodily growth that major abnormalities develop when it does not function properly.**
- **Links to Bone development 5.1, Muscle growth 6.1**

As you read in Section 15.3, growth hormone from the anterior pituitary affects target cells throughout the body. One main effect is stimulating the growth of cartilage and bone and increasing muscle mass. You may recall from Chapter 5 that GH prevents the epiphyseal plates at the ends of growing long bones from hardening during childhood and adolescence. Because this hormone has such major effects on bodily growth, if the pituitary secretes too much or too little of it the impact can be profound.

For instance, **gigantism** results when the anterior lobe of the pituitary overproduces it during childhood. Affected adults are proportionally like an average-sized person but much larger (Figure 15.5*a*). If too much GH is secreted during adulthood, bones, cartilage, and other connective tissues in the hands, feet, and jaws thicken abnormally. So do epithelia of the skin, nose, eyelids, lips, and tongue. The result is **acromegaly** (Figure 15.5*b*).

Both gigantism and acromegaly usually develop as the result of a benign (noncancerous) pituitary tumor.

Pituitary dwarfism occurs when the pituitary makes too little GH, or when receptors cannot respond normally to it. Affected people are quite short but have normal proportions. Pituitary dwarfism can be inherited (Figure 15.5c) or it can result from a pituitary tumor or injury.

Human growth hormone is now made through genetic engineering (Chapter 21). Children who have a naturally low GH level may receive injections of recombinant human growth hormone (rhGH), although the treatment is expensive (up to $20,000 a year) and controversial. Some physicians and ethicists object to short stature being treated as a defect to be cured.

Injections of rhGH are also used to treat adults who have a low GH level as the result of an injury or a tumor of the pituitary or hypothalamus. The injection can help maintain healthy bone and muscle mass while reducing body fat. Entrepreneurs and others have touted rhGH injections as a means to slow normal aging or boost athletic performance. Thus far clinical trials don't bear out this claim, and the drug is not approved for those uses. Negative side effects include increased risk of high blood pressure and diabetes.

Take-Home Message

What are the effects of too much or too little growth hormone?

- Excessive GH causes faster than normal bone growth that leads to gigantism in children and acromegaly in adults. A deficiency during childhood can cause dwarfism.

Figure 15.5 Disorders in bodily growth result from too much or too little growth hormone.

(**a**) This twelve-year-old boy with pituitary gigantism is six feet, five inches tall and towers over his mother.

(**b**) A woman before and after she became affected by acromegaly. Notice how her chin became elongated.

(**c**) Dr. Hiralal Maheshwari, right, with two men from a village in Pakistan where an inherited form of dwarfism is common. Men of the village average a little over 4 feet (130 cm) tall. Dr. Maheshwari found they make less than the typical amount of GH because their pituitary gland does not respond to the releaser hormone from the hypothalamus that usually stimulates GH secretion.

15.6 The Thyroid and Parathyroid Glands

- **Hormones from the thyroid gland are vital to normal development and metabolism. Parathyroid hormone helps regulate calcium levels in the blood.**
- **Links to Bone growth and remodeling 5.1, Autoimmune disorders 9.10, Major dietary minerals 11.11**

Thyroid hormones affect metabolism, growth, and development

The **thyroid gland** is located at the base of the neck in front of the trachea, or windpipe (Figure 15.6). Its main secretions, thyroxine (T_4) and triiodothyronine (T_3), are known jointly as *thyroid hormone* (TH). TH affects the body's overall metabolic rate, growth, and development. The thyroid also makes calcitonin. This hormone helps lower the level of calcium (and of phosphate) in blood. Proper feedback control is essential to the functioning of both these hormones.

For instance, thyroid hormones cannot be synthesized without iodide, a form of iodine. Iodine-deficient diets cause one or both lobes of the thyroid gland to enlarge (Figure 15.7). The enlargement, a **simple goiter**, occurs after low blood levels of thyroid hormones cause the anterior pituitary to secrete TSH (the thyroid-stimulating hormone thyrotropin). The thyroid attempts to make the hormones but cannot do so, which leads to continued secretion of TSH, and so on, in a sustained, but abnormal feedback loop. *Hypothyroidism* is the clinical name for low blood levels of thyroid hormones. Affected adults tend to be overweight, sluggish, intolerant of cold, confused, and depressed. Simple goiter is no longer common in places where people use iodized salt.

Some other forms of goiter and **Graves disease** are the result of *hyperthyroidism*, or excess thyroid hormones in the blood. Symptoms include increased heart rate and blood pressure and unusually heavy sweating. Some cases are autoimmune disorders, in which antibodies wrongly stimulate thyroid cells. In other cases the cause can be traced to inflammation or a tumor in the thyroid gland. Some people are genetically predisposed to the develop the disorder.

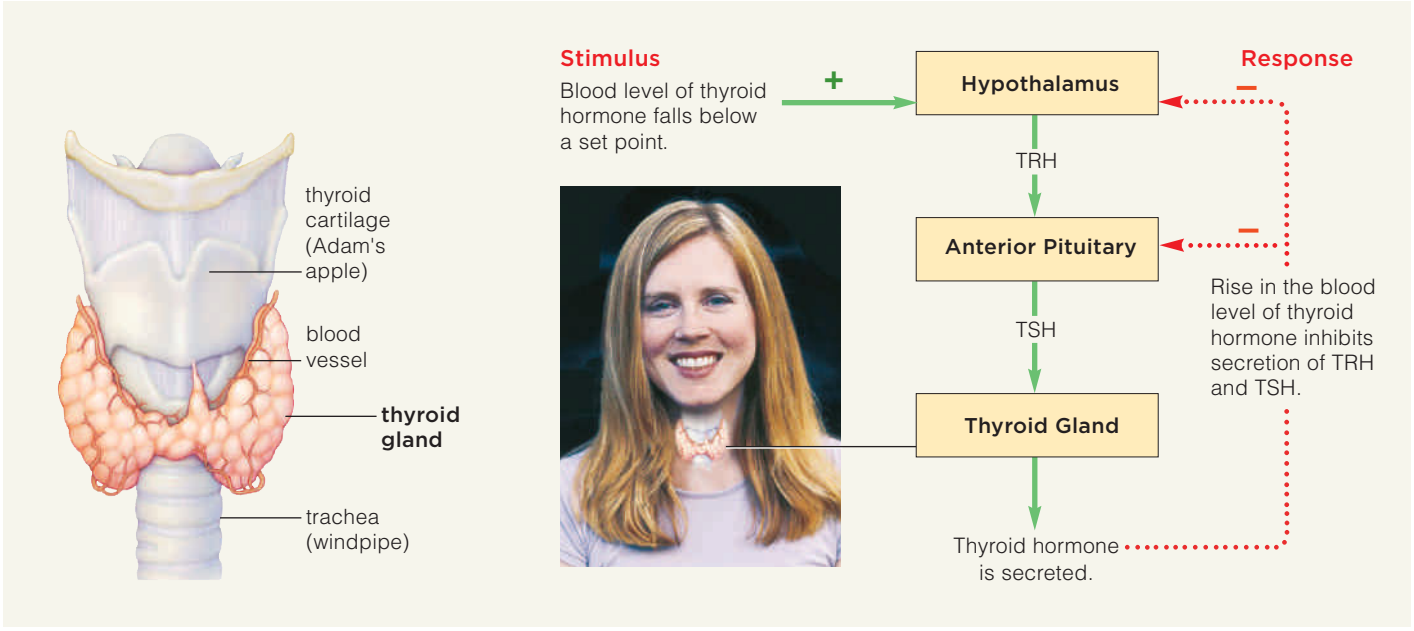


Figure 15.6 Animated! **A negative feedback loop controls the secretion of thyroid hormone.**

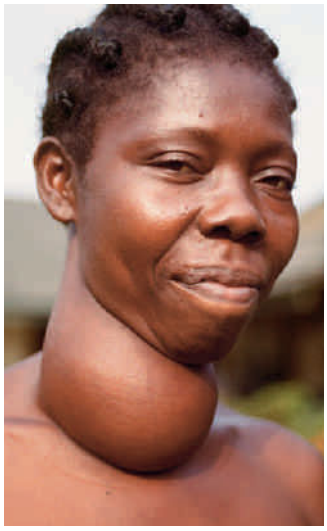
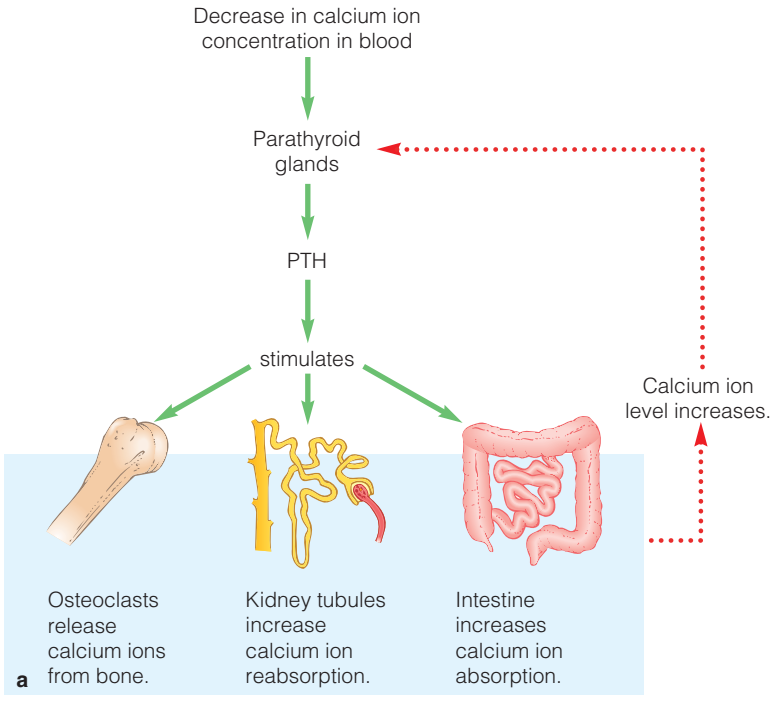


Figure 15.7 **A diet low in the micronutrient iodine may cause a goiter.**



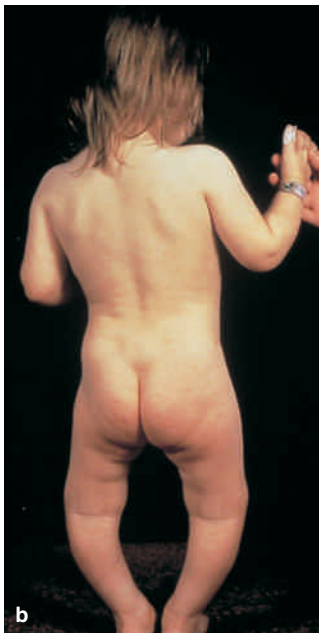
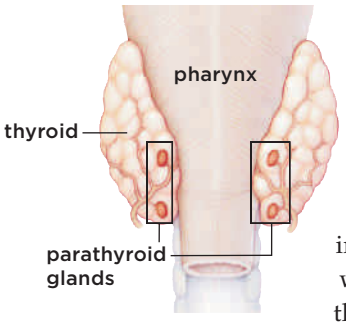


Figure 15.8 **PTH regulates calcium homeostasis.** The diagram in (**a**) shows the feedback loop that controls the release of PTH. (**b**) A child with legs bowed by rickets.

PTH from the parathyroids is the main calcium regulator



Each of us has four **parathyroid glands** located on the back of the thyroid gland, as shown in the diagram here. These little glands secrete parathyroid hormone (PTH), the main regulator of the calcium level in blood. Calcium is important for muscle contraction as well as for the activation of enzymes, the formation of bone, blood clotting, and other tasks. The parathyroids secrete more PTH when the blood level of calcium falls below a set point, and they reduce their secretions when the calcium level rises. The hormone calcitonin from the thyroid gland contributes to processes that remove calcium from the blood.

You may remember that Section 5.1 discussed bone remodeling, the process in which bone is deposited or broken down, depending on the level of calcium in the blood. PTH is the hormone in charge of remodeling, and it acts on the skeleton and kidneys. When the blood level of calcium falls below a set point, PTH prompts the bone cells called osteoclasts to secrete enzymes that digest bone tissue (Figure 15.8). This process releases calcium ions (and phosphate) that can be used elsewhere in the body.

In the kidneys, PTH also stimulates the reabsorption of calcium from the filtrate flowing through nephrons. At the same time, PTH helps to activate vitamin D. The activated form, which is also a hormone, improves the absorption of calcium from food in the GI tract.

In children who have vitamin D deficiency, too little calcium and phosphorus are absorbed, so the rapidly growing bones do not develop properly. Children who have the resulting bone disorder, **rickets** (Figure 15.8*b*), develop bowed legs and other skeletal abnormalities.

Calcium is so essential in the body that disorders related to parathyroid functioning can be quite serious. For example, excess PTH (*hyperparathyroidism*) causes so much calcium to be withdrawn from a person's bones that the bone tissue is dangerously weakened. The excess calcium in the bloodstream may cause kidney stones, and muscles don't function normally. The central nervous system's operations may be so seriously harmed that the affected person dies.

Take-Home Message

What are the roles of hormones from the thyroid and parathyroids?

- Thyroid hormones affect metabolism, growth, and development. Negative feedback loops control the output of these and other endocrine glands.
- Parathyroid glands release PTH, the main regulator of calcium levels in blood.

15.7 Adrenal Glands and Stress Responses

- **Different parts of the adrenal glands secrete hormones that help regulate blood levels of glucose, influence blood pressure, and regulate blood circulation.**
- **Links to Inflammation 9.4, Nutrient processing 11.8, Urine formation 12.4, Stress responses 13.7**

The adrenal cortex produces glucocorticoids and mineralocorticoids

We have two adrenal glands, one on top of each kidney. The outer part of each gland is the **adrenal cortex** (Figure 15.9). There, cells secrete two major types of steroid hormones, the glucocorticoids and mineralocorticoids.

Glucocorticoids raise the blood level of glucose. For instance, the body's main glucocorticoid, *cortisol*, is secreted when the body is stressed and glucose is in such demand that its blood level drops to a low set point. That level is an alarm signal and starts a stress response, which a negative feedback mechanism later cuts off. Among other effects, cortisol promotes the breakdown of muscle proteins and stimulates the liver to take up amino acids, from which liver cells synthesize glucose in a process called **gluconeogenesis**. Cortisol also reduces how much glucose tissues such as skeletal muscle take up from the blood. This effect is sometimes called "glucose sparing." Glucose sparing is extremely important in homeostasis, for it helps ensure that the blood will carry enough glucose to supply the brain, which usually cannot use other molecules for fuel. Cortisol also promotes the breakdown of fats and the use of the resulting fatty acids for energy.

Figure 15.9 diagrams the negative feedback loop for cortisol. When the blood level of cortisol rises above a set point, the hypothalamus begins to produce less of the releasing hormone CRH. The anterior pituitary responds by secreting less ACTH, and the adrenal cortex secretes less cortisol. In a healthy person, daily cortisol secretion is highest when the blood glucose level is lowest, usually in the early morning. Chronic severe **hypoglycemia**, or low blood sugar, can develop when the adrenal cortex makes too little cortisol. Then, mechanisms that spare glucose and make new supplies in the liver don't work properly.

Glucocorticoids also reduce inflammation. The adrenal cortex pumps out more of these chemicals at times of unusual physical stress such as a painful injury, severe illness, or a strong allergic reaction. The extra cortisol and other signaling molecules helps speed recovery. That is why doctors prescribe cortisol-like drugs such as cortisone for patients with asthma or serious inflammatory disorders. Cortisone is the active ingredient in many over-the-counter products for treating skin irritations.

Unfortumately, long-term use of heavy doses of glucocorticoids has serious side effects, including suppressing the immune system. Long-term stress has the same effect, as described shortly.

For the most part, **mineralocorticoids** adjust the concentrations of mineral salts, such as potassium and sodium, in the extracellular fluid. The most abundant mineralocorticoid is aldosterone. You may recall from Section 12.4 that aldosterone acts on the distal tubules of kidney nephrons, stimulating them to reabsorb sodium ions and excrete potassium ions. The reabsorption of sodium in turn promotes reabsorption of water from the tubules as urine is forming. A variety of circumstances can cause the release of aldosterone. Common triggers include falling blood pressure or falling blood levels of sodium—which reduces blood volume because water moves out of the bloodstream by osmosis.

In a fetus and early in puberty, the adrenal cortex also makes large amounts of sex hormones. The main ones are androgens (male sex hormones), but female sex hormones (estrogens and progesterone) also are produced. In adults, the reproductive organs generate most sex hormones.

Hormones from the adrenal medulla help regulate blood circulation

The **adrenal medulla** is the inner part of the adrenal gland shown in Figure 15.9. It contains neurons that release two substances, epinephrine and norepinephrine. Both act as neurotransmitters when they are secreted by neurons elsewhere in the body. When the adrenal medulla secretes them, however, their hormonelike effects help regulate blood circulation and carbohydrate use when the body is stressed or excited. For example, they increase the heart rate, dilate arterioles in some areas and constrict them in others, and dilate bronchioles. Thus the heart beats faster and harder, more blood is shunted to heart and muscle cells from other regions, and more oxygen flows to energy-demanding cells throughout the body. These are aspects of the fight–flight response noted in Chapter 13.

The operation of the adrenal medulla provides another example of negative feedback control. For example, when the hypothalamus sends the necessary signal (by way of sympathetic nerves) to the adrenal medulla, the neuron axons will start to release norepinephrine into the synapse

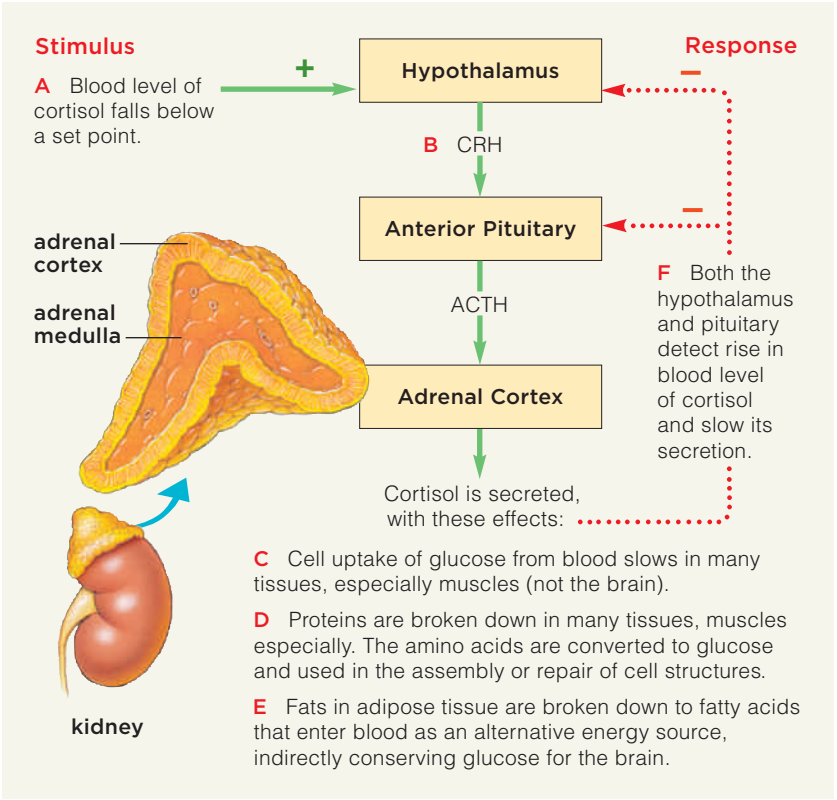


Figure 15.9 Animated! **The adrenal glands produce cortisol, the stress hormone.** Each gland rests atop a kidney. The diagram shows a negative feedback loop that governs the secretion of cortisol.

Figure 15.10 Reducing stress may benefit your health. Physical exercise and social activities are good stress reducers.

between the axon endings and the target cells. Soon, norepinephrine molecules collect in the synapse, setting the stage for a localized negative feedback mechanism. As the accumulating norepinephrine binds to receptors on the axon endings, the release of norepinephrine soon shuts down.

Long-term stress can damage health

As you've just read, when the body is stressed, nervous system commands trigger the fight–flight response and the release of cortisol, epinephrine, and norepinephrine. In daily life, most people also encounter a wide variety of psychosocial stressors—an exam, financial difficulties, a new job or romance, and the like. As you can see from this short list, some stressors are positive, others are negative. Not everyone reacts the same way to life's challenges, but there is ample evidence that being routinely "stressed out" by negative stressors may contribute to hypertension and related cardiovascular disease. And because cortisol suppresses the immune system, people who experience a lot of "bad" stress also may be more susceptible to disease. Chronic negative stress also is linked to insomnia, anxiety, and depression.

Fortunately, research also shows that social connections seem to moderate the effects of stress, as does regular physical exercise (Figure 15.10). Friends, family, support groups, and counselors can not only make you feel better, they may make you healthier as well.

Take-Home Message

What are the roles of hormones from the adrenal glands?

- The adrenal cortex secretes glucocorticoids such as cortisol and mineralocorticoids such as aldosterone.
- Cortisol raises blood glucose levels and suppresses inflammation. Aldosterone helps regulate blood pressure by adjusting reabsorption of potassium and sodium in the kidneys.
- The adrenal medulla makes epinephrine and norepinephrine. They adjust blood circulation and the use of blood sugar in the fight–flight response to stress.

15.8 The Pancreas: Regulating Blood Sugar

- **The pancreas hormones insulin and glucagon work antagonistically—the action of one opposes the action of the other. Controls over the release of these hormones maintain the glucose level in blood.**
- **Link to Accessory organs of digestion 11.5**

The pancreas has both exocrine *and* endocrine functions. As Chapter 11 noted, its exocrine cells release digestive enzymes into the small intestine. It also has some 2 million scattered clusters of endocrine cells. Each cluster is a **pancreatic islet** and contains three types of hormone-secreting cells:

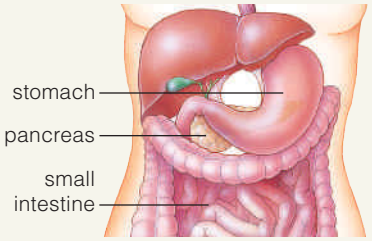
1. *Alpha cells* secrete **glucagon**. Between meals, cells use the glucose delivered to them by the bloodstream. When the blood glucose level decreases below a set point, secreted glucagon acts on cells in the liver and muscles. It causes glycogen (a storage polysaccharide) and amino acids to be converted to glucose. In this way glucagon raises the glucose level in the blood.
2. *Beta cells* secrete the hormone **insulin**. After meals, when a lot of glucose is circulating in the blood, insulin stimulates muscle and adipose cells to take up glucose. It also promotes synthesis of fats, glycogen, and to a lesser extent, proteins, and inhibits the conversion of proteins to glucose. In this way insulin lowers the glucose level in the blood.
3. *Delta cells* secrete **somatostatin**. This hormone acts on beta cells and alpha cells to inhibit secretion of insulin and glucagon, respectively. Somatostatin is part of several hormone-based control systems. For example, it is released from the hypothalamus to block secretion of growth hormone; it is also secreted by cells of the GI tract, where it acts to inhibit the secretion of various substances involved in digestion.

Even with all the variations in when and how much we eat, pancreatic hormones help keep blood glucose levels fairly constant (Figure 15.11).

Take-Home Message

How do endocrine cells of the pancreas regulate blood sugar?

- Alpha cells of the pancreatic islets secrete glucagon when the blood level of glucose (sugar) falls below a set point.
- Beta cells secrete insulin when blood levels of glucose rise above the set point.
- Somatostatin from delta cells regulates the functioning of alpha and beta cells.



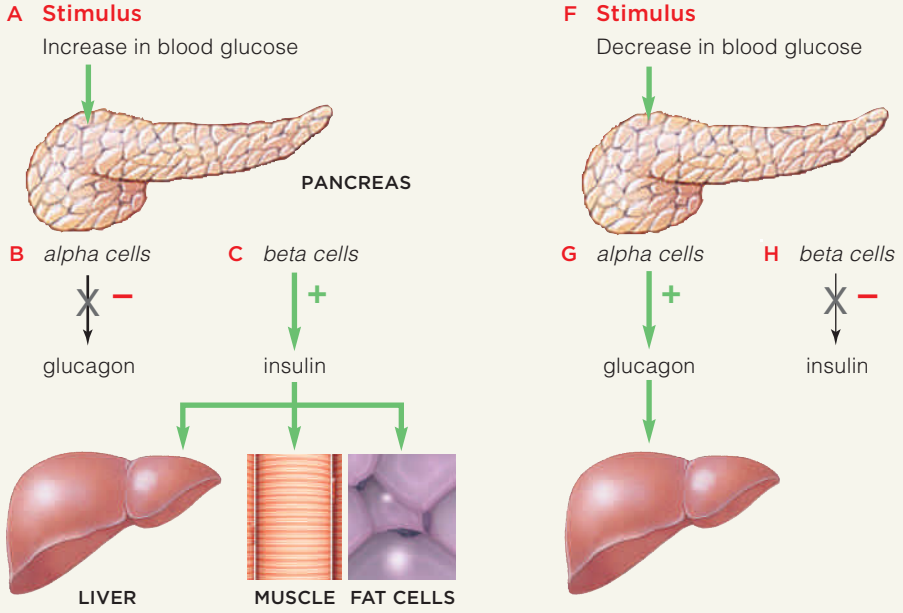


Figure 15.11 Animated! Cells that secrete insulin and glucagon respond to a change in the level of glucose in blood. These two hormones work antagonistically to maintain normal blood sugar levels.

(**a**) *After* a meal, the blood level of glucose increases. In the pancreas, the increase (**b**) stops alpha cells from secreting glucagon and (**c**) stimulates beta cells to secrete insulin. In response to insulin, (**d**) adipose and muscle cells take up and store glucose, and liver cells make more glycogen. As a result, insulin *lowers* blood sugar (**e**).

(**f**) *Between* meals, blood sugar falls. The decrease (**g**) stimulates alpha cells to secrete glucagon and (**h**) slows the insulin secretion by beta cells. (**i**) In the liver, glucagon causes cells to convert glycogen back to glucose, which enters the blood. As a result, glucagon *raises* blood sugar (**j**).

15.9 Blood Sugar Disorders

Too little insulin can lead to **diabetes mellitus**. Because target cells can't take up glucose from blood, glucose builds up in the blood (*mellitus* means "honey" in Greek). The kidneys move excess sugar into the urine, water is also lost, and the body's water–solute balance is upset. Affected people become dehydrated and extremely thirsty. They also lose weight as their glucose-starved cells break down protein and fats for energy. Fat breakdown releases ketones, so these acids build up in the blood and urine. This can lead to dangerously low blood pressure and **metabolic acidosis**, a blood pH so slow (acidic) that it may harm functioning of the brain.

About 1 in 10 diabetics has **type 1 diabetes**, in which an autoimmune response destroys pancreas beta cells. It may be caused by a viral infection in combination with genetic susceptibility. Symptoms usually appear early in life. Affected people survive with insulin injections.

Type 2 diabetes is a global health crisis

In **type 2 diabetes**, insulin levels are near or above normal, but for any of several reasons target cells can't respond properly to the hormone. The beta cells break down and steadily produce less insulin. According to the World Health Organization, in developed countries type 2 diabetes has reached crisis proportions, along with its major risk factor, obesity.

Blood containing too much sugar damages capillaries. Over time, the blood supply to the kidneys, eyes, and lower limbs may be so poor that tissues die and terrible complications may develop (Table 15.5).

Diabetes also correlates strongly with cardiovascular disease. Even diabetics in their 20s and 30s are at high risk of suffering a stroke or heart attack.

Metabolic syndrome is a warning sign

As many as 20 million Americans have "prediabetes"—slightly elevated blood sugar that increases the risk of developing type 2 diabetes. An early indicator that someone may be at risk for diabetes is a set of features that are lumped together as **metabolic syndrome**:

- An "apple shape,"with a waist measuring more than 35 inches for males, more than 40 inches for females.
- Blood pressure of 130/85 mm Hg or higher
- Low levels (under 40 mg/dL for males, 50 mg/dL for females) of HDL, the "good" cholesterol
- Fasting glucose of 110 mg/dL or higher
- Fasting triglyceride level of 150 mg/dL or higher

Type 2 diabetes can be controlled by a combination of proper diet, regular exercise, and sometimes by drugs that improve insulin secretion or activity (Figure 15.12).

Low blood sugar threatens the brain

In **hypoglycemia**, so much sugar is removed from the blood that cells in the brain and elsewhere may suddenly have too little fuel to function properly. Anything that raises the blood level of insulin, such as a miscalculated insulin injection or an insulin-secreting tumor, can cause hypoglycemia. The result can be life-threatening *insulin shock*, in which the brain essentially "stalls" as its fuel dwindles. A person experiencing insulin shock may feel dizzy and confused and have trouble talking. Anything that quickly raises blood sugar, including a shot of glucagon, solves the problem.

TABLE 15.5 Some Complications of Diabetes

Eyes	Changes in lens shape and vision; damage to blood vessels in retina; blindness
Skin	Increased susceptibility to bacterial and fungal infections; patches of discoloration; thickening of skin on the back of hands
Digestive system	Gum disease; delayed stomach emptying that causes heartburn, nausea, vomiting
Kidneys	Increased risk of kidney disease and failure
Heart and blood vessels	Increased risk of heart attack, stroke, high blood pressure, and atherosclerosis
Hands and feet	Impaired sensations of pain; formation of calluses, foot ulcers; possible amputation of a foot or leg because of necrotic tissue that formed owing to poor circulation

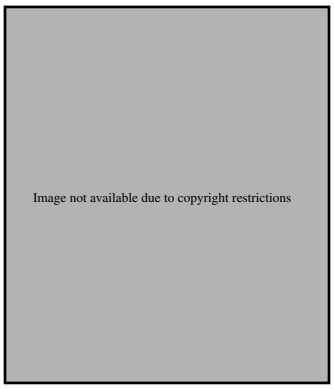


Figure 15.12 A diabetic checks his blood glucose by placing a blood sample into a glucometer. Compared with Caucasians, Hispanics and African Americans are about 1.5 times more likely to be diabetic. Native Americans and Asians are at even greater risk. Proper diet helps control blood sugar, even in type 1 diabetics.

15.10 Other Hormone Sources

- **Endocrine cells in the gonads, parts of the brain, the thymus, the heart, and the GI tract make hormones.**
- **Links to the Heart 7.2, Controls over digestion 11.8, Lymphatic system 9.2**

The gonads produce sex hormones

The human primary sex organs are called **gonads**. Most people know them by their more familiar biological names, ovaries in females and testes in males (Figure 15.13). In addition to producing sex cells—eggs in ovaries, sperm in testes—the gonads also make sex hormones. The ovaries make **estrogens** and **progesterone**. The testes make mostly **testosterone**, but they also make a little bit of estrogen and progesterone. Small amounts of these "female" hormones are required for proper development of sperm. Similarly, a female's ovaries make small amounts of testosterone. It contributes to libido, the desire for sex.

The pineal gland makes melatonin

Many ancient vertebrates had a light-sensitive "third eye" on top of the head. In humans a version of this organ still exists, as a lump of tissue in the brain called the **pineal gland**. It releases the hormone *melatonin* into cerebrospinal fluid and the bloodstream. Melatonin influences sleep/wake cycles. It is secreted in the dark, so the amount in the bloodstream varies from day to night. It also changes with the seasons, because winter days are shorter than summer days.

The human cycle of sleep and arousal is evidence of an internal **biological clock** that apparently monitors day length. Melatonin seems to influence the clock, which can be disturbed by circumstances that alter a person's accustomed exposure to light and dark. Jet lag is an example.

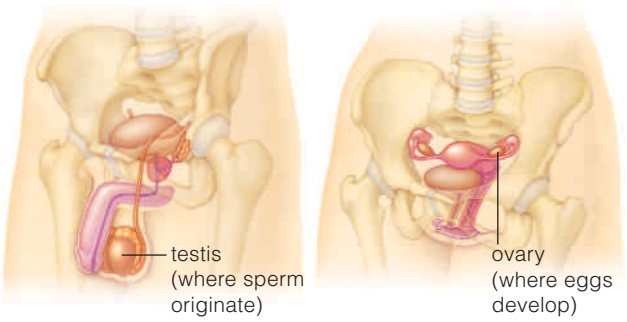
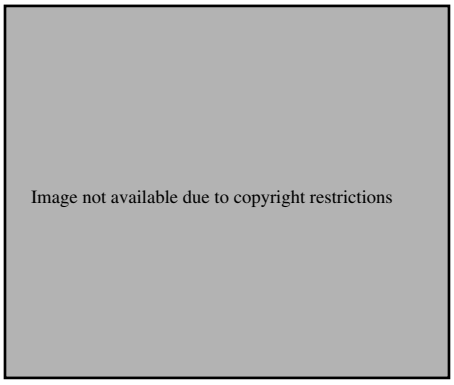


Figure 15.13 **Male and female gonads produce sex hormones as well as sex cells (sperm in males and eggs in females).**

Some air travelers use melatonin supplements to try to adjust their sleep/wake cycles more quickly.



Depression, intense sleepiness, and other symptoms of seasonal affective disorder, or **SAD**, hit some people in winter. SAD may be due to a biological clock that is out of sync with changes in day length during winter, when days are shorter and nights longer. The symptoms get worse when a person takes melatonin. They improve when the person is exposed to intense light, which shuts down the pineal gland.

Melatonin may affect the gonads. A decline in melatonin production starts at puberty and may help trigger it. Some pineal gland disorders accelerate or delay puberty.

The thymus, heart, and GI tract also produce hormones

The thymus gland (see Figure 15.1) releases hormones called thymosins that help infection-fighting T cells mature. The two heart atria secrete *atrial natriuretic peptide*, or ANP. When your blood pressure rises, ANP acts to inhibit the reabsorption of sodium ions—and hence water—in the kidneys. As a result, more water is excreted, the blood volume decreases, and blood pressure falls.

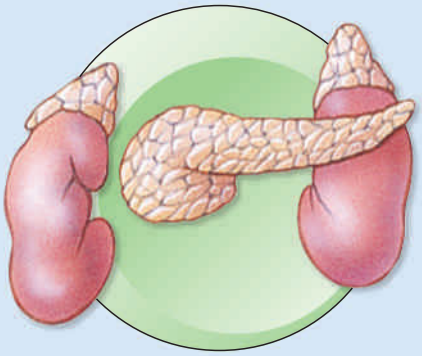
Chapter 11 indicated that the digestive tract produces several hormones that influence appetite or have roles in digestion. For example, gastrin stimulates the release of stomach acid when proteins are being digested. Secretin stimulates the pancreas to secrete bicarbonate.

Take-Home Message

What are the endocrine roles of the gonads, pineal gland, thymus, heart, and GI tract?

- A female's ovaries or a male's testes are gonads that produce sex hormones as well as gametes (eggs or sperm).
- The pineal gland is in the brain and produces melatonin, which influences sleep-wake cycles and the onset of puberty.
- The thymus is in the chest and secretes thymosins that are necessary for the maturation of T cells.
- The heart atria produce ANF, which helps regulate blood pressure. The GI tract produces hormones that have roles in digestion.

15.11 CONNECTIONS: The Endocrine System in Homeostasis

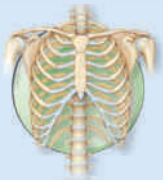


The Endocrine System

The endocrine system produces hormones, signaling molecules that travel in the bloodstream to nearly all body cells. Each kind of hormone adjusts the metabolic activity of its target cells. Together with signals of the nervous system, these changes adjust body functions in ways that maintain homeostasis in the body as whole.

In general, responses to hormones take longer and last longer than responses to nerve impulses. Hormones govern long-term events such as bodily growth and metabolism.

Skeletal system

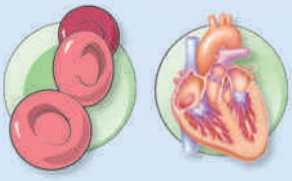


Growth hormone stimulates the growth of bones. Calcitonin stimulates uptake of calcium from blood as needed to form bone tissue.

Muscular system

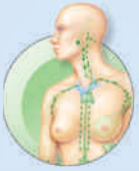
Growth hormone stimulates development of skeletal muscle mass. Parathyroid hormone (PTH) adjusts blood levels of calcium and potassium, electrolytes that are essential for muscle contraction.

Cardiovascular system and blood



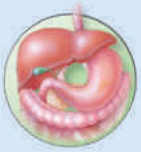
Epinephrine adjusts heart rate and helps maintain blood pressure. Erythropoietin from the kidneys stimulates production of red blood cells. Aldosterone indirectly (via the kidneys) helps restore falling blood volume and pressure. PTH adjusts blood levels of electrolytes needed for cardiac muscle contraction.

Immunity and the lymphatic system



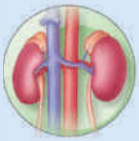
Thymus hormones stimulate T cells to mature. Cortisol from the adrenal cortex increases blood levels of glucose, amino acids, and other molecules used in tissue repair.

Digestive system



Insulin and GH support the delivery of nutrients to all cells by stimulating cells to take up glucose from the bloodstream.

Urinary system



Aldosterone and ANP support the urinary system's management of salt–water balance by promoting or reducing the reabsorption of sodium.

Nervous system

Epinephrine supports the sympathetic nervous system in the fight–flight response and helps the CNS regulate blood pressure. Hormones that regulate blood sugar ensure adequate fuel for brain cells.

Reproductive system

The hypothalamus regulates the release of sex hormones that govern the development and functioning of ovaries and testes (the gonads). Oxytocin triggers uterine muscle contractions during labor and (with prolactin) for milk release for a nursing infant. Luteinizing hormone (LH) and follicle-stimulating hormone (FSH) also have key roles in reproduction.

IMPACTS, ISSUES

Hormones in the Balance

How Would You Vote?

Should potentially harmful chemicals stay on the market while researchers study their safety? See CengageNOW for details, then vote online.

RECENTLY a study of geographic differences in the quality of semen showed that men from Columbia, Missouri, had fewer healthy sperm than men from New York, Minneapolis, or Los Angeles. The researchers suspect that the reduced sperm counts may be related to exposure to agricultural chemicals. More studies are under way.

Summary

Section 15.1 Hormones are produced by cells and glands of the endocrine system. They move through the bloodstream to distant target cells.

Other signaling molecules include neurotransmitters and local signaling molecules such as prostaglandins. All are chemicals released in small amounts by one cell and adjust the behavior of other, target cells. Any cell with receptors for the signal is the target.

Hormones may interact in opposition, synergistically (in cooperation), or permissively (a target cell must first be primed by one hormone in order to respond to a second one).

Section 15.2 Steroid and nonsteroid hormones act on target cells by different mechanisms.

Receptors for steroid (and thyroid) hormones are inside target cells. A hormone-receptor complex binds to DNA. Binding activates genes and protein-making processes.

Amine, peptide, and protein hormones interact with receptors on the plasma membrane of target cells. Often a second messenger, such as cyclic AMP, carries their signals inside the cell.

Most of nonsteroid hormones alter the activity of target cell proteins. The resulting target cell responses help maintain homeostasis in extracellular fluid or contribute to normal development or reproductive functioning.

Section 15.3 The hypothalamus and pituitary gland interact to integrate many body activities.

ADH and oxytocin from the hypothalamus are stored in and released from the posterior lobe of the pituitary. ADH influences fluid volume. Oxytocin affects reproductive functions such as lactation and labor..

Additional hypothalamic hormones are releasers or inhibitors of hormones secreted by the anterior lobe of the pituitary gland.

Of the six hormones produced in the anterior lobe, two (prolactin and growth hormone) have widespread effects on body cells. Four (ACTH, TSH, FSH, and LH) act on specific endocrine glands.

- Use the animation and interaction on CengageNOW to study how the hypothalamus and pituitary interact.

Section 15.4 Hormones are released by a wide variety of organs, tissues, and cells. They typically regulate events that occur over an extended period, such as bodily growth.

Section 15.5 Growth hormone (GH) influences growth throughout the body, but effects are most obvious in bones and skeletal muscles.

Section 15.6 Thyroid hormone affects overall metabolism, growth, and development. The thyroid also makes calcitonin, which helps lower blood levels of calcium and phosphate. Parathyroid hormone is the main regulator of blood calcium levels.

Section 15.7 The adrenal cortex makes two kinds of steroid hormones, the glucocorticoids andmineralocorticoids. Cortisol and other glucocorticoids raise the blood level of glucose and reduce inflammation. Mineralocorticoids adjust levels of minerals such as potassium and sodium in body fluids.

The adrenal medulla releases epinephrine and norepinephrine. Their hormonelike effects include the regulation of blood pressure and the metabolism of carbohydrates. (Some neurons also release them as neurotransmitters.)

- Use the animation and interaction on CengageNOW to see how negative feedback maintains cortisol levels.

Section 15.8, 15.9 Blood levels of glucose are regulated by insulin and glucagon, which are secreted in the pancreatic islets by beta and alpha cells, respectively. Insulin stimulates muscle and adipose cells to take up glucose, while glucagon stimulates glucose-releasing reactions in muscle and the liver. Negative feedback governs both processes. Somatostatin released by islet delta cells can inhibit the release of insulin, glucagon, and some other hormones.

In blood sugar disorders, too little or too much insulin unbalances the usual controls over blood glucose levels.

- Use the animation and interaction on CengageNOW to see how insulin and glucagon regulate blood sugar.

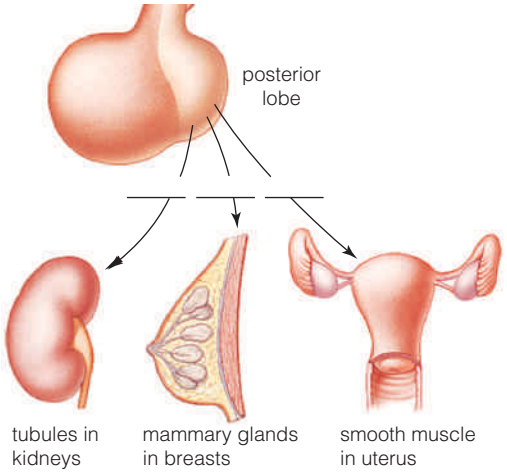
Section 15.10 The gonads produce sex hormones. A female's ovaries mainly make estrogens and progesterone and a male's testes mainly make testosterone. The pineal gland in the brain produces melatonin in response to

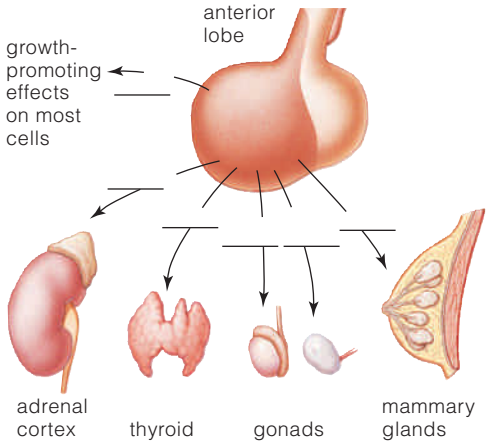
light/dark cycles. Melatonin influences sleep/wake cycles as part of an internal biological clock.

The thymus makes hormones that help T cells mature. The heart secretes ANF, which helps regulate blood pressure. The GI tract secretes several hormones that function in digestion.

Review Questions

1. Distinguish among hormones, neurotransmitters, local signaling molecules, and pheromones.
2. A hormone molecule binds to a receptor on a cell membrane. It doesn't enter the cell; rather, the binding activates a second messenger inside the cell that triggers an amplified response to the hormonal signal. Is the signaling molecule a steroid or a nonsteroid hormone?
3. Which hormones produced in the posterior and anterior lobes of the pituitary gland have the targets indicated? *(Below, fill in the blanks using the abbreviations noted in Section 15.3.)*
4. Name the main endocrine glands and state where each is located in the body.
5. Give two examples of feedback control of hormone activity.





Self-Quiz *Answers in Appendix V*

1. _____ are molecules released from a signaling cell that have effects on target cells.
   a. Hormones
   b. Neurotransmitters
   c. Local signaling molecules
   d. Pheromones
   e. a and b
   f. All of the above
2. Hormones are produced by _____.
   a. endocrine glands and cells
   b. some neurons
   c. exocrine cells
   d. a and b
   e. a and c
   f. a, b, and c
3. ADH and oxytocin are hypothalamic hormones secreted from the pituitary's _____ lobe.
   a. anterior
   b. posterior
   c. primary
   d. secondary
4. _____ has effects on body tissues in general.
   a. ACTH
   b. TSH
   c. LH
   d. Growth hormone
5. Which of the following stimulate the secretion of hormones?
   a. neural signals
   b. local chemical changes
   c. hormonal signals
   d. environmental cues
   e. All of the above can stimulate hormone secretion.
6. _____ lowers blood sugar levels; _____ raises the level of blood sugar.
   a. Glucagon; insulin
   b. Insulin; glucagon
   c. Gastrin; insulin
   d. Gastrin; glucagon
7. The pituitary detects a rising hormone concentration in blood and inhibits the gland that is secreting the hormone. This is a _____ feedback loop.
   a. positive
   b. negative
8. Second messengers assist _____.
   a. steroid hormones
   b. nonsteroid hormones
   c. only thyroid hormones
   d. both a and b
9. Match the hormone source with the closest description.

____ adrenal cortex	a. affected by day length
____ adrenal medulla	b. cortisol source
____ thyroid gland	c. roles in immunity
____ parathyroids	d. adjust(s) blood calcium level
____ pancreatic islets	e. epinephrine source
____ pineal gland	f. insulin, glucagon
____ thymus	g. hormones require iodine

10. Match the endocrine control concepts.

____ oxytocin	a. released by the anterior pituitary and affects the adrenal gland
____ ACTH	b. influences extracellular fluid volume
____ ADH	c. has general effects on growth
____ growth hormone	d. triggers uterine contractions
____ estrogen	e. a steroid hormone

Critical Thinking

1. Addison's disease develops when the adrenal cortex does not secrete enough mineralocorticoids and glucocorticoids. President John F. Kennedy was diagnosed with the disease when he was a young man. Before he started treatment with hormone replacement therapy, he was hypoglycemic and lost weight. Which missing hormone was responsible for his weight loss? How might Addison's disease have affected his blood pressure?
2. A physician sees a patient whose symptoms include sluggishness, depression, and intolerance to cold. After eliminating other possible causes, the doctor diagnoses a hormone problem. What disorder fits the symptoms? Why does the doctor suspect that the underlying cause is a malfunction of the anterior pituitary gland?
3. Marianne has type 1 diabetes. One day, after accidentally injecting herself with too much insulin, she starts to shake and feels confused. Following her doctor's suggestion, she drinks a glass of orange juice—a ready source of glucose—and soon her symptoms subside. What caused her symptoms? How would a glucose-rich snack help?
4. Secretion of the hormone ADH may decrease or stop if the pituitary's posterior lobe is damaged, as by a blow to the head. This is one cause of *diabetes insipidus*. People with this form of diabetes excrete so much dilute urine that they may become seriously dehydrated. Where are the target cells of ADH?

EXPLORE ON YOUR OWN

This Student Stress Scale lists a variety of life events that cause stress for young adults. The score for each event represents its relative impact on stress-related physiological responses. In general, people who score 300 points or more have the highest stress-related health risk. A score of 150–300 points indicates a moderate (50–50) stress-related health risk. A score below 150 indicates the lowest stress-related health risk, about a 1 in 3 chance of a significant, negative change in health status.

Although this test is only a general measure of stress, it can help you decide if you can benefit from adding to or improving your stress management activities, such as getting exercise, including some "down time" in your daily schedule, or seeking counseling.

Event	Points	
Death of a close family member	100	___
Death of a close friend	73	___
Parents' divorce	65	___
Jail term	63	___
Major personal injury or illness	63	___
Marriage	58	___
Being fired from a job	50	___
Failing an important course	47	___
Change in health of family member	45	___
Pregnancy (or causing one)	45	___
Sex problems	44	___
Serious argument with close friend	40	___
Change in financial status	39	___
Change of major	39	___
Trouble with parents	39	___
New romantic interest	38	___
Increased workload at school	37	___
Outstanding personal achievement	36	___
First quarter/semester in college	35	___
Change in living situation	31	___
Serious argument with instructor	30	___
Lower grades than expected	29	___
Change in sleeping habits	29	___
Change in social activities	29	___
Change in eating habits	28	___
Chronic car trouble	26	___
Change in number of family get-togethers	26	___
Too many missed classes	25	___
Change of college	24	___
Dropping more than one class	23	___
Minor traffic violations	20	___

Total _____

Adapted from the Holmes and Rahe Life Event Scale.

Reproductive Systems

16

IMPACTS, ISSUES

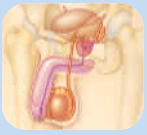
Fertility Plus

IN December of 1998, a Texas mother gave birth to octuplets—six girls and two boys. She had received a fertility drug, which caused many eggs to mature and be ovulated at the same time. Born prematurely, her babies' combined weight was just over ten pounds. Missing from the photo on the left is Odera, the smallest, who weighed less than a pound (520 grams) and died of heart and lung failure after six days. The other newborns had to remain in the hospital for three months.

Since the mid-1980s, the incidence of triplets and other higher-order multiple births has quadrupled. This sharp increase worries some doctors. Carrying more than one embryo increases the risk of miscarriage, prematurity, and delivery complications that require surgery, such as cesarean section. Compared to single births, newborn weights are lower and mortality rates are higher. The babies also are more likely to have development delays.

In this chapter we turn our focus to the reproductive system, the only body system that does not contribute to homeostasis. Instead, its role is to continue our species. In Chapter 15 we noted that human **reproductive systems** consist of a pair of gonads, or primary reproductive organs—testes in males, ovaries in females—plus accessory glands and ducts. Testes make sperm and ovaries make eggs. Our reproductive organs also release powerful sex hormones that guide reproduction and the development of secondary sexual traits.

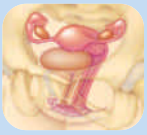
KEY CONCEPTS



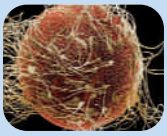
The Male Reproductive System

A male's reproductive system consists of testes and accessory ducts and glands. Hormones control its functions, including making sperm. Sections 16.1, 16.2

The Female Reproductive System



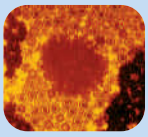
Ovaries are the primary reproductive organs of females. Hormones control their functions, such as the development of oocytes (eggs). Sections 16.3, 16.4



Sexual Intercourse and Fertility

Sexual intercourse between a male and female is the usual first step toward pregnancy. Various methods exist for limiting or enhancing fertility. Sections 16.5–16.8

Sexually Transmitted Diseases and Cancers of the Reproductive System



Sexual contact can transmit bacteria, viruses, and other disease-causing pathogens. Sections 16.9–16.12

LINKS TO EARLIER CONCEPTS

- This chapter builds on knowledge of hormones, including the steroid sex hormones estrogen and testosterone (15.1, 15.2).
- You will see how negative feedback loops (4.10) regulate the production of sperm in males and the menstrual cycle in females.
- You will also learn more about the specialized cell structures called flagella, which propel sperm (3.9), and about chromosomes, the structures that carry genes (3.6).
- You will read about the viruses, bacteria, and other pathogens that cause sexually transmitted diseases, and gain a fuller understanding of major reproductive cancers.

How Would You Vote?

Fertility drugs make many eggs mature at the same time and increase the odds of multiple pregnancies. Should the use of such drugs be discouraged to lower the number of high-risk pregnancies? See CengageNOW for details, then vote online.

16.1 The Male Reproductive System

- A male's testes produce sperm and hormones that govern male reproductive functions and traits.
- Links to Flagella 3.9, Testosterone 15.10

TABLE 16.1 Male Reproductive System

Reproductive organs	
Testes (2)	Sperm, sex hormone production
Epididymides (2)	Site of sperm maturation and subsequent storage
Vasa deferentia (2)	Rapid transport of sperm
Ejaculatory ducts (2)	Conduct sperm to penis
Penis	Organ of sexual intercourse
Accessory glands	
Seminal vesicles (2)	Secrete most fluid in semen
Prostate gland	Secretes some fluid in semen
Bulbourethral glands (2)	Secrete lubricating mucus

Gonads produce gametes—cells that may unite for sexual reproduction

A male's gonads contain **germ cells** that produce sperm. As you'll read shortly, similar cells in ovaries produce eggs. The word *germ* comes from a Latin word that means "to sprout." Sperm and eggs are sometimes called **gametes** (GAM-eets), from a Greek word that means "to marry." Later on in this chapter we will consider how the process of fertilization brings sperm and eggs together to form the first cell of a new individual. With these ideas in mind, let's begin our tour of the male reproductive system.

Sperm form in testes

Figure 16.1 shows an adult male's reproductive system and Table 16.1 lists the functions of its organs. In an embryo that will develop as a male, two testes form on the abdominal cavity wall. Before birth, the testes descend into the scrotum, a pouch of skin suspended below the pelvic girdle (Figure 16.2). Inside this pouch, smooth muscle encloses the **testes**.

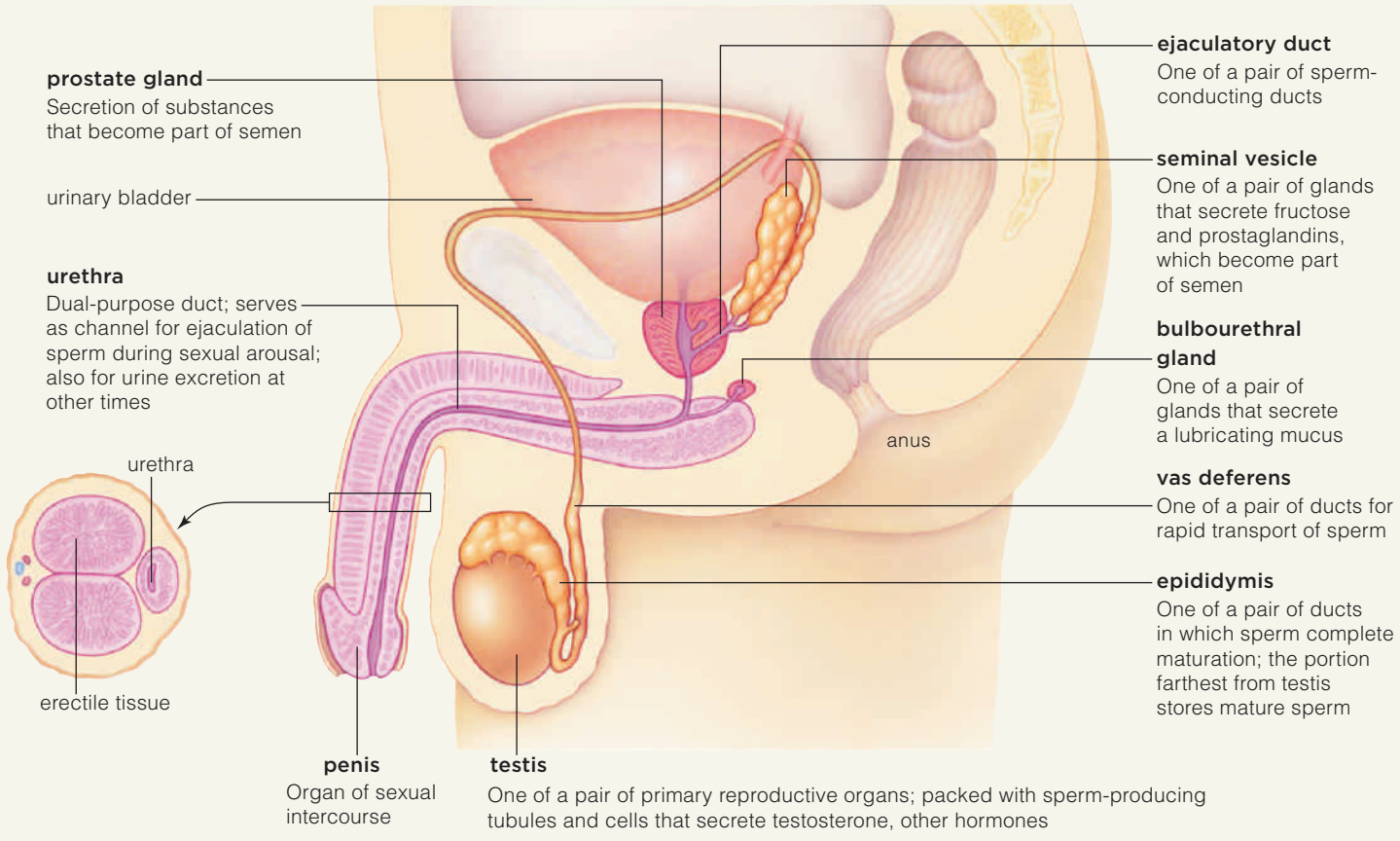


Figure 16.1 Animated! The male reproductive system includes testes and many accessory structures.

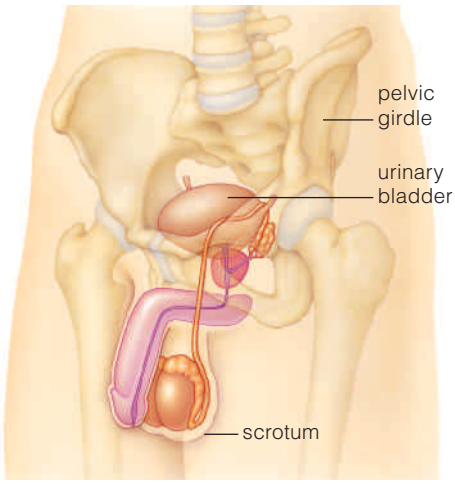


Figure 16.2 **The male reproductive system is located in the lower pelvic region.**

For sperm cells to develop properly, the temperature inside the scrotum must be a few degrees cooler than body core temperature. To this end, a control mechanism helps assure that the scrotum's internal temperature is always close to 95°F. When a male feels cold or afraid, contractions draw his testes closer to his body. When he feels warm, the muscles relax and allow the testes to hang lower, so the sperm-making cells do not overheat.

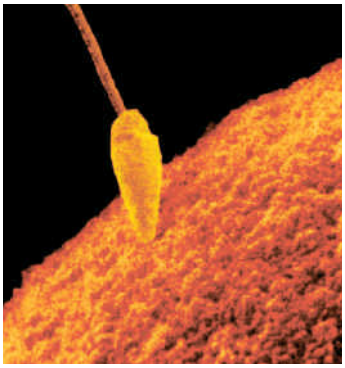
Sperm mature and are stored in the coiled epididymis

When sperm leave the testes they enter a pair of long, coiled ducts, the epididymides (singular: epididymis). At this point, the sperm are not yet mature. Gland cells in the walls of the epididymides secrete substances that trigger the finishing touches. Until sperm leave the body, they are stored in the last stretch of each epididymis.

When a male is sexually aroused, contracting muscle in the walls of his reproductive organs propels mature sperm into and through a pair of thick-walled tubes, the **vas deferentia** (singular: vas deferens). From there, contractions move sperm through the two ejaculatory ducts and on through the urethra to the outside. The urethra passes through the **penis**, the male sex organ, and also carries urine.

Substances from seminal vesicles and the prostate gland help form semen

Secretions from several glands mix with sperm as they travel through the urethra. The result is **semen**, a thick fluid that is eventually expelled from the penis during sexual activity. As semen is beginning to form, a pair of **seminal vesicles** secrete fructose. The sperm use this sugar for energy. Seminal vesicles also secrete certain kinds of prostaglandins. You may recall from Chapter 15 that these signaling molecules can trigger muscle contractions. During sex, the prostaglandins cause contractions in muscles of a female's reproductive tract, and so aid the movement of sperm through it toward the egg.



Sperm cell arriving at an egg

Substances secreted by the **prostate gland** probably help buffer the acidic environment that sperm encounter in the female reproductive tract. The vaginal pH is about 3.5 to 4.0, but sperm motility improves at pH 6. Two **bulbourethral glands** secrete mucus-rich fluid into the urethra when a male is sexually aroused. This fluid neutralizes acids in any traces of urine in the urethra, and this more alkaline environment creates a more favorable chemical environment for the 150 to 350 million sperm that pass through the channel in a typical ejaculation.

Cancer can develop in both the testes and prostate gland. About 5,000 cases of testicular cancer are diagnosed each year in the United States, mostly among young men. This cancer kills about half of its victims. Prostate cancer, which is more common among men over 50, kills 40,000 older men annually—almost the same mortality rate recorded for breast cancer in women. As with other cancers, early detection is the key to survival. We will look in more depth at testicular and prostate cancer later on.

Take-Home Message

What are the main parts of the male reproductive system?

- Males have a pair of testes, primary reproductive organs that produce sperm and sex hormones.
- The male reproductive system also includes accessory glands and ducts.
- When sperm are nearly mature, they leave each testis and enter the long, coiled epididymis, where they remain until ejaculated.
- Secretions from the seminal vesicles and the prostate gland mix with sperm to form semen.

16.2 How Sperm Form

- **In his reproductive years, a male continually produces new germ cells, or sperm, which develop in a series of steps controlled by hormones.**
- **Links to Flagella 3.9, Hormones from the hypothalamus and pituitary 15.3**

Sperm form in seminiferous tubules

Packed inside each of a male's testes are 125 meters—over 400 feet—of **seminiferous tubules**. As many as 30 wedge-shaped lobes divide the inside of a testis and each lobe holds two or three coiled tubules (Figure 16.3*a*).

Inside the walls of seminiferous tubules are cells called *spermatogonia* (Figure 16.3*c*). They are the starting point for several rounds of cell division, including a type called *mitosis* and a type called *meiosis*. You'll read more about mitosis and meiosis in Chapter 18; here the main thing to keep in mind is that meiosis is necessary to form sperm and eggs.

Spermatogonia develop into *primary spermatocytes*, which become *secondary spermatocytes* after a first round of meiosis (meiosis I). A second round (meiosis II) forms *spermatids*. The spermatids develop into *spermatozoa*, or simply **sperm**, the male gametes. The "tail" of each sperm, a flagellum, forms at the end of the process, which takes nine to ten weeks. Meanwhile, the developing cells receive nourishment and chemical signals from **Sertoli cells** that line the seminiferous tubule.

The testes produce sperm from puberty onward. Millions are in different stages of development on any given day. A mature sperm has a tail, a midpiece, and a head (Figure 16.4). Inside the head, a nucleus contains DNA organized into chromosomes. An enzyme-containing cap, the **acrosome**, covers most of the head. Its enzymes help the sperm penetrate protective material around an egg

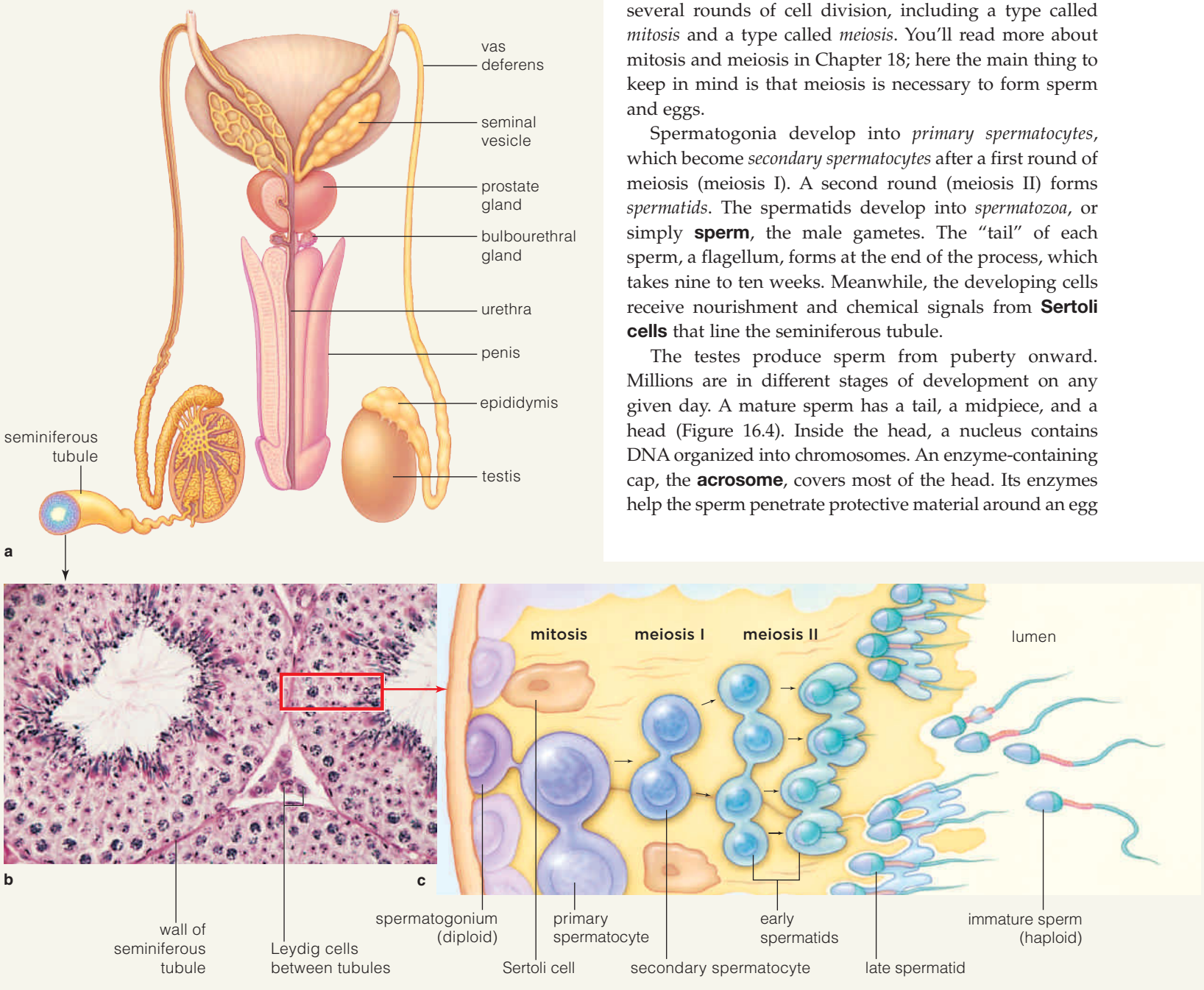


Figure 16.3 Animated! **Seminiferous tubules, where sperm form, are coiled inside the lobes of the testes.** (**a**) The male reproductive tract from behind. (**b**) Cells in three neighboring seminiferous tubules. Leydig cells in spaces between tubules make testosterone. (**c**) How sperm form, starting with a diploid germ cell. Cell division by two mechanisms, first mitosis, then meiosis, produce haploid cells that develop into sperm.

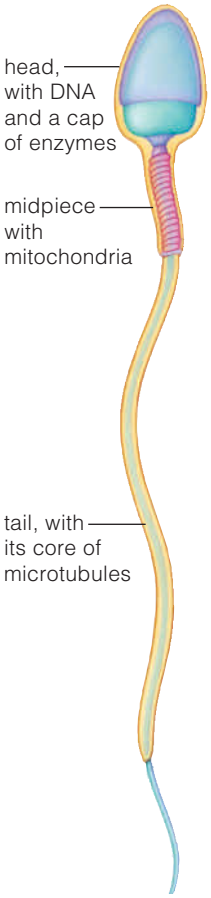


Figure 16.4 **A mature sperm has a head, a midpiece, and a tail.**

at fertilization. In the midpiece, mitochondria supply energy for the tail's movements.

Hormones control sperm formation

Male reproductive function depends on testosterone, LH, and FSH. **Leydig cells** (also called interstitial cells), located in tissue between the seminiferous tubules in testes (Figure 16.3*b*), secrete **testosterone**. This hormone governs the growth, form, and functions of the male reproductive tract. It stimulates sexual behavior, and at puberty it promotes the development of male **secondary sexual traits**, including facial hair and deepening of an adolescent male's voice.

LH (luteinizing hormone) and **FSH** (follicle-stimulating hormone) are released from the anterior lobe of the pituitary gland (Figure 16.5). These two hormones were named for their effects in females, but are chemically the same in males.

Since the hypothalamus controls secretions of LH, FSH, and testosterone, it controls the formation of sperm. When the testosterone level in a male's blood falls below a set point, the hypothalamus secretes GnRH. This releasing hormone prompts the pituitary's anterior lobe to release LH and FSH, which have targets in the testes. LH stimulates Leydig cells to secrete testosterone, which stimulates diploid germ cells to become sperm.

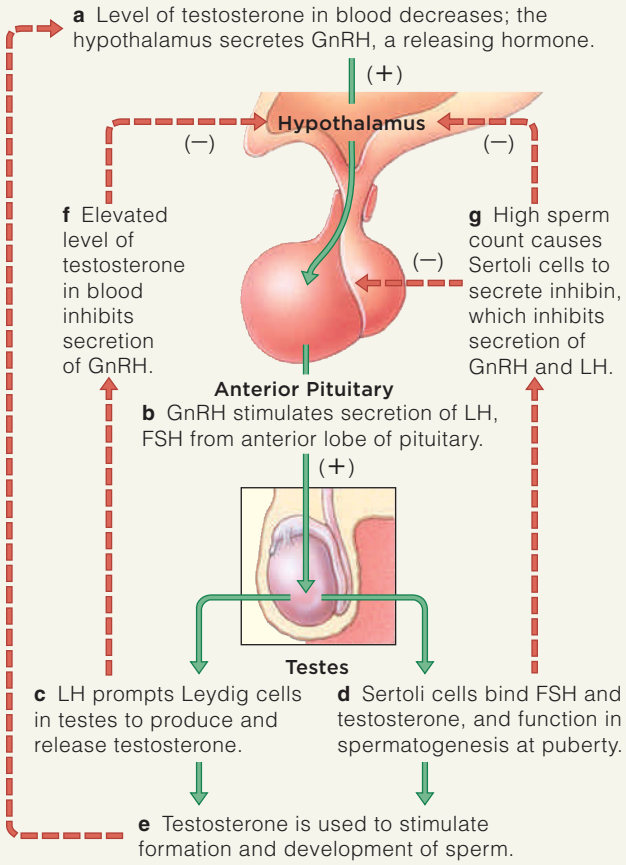


Figure 16.5 **Animated! Negative feedback loops regulate the release of male reproductive hormones.**

Sertoli cells have FSH receptors. FSH is crucial to starting sperm formation (called **spermatogenesis**) at puberty, but we do not know whether it is needed for a grown man's testes to function normally.

A high level of testosterone in a male's blood inhibits the release of GnRH. Also, when a male's sperm count is high, Sertoli cells release inhibin, a hormone that acts on the hypothalamus and pituitary to inhibit the release of GnRH and FSH. Now feedback loops to the hypothalamus begin to operate, so the secreation of testosterone and the formation of sperm decline.

Take-Home Message

How do sperm form and what role do hormones play?

- Cell divisions in germ cells in seminiferous tubules of the testes form sperm.
- Testosterone, LH, and FSH guide the steps by which sperm form. Testosterone also governs the development of male secondary sexual traits.
- Feedback loops from the testes to the hypothalamus and pituitary gland control the secretion of these hormones.

16.3 The Female Reproductive System

- **The biological function of the female reproductive system is to nurture developing offspring from the time of conception until birth.**

Ovaries are a female's primary reproductive organs

Figure 16.6 shows the parts of the female reproductive system and Table 16.2 summarizes their functions. A female's primary reproductive organs are her two **ovaries**. The ovaries release sex hormones, and during a woman's reproductive years they also produce eggs. Hormones from the ovaries influence the development of female secondary sexual traits, such as the "filling out" of breasts, hips, and buttocks by fat deposits.

Immature eggs are called **oocytes**. When an oocyte is released from an ovary, it moves into a nearby **oviduct** (also called a *fallopian tube*). Fertilization usually occurs while an egg is in an oviduct. Regardless, an egg travels down the oviduct into the **uterus**. In this organ, a baby can grow and develop. The wall of the uterus consists of a thick layer of smooth muscle (the myometrium) and a lining, the **endometrium**. The endometrium includes epithelium, connective tissue, glands, and blood vessels. The lower part of the uterus is the **cervix**. The muscular **vagina** leads from the cervix to the outside. It receives the penis and sperm and serves as part of the birth canal.

A female's outer genitals collectively form the *vulva*. Outermost are a pair of fat-padded skin folds, the *labia majora*. They enclose a smaller pair of folds, the *labia minora*, that are laced with blood vessels. The labia minora partly enclose the *clitoris*, a small organ that is sensitive to sexual stimulation.

A female's urethra opens about midway between her clitoris and her vaginal opening. Whereas in males the urethra carries both urine and sperm, in females it is separate and is not involved in reproduction.

TABLE 16.2 Female Reproductive Organs

Ovaries	Produce oocytes and sex hormones
Oviducts	Conduct oocytes from ovary to uterus
Uterus	Chamber where new individual develops
Cervix	Secretes mucus that enhances sperm movement into uterus and (after fertilization) reduces the embryo's risk of bacterial infection
Vagina	Organ of sexual intercourse; birth canal

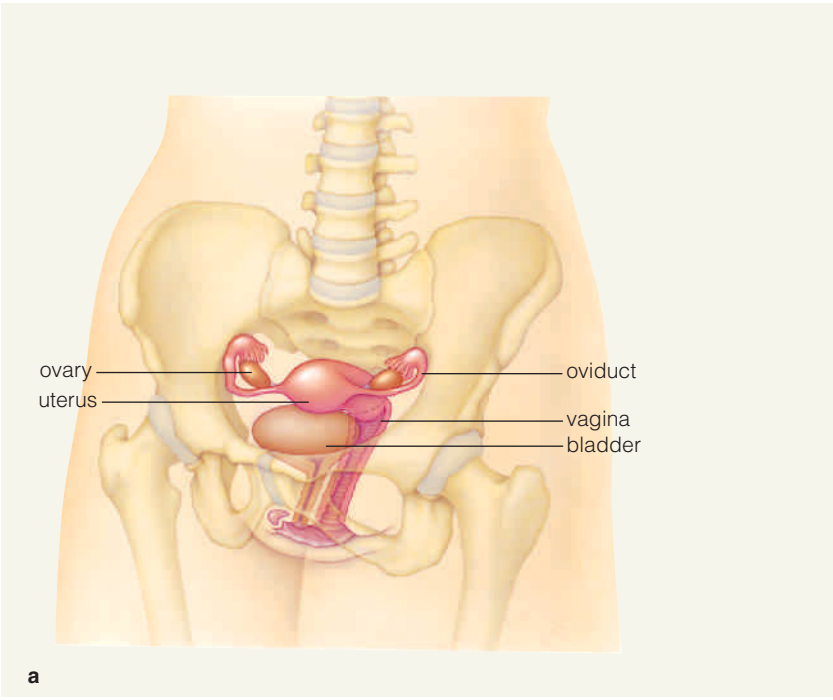


Figure 16.6 Animated! The female reproductive system is located in the pelvic cavity. (**a**) Position of the female reproductive system relative to the pelvic girdle and urinary bladder. (**b**) Parts of the system and their functions.

During the menstrual cycle, an oocyte is released from an ovary

Like all female primates, a woman has a **menstrual cycle**. It takes about twenty-eight days to complete one cycle, although this can vary from month to month and from woman to woman. During the cycle, an oocyte matures and is released from an ovary. Meanwhile, hormones are preparing the endometrium to receive and nourish an embryo in case the oocyte is fertilized. If the oocyte is *not* fertilized, a blood-rich fluid starts flowing out through the vaginal canal. This flow is **menstruation**, and it marks the first day of a new cycle. The disintegrating endometrium is being sloughed off, only to be rebuilt once again during the next cycle.

The menstrual cycle advances through three phases (Table 16.3). It starts with a *menstrual phase*. This is the time of menstruation, when the endometrium disintegrates. Next comes the *proliferative phase*, when the endometrium begins to thicken again. The end of this phase coincides with ovulation—the release of an oocyte from an ovary. During the cycle's final phase, called the *progestational* ("before pregnancy") *phase*, an endocrine structure called the corpus luteum ("yellow body") forms. It secretes a flood of the sex hormones **progesterone** and **estrogen**, which prime the endometrium for pregnancy.

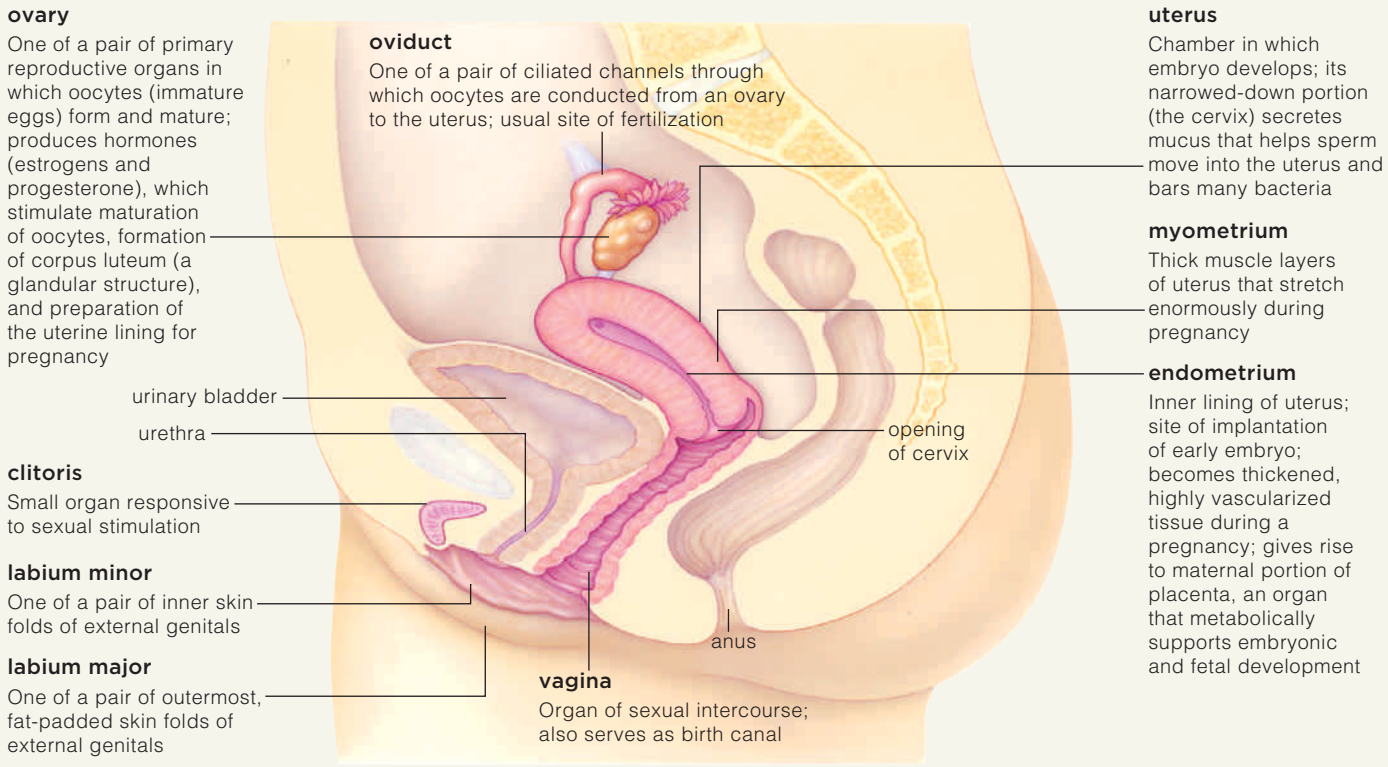


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TABLE 16.3 Phases of the Menstrual Cycle

Phase	Events	Days of the Cycle*
Menstrual phase	Menstruation; endometrium breaks down	1–5
	Follicle matures in ovary; endometrium rebuilds	6–13
Proliferative phase	Endometrium begins to thicken, ovulation occurs	14
Progestational phase	Lining of endometrium develops to receive a possible embryo	15–28

*Assumes a 28-day cycle.

Feedback loops to the hypothalamus and pituitary gland from the ovaries govern the menstrual cycle. Hormones also promote corresponding cyclic changes in the ovaries, as you will read in Section 16.4.

A female's first menstruation, or *menarche*, usually occurs between the ages of ten and sixteen. Menstrual cycles continue until **menopause**, which usually occurs in a woman's late 40s or early 50s. By then, her ovaries are making less estrogen and progesterone, and also are less sensitive to reproductive hormones from the pituitary. Falling estrogen levels may trigger a range of temporary symptoms, including moodiness, insomnia, and "hot flashes" (sudden bouts of sweating and feeling uncomfortably warm). Other physiological changes include thinning of the vaginal walls and some loss of natural lubrication. When a woman's menstrual cycles stop altogether, the fertile phase of her life is over.

Endometriosis is a distressing disorder of the female reproductive tract. Endometrial tissue spreads and grows outside the uterus. Scar tissue may form on one or both ovaries or oviducts, leading to infertility. In the United States, as many as 10 million women are affected each year. Endometriosis may develop when menstrual flow backs up through the oviducts and spills into the pelvic cavity. Or perhaps some cells became situated in the wrong place when the woman was a developing embryo, then were stimulated to grow during puberty, when her sex hormones became active. Regardless, the symptoms include pain during menstruation, sex, or urination. Treatment ranges from doing nothing in mild cases to surgery to remove the abnormal tissue or sometimes even the whole uterus.

Take-Home Message

What is the main function of ovaries and what role do hormones play?

- Ovaries, a female's primary reproductive organs, produce oocytes (immature eggs) and sex hormones. Endometrium lines the uterus, where embryos develop.
- Sex hormones—estrogens and progesterone—are released as part of a recurring menstrual cycle during a female's reproductive years.

16.4 The Ovarian Cycle: Oocytes Develop

- **As the menstrual cycle advances, a cycle in the ovaries forms an oocyte that may develop into an egg.**
- **Links to the Limbic system 13.9, Hormones from the hypothalamus and pituitary 15.3**

Hormones guide ovulation

A newborn girl's ovaries contain about 2 million cells called primary oocytes ("first egg-forming cells"). All but about 300 are later resorbed, although the ovaries may make fresh oocytes later on. In each oocyte, meiosis I begins but then is stopped by genetic controls. This gamete-forming type of cell division restarts, usually in one oocyte at a time, with each of a woman's menstrual cycles. The shift is part of the **ovarian cycle**, in which a primary oocyte matures and is ovulated (Figure 16.7).

Step *a* shows a primary oocyte near an ovary's surface. It is surrounded by a layer of cells that nourish it. This layer and the primary oocyte make up a **follicle**. At this point, the hypothalamus is secreting enough GnRH, a releasing hormone, to make the anterior pituitary secrete more FSH and LH. As the blood level of those two hormones rises, the follicle grows. (FSH, recall, is short for follicle-stimulating hormone.) More cell layers form around it. In between, proteins form a layer called the **zona pellucida**.

FSH and LH stimulate cells outside the zona pellucida to make estrogens, so estrogen-rich fluid builds up in the follicle. The blood level of estrogen also rises. Several hours before it is ovulated, an oocyte completes the cell division, meiosis I, that was arrested years before. Now, there are two cells. The smaller one, called the "first polar body," may divide again. (Polar bodies contain unneeded material and eventually disintegrate.) The larger cell, the **secondary oocyte**, gets most of the cytoplasm. It now begins another round of meiosis (meiosis II). As before, this division is not completed. That happens only if the oocyte is fertilized.

About halfway through the ovarian cycle, a woman's pituitary gland detects the rising estrogen level. It releases LH, which causes changes that make the follicle swell. The surge also causes enzymes to break down the bulging follicle wall, which soon ruptures. Fluid escapes, along with the secondary oocyte and polar body (Figure 16.7*e*). The midcycle surge of LH has triggered **ovulation**—the release of a secondary oocyte from the ovary.

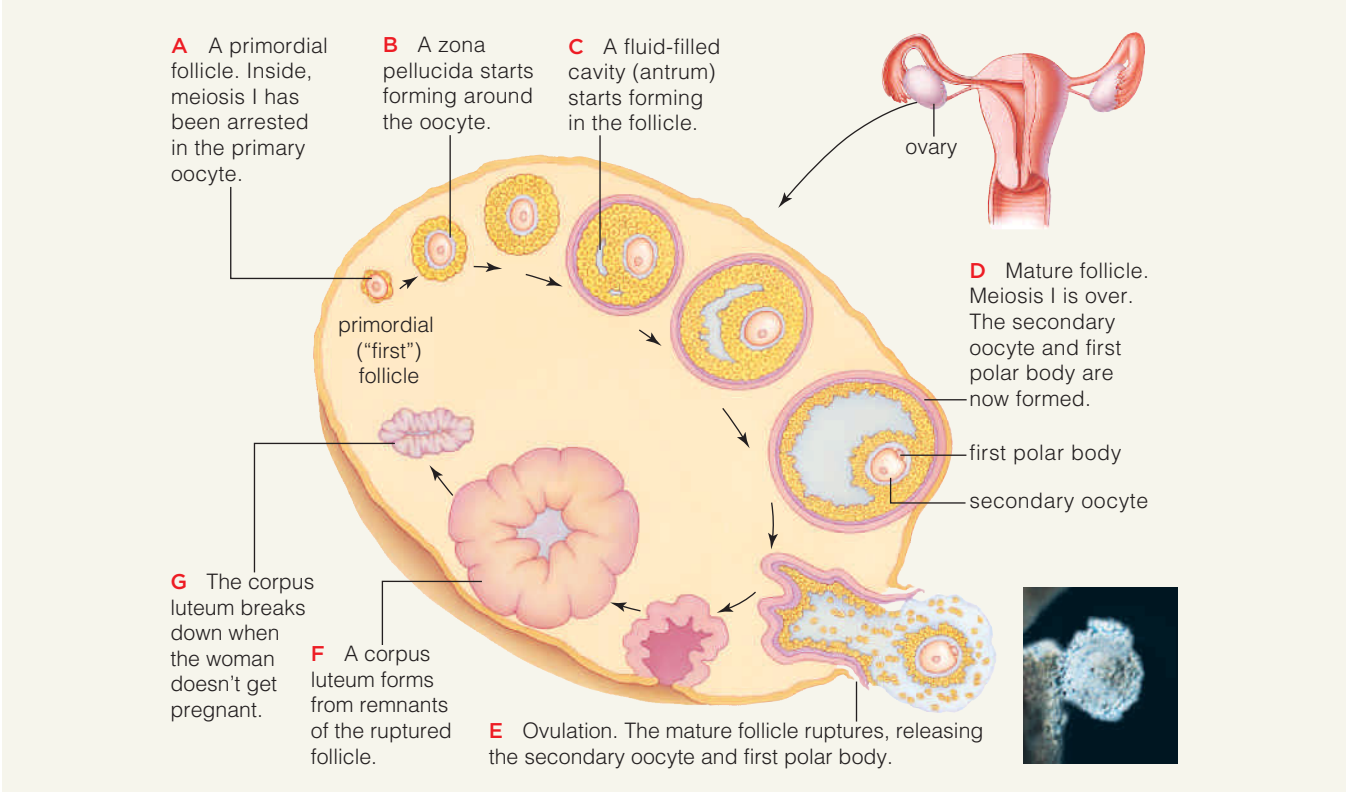


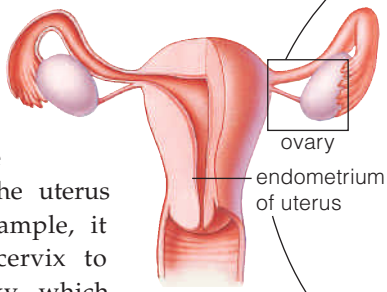
Figure 16.7 Animated! Oocytes develop by way of cyclic changes in the ovary. A follicle stays in the same place in an ovary all through the menstrual cycle. It does not "move around" as in this diagram, which shows the sequence of events. In the cycle's first phase, a follicle grows and matures. The micrograph shows a secondary oocyte being released from an ovary. It will enter an oviduct, the channel to the uterus.

Once it is in the abdominal cavity, the secondary oocyte enters an oviduct. Long, ciliated projections from the oviduct (called *fimbriae*) extend over part of the ovary. Movements of the projections and cilia sweep the oocyte into the channel. If fertilization takes place, the oocyte will finish meiosis II and become a mature egg.

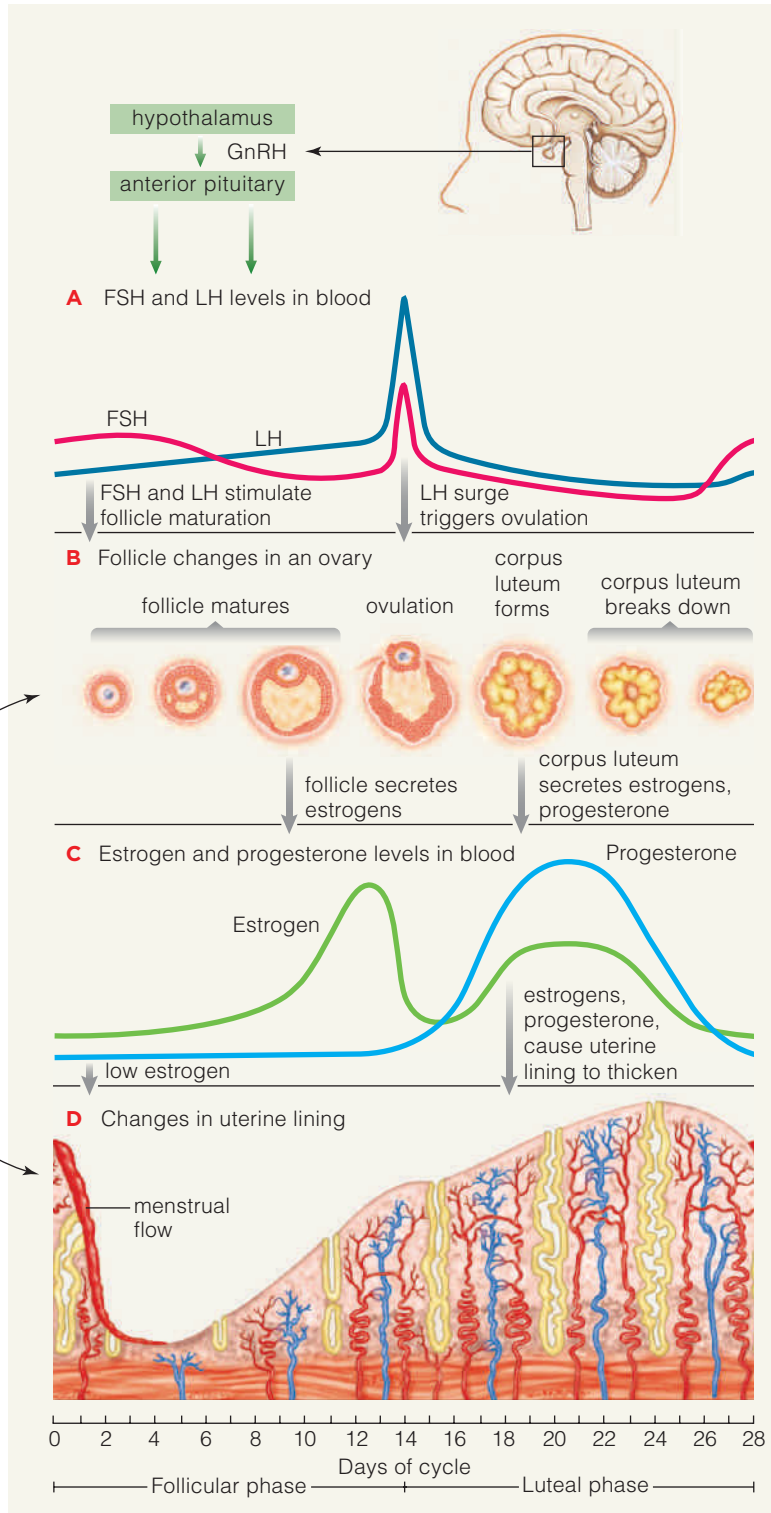
The ovarian and menstrual cycles dovetail

You may remember from Section 16.3 that estrogens released early in the menstrual cycle stimulate growth of the endometrium and its blood vessels and glands. These changes pave the way for a possible pregnancy. Just before the midcycle LH surge, cells of the follicle wall start releasing estrogens and progesterone. When ovulation occurs, the estrogens act on tissue around the cervical canal, which opens into the vagina. The cervix starts to secrete large amounts of a thin, clear mucus, which is ideal for sperm to swim through.

As diagrammed in Figure 16.8, the midcycle surge of LH triggers formation of a **corpus luteum** ("yellow body"). This structure develops from cells left behind in the follicle, and it secretes both some estrogen and progesterone. The progesterone prepares the uterus for an embryo. For example, it causes mucus in the cervix to become thick and sticky, which may prevent bacteria from entering the uterus. Progesterone also maintains the endometrium during a pregnancy.



A corpus luteum lasts for about twelve days. In that time, the hypothalamus signals for a decrease in FSH, which prevents other follicles from developing. If no embryo implants in the endometrium, the corpus luteum begins to disintegrate. After it breaks down, progesterone and estrogen levels drop, so the endometrium also breaks down and menstruation begins.



Days of menstrual cycle (28-day average duration):

Take-Home Message

What are the steps leading to ovulation of a secondary oocyte?

- Shifts in FSH and LH cause a follicle (primary oocyte and support cells) to grow. A midcycle surge of LH triggers ovulation, in which a secondary oocyte is released from the ovary.
- The cyclic release of hormones helps pave the way for fertilization of an egg and pregnancy.

Figure 16.8 Animated! **Hormones govern the menstrual and ovarian cycles.** (**a**) GnRH, a releasing hormone from the hypothalamus, stimulates the anterior pituitary to secrete FSH and LH. (**b**) FSH and LH stimulate a follicle to grow, an oocyte to mature, and the ovaries to secrete progesterone and estrogens that stimulate the endometrium to rebuild. (**c**) A midcycle LH surge triggers ovulation and the formation of a corpus luteum. Progesterone and some estrogens released by the corpus luteum maintain the endometrium, but if no pregnancy occurs, they stop being released and the corpus luteum breaks down (**d**).

16.5 Sexual Intercourse

- **The penis and vagina are mechanically compatible for sexual intercourse, which may lead to pregnancy.**

In sexual intercourse, both partners experience physiological changes

Coitus and copulation are both technical terms for sexual intercourse. The male sex act involves an *erection*, in which the limp penis stiffens and lengthens. It also involves *ejaculation*, the forceful expulsion of semen into the urethra and out from the penis. As shown in Figure 16.1, the penis has lengthwise cylinders of spongy tissue. The outer cylinder has a mushroom-shaped tip (the glans penis). Inside it is a dense array of sensory receptors that are activated by friction. In a male who is not sexually aroused, the large blood vessels leading into the cylinders are constricted. In aroused males, these blood vessels vasodilate, so blood flows into the cylinders faster than it flows out. Blood collects in the spongy tissue, and the organ stiffens and lengthens—a mechanism that helps the penis penetrate into the female's vagina.

In a female, arousal includes vasodilation of blood vessels in her genital area. This causes vulvar tissues to engorge with blood and swell. Mucus-rich secretions flow from the cervix, lubricating the vagina.

During coitus, pelvic thrusts stimulate the penis as well as the female's clitoris and vaginal wall. The stimulation triggers rhythmic, involuntary contractions in smooth muscle in the male reproductive tract, especially the vas deferens and the prostate. The contractions rapidly force sperm out of each epididymis. They also force the contents of seminal vesicles and the prostate gland into the urethra. The resulting mixture, semen, is ejaculated into the vagina.

During ejaculation, a sphincter closes off the neck of the male's bladder and prevents urine from being excreted. Ejaculation is a reflex response. This means that once it begins, it cannot be stopped.

Emotional intensity, heavy breathing, and heart pounding, as well as generalized contractions of skeletal muscles, accompany the rhythmic throbbing of the pelvic muscles. For both partners, **orgasm**—the culmination of the sex act—typically is accompanied by strong sensations of release, warmth, and relaxation.

Some people mistakenly believe that unless a woman experiences orgasm, she cannot become pregnant. This is not true, however. A female can become pregnant from intercourse regardless of whether she experiences orgasm, and even if she is not sexually aroused. All that is required is that a sperm meet up with a secondary oocyte that is traveling down one of her oviducts.

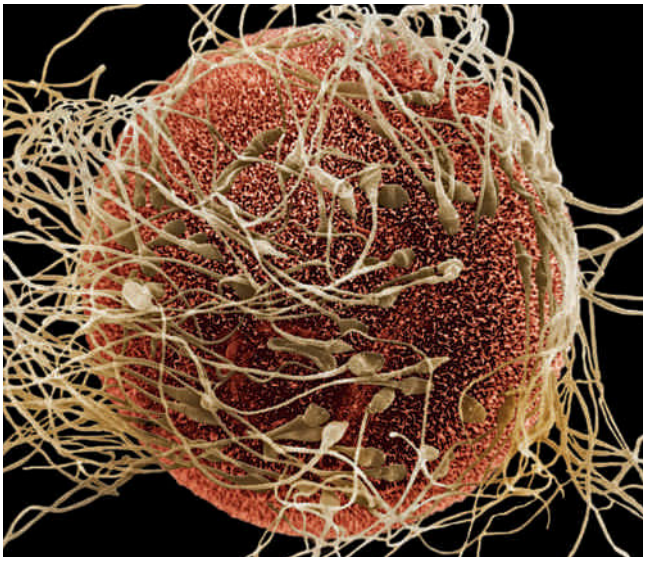


Figure 16.9 This image shows a secondary oocyte surrounded by sperm. If fertilization occurs, it will set the stage for a new individual to develop, continuing the human life cycle.

Intercourse can produce a fertilized egg

If sperm enter the vagina a few days before or after ovulation or anytime between, an ovulated egg may be fertilized. Within thirty minutes after ejaculation, muscle contractions in the uterus move the sperm deeper into the female reproductive tract. Only a few hundred sperm will actually reach the upper portion of the oviduct, which is where fertilization usually takes place. The remarkable micrograph in Figure 16.9 shows living sperm around a secondary oocyte.

Take-Home Message

What bodily changes occur during sexual intercourse?

- Sexual intercourse (coitus) typically involves a series of physiological changes in both partners.
- During arousal, blood vessels dilate so that more blood flows to the penis (males) and vulva (females). Orgasm involves muscular contractions (including those leading to ejaculation of semen into the vagina) and sensations of release, warmth, and relaxation.
- Intercourse may lead to a pregnancy even if the female is not sexually aroused or she does not experience orgasm.

16.6 Fertilization

- **Fertilization combines chromosomes in the father's sperm with those in the mother's egg. Thus the new cell of a new individual has a full set of chromosomes and DNA.**

Fertilization begins when a sperm enters a secondary oocyte. After a sequence of steps, fertilization produces a **zygote** (ZYE-goat, "yoked together"), the first cell of the new individual. Figure 16.10 shows these steps

As sperm swim through the cervix and uterus and into the oviducts, they are not quite ready to fertilize an oocyte. First, *capacitation* occurs. In this process, chemical changes weaken the membrane over the sperm's acrosome. Only a sperm that is capacitated ("made able") can fertilize an oocyte. Of the millions of sperm in the vagina after an ejaculation, just several hundred reach the upper part of an oviduct, where fertilization usually occurs. Contractions of smooth muscle in the uterus help move sperm toward the oviducts.

When a capacitated sperm contacts an oocyte, enzymes are released from the now-weakened cell membrane over the acrosome. Many sperm can reach and bind to the oocyte, and acrosome enzymes clear a path through the zona pellucida. Usually, however, only one sperm fuses with the oocyte. Rapid chemical changes in the oocyte's cell membrane prevent more sperm from entering.

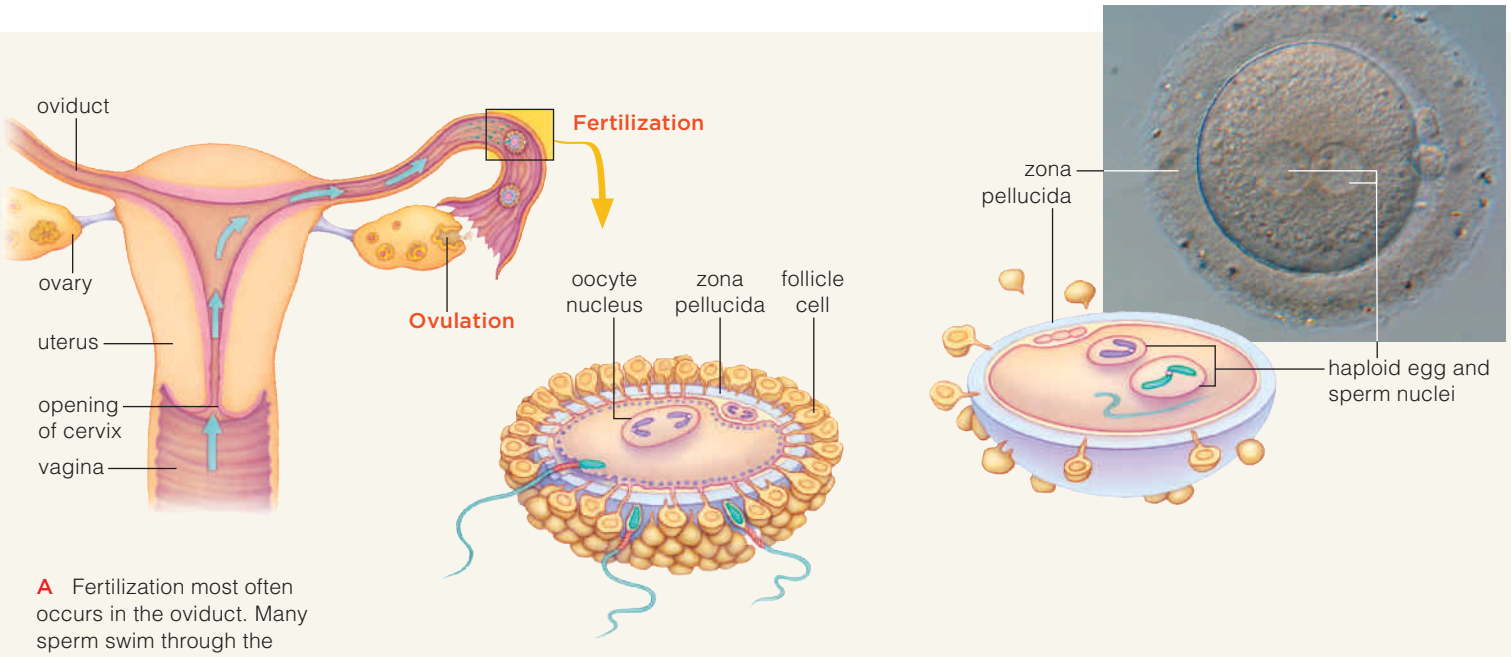
Fusion with a sperm prompts the completion of the cell division process (meiosis II) that began when the oocyte was being formed in an ovary (Section 16.4). The result is a mature egg, or **ovum** (plural: ova), plus another polar body. (Remember from Section 16.4 that one or two polar bodies are produced when meiosis I gives rise to the secondary oocyte. Often three tiny polar bodies eventually are packaged with the ovum.) The nuclei of the sperm and ovum swell up, then fuse.

Each sperm and oocyte has twenty-three chromosomes, half the number in other body cells. Fertilization combines them into a full diploid set of forty-six chromosomes. Thus a zygote has all the DNA required to guide proper development of the embryo.

Take-Home Message

What happens in fertilization?

- Fertilization of an egg by a sperm produces a zygote, a single cell with a full set of chromosomes—half from the mother and half from the father.



A Fertilization most often occurs in the oviduct. Many sperm swim through the vagina into oviducts (*blue* arrows).

Inside an oviduct, the sperm surround a secondary oocyte that was released by ovulation.

B Enzymes released from the cap of each sperm clear a path through the zona pellucida. Penetration of the secondary oocyte by a sperm causes the oocyte to release substances that prevent other sperm from binding.

C The oocyte completes meiosis II. The sperm's tail and other organelles degenerate.

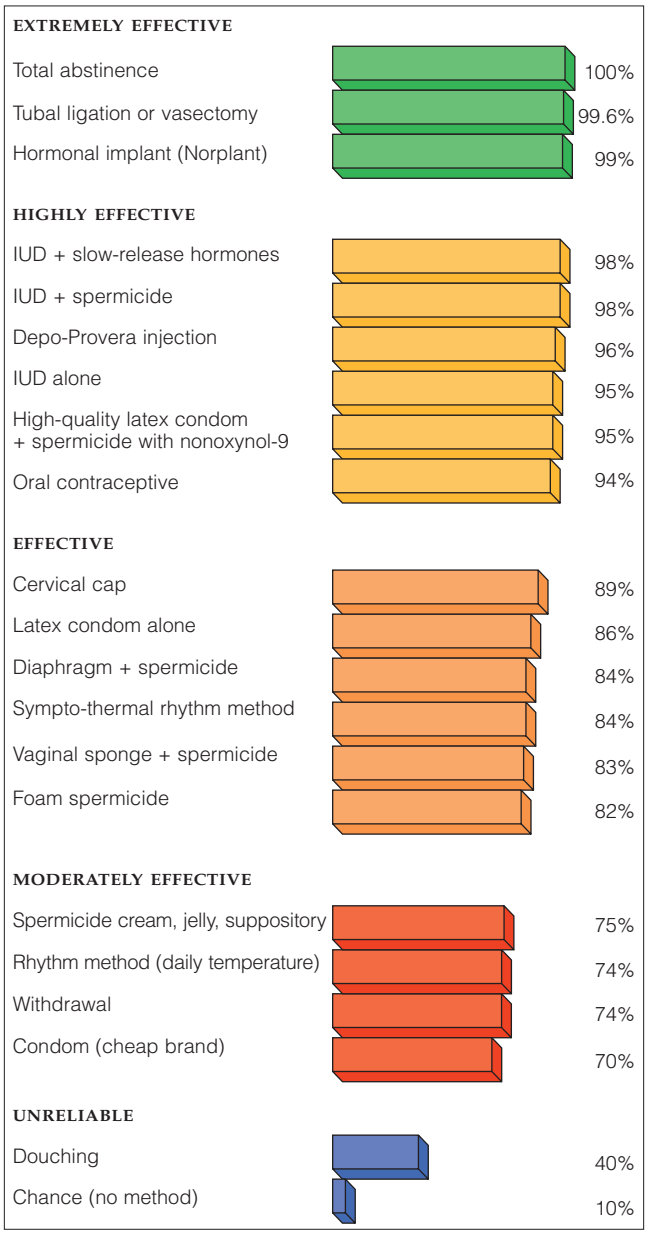
Later, the egg and sperm nuclei will fuse and the zygote will form.

Figure 16.10 Animated! Fertilization unites a sperm and oocyte.

16.7 Controlling Fertility

- **People who choose to control whether their sexual activity produces a child have a variety of options.**

The most effective method of birth control is complete *abstinence*—no sexual intercourse whatsoever. A modified form of abstinence is the *rhythm method*, also called the "fertility awareness" or *sympto-thermal method*. The idea is to refrain from intercourse during the woman's fertile period, starting a few days before ovulation and ending a few days after. Her fertile period is identified and tracked by keeping records of the length of her menstrual cycles and sometimes by examining her cervical secretions and taking her temperature each morning when she wakes up.



(Core body temperature rises by one-half to one degree just after ovulation.) The method is not very reliable (Figure 16.11). Ovulation can be irregular, and it can be easy to miscalculate. Also, sperm already in the vaginal tract may survive until ovulation.

Withdrawal, removing the penis from the vagina before ejaculation, also is not very effective because fluid released from the penis before ejaculation may contain sperm. *Douching*, or rinsing out the vagina with a chemical right after intercourse, is next to useless. It takes less than 90 seconds for sperm to move past the cervix into the uterus.

Surgery and barrier methods are the most effective options

Controlling fertility by surgery is less chancy but usually irreversible step. In *vasectomy*, a physician makes a tiny incision in a man's scrotum, then severs and ties off each vas deferens (Figure 16.12*a*). Afterward, sperm can't leave the testes and so can't be present in the man's semen. A vasectomy does not change a man's sex hormones or sex drive. An alternative is the Vasclip, a device about the size of a rice grain that simply closes off the vas deferens.

In *tubal ligation*, a woman's oviducts are cauterized or cut and tied off (Figure 16.12*b*), so sperm cannot reach ovulated oocytes.

Spermicides kill sperm. They are packaged inside an applicator and placed in a woman's vagina just before intercourse. Neither is reliable unless used with another device, such as a diaphragm or condom.

A *diaphragm* is a flexible, dome-shaped device that is positioned over the cervix before intercourse. It must be fitted by a doctor, used with foam or jelly, and inserted correctly with each use. A *cervical cap* is a similar but smaller device and can be left in place for up to three days. The *contraceptive sponge* is a disposable disk that contains a spermicide and covers the cervix. After being wetted it is inserted up to 24 hours before intercourse. No prescription or special fitting is required.

The *intrauterine device*, or IUD, is a plastic or metal device that is placed into the uterus, where it hampers implantation of a fertilized egg. Available by prescription, IUDs have been associated with a variety of complications and should be discussed fully with a physician.

Figure 16.11 Some contraceptive methods are more effective than others. Percentages shown are the number of unplanned pregnancies per 100 couples who used the method as the only form of birth control for a year. For example, "94% effectiveness" for birth control pills means that, on average, 6 of every 100 women using them will become pregnant.

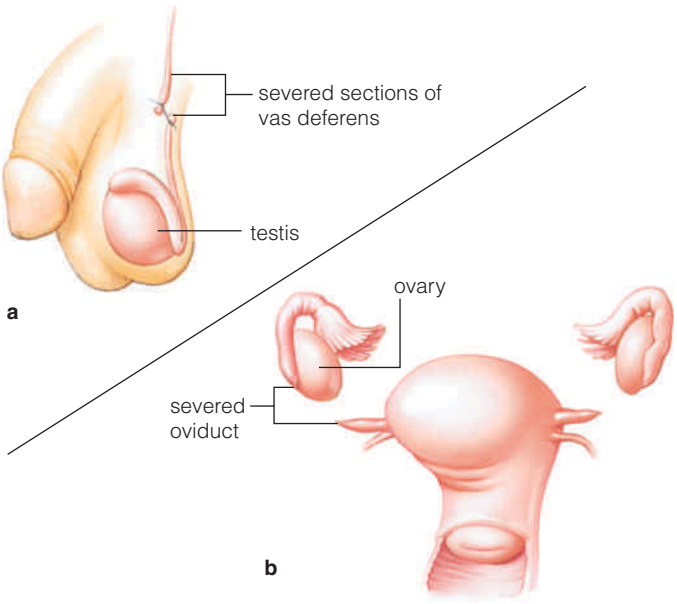


Figure 16.12 Both men and women may opt for surgical methods of birth control. (**a**) Vasectomy and (**b**) tubal ligation.

TABLE 16.4 Common Methods of Contraception

Method	Description
Abstinence	Avoid intercourse entirely
Rhythm method	Avoid intercourse in female's fertile period
Withdrawal	End intercourse before male ejaculates
Douche	Wash semen from vagina after intercourse
Vasectomy	Cut or close off male's vasa deferentia
Tubal ligation	Cut or close off female's oviducts
Condom	Enclose penis, block sperm entry to vagina
Diaphragm, cervical cap	Cover cervix, block sperm entry to uterus
Spermicides	Kill sperm
Intrauterine device	Prevent sperm entry to uterus or prevent implantation of embryo
Oral contraceptives	Prevent ovulation
Hormone patches, implants, or injections	Prevent ovulation
Emergency contraception pill	Prevent ovulation

Condoms are thin, tight-fitting sheaths of latex or animal skin worn over the penis during intercourse. Good brands may be as much as 95 percent effective when used with a spermicide. Latex condoms help prevent the spread of sexually transmitted diseases.

A *birth control pill*, with its synthetic estrogens and progesterone-like hormones, blocks the maturation and ovulation of oocytes. Oral contraceptives are one of the most common methods of contraception (Table 16.4). Some users experience (usually temporary) side effects, including nausea and weight gain. Continued use may lead to blood clots in at-risk women. Complications are more likely in women who smoke, and most physicians won't prescribe an oral contraceptive for a smoker.

A *birth control patch* is a small, flat, adhesive patch applied to the skin. It delivers the same hormones as a birth control pill and blocks ovulation the same way. It also has the same risks as oral contraceptives.

Progestin injections or implants prevent ovulation or implantation of an embryo. They may cause heavier menstrual periods and implants can be difficult to remove.

Some women use *emergency contraception* after a condom tears, or after unprotected consensual sex or rape. These "*morning-after pills*" suppress ovulation and in most places are available without a prescription to women eighteen and older. They work best taken right away but may be effective up to five days after intercourse.

Abortion is highly controversial

An induced or surgical **abortion** removes or dislodges an embryo or fetus from the womb. In the United States about half of unplanned pregnancies end in induced abortion. The difficult legal and ethical conflict over legalized abortion rages on.

During the first trimester (twelve weeks), abortions performed in a clinical setting usually are fast, painless, and free of complications. Even so, polls show that for both medical and moral reasons, most people in the U.S. prefer sexually responsible behavior over abortion. Aborting a late-term fetus is quite controversial unless the mother's life is threatened.

This science book can't offer any "right" answers to questions about the morality of abortion or any other reproductive decision. It can only offer an explanation of how a new individual develops to help you objectively assess the biological basis of human life. We discuss development in Chapter 17.

Take-Home Message

What are effective methods of fertility control?

- The most effective methods for preventing conception are abstinence, chemical barriers to conception, and surgery or implants that block the vas deferens or oviducts.

16.8 Options for Coping with Infertility

- **In the United States, about one in every six couples is infertile—unable to conceive a child after a year of trying. Causes run the gamut from hormonal imbalances that prevent ovulation, oviducts blocked by effects of disease, a low sperm count, or sperm that are defective in a way that impairs fertilization.**
- **Link to Hormones of the hypothalamus and pituitary gland 15.3**

Fertility drugs stimulate ovulation

In about one-third of cases, infertility can be traced to poor quality oocytes or to irregular or absent ovulation. These situations are most common in women over the age of 37. A couple's first resort may be fertility drugs, in the hope that one or more ovarian follicles will produce a healthy oocyte. One commonly used drug, clomiphene, stimulates the pituitary gland to release FSH. As noted in Section 15.3, this hormone triggers ovulation. A drug called *human menopausal gonadotropin* (hMG) is basically a highly purified form of FSH. Injected directly into the bloodstream, it stimulates ovulation in 70 to 90 percent of women who receive it.

Although fertility drugs have been used with great success since the 1970s, they can cause undesirable side effects, including the fertilization of several eggs at once. The result is a high-risk pregnancy that can result in babies with neurological and other problems.

Assisted reproductive technologies include artificial insemination and IVF

Artificial insemination was one of the first methods of *assisted reproductive technology*, or ART. In this approach, semen is placed into a woman's vagina or uterus, usually by syringe, around the time she is ovulating. This procedure may be chosen when a woman's partner has a low sperm count, because his sperm can be concentrated prior to the procedure. In *artificial insemination by donor* (AID), a sperm bank provides sperm from an anonymous donor. AID produces about 20,000 babies in the United States every year.

In vitro fertilization (IVF) is literally "fertilization in glass." If a couple's sperm and oocytes are normal, they can be used. Otherwise, variations of the technology are available that use sperm, oocytes, or both, from donors (Figure 16.13). Sperm and oocytes are placed in a glass laboratory dish in a solution that simulates the fluid in oviducts. If fertilization takes place, about 12 hours later *zygotes* (fertilized eggs in the first stage of development) are transferred to a chemical solution that will support further development. Two to four days later, one or more embryos are transferred to the woman's uterus. An embryo implants in about 20 percent of cases. In vitro fertilization often produces more embryos than can be used in a given procedure. The fate of unused embryos (which are stored frozen) has prompted ethical debates, such as whether such embryos should be used as a source of embryonic stem cells (Chapter 4).

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Figure 16.13 ART may allow a couple to overcome infertility. Above: Doctor inserting a human sperm into an egg during in vitro fertilization. He is viewing the cell through a microscope. The procedure is magnified on a monitor. The egg, held in place by the tip of a pipette, is being pierced by a micromanipulator (the thin "line" on the right).

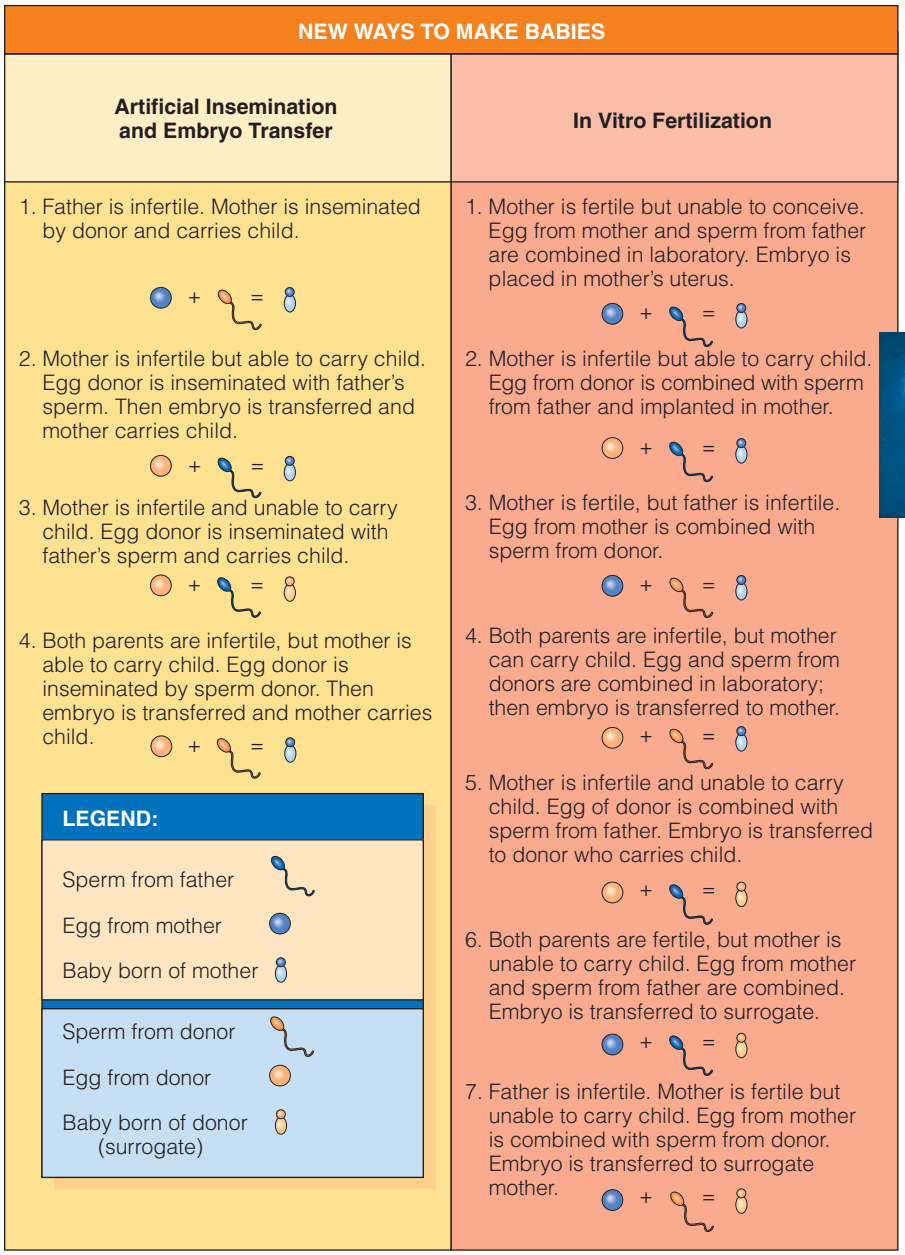


Figure 16.14 **Some options for assisted reproductive technologies.**

A procedure called ICSI is a variation on IVF. ICSI stands for *i*ntrac*y*toplasmic *s*perm *i*njection. A single sperm is injected into an egg using a tiny glass needle. Although IVF and ICSI are both in common use, evidence is mounting that babies conceived through any form of in vitro fertilization have a much higher risk of low birth weight and related developmental problems later on.

In *IVF with embryo transfer* (Figure 16.14) a fertile female volunteer is inseminated with sperm from a man whose female partner is infertile. If a pregnancy results, the developing embryo is transferred to the infertile woman's uterus or to a "surrogate mother." This approach is technically difficult and has major legal complications. It isn't a common solution to infertility.

In a technique called GIFT (*g*amete *i*ntra*f*allopian *t*ransfer) sperm and oocytes are collected and placed into an oviduct (fallopian tube). About 20 percent of the time, a normal pregnancy follows. An alternative is ZIFT (*z*ygote *i*ntra*f*allopian *t*ransfer). First, oocytes and sperm are placed in a laboratory dish. If fertilization occurs, the zygote is placed in a woman's oviducts. GIFT and ZIFT have about the same success rate as in vitro fertilization.

Take-Home Message

What are common methods of overcoming infertility?

- Fertility drugs include hormones that stimulate ovulation.
- In vitro fertilization brings together sperm and oocytes in a laboratory dish, where conception may occur.
- Intrafallopian transfers and artificial insemination are other techniques for overcoming infertility.

16.9 A Trio of Common Sexually Transmitted Diseases

- **Sexual activity can transmit disease. Three of the most common STDs are chlamydia, gonorrhea, and syphilis, all caused by bacteria.**
- **Links to Infectious disease 1.7, the Lymphatic system 9.2, Disease spread 9.12**

Chlamydia infections and PID are most common in young sexually active people

One of the most common **sexually transmitted diseases (STDs)** is caused by the bacterium *Chlamydia trachomatis* (Figure 16.15*a*). This infection is often called **chlamydia** for short. Each year an estimated 3 million Americans are infected, about two-thirds of them under age 25. Around the world, *C. trachomatis* infects roughly 90 million people annually. At least 30 percent of newborns who are treated for eye infections and pneumonia were infected with *C. trachomatis* during birth.

The bacterium infects cells of the genital and urinary tract. Infected men may have a discharge from the penis and a burning sensation when they urinate. Women may have a vaginal discharge as well as burning and itching. Often, however, *C. trachomatis* is a "stealth" STD with no outward signs of infection. About 80 percent of infected women and 40 percent of infected men don't have obvious symptoms—yet they can still pass the bacterium to others.

Once a bout of chlamydia is under way, the bacteria will migrate to the person's lymph nodes, which become enlarged and tender. Impaired lymph drainage can cause swelling in the surrounding tissues.

Chlamydia can be treated with antibiotics. However, because so many people are unaware they're infected, this STD does a lot of damage. Between 20 and 40 percent of women with genital chlamydial infections develop **pelvic inflammatory disease (PID)**. PID strikes about 1 million women each year, most often sexually active women in their teens and twenties.

Although PID can arise when microorganisms that normally inhabit the vagina ascend into the pelvic region (typically as a result of too much douching), it is also a serious complication of both chlamydia and gonorrhea. Usually, a woman's uterus, oviducts, and ovaries are affected. Pain may be so severe that infected women often think they are having an attack of acute appendicitis. If the oviducts become scarred, additional complications, such as chronic pelvic pain and even sterility, can result. PID is the leading cause of infertility among young women. An affected woman may also develop chronic menstrual problems.

As soon as PID is diagnosed, a woman usually will be prescribed antibiotics. Advanced cases can require removal of the uterus (hysterectomy). A woman's partner should also be treated, even if there are no symptoms.

Gonorrhea may have no symptoms at first

Like chlamydia, **gonorrhea** can be cured if it is diagnosed soon after the infection starts. Gonorrhea is caused by *Neisseria gonorrhoeae* (Figure 16.15*b*). This bacterium, also called gonococcus, can infect epithelial cells of the genital

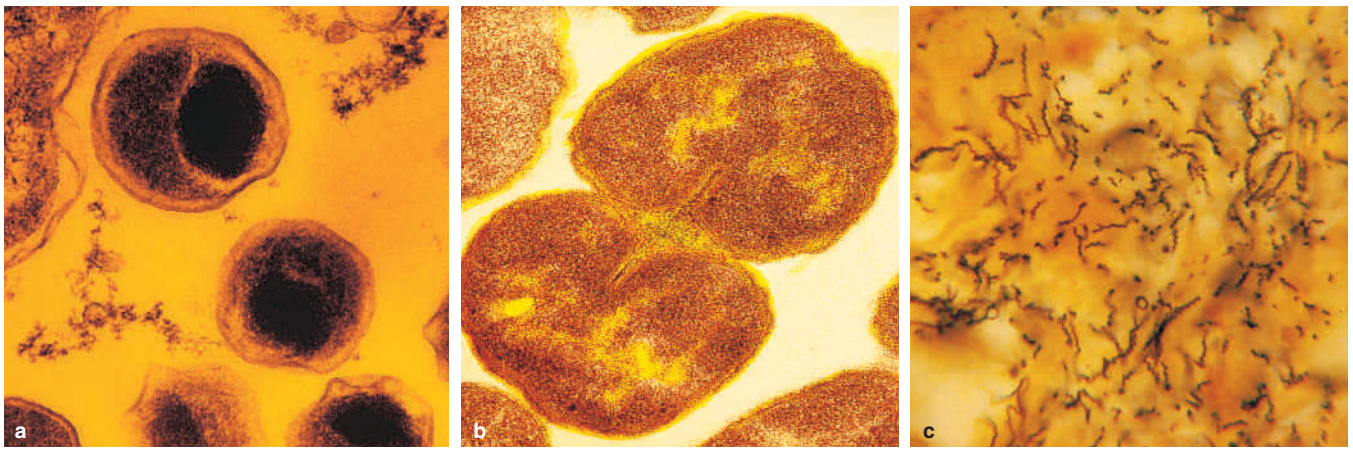


Figure 16.15 Chlamydia, gonorrhea, and syphilis all are caused by bacteria. (**a**) Color-enhanced micrograph of *Chlamydia trachomatis* bacteria. (**b**) Neisseria *gonorrhoeae*, or gonococcus, a bacterium that typically is seen as paired cells, as shown here. (**c**) The bacteria that cause syphilis.

tract, the rectum, eye membranes, and the throat. Each year in the United States there are about 650,000 new cases reported; there may be up to 10 million unreported cases. Part of the problem is that the initial stages of the disease can be so uneventful that, as with chlamydia, a carrier may be unaware of being infected.

Early symptoms in males usually are easy to see. Pus begins to ooze from the penis and urinating becomes painful and more frequent. A man can become sterile if untreated gonorrhea leads to inflammation of his testicles or scarring of the vas deferens.

In females, the early stages of gonorrhea can be much more difficult to notice. For example, a woman may not experience burning while urinating, and she may not have an abnormal vaginal discharge. As a result, a woman's gonorrhea infection may well go untreated while the gonococcus is spreading into her oviducts. Eventually, she may experience violent cramps, fever, and vomiting. She may even become sterile if PID develops and her oviducts become blocked with scar tissue.

Antibiotics can kill the gonococcus and thus prevent complications of gonorrhea. Penicillin was once the most commonly used drug treatment. Unfortunately, antibiotic-resistant strains of gonococcus have developed. As a result, many doctors now order testing to determine the strain responsible for a particular patient's illness and then treat the infection with an appropriate antibiotic.

Many people believe that once cured of gonorrhea, they can't be reinfected. That is not true, partly because there are at least sixteen different strains of *N. gonorrhoeae*.

Syphilis eventually affects many organs

Syphilis is caused by the bacterium *Treponema pallidum* (Figure 16.15*c*). The bacterium is transmitted by sexual contact. Once it reproduces, an ulcer called a chancre ("shanker," Figure 16.16*a*) develops. Usually the chancre is flat rather than bumpy, is not painful, and teems with treponemes. It becomes visible 1 to 8 weeks after infection and is a symptom of the *primary stage* of syphilis. Syphilis can be diagnosed in a cell sample taken from a chancre. By then, however, bacteria have already moved into the person's bloodstream.

The *secondary stage* of syphilis begins a couple of months after the chancre appears. Lesions can develop in mucous membranes, the eyes, bones, and the central nervous system. A blotchy rash breaks out over much of the body (Figure 16.16*b*). After the rash heals, the infection enters a latent stage that can last for years. During that time, the disease does not produce major outward symptoms and can be detected only by laboratory tests.

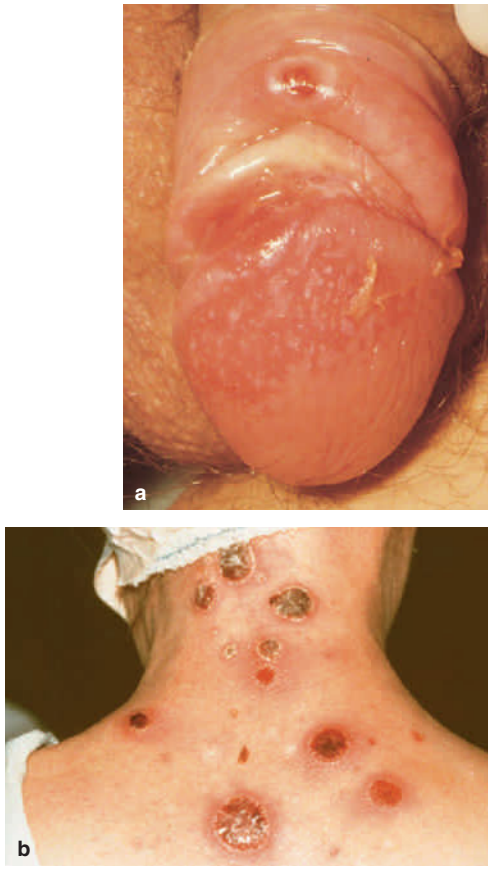


Figure 16.16 Skin ulcers are signs of syphilis. (**a**) An ulcer called a chancre ("shanker"), a sign of the first stage of syphilis. It appears anytime from about 9 days to 3 months after infection, on the genitals or near the anus or the mouth. (**b**) This photograph shows chancres typical of secondary syphilis.

The *tertiary stage* of syphilis usually begins from 5 to 20 years after infection. Lesions may develop in the skin and internal organs, including the liver, bones, and aorta. Scars form; the walls of the aorta can weaken. Treponemes also damage the brain and spinal cord in ways that lead to various forms of insanity and paralysis. Infected women who become pregnant typically have miscarriages, stillbirths, or sickly infected infants.

Penicillin may cure syphilis during the early stages, although antibiotic-resistant strains have now developed.

Take-Home Message

What are the causes of chlamydia, gonorrhea, and syphilis?

- Chlamydia, gonorrhea, and syphilis are all caused by bacteria. Chalmydia is the most common bacterial STD.
- Antibiotics can cure most bacterial STDs, although there are now antibiotic-resistant strains of the gonorrhea and syphilis bacteria.
- Pelvic inflammatory disease is a dangerous complication of chlamydial infection and gonorrhea.

16.10 STDs Caused by Viruses and Parasites

- **Viruses, parasites, and other pathogens also cause disorders that can be transmitted by sexual contact.**

Genital herpes is a lifelong infection

Like HIV infections (Section 9.11 and Figure 16.17), herpes virus infections are extremely contagious. Herpes simplex is transmitted by contact with active viruses or sores that contain them (Figure 16.18). Mucous membranes of the mouth or genitals and broken or damaged skin are most susceptible.

In 2005 the National Institutes of Health estimated that in the United States, one in five people over the age of twelve—roughly 45 million people—have one of the two viral strains of that cause **genital herpes**. Type 1 strains infect mainly the lips, tongue, mouth, and eyes. Type 2 strains cause most genital infections.

Symptoms usually develop within two weeks after infection, although sometimes they are mild or absent. Usually, small, painful blisters erupt on the penis, vulva, cervix, urethra, or around the anus. The sores can also occur on the buttocks, thighs, or back. The first flare-up may cause brief flulike symptoms. Within three weeks the sores crust over and heal.

Every so often the virus may be reactivated. Then it produces new, painful sores at or near the original site of infection. Recurrences can be triggered by stress, sexual intercourse, menstruation, a rise in body temperature, or other infections.

There is no cure for herpes. Between flare-ups, the virus simply is latent in nervous tissue. However, several antiviral drugs inhibit its ability to reproduce. They also reduce the shedding of virus particles from sores, and sores are often less painful and heal faster.

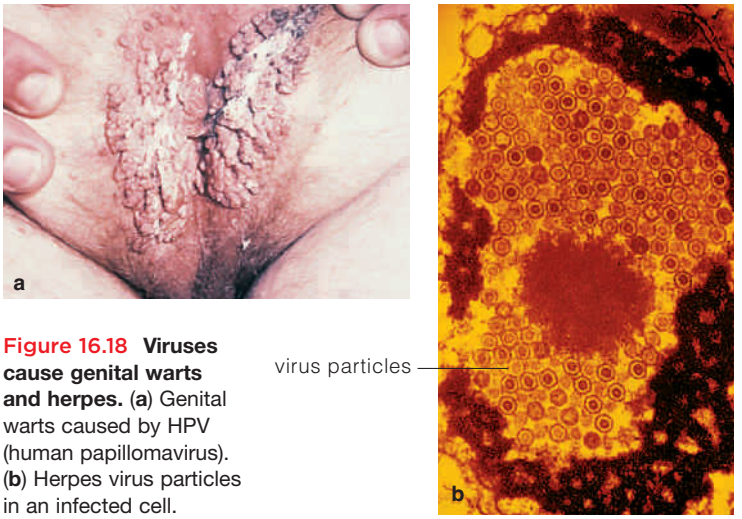


Figure 16.18 Viruses cause genital warts and herpes. (**a**) Genital warts caused by HPV (human papillomavirus). (**b**) Herpes virus particles in an infected cell.

Human papillomavirus can lead to cancer

Genital warts are painless growths caused by infection of epithelium by the **human papillomavirus (HPV)**. The warts can develop months or years after a person is exposed to the virus. Usually they occur in clusters on the penis, the cervix, or around the anus (Figure 16.18*b*). Certain forms of HPV are thought to cause more than 80 percent of cases of invasive cervical cancer, a rare but serious form of cervical cancer. Any woman who has a history of genital warts should tell her physician, who may recommend an annual *Pap smear*, which is a test for abnormal growth of cervix cells. An anti-HPV vaccine has recently become available. Ideally it is administered before a female becomes sexually active.

Figure 16.17 NBA legend Magic Johnson, a torchbearer of the 2002 Winter Olympics. He got HIV through heterosexual sex and credits his survival to AIDS drugs and informed medical care. He continues his campaign to educate others about AIDS.

Hepatitis can be sexually transmitted

Two types of hepatitis can be transmitted through sex. Like HIV, the **hepatitis B** virus (HBV) is transmitted in blood or body fluids such as saliva, vaginal secretions, and semen. However, HBV is far more contagious than HIV. The number of sexually transmitted hepatitis B cases is growing; in the United States, hundreds of thousands of people live with the disease, and about 80,000 new cases are reported each year. The virus attacks the liver. A key symptom is jaundice, yellowing of the skin and whites of the eyes as the liver loses its ability to process bilirubin pigments produced when liver cells break down hemoglobin from red blood cells. In some cases the infection becomes chronic and can lead to liver cirrhosis or cancer. The only treatment is rest. However, people at known risk for getting the disease (such as health care workers and anyone who requires repeated blood transfusions) can be vaccinated against HBV.

In 2005 more than 170 million people worldwide were living with the **hepatitis C** virus (HCV), which causes severe liver cirrhosis and sometimes cancer. It is carried in the blood and can reside in the body for years before symptoms develop. A blood-borne disease, HCV can be transmitted sexually if contaminated blood enters a sex partner's body through cut or torn skin.

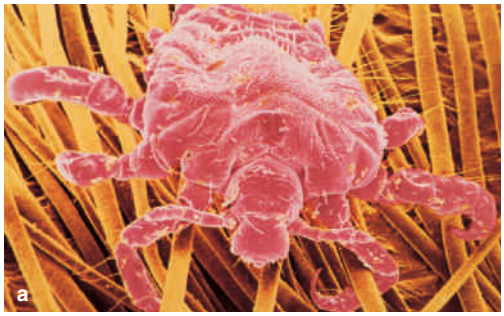


Figure 16.19 Animal parasites also cause STDs. (**a**) A crab louse, magnified 120 times. Crab lice may be visible as moving brownish dots. (**b**) The protozoan *Trichomonas vaginalis*, which causes trichomoniasis.

Parasites cause some STDs

Several animal parasites can be transmitted by close body contact. One is **pubic lice**, also called crab lice or simply "crabs" (Figure 16.19*a*). These tiny relatives of spiders usually turn up in the pubic hair, although they can make their way to any hairy spot on the body. They cling to hairs and attach their small, whitish eggs ("nits") to the base of the hair shaft. Itching and irritation can be intense when the parasites bite into the skin and suck blood. Antiparasitic drugs get rid of pubic lice.

Many microorganisms may live inside the vagina, although its rather acidic pH usually keeps pathogens in check. When certain vaginal infections do occur, they can be transmitted to a sex partner during intercourse. Any factor that alters the vagina's usual chemistry (such as taking an antibiotic) can trigger overgrowth of *Candida albicans*, a type of yeast (a fungus) that often lives in the vagina. A vaginal yeast infection, or **candidiasis**, causes a "cottage cheesy" discharge and itching and irritation of the vulva. A male may notice itching, redness, and flaky skin on his penis. Yeast infections are easily treated by over-the-counter and prescription medications, but both partners may need to be treated to prevent reinfection.

Trichomonas vaginalis, a protozoan parasite (Figure 16.19*b*), can cause the severe vaginal inflammation called **trichomoniasis**. The symptoms include a foul-smelling vaginal discharge and burning and itching of the vulva. An infected male may experience painful urination and have a discharge from the penis, both due to an inflamed urethra. Usually both partners are treated with antibiotics.

16.11 Eight Steps to Safer Sex

The only people who are not at risk of STDs are those who are celibate (never have sex) or who are in a long-term, mutually monogamous relationship in which both partners are disease-free. The following guidelines can help you minimize your risk of acquiring or spreading an STD.

1. Use a latex condom during either genital or oral sex to greatly reduce your risk of being exposed to HIV, gonorrhea, herpes, and other diseases. With the condom, use a spermicide that contains nonoxynol-9, which may help kill virus particles. Condoms are available for men and women.
2. Limit yourself to one partner who also has sex only with you.
3. Get to know a prospective partner before you have sex. A friendly but frank discussion of your sexual histories, including any previous exposure to an STD, is very helpful.
4. If you decide to become sexually intimate, be alert to the presence of sores, a discharge, or any other sign of possible trouble in your partner's genital area.
5. Avoid abusing alcohol and drugs. Studies show that alcohol and drug abuse both are correlated with unsafe sex practices.
6. Learn about and be alert for symptoms of STDs. If you have reason to think you have been exposed, abstain from sex until a medical checkup rules out any problems. Self-treatment won't help. See a doctor or visit a clinic.
7. Take all prescribed medication and don't share it with a partner. Unless both of you take a full course of medication, your chances of reinfection will be great. Your partner may need to be treated even if he or she does not have symptoms.
8. If you do become exposed to an STD, avoid sex until medical tests confirm that you are not infected.

Take-Home Message

What are some common non-bacterial STDs?

- Viruses cause genital herpes, genital warts, and types B and C hepatitis. Sexual contact also transmits some fungi and parasites.

16.12 Cancers of the Breast and Reproductive System

- **In the United States, breast cancer is a major killer of women. In both females and males, reproductive system cancers also are major health concerns.**

Breast cancer is a major cause of death

In the United States, about one woman in eight and a small number of men under age 35 develop breast cancer. Of all cancers in women, breast cancer currently ranks second only to lung cancer as a cause of death.

Obesity, early puberty, late childbearing, late menopause, excessive estrogen levels, and a fatty diet are risk factors for women. The risk is much greater for women with a family history of the disease. They may carry a faulty version of a tumor suppressor gene such as BRCA1 or BRCA2. (Cancer is more likely when such genes are mutated.) Only 20 percent of breast lumps are cancer, but a woman should see a doctor about any breast lump, thickening, dimpling, breast pain, or discharge.

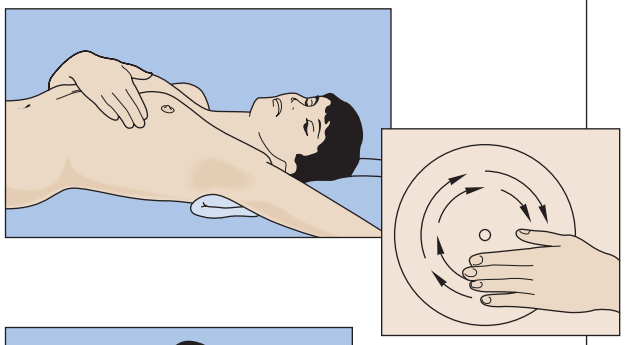
Chances for cure are excellent if breast cancer is detected early. Hence a woman should examine her breasts every month (about a week after her menstrual period, during her reproductive years). Figure 16.20 shows the steps of a self-exam. Low-dose mammography (breast X-ray) combined with ultrasound is the most effective method for detecting small breast cancers. The American Cancer Society recommends an annual mammogram for women over 40 and for younger women at high risk.

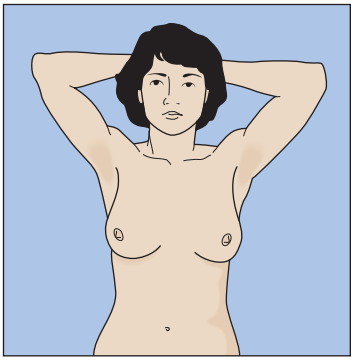
Early breast cancer often is treated by *lumpectomy*, which removes the tumor but leaves nearly all of the breast tissue. In *modified radical mastectomy*, the affected breast tissue, overlying skin, and nearby lymph nodes are removed. When the cancer has spread to muscles of the chest wall, they also must be taken out (*radical mastectomy*). In all cases, lymph nodes are examined because they reveal whether the cancer has begun to spread.

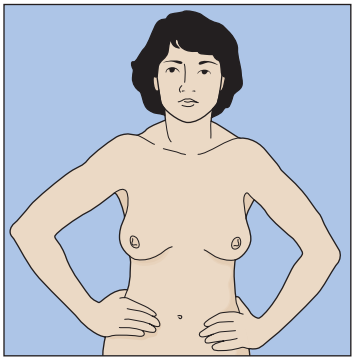
Various chemotherapy drugs are also used in the fight against breast cancer. A few can sometimes shrink tumors.

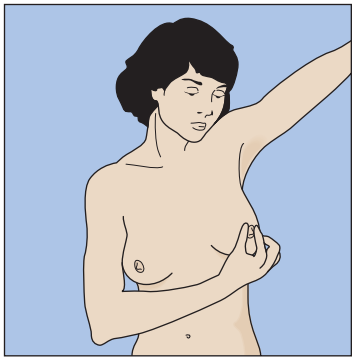
Figure 16.20 Women should perform monthly breast self-examination. The diagram below shows how to perform a breast self-examination. The mammogram shown at right has revealed a breast cancer tumor.

1. Lie down and put a folded towel under your left shoulder, then put your left hand behind your head. With the right hand (fingers flat), begin the examination of your left breast by following the outer circle of arrows shown. Gently press the fingers in small, circular motions to check for any lump, hard knot, or thickening. Next, follow the inner circle of arrows. Continue doing this for at least three more circles, one of which should include the nipple. Then repeat the procedure for the right breast. For a complete examination, repeat the procedure while standing in a shower. Hands glide more easily over wet skin.



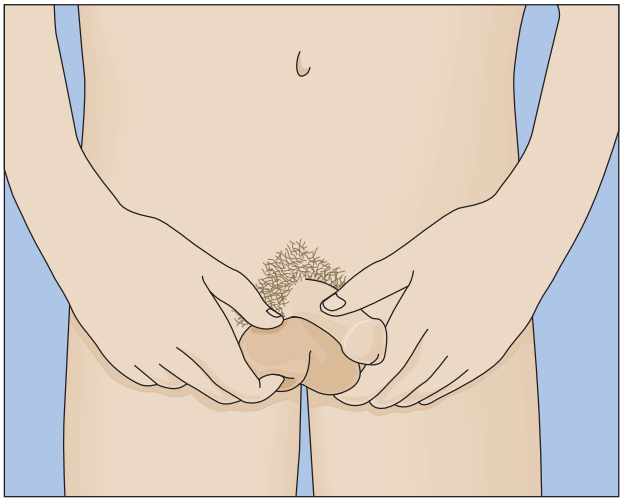






2. Stand before a mirror, lift your arms over your head, and look for any unusual changes in the contour of your breasts, such as a swelling, dimpling, or retraction (inward sinking) of the nipple. Also check for any unusual discharge from the nipple.

If you discover a lump or any other change during a breast self-examination, it's important to see a physician at once. Most changes are not cancerous, but let the doctor make the diagnosis.



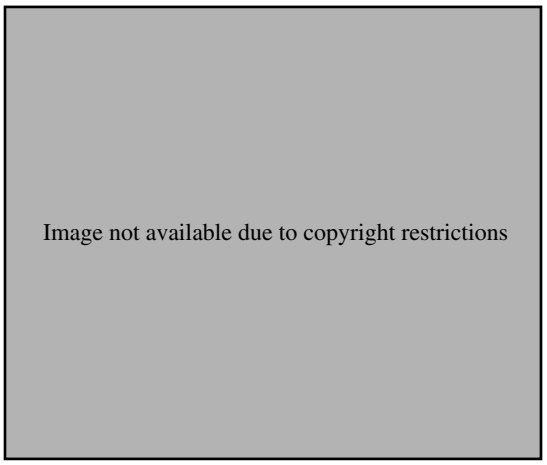


Figure 16.21 Men should perform testicular self-examination monthly. The instructions below are the method recommended by the American Cancer Society. Do the exam when the scrotum is relaxed, as it is after a warm bath or shower. Simply roll each testicle between the thumb and forefinger, feeling for any lumps or thickening. As with breast lumps, most such changes are not cancer, but a doctor must make the diagnosis. Right: International cycling champion Lance Armstrong, a survivor of testicular cancer.

Uterine and ovarian cancer affect women

Cancers of the uterus most often affect the endometrium (uterine lining) and the cervix. Various types are treated by surgery, radiation, or both. The incidence of uterine cancers is falling, in part because precancerous phases of cervical cancer can be easily detected by the *Pap smear* that is part of a routine gynecological examination. The risk factors for cervical cancer include having many sex partners, early age of first intercourse, cigarette smoking, and genital warts (Section 16.10). Endometrial cancer is more common during and after menopause.

Ovarian cancer is often lethal because its chief symptom, an enlarged abdomen, doesn't show up until the cancer is advanced and has spread. The first sign may be abnormal vaginal bleeding or abdominal discomfort. Risk factors include family history of the disease, having breast cancer, and not bearing children. Surgery to remove the ovaries and other affected tissue is the usual first step in treatment. Patients often also receive chemotherapy, which is moderately successful, especially in early stages of the disease.

Testicular and prostate cancer affect men

Several thousand cases of testicular cancer are diagnosed annually in the United States. In early stages this cancer is painless. However, it can spread to lymph nodes in a man's abdomen, chest, neck, and, eventually, his lungs. Once a month from high school onward, men should examine each testicle separately after a warm bath or shower (when the scrotum is relaxed). The testis should be rolled gently between the thumb and forefinger to check for any unusual lump, enlargement, or hardening (Figure 16.21). Because the epididymis may be confused with a lump, the important thing is to compare the two testes. A lump may not be painful, but only a physician can rule out the possibility of disease. Surgery is the usual treatment, and the success rate is high when the cancer is caught before it can spread.

Prostate cancer is second only to lung cancer in causing cancer deaths in men. There are no definite risk factors other than having a family history of the disease. Symptoms include various urinary problems, although these can also signal simply a noncancerous enlarged prostate. For men over 40, an annual digital rectal examination, which enables a physician to feel the prostate, is the first step in detecting unusual lumps. The PSA blood test can screen for suspiciously large amounts of that tumor marker. If a physician suspects cancer after these two tests have been performed, the next step is a biopsy—removing a small tissue sample for microscopic analysis. Over 90 percent of prostate tumors detected early are cured.

Many prostate cancers grow slowly and cause few problems. In such cases a physician may recommend simply monitoring the tumor for worrisome changes.

Take-Home Message

- Breast cancer affects about one woman in eight. Rarely, it also occurs in males under age 40.
- The most common reproductive cancers in women develop in the ovaries and uterus. In males, cancers of the testis and prostate gland are the most common reproductive cancers.
- Chances for a cure are best when cancer is detected early. Monthly self-examination is a crucial tool for early detection.

IMPACTS, ISSUES

Fertility Plus

MOST fertility drugs dramatically increase the odds that three or more embryos will develop. In addition to the risks for the mother and her babies, such high-order multiple pregnancies often incur tremendous financial costs that are passed on to society at large.

How Would You Vote?

Should physicians restrict the use of fertility drugs so as to limit the number of embryos that form? See CengageNow for details, then vote online.

Summary

Section 16.1 Testes are a male's primary reproductive organs. The male reproductive system also includes accessory ducts and glands.

Sperm develop mostly in the seminiferous tubules and mature in the epididymis. The seminal vesicles, bulbourethral glands, and prostate gland produce fluids that mix with sperm, forming semen.

A vas deferens leading from each testis transports sperm outward when a male ejaculates.

- Use the animation and interaction on CengageNOW to learn about the male reproductive system.

Section 16.2 The hormones testosterone, LH (luteinizing hormone), and FSH (follicle-stimulating hormone) control the formation of sperm. They are part of feedback loops among the hypothalamus, anterior pituitary, and testes. Sertoli cells, which line the seminiferous tubules, nourish sperm. Leydig cells in tissue between the tubules secrete testosterone.

A mature sperm cell has a head, midpiece, and tail. Covering much of the head is the acrosome, which contains enzymes that help a sperm penetrate an egg.

In both males and females, gonadotropin-releasing hormone (GnRH) from the hypothalamus stimulates the anterior pituitary to release LH and FSH.

Section 16.3 The paired ovaries, which produce eggs, are a female's primary reproductive organs. Accessory glands and ducts, such as the oviducts, are also part of the female reproductive system. Oviducts open into the uterus, which is lined by the endometrium.

Unless a fertilized egg begins to grow in the uterus, the endometrium proliferates, then is shed in the three-phase menstrual cycle, which averages about 28 days.

- Use the animation and interaction on CengageNOW to learn about the female reproductive system.

Sections 16.4, 16.5 The menstrual cycle overlaps with an ovarian cycle. At the end of each menstrual period, a follicle (containing an oocyte) matures in an ovary. Under the influence of hormones, the endometrium starts to rebuild.

A midcycle peak of LH triggers ovulation, the release of a secondary oocyte from the ovary.

TABLE 16.5 New STD Cases Annually*

STD	U.S. Cases	Global Cases
HPV infection	5,500,000	20,000,000
Trichomoniasis	5,000,000	174,000,000
Chlamydia	3,000,000	92,000,000
Genital herpes	1,000,000	20,000,000
Gonorrhea	650,000	62,000,000
Syphilis	70,000	12,000,000
AIDS	40,000	4,900,000

*Global data on HPV and genital herpes were last compiled in 1997.

A corpus luteum forms from the rest of the follicle. It secretes progesterone that prepares the endometrium to receive a fertilized egg and helps maintain the endometrium during pregnancy. When no egg is fertilized, the corpus luteum degenerates, and the endometrial lining is shed through menstruation.

Estrogen, progesterone, FSH, and LH control the maturation and release of eggs, as well as changes in the endometrium. They are part of feedback loops involving the hypothalamus, anterior pituitary, and ovaries.

- Use the animation and interaction on CengageNOW to observe the cyclic changes in an ovary and the effects of hormones on the menstrual cycle.

Section 16.6 Sexual intercourse (coitus) is the usual way an egg (a secondary oocyte) and sperm meet for fertilization. It typically involves a sequence of physiological changes in both partners and may culminate in orgasm.

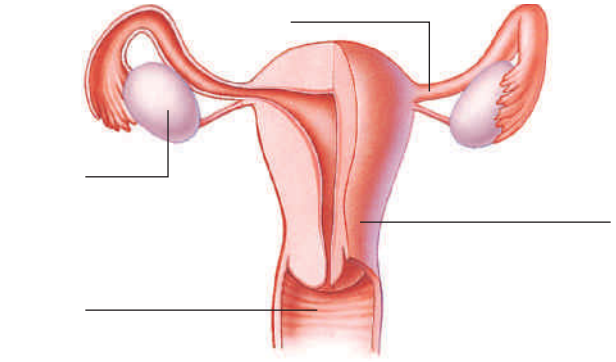
Sections 16.7, 16.8 Physical, chemical, surgical, and behavioral strategies are available for controlling unwanted pregnancies and helping infertile couples. Efforts to control fertility raise important ethical questions.

Sections 16.9–16.11 Sexually transmitted diseases (STDs) are passed by sexual activity (Table 16.5). Bacteria cause chlamydia, gonorrhea, and syphilis. In addition to AIDS, viral STDs include genital herpes, genital warts (HPV), and viral hepatitis. Untreated STDs can seriously harm health. Only people who abstain from sexual contact or who are in an infection-free monogamous relationship can be sure of not being exposed to an STD.

Section 16.12 Major reproductive cancers include breast cancer and cancers of the testes and prostate.

Review Questions

1. Distinguish between:
   a. seminiferous tubule and vas deferens
   b. sperm and semen
   c. Leydig cells and Sertoli cells
   d. primary oocyte and secondary oocyte
   e. follicle and corpus luteum
   f. the three phases of the menstrual cycle
2. Which hormones influence the development of sperm?
3. Which hormones influence the menstrual and ovarian cycles?
4. List four events that are triggered by the surge of LH at the midpoint of the menstrual cycle.
5. What changes occur in the endometrium during the ovarian cycle?
6. Label the parts of the female reproductive system and list their functions.
7. Label the parts of the male reproductive system and state their functions.



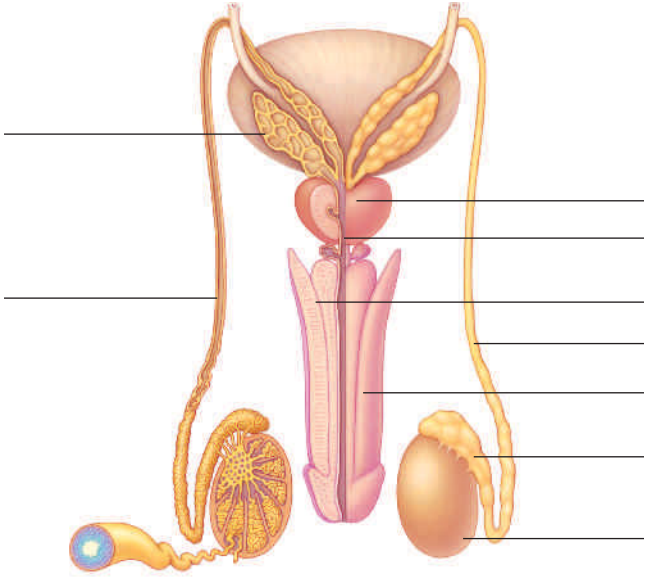


Figure 16.22 **The entrance to an oviduct, the tubelike channel to the uterus.**

8. Figure 16.22 shows the billowing opening to the oviduct into which an ovulated oocyte is swept. Which oocyte stage is ovulated? What happens to it if (a) it encounters a sperm cell there or (b) it does not meet up with sperm?

Self-Quiz *Answers in Appendix V*

1. Besides producing gametes (sperm and eggs), the primary male and female reproductive organs also produce sex hormones. The _____ and the pituitary gland control secretion of both.
2. _____ production is continuous from puberty onward in males; _____ production is cyclic and intermittent in females.
   a. Egg; sperm
   b. Sperm; egg
   c. Testosterone; sperm
   d. Estrogen; egg
3. The secretion of _____ controls the formation of sperm.
   a. testosterone
   b. LH
   c. FSH
   d. all of the above are correct
4. During the menstrual cycle, a midcycle surge of _____ triggers ovulation.
   a. estrogen
   b. progesterone
   c. LH
   d. FSH
5. Which is the correct order for one turn of the menstrual cycle?
   a. corpus luteum forms, ovulation, follicle forms
   b. follicle grows, ovulation, corpus luteum forms
6. In order for sexual intercourse to produce a pregnancy, both partners must experience _____.
   a. orgasm
   b. ejaculation
   c. affection
   d. none of the above

Critical Thinking

1. Counselors sometimes advise a couple who wish to conceive a child to use an alkaline (basic) douche immediately before intercourse. Speculate about what the doctors' reasoning might be.
2. In the "fertility awareness" method of birth control, a woman gauges her fertile period each month by monitoring changes in the consistency of her vaginal mucus. What kind of specific information does such a method provide? How does it relate to the likelihood of getting pregnant?
3. Some women experience premenstrual syndrome (PMS), which can include a distressing combination of mood swings, fluid retention (edema), anxiety, backache and joint pain, food cravings, and other symptoms (*right*). PMS usually develops after ovulation and lasts until just before or just after menstruation begins. A woman's doctor can recommend strategies for managing PMS, which often include diet changes, regular exercise, and use of diuretics or other drugs. Many women find that taking vitamin B_6 and vitamin E helps reduce pain and other symptoms. Although the precise cause of PMS is unknown, it seems clearly related to the cyclic production of ovarian hormones. After reviewing Figure 16.8, suggest which hormonal changes may trigger PMS.

4. Some infertile couples are willing to go to considerable lengths to have a baby. From your reading of Section 16.8, which of the variations of reproductive technologies produces a child that is least related (genetically) to the infertile couple? Would you view having a child by that method as preferable to adopting a baby? Why or why not?
5. The absence of menstrual periods, or amenorrhea, is normal in pregnant and postmenopausal women and in girls who have not yet reached puberty. However, in females of reproductive age amenorrhea can result from tumors of the pituitary or adrenals. Based on discussions in this chapter and Chapter 15, speculate about why such tumors might disrupt monthly menstruation.

EXPLORE ON YOUR OWN

Public health agencies maintain statistics on the incidence of STDs. They use the numbers to measure the success of public education efforts, to identify increases in reported cases of various STDs, and to monitor the appearance of drug-resistant strains of disease-causing organisms. Infection by human papillomavirus (HPV) is the most widespread and fastest growing STD in the United States. Table 16.5 in the chapter summary lists the seven most prevalent STDs globally.

To explore how these health concerns are affecting your community or state, go online and find out if your local or state public health department maintains statistics on STDs (most do). Then see which are the most prevalent STDs in your area and whether the numbers have been rising or declining. If someone thinks they may have been exposed, what resources are available for confidential testing?

Development and Aging

17

IMPACTS, ISSUES

Male or Female? Body or Genes?

ATHLETE Santhi Soundarajan, shown below, overcame poverty and malnutrition to become a world-class runner. In 2006 she won a silver medal in the Pan Asian Games, but was stripped of her medal days later. Although raised as a female, unbeknownst to her Santhi is a genetic male.

Evidently, Santhi was born with one of several known intersex conditions. She inherited the gene that usually results in a male embryo, but she also inherited a genetic abnormality that prevented her cells from responding to the male sex hormone testosterone. When this happens, a fetus that would otherwise develop male genitals instead has female genitals. She does not have ovaries or a uterus, but at puberty her body will develop female secondary sexual characteristics.

Other intersex conditions come about when some aspect of early development is skewed. In some cases, babies are born with ambiguous genitals. A boy may have a tiny penis and testes embedded in his abdomen. A girl may have a large clitoris but no opening to her vagina.

In the United States, babies who have unusual genitals nearly always are operated on to make their genitals appear as normal as possible, even if that means assigning the child to the opposite genetic sex—a procedure that some doctors and intersex individuals strongly oppose. They advocate postponing action until after puberty, when affected people can make their own decision about what type of surgery, if any, they want to have.

With this chapter, we consider the many aspects of how a human develops. We start with principles that govern how all the specialized cells and tissues of an adult come into being—a biological journey we all have made.

LINKS TO EARLIER CONCEPTS

- This chapter builds on the principles of reproduction introduced in Chapter 16 and draws on your understanding of hormones that influence the menstrual cycle (16.3, 16.4).
- Here you will learn the basics of how organ systems start to develop in an embryo (4.8). You will use your knowledge of the cardiovascular system (7.1) as you study some special features of this system in a developing fetus.
- You will also see how a cascade of hormones from the hypothalamus and pituitary set the stage for birth (15.3), and you will learn more about the bodily effects of aging.

How Would You Vote?

Children born with intersex disorders have traditionally had surgery early in life. Some people think such surgery should be delayed until after puberty so a child can choose or reject it. Would you delay surgery if your child were affected? See CengageNOW for details, then vote online.

KEY CONCEPTS

Development Begins

A new individual develops in steps that produce tissues and organs. Each step is guided by genes and builds on body structures that are formed in the preceding stage. Sections 17.1–17.5

Prenatal Development

Early development forms a multicellular embryo and its organs. In the fetal phase, organs and other structures grow and mature. Sections 17.6, 17.7

Birth and Later Life Stages

Body structures and their functioning change throughout life as a person moves from infancy into childhood, adolescence, adulthood, and the later years. Sections 17.8–17.12

17.1 Overview of Early Human Development

- **Like all animals, humans begin life as a single cell from which tissues and organs soon begin to develop.**
- **Links to Organ systems 4.8, How sperm and eggs form 16.2, 16.4, Fertilization 16.6**

After fertilization, the zygote soon becomes a ball of cells

Section 16.12 described how fertilization produces a zygote, the first cell of a new individual. Within a day or two after fertilization, cell divisions convert the zygote to a ball of cells (Figure 17.1). This process is called **cleavage**. It occurs while the zygote is traveling down the oviduct toward the uterus. By the time it reaches the uterus, the zygote is a cluster of sixteen cells called a *morula* (MOE-roo-lah, from a Latin word for mulberry).

Each new cell that forms during cleavage is called a **blastomere**. Each one ends up with a different portion of the egg's cytoplasm. Which bit of cytoplasm a blastomere receives helps determine the developmental fate of cells that arise from it later on. For example, its fate may be to become the forerunner of some kind of nervous tissue or perhaps of epithelium.

Three primary tissues form

After cleavage comes **gastrulation** (gas-tru-LAY-shun), a process that rearranges the morula's cells. It lays out the basic organization for the body as cells are arranged into three primary tissues, the **germ layers** (Table 17.1). The outer one is called **ectoderm**, the middle one **mesoderm**, and the inner one **endoderm**. Body tissues and organs will develop from groups of cells in each layer.

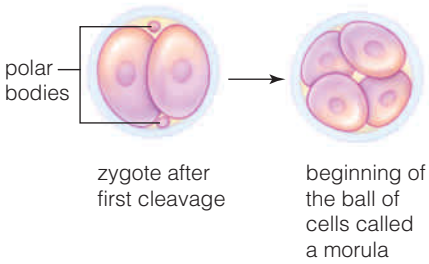


Figure 17.1 Cleavage in a zygote creates a ball of cells. In the diagram of the first cleavage, on the left, the small spheres are polar bodies (Section 16.4).

Next, cells become specialized

In the germ layers, different genetic instructions begin to operate in different groups of cells. This is the start of **cell differentiation**. In simple terms, this process makes cells "specialists" for a particular function. For example, you may remember from Chapter 9 how various subsets of T cells, each with a different function, differentiate in the thymus.

An adult has about 200 differentiated cell types. In each type, the genetic instructions needed for its specialized function operate. For instance, as your eyes developed, certain cells turned on genes for a transparent protein called crystallin. These differentiated cells then formed the lens of each eye. They are the only body cells that make crystallin.

Although each type of differentiated cell has its own particular genetic marching orders, a differentiated cell still has all the genes that parents pass to an embryo. Efforts to "reverse engineer" adult cells back into stem cells, as described in the introduction to Chapter 4, rely on this fact. It also is why scientists have been able to clone adult animals—that is, to create a genetic copy—from some types of differentiated cells. Chapter 21 discusses some examples of cloning.

The Three Germ Layers and Tissues and Organs That Form from Them

Germ Layer	Body Parts in an Adult
Ectoderm	Nervous system and sense organs
	Pituitary gland
	Outer layer of skin (epidermis) and its associated structures, such as hair
Mesoderm	Cartilage, bone, muscle, and various connective tissues
	Cardiovascular system and blood
	Lymphatic system
	Urinary system
	Reproductive system
	Outer layers of the digestive tube and of structures that develop from it, including parts of the respiratory system
Endoderm	Lining of the digestive tube and of structures that develop from it, such as the lining of the respiratory airways

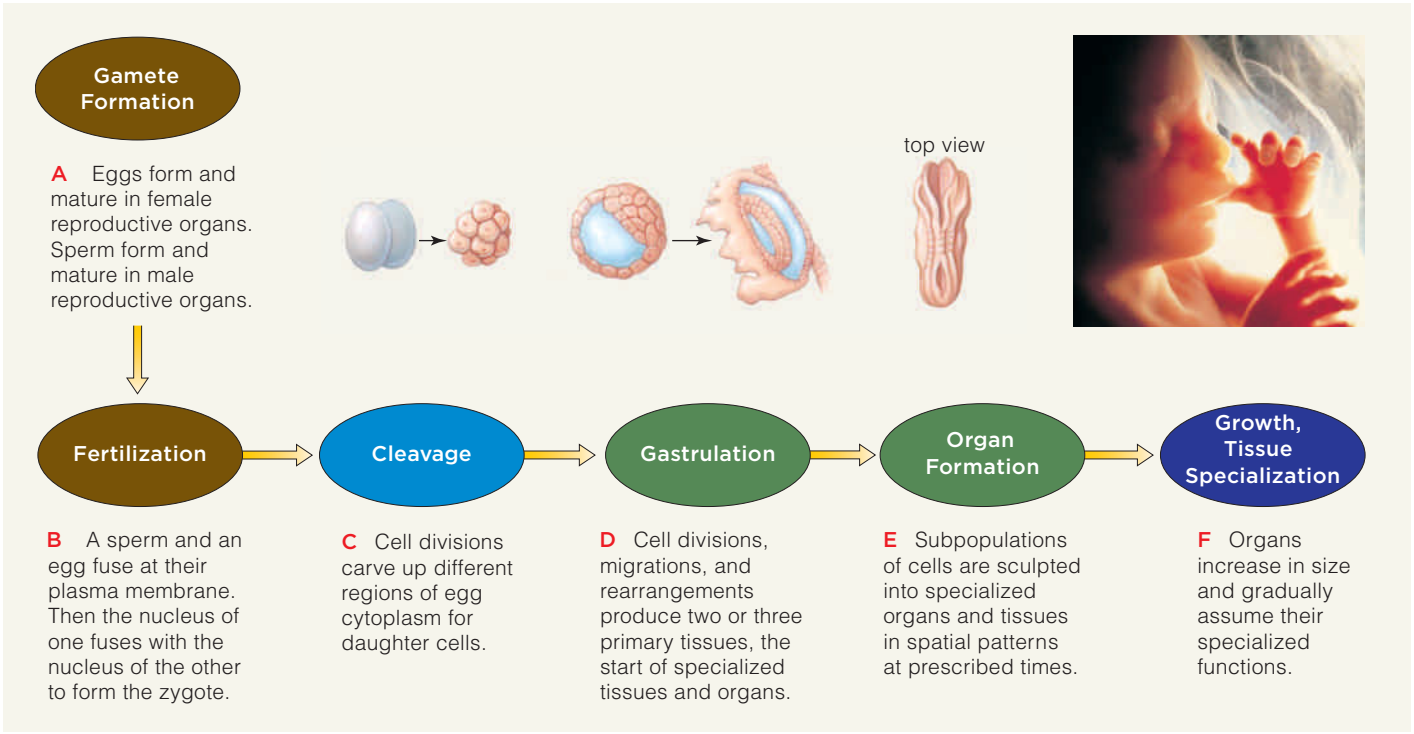
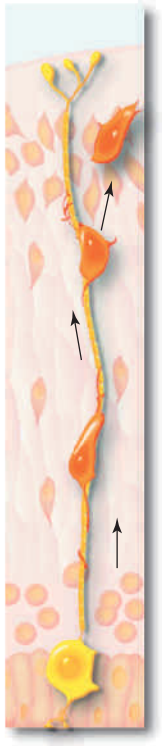


Figure 17.2 Animated! **An early embryo begins to develop soon after fertilization.** This flow chart shows the stages from fertilization to about 6 weeks. (**a–f**) For clarity, membranes surrounding the embryo are not shown. Several stages are shown in cross section.



Organs form by the process of morphogenesis

Morphogenesis ("the beginning of form") is the process by which body tissues and organs form. Several factors influence these changes. They include cell division in certain areas and the growth and movement of cells and tissues from one place to another.

For example, most of the bones of your face descended from cells that migrated from the back of your head when you were an early embryo. In a similar way, neurons in the center of the developing brain creep along parts of glial cells or axons of other neurons until they reach their final destination (Figure 17.3). Morphogenesis also requires sheets of tissue to fold and certain cells to die on cue. You will read about some other examples of these events in Section 17.4.

Figure 17.3 **Cells migrate as tissues and organs form.** This diagram gives an idea of how a neuron migrates along the axon of another neuron as it travels to its final position.

Figure 17.2 summarizes the stages of development we have been discussing. It is important to remember that by the end of each stage, the embryo is more complex than it was before. Normal development requires that each stage be completed before the next one begins.

Take-Home Message

What are the basic events of early development?

- Cleavage of the zygote into a ball of cells occurs shortly after fertilization.
- Gastrulation forms the three primary tissues ectoderm, mesoderm, and endoderm.
- Cell differentiation specializes cells for their final roles in the body. Tissues and organs form during morphogenesis.
- Each stage of early embryonic development builds on structures that were formed during the preceding stage. For proper development, a stage must be successfully completed before the next one begins.

17.2 From Zygote to Implantation

- **A newly formed embryo cannot survive unless it implants in the mother's uterus.**
- **Link to Fertilization 16.6**

The previous section gave you an overview of the basic processes of human development. In the next few sections we look in more depth at how these processes culminate in a newborn baby.

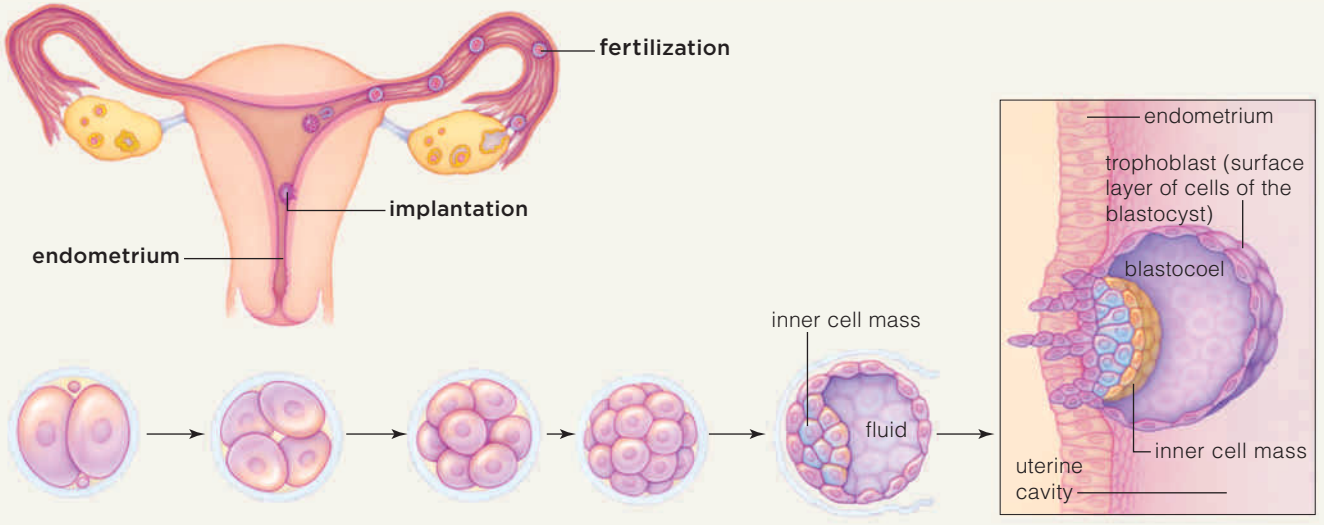
Cleavage produces a multicellular embryo

As you've read, the zygote spends several days moving down the oviduct before it reaches the mother's uterus. During this time it is sustained by nutrients from the ovum or from substances secreted by the mother's tissues. On the way, the three cleavages described in Section 17.1 occur, converting the single-celled zygote into a morula (Figure 17.4).

When the morula finally reaches the uterus, cavity filled with fluid begins to open up inside it. This change transforms the morula into a **blastocyst** (*blast-* means bud). The blastocyst has two tissues: a surface epithelium called the *trophoblast* (*tropho-* means to nourish) and a small clump of cells called the **inner cell mass** (Figure 17.4*e*). The **embryo** develops from the inner cell mass.

Sometimes a split separates the two cells produced by the first cleavage, the inner cell mass, or an even later stage. Then, separate embryos develop as *identical twins*, who have the same genetic makeup. *Fraternal twins* result when two eggs are fertilized at roughly the same time by different sperm. Fraternal twins need not be the same sex and they don't necessarily look any more alike than other siblings do. *Focus on Health* on the facing page looks at health issues that may arise with twinning.

Identical twin sisters



A DAYS 1–2. The first cleavage furrow extends between the two polar bodies.

B DAY 3. After the third cleavage, cells form a compact ball.

C DAY 4. By 96 hours there is a ball of 16 to 32 cells. This is the morula. Cells of the surface layer will function in implantation and will give rise to a membrane, the chorion.

D DAY 5. A fluid-filled cavity forms in the morula. By the 32-cell stage, differentiation is occurring in an inner cell mass that will give rise to the embryo. This embryonic stage is the blastocyst.

E DAYS 6–7. Some of the blastocyst's surface cells attach themselves to the endometrium and start to burrow into it. Implantation has started.

Figure 17.4 Animated! Implantation begins about one week after an egg is fertilized.

17.3 A Baby Times Two

Implantation gives the embryo a foothold in the uterus

About a week after fertilization, **implantation** begins as the blastocyst breaks out of the zona pellucida. Cells of the epithelium then invade the endometrium and cross into the underlying connective tissue. This gives the blastocyst a foothold in the uterus. As time passes it will sink deep into the connective tissue of the uterus, and the endometrium will close over it.

Occasionally a fertilized egg implants in the wrong place—in the oviduct or even in the external surface of the ovary or in the abdominal wall. This *ectopic (tubal) pregnancy* cannot go to full term and must be terminated by surgery. It may lead to permanent infertility.

Implantation is complete two weeks after the secondary oocyte was ovulated. Menstruation, which would begin at this time if the woman were not pregnant, does not occur because the implanted blastocyst secretes HCG (human chorionic gonadotropin). HCG stimulates the corpus luteum to continue secreting both estrogen and progesterone, which prevent the uterus lining from being shed. By the third week of pregnancy, HCG can be detected in the mother's blood or urine. At-home pregnancy tests use chemicals that change color when urine contains HCG.

Take-Home Message

What early developmental events occur after fertilization?

- After cleavage has produced a morula, the ball of cells develops into a multicellular blastocyst.
- The blastocyst implants in the endometrium of the uterus. This stage is complete by two weeks after the original oocyte was ovulated.

As Section 17.2 mentioned, fraternal twins result when two eggs are fertilized at once, and identical twins result when a very early stage embryo splits into two. We now know more about some patterns of twinning, such as twins "running in families" and cases of conjoined twins.

Conjoined twins form when an embryo partially splits after day 12 of development. The twins remain joined, usually at the chest or abdomen, although other configurations also are possible (Figure 17.5*a*). Doctors usually try to surgically separate conjoined twins early in life so that each twin can develop as normally as possible.

A high level of the hormone FSH, which stimulates the maturation of woman's eggs (Section 16.4), increases the likelihood of fraternal twins. Genetic quirks explain why twinning runs in some families and is more common in some ethnic groups. A woman who herself is a fraternal twin has double the average chance of giving birth to fraternal twins, and once she does her odds triple for having a second set. The Yoruba people of Africa have the world's highest fraternal twinning rate. Yoruba women have unusually high levels of FSH. Unfortunately, many Yoruba mothers lack access to good medical care and half of twins die soon after birth (Figure 17.5*b*).

a **b**

Figure 17.5 **Twinning may bring health issues.** The Guatemalan sisters in (**a**) were joined at the head until doctors at UCLA's Mattel Hospital separated them. (**b**) This grieving Yoruba mother of twins carries a doll as a ritual point of contact for one of her infants, who died.

17.4 How the Early Embryo Develops

- **The embryonic period lasts for eight weeks. During that time, the basic body plan of the embryo takes shape.**

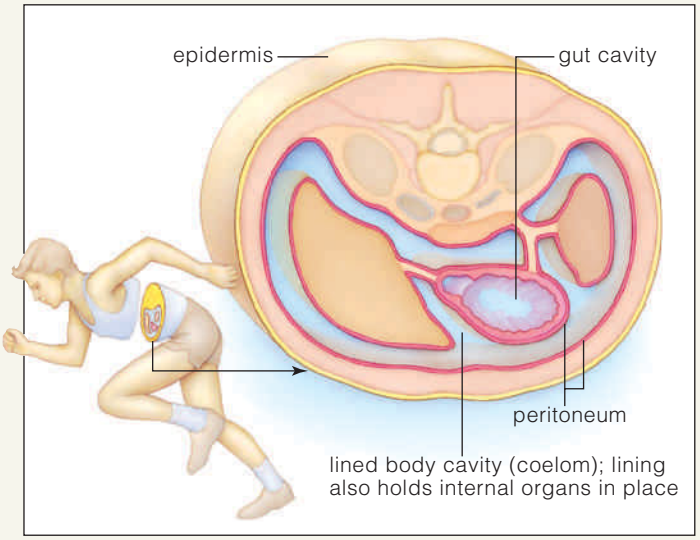
A developing baby is considered an embryo for most of the first trimester, or three months, of the nine months of gestation. When the three germ layers—the ectoderm, mesoderm, and endoderm—are in place, morphogenesis begins and the embryo's organ systems start to develop.

First, the basic body plan is established

By the time a woman has missed her first menstrual period, the embryo has implanted and the inner cell mass has been transformed into a pancake-shaped **embryonic disk**. Around day 15, gastrulation has rearranged cells so that a faint "primitive streak" appears at the midline of the disk (Figure 17.6*a*). Now, ectoderm along the midline thickens to establish the beginnings of a **neural tube**. This tube is the forerunner of the embryo's brain and spinal cord. Some of its cells also give rise to a flexible rod of cells called a *notochord*. The vertebral column will form around this rod.

These events establish the body's long axis and its bilateral symmetry. In other words, the embryonic disk is reshaped in ways that provide the body with the basic form we see in all vertebrates.

On the surface of the embryonic disk near the neural tube, the third primary tissue layer—mesoderm—also has been forming. Toward the end of the third week, some mesoderm gives rise to **somites** (SOE-mites). These are paired blocks of mesoderm, and they will be the source of most bones and skeletal muscles of the neck and trunk. The dermis overlying these regions comes from somites as well. Structures called pharyngeal arches start to form. They will contribute to development of the face, neck, mouth, and associated parts. In other mesodermal tissues spaces open up. Eventually, these spaces will merge to form the cavity (called the *coelom*, SEE-lahm) between the body wall and the digestive tract.



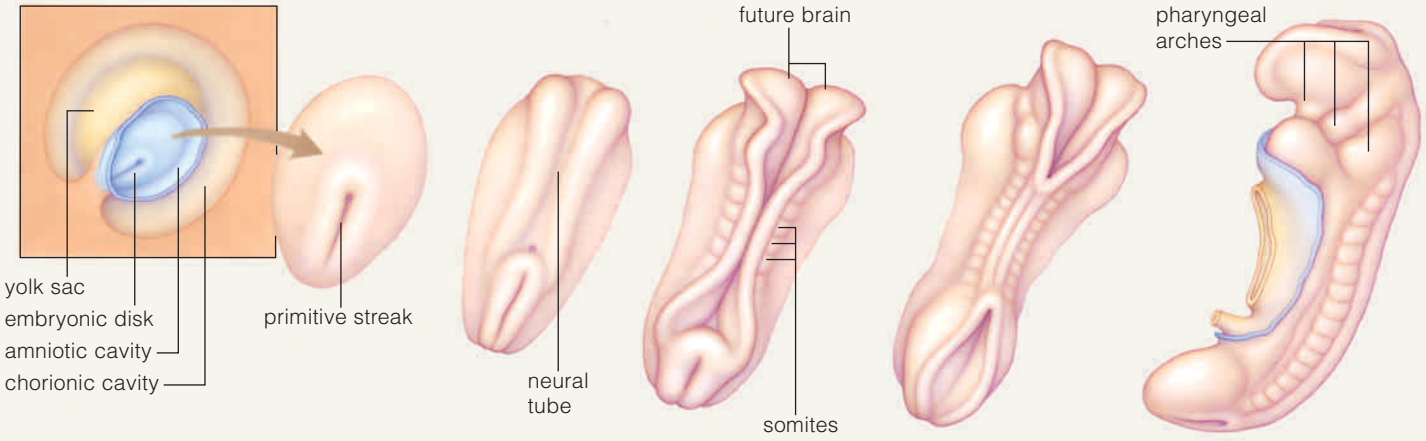


Figure 17.6 Animated! **Several important steps mark the embryonic period of development.** These steps include the appearance of a primitive streak foreshadowing the brain and spinal cord and the formation of somites and pharyngeal arches. These are dorsal views (of the embryo's back) except for days 24–25, which is a side view.

A **DAY 15.** A primitive streak appears along the axis of the embryonic disk. This thickened band of cells marks the onset of gastrulation.

B **DAYS 19–23.** Cell migrations, tissue folding, and other morphogenetic events lead to the formation of a hollow neural tube and to somites (bumps of mesoderm). The neural tube gives rise to the brain and spinal cord. Somites give rise to most of the axial skeleton, skeletal muscles, and much of the dermis.

C **DAYS 24–25.** By now, some cells have given rise to pharyngeal arches, which contribute to the face, neck, mouth, nasal cavities, larynx, and pharynx.

Next, organs develop and take on the proper shape and proportions

After gastrulation, organs and organ systems begin to form. An example is neurulation, the first stage in the development of the nervous system. Figure 17.7 shows how cells of ectoderm at the embryo's midline elongate and form a neural plate, the first sign that a region of ectoderm is starting to develop into nervous tissue. Next, cells near the middle become wedge-shaped. The changes in cell shape cause the neural plate to fold over and meet at the embryo's midline to form the neural tube.

The folding of sheets of cells is extremely important in morphogenesis. The folding takes place as microtubules lengthen and rings of microfilaments in cells tighten like purse strings.

Section 17.1 mentioned that morphogenesis also requires cells to move from one place to another. Migrating cells find their way in part by following so-called adhesive cues. For instance, as the nervous system is developing, migrating Schwann cells stick to adhesion proteins on the surface of axons but not on blood vessels. Adhesive cues also tell the cells when to stop. Cells migrate to places where the signals are strongest, then stay there once they arrive.

Successful development of an embryo requires that body structures form according to normal patterns, in a certain sequence. Genetically programmed cell death, a process called *apoptosis* (ay-poe-TOE-sis) helps sculpt body parts. Inside cells that are destined to die, enzymes switch on and begin digesting cell parts. For instance, morphogenesis at the ends of limb buds first produced paddle-shaped hands at the ends of your arms (Figure 17.8*a*). Then epithelial cells between the lobes in the paddles died on cue, leaving separate fingers (Figure 17.8*b*). Figure 17.8*c* shows what can happen when apoptosis does not occur normally while a hand is forming.

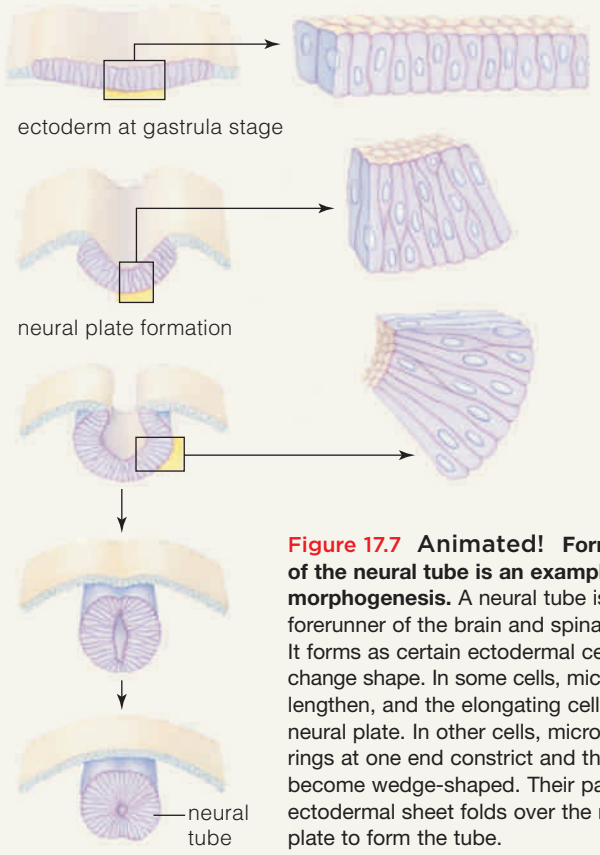


Figure 17.7 Animated! **Formation of the neural tube is an example of morphogenesis.** A neural tube is the forerunner of the brain and spinal cord. It forms as certain ectodermal cells change shape. In some cells, microtubules lengthen, and the elongating cells form a neural plate. In other cells, microfilament rings at one end constrict and the cells become wedge-shaped. Their part of the ectodermal sheet folds over the neural plate to form the tube.

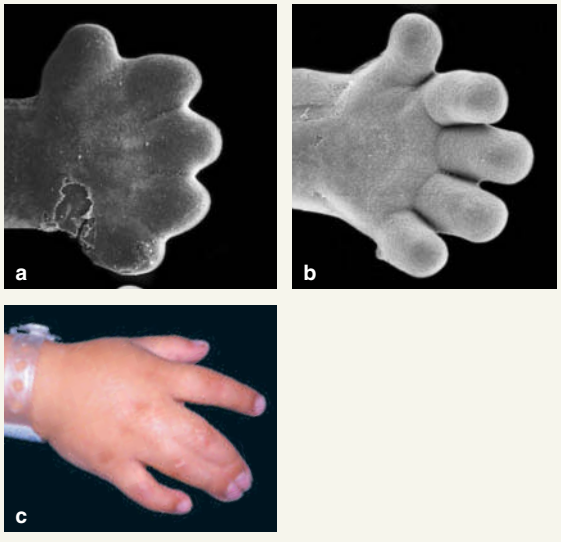


Figure 17.8 Animated! **Programmed cell death separates the digits when fingers form.** (**a**) At first webs of tissue connect the digits. (**b**) Then, cells in the webs die by apoptosis and the digits are separated. (**c**) These fingers remained attached when embryonic cells did not die on cue.

Take-Home Message

What are the main steps in the formation of the early embryo?

- In the third week after fertilization theembryo's basic body plan is established. Then morphogenesis produces the shape and proportions of body parts.
- During morphogenesis, cells divide and migrate to their proper locations, tissues grow and fold, and certain cells die by apoptosis. Genes govern all these events.

17.5 Vital Membranes Outside the Embryo

- **During implantation and over the next few weeks, four specialized membranes form outside the embryo. These membranes include the all-important placenta.**
- **Links to Hormones of the hypothalamus and pituitary 15.3, The female reproductive system 16.3**

Four extraembryonic membranes form

Recall that during implantation, the inner cell mass of the blastocyst is transformed into an embryonic disk (Figure 17.9*a*). Only certain cells of the disk will give rise to the embryo. Others give rise to **extraembryonic membranes**: the yolk sac, the amnion, the allantois, and the chorion (Table 17.2).

Extraembryonic membranes are not part of the embryo. One of them, the **yolk sac**, forms below the embryonic disk. It produces early blood cells and germ cells that will become gametes, then it disintegrates. Parts of it also give rise to the embryo's digestive tube.

The **amnion** forms a fluid-filled sac that encloses the embryo. The amniotic fluid insulates the embryo, absorbs shocks, and prevents the embryo from drying out. Just outside it is the **allantois**, which gives rise to blood vessels that will invade the **umbilical cord**. These vessels are the embryo's contribution to circulatory "plumbing" that will link the embryo with its lifeline, the placenta.

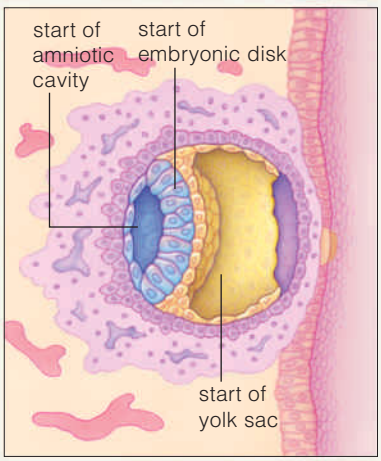
The **chorion** wraps around the embryo and the other three membranes (Figure 17.9*c*). It continues the secretion of HCG that began when the embryo implanted. HCG will prevent the lining of the uterus (the endometrium) from breaking down until the placenta can produce enough estrogen and progesterone to maintain the lining.

The placenta is a pipeline for oxygen, nutrients, and other substances

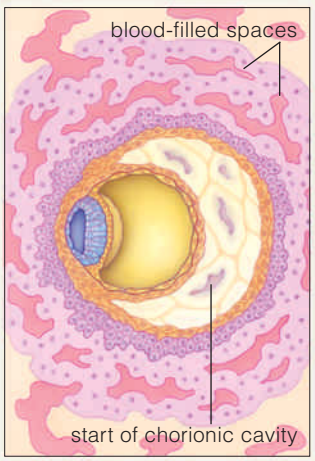
Three weeks after fertilization, almost a fourth of the inner surface of the uterus has become a spongy tissue, the developing **placenta**. It is the link through which nutrients and oxygen pass from the mother to the embryo and waste products from the embryo pass back to the mother's bloodstream. Said another way, the placenta is a way of sustaining a developing baby while allowing its blood vessels to develop apart from the mother's.

Although the fully developed placenta is considered an organ, it's useful to think of it as a close association of the chorion and the upper cells of the endometrium where the embryo implanted. The mother's side of the placenta is endometrial tissue that contains arterioles and venules. As the chorion develops (from the trophoblast), tiny projections sent out from the implanting blastocyst develop into many *chorionic villi*. Inside each villus are small blood vessels (Figure 17.10).

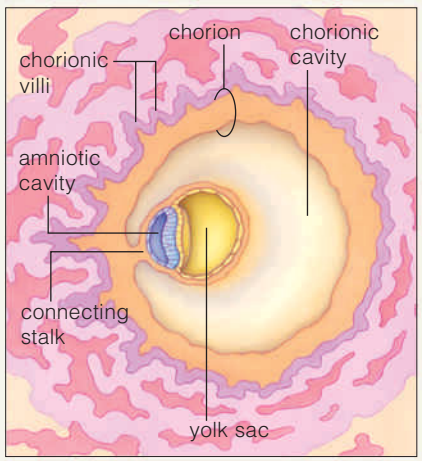
While chorionic villi are developing, the erosion of the endometrium that began with implantation continues. As capillaries in the endometrium are broken down, spaces in the disintegrating endometrial tissue fill with maternal



A DAYS 10–11. The yolk sac, embryonic disk, and amniotic cavity have started to form from parts of the blastocyst.



B DAY 12. Blood-filled spaces form in maternal tissue. The chorionic cavity starts to form.



C DAY 14. A connecting stalk has formed between the embryonic disk and chorion. Chorionic villi, which will be features of a placenta, start to form.

Figure 17.9 Animated! Extraembryonic membranes begin to form during the first two weeks of life.

TABLE 17.2 Extraembryonic Membranes	
Amnion	Encloses, protects embryo in a fluid-filled, buoyant cavity
Yolk sac	Becomes site of red blood cell formation; germ cell source
Chorion	Lines amnion and yolk sac, becomes part of placenta
Allantois	Origin of urinary bladder and blood vessels for placenta

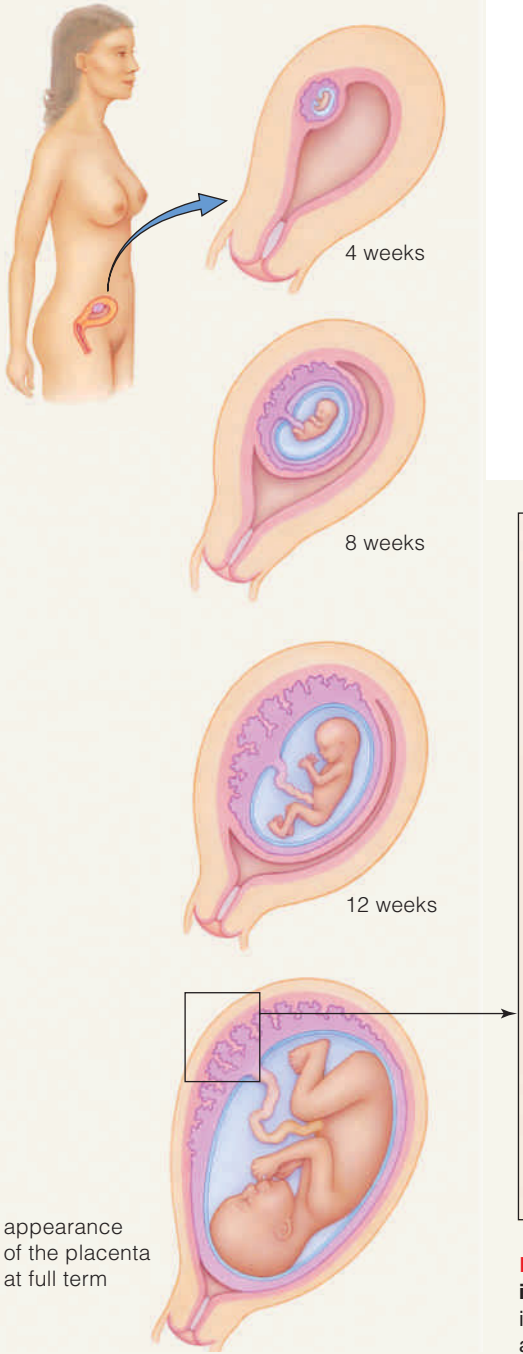
blood. The chorionic villi extend into these spaces. As the embryo develops, very little of its blood ever mixes with that of its mother. Oxygen and nutrients simply diffuse out of the mother's blood vessels, across the blood-filled spaces in the endometrium, then into the embryo's blood vessels. Carbon dioxide and other wastes diffuse in the opposite direction, leaving the embryo.

Besides nutrients and oxygen, many other substances taken in by the mother—including alcohol, caffeine, drugs, pesticide residues, and toxins in cigarette smoke—can cross the placenta, as can HIV.

Take-Home Message

What are extraembryonic membranes and what does each do?

- Extraembryonic membranes begin to form soon after implantation.
- The amnion forms a fluid-filled sac around the embryo. The allantois gives rise to blood vessels of the umbilical cord. The chorion helps protect the embryo and secretes HCG.
- The placenta is a spongy tissue in which maternal and embryonic blood vessels are in close contact. It provides nutrients and oxygen to the embryo from the mother's bloodstream. The embryo's bloodstream also discharges wastes that the mother's bloodstream will transport away.



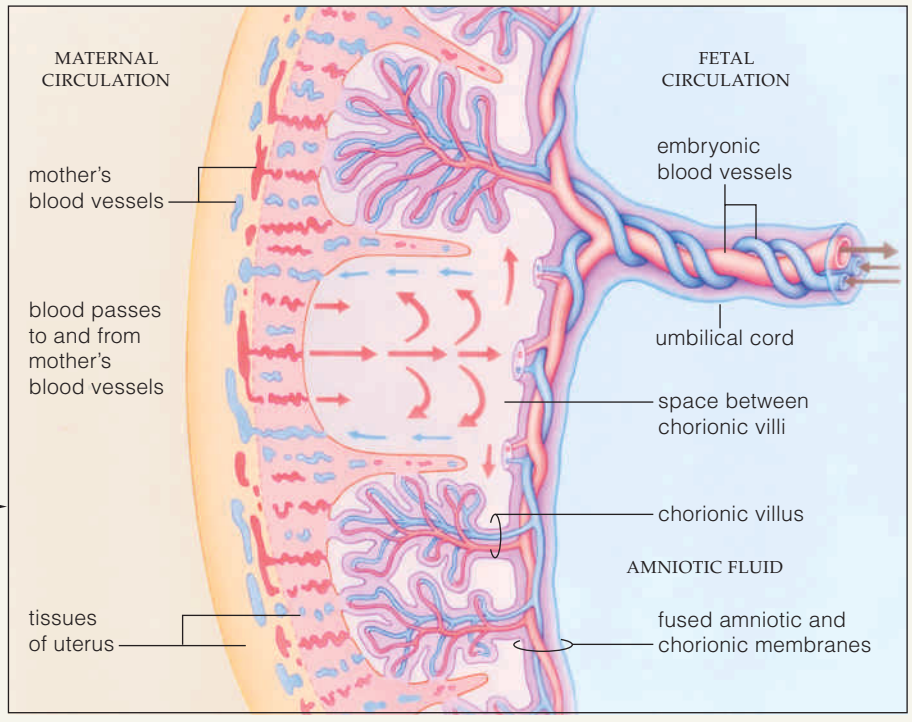


Figure 17.10 Animated! **Blood vessels of the mother and fetus are in close contact in a full-term placenta.** Blood vessels from the fetus extend through the umbilical cord and into chorionic villi. Maternal blood spurts into spaces between villi. Oxygen, carbon dioxide, and other small solutes diffuse across the surface of the placental membrane; there is no large-scale mingling of the two bloodstreams.

17.6 The First Eight Weeks: Human Features Appear

- **By the end of four weeks, the embryo has grown to 500 times its original size. Over the next several weeks it will develop recognizable human features.**

In an embryo's first few weeks of life, it grows rapidly and its cells begin to specialize. Morphogenesis begins to sculpt limbs, fingers, and toes. The circulatory system becomes more intricate, and the umbilical cord forms. Growth of the all-important head now surpasses that of any other body region (Figure 17.11*a*). The embryonic period ends as the eighth week draws to a close. The embryo is no longer merely "a vertebrate." As you can see from Figure 17.11*c*, it now clearly looks like a human being.

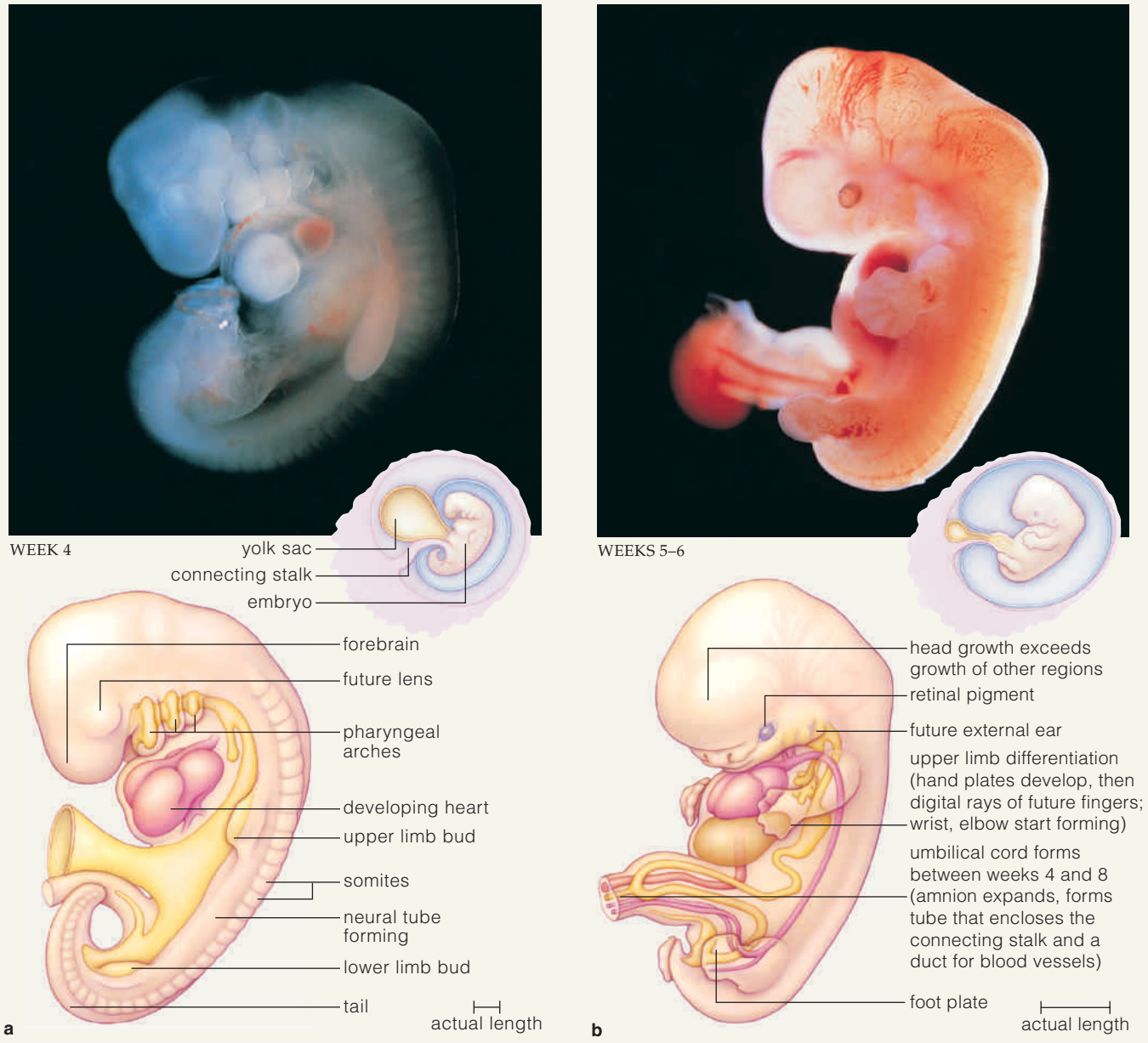
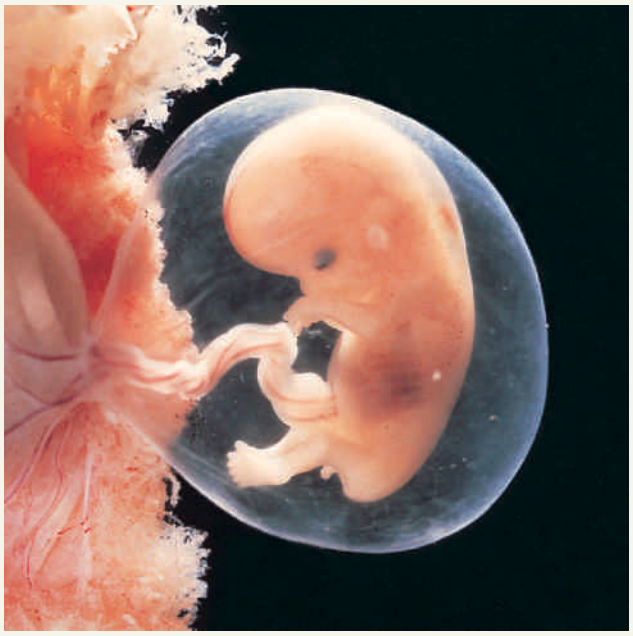


Figure 17.11 Animated! Amazing photographs show the development of a human embryo. (**a**) Human embryo at four weeks. It has tail and pharyngeal arches, which all verebrate embryos have. (**b**) The embryo at five to six weeks after fertilization. (**c**, *facing page*) An embryo at the boundary between the embryonic and fetal periods. It is floating in fluid within the amniotic sac. The chorion, which normally covers the amniotic sac, has been opened and pulled aside.

As the second half of the first trimester begins, gonads begin to develop. In an embryo that has inherited X and Y sex chromosomes, a sex-determining portion of the Y chromosome now triggers development of testes (Figure 17.12). Sex hormones made by the testes then influence the development of the entire reproductive system. An embryo with XX sex chromosomes will be female, and female reproductive structures begin to form in her body. Notice that no hormones are required to stimulate development of female gonads—all that is necessary is the absence of testosterone.

After eight weeks the embryo is just over 1 inch long, its organ systems are formed, and it is designated a **fetus**. As the first trimester ends, a heart monitor can detect its heartbeat. Its genitals are well formed, and an ultrasound image often will reveal the baby's sex.



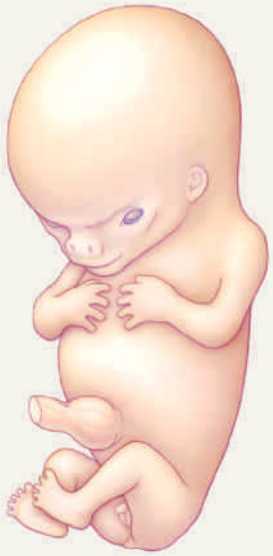
WEEK 8

final week of embryonic period; embryo looks distinctly human compared to other vertebrate embryos

upper and lower limbs well formed; fingers and then toes have separated

early tissues of all internal, external structures now developed

tail has become stubby



actual length

c

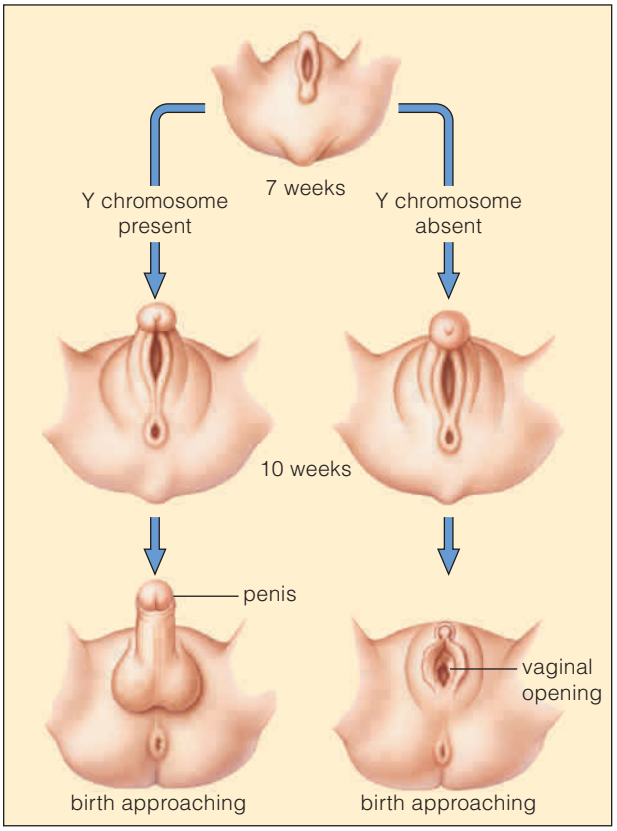


Figure 17.12 Genitals of all embryos start out the same. The male sex hormone testosterone must be present in order for male genitals to develop.

Miscarriage is the spontaneous expulsion of an embryo or fetus. It occurs in more than 20 percent of all conceptions, usually during the first trimester. Many factors can trigger a miscarriage (also called spontaneous abortion), but in up to half of cases the embryo (or the fetus) has one or more genetic disorders that prevent normal development.

Take-Home Message

What happens during the first eight weeks of development?

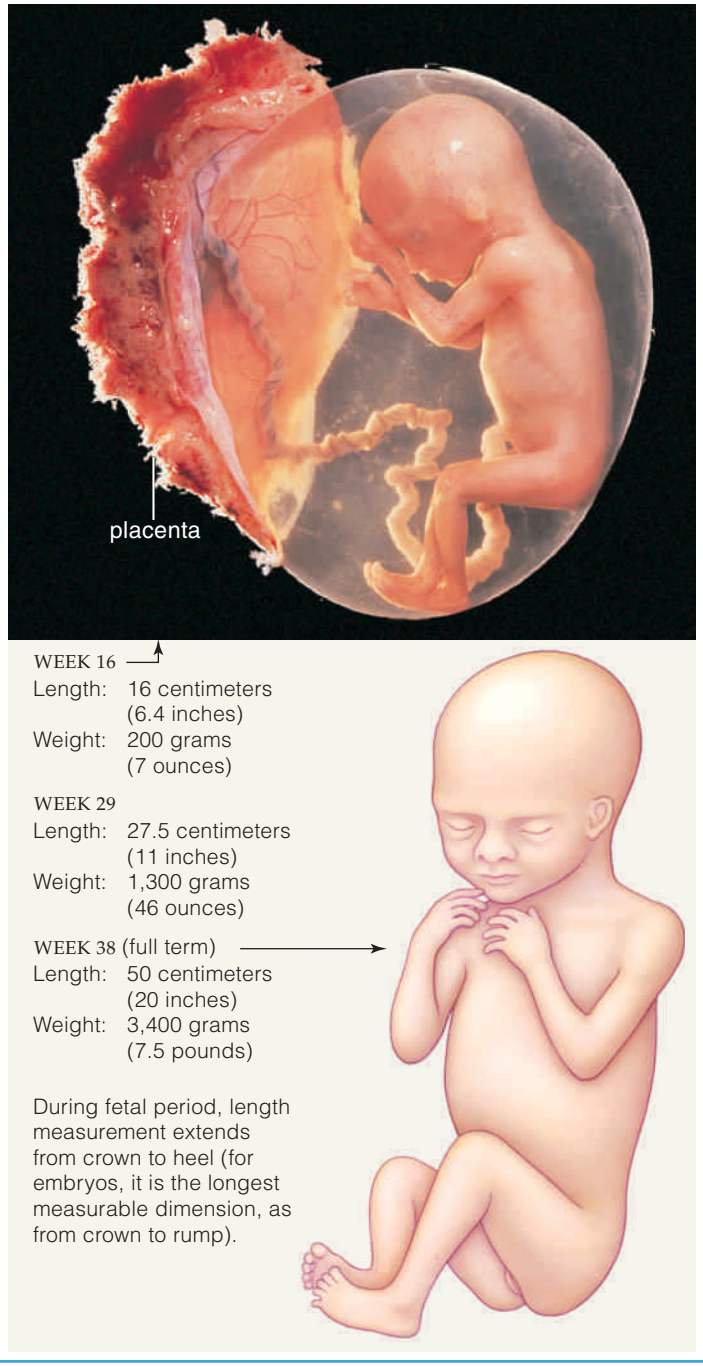
- During its first eight weeks an embryo develops distinctly human body features. At the end of eight weeks it is termed a fetus.

17.7 Development of the Fetus

- **In the second and third trimesters, organs and organ systems gradually mature in preparation for birth.**
- **Links to the Cardiovascular system 7.1, Red blood cells 8.1, Gas exchange in the lungs 10.2**

In the second trimester, movements begin

When the fetus is three months old, it is about 4.5 inches long. Soft, fuzzy hair (the lanugo) covers its body. Its reddish skin is wrinkled and protected from chafing by a thick, cheesy coating called the *vernix caseosa*.



The second trimester of development extends from the start of the fourth month to the end of the sixth. Figure 17.13 shows what the fetus looks like at 16 weeks. Its tiny facial muscles now produce frowns, squints, and sucking movements—evidence of a sucking reflex. Before the second trimester ends, the mother can easily feel her fetus's arms and legs move. During the sixth month, its eyelids and eyelashes form.

Organ systems mature during the third trimester

The third trimester extends from the seventh month until birth. At seven months the fetus is about 11 inches long, and soon its eyes will open. Although the fetus is growing larger and rapidly becoming "babylike," it will not be able to survive on its own until the middle of the third trimester. At seven months few fetuses can maintain a normal body temperature or breathe normally. However, with intensive medical care, fetuses as young as 23 to 25 weeks have survived early delivery. A baby born before seven months' gestation is at high risk of *respiratory distress syndrome* (described in Chapter 10) because its lungs lack surfactant and so can't expand adequately. The longer the baby can stay in its mother's uterus, the better. By the ninth month, its survival chances are about 95 percent.

The blood and circulatory system of a fetus have special features

The steady maturation of its organs and organ systems readies the fetus for independent life. For the circulatory system, however, the path toward independence requires a detour. Several temporary bypass vessels form and will function until birth. As Figure 17.14 shows, two umbilical arteries inside the umbilical cord transport deoxygenated blood and metabolic wastes from the fetus to the placenta. There, the fetal blood gives up wastes, takes on nutrients, and exchanges gases with the mother's blood. Fetal hemoglobin binds oxygen more easily than adult hemoglobin does. This helps ensure that enough oxygen will reach developing fetal tissues. The oxygenated blood, enriched with nutrients, returns from the placenta to the fetus in the umbilical vein.

Figure 17.13 At 16 weeks a fetus is well formed and can move. Movements begin as soon as nerves establish functional connections with developing muscles. Legs kick, arms wave, fingers grasp, the mouth puckers. These reflex actions will be vital skills in the world outside the uterus. The drawing shows a baby at full term—ready to be born.

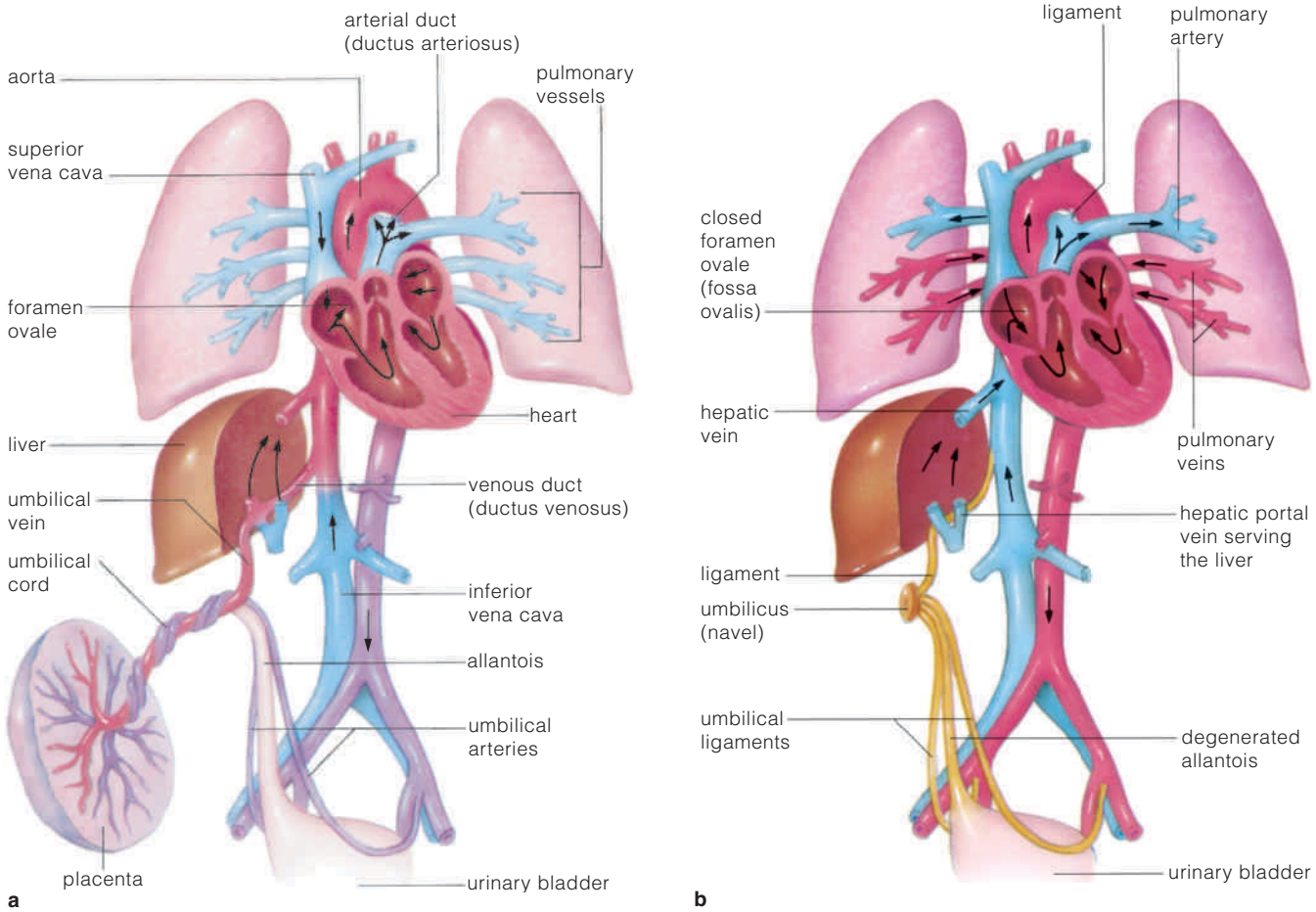


Figure 17.14 Blood circulates in a special pattern in a fetus (*arrows*). (**a**) Umbilical arteries carry deoxygenated blood and wastes from fetal tissues to the placenta. Blood in the umbilical vein picks up oxygen and nutrients from the mother's bloodstream and returns to the fetus. Blood mainly bypasses the lungs, moving through the foramen ovale and the arterial duct. It bypasses the liver by moving through the venous duct. (**b**) At birth the foramen ovale closes, and the pulmonary and systemic circuits of blood flow become completely separate. The arterial duct, venous duct, umbilical vein, and portions of the umbilical arteries become ligaments, and the allantois degenerates.

Other temporary vessels divert blood past the lungs and liver. These organs don't develop as rapidly as some others, because (by way of the placenta) the mother's body can perform their functions. The lungs of a fetus are collapsed and won't begin gas exchange until the newborn takes its first breaths. Until then, its lungs receive only enough blood to sustain their development.

Some of the blood entering the heart's right atrium flows into the right ventricle and on to the lungs. Most of it, however, travels through a gap in the interior heart wall (called the *foramen ovale*, or "oval opening") or into an arterial duct (*ductus arteriosus*) that bypasses the lungs.

Similarly, most blood bypasses the fetal liver because the mother's liver performs most liver functions until birth. Nutrient-rich blood from the placenta travels through a venous duct (the *ductus venosus*) past the liver and on to the heart, which pumps it to body tissues. At birth, blood pressure in the heart's left atrium increases. This causes a flap of tissue to close off the foramen ovale, which then gradually seals and separates the pulmonary and systemic circuits of blood flow (Figure 17.14*b*). The temporary vessels that have formed in a fetus gradually close during the first few weeks after birth.

Take-Home Message

What are the major events of fetal development?

- The organs and organ systems of a fetus mature during the second and third trimesters. Because the fetus exchanges gases and receives nutrients via its mother's bloodstream, its circulatory system develops temporary vessels that bypass the lungs and liver until birth.

17.8 Birth and Beyond

- **Birth, or parturition, takes place about 39 weeks after fertilization—about 280 days from the start of the woman's last menstrual period.**
- **Link to Hormones of the hypothalamus and pituitary 15.3**

Hormones trigger birth

Usually within two weeks of a pregnant woman's "due date," the birth process, "labor," begins when smooth muscle in her uterus starts to contract. These contractions are the indirect result of a cascade of hormones from the fetus's hypothalamus, pituitary, and adrenal glands, which is triggered by an as-yet-unknown signal that says, in effect, it's time to be born. The hormonal flood causes the placenta to produce more estrogen. Rising estrogen in turn calls for a rush of oxytocin and of prostaglandins (also produced by the placenta), which jointly stimulate the uterine contractions. For about the next 2 to 18 hours, the contractions will become stronger, more painful, and more frequent.

Labor has three stages

Labor is divided into three stages that we can think of loosely as "before, during, and after." In the first stage, uterine contractions push the fetus against its mother's cervix. Initial contractions occur about every 15 to 30 minutes and are relatively mild. As the cervix gradually dilates to a diameter of about 10 centimeters (4 inches, or "5 fingers"), contractions become more frequent and intense. Usually, the amniotic sac ruptures during this stage, which can last 12 hours or more.

The second stage of labor, actual birth of the fetus, typically occurs less than an hour after the cervix is fully dilated. This stage is usually brief—under 2 hours. Strong contractions of the uterus and abdominal muscles occur every 2 or 3 minutes, and the mother feels an urge to push. Her efforts and the intense contractions move the soon-to-be newborn through the cervix and out through the vaginal canal, usually head first (Figure 17.15). Complications can develop if the baby begins to emerge in a "bottom-first" or *breech* position. In that case the doctor may use hands or forceps to aid the delivery.

After the baby is born, the third stage of labor gets under way. More uterine contractions force fluid, blood, and the placenta (now called the afterbirth) from the mother's body. The umbilical cord—the lifeline to the mother—is now severed. A lifelong reminder of this separation is the scar we call the navel, the site where the umbilical cord was attached.

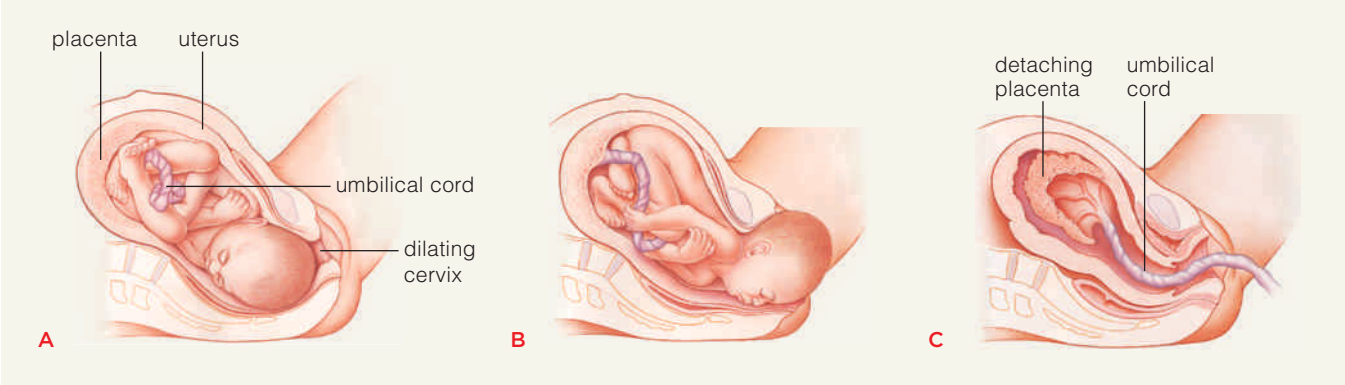


Figure 17.15 Animated! **During birth, the fetus is pushed out of the uterus.** The afterbirth—the placenta, fluid, and blood—is expelled shortly afterward.

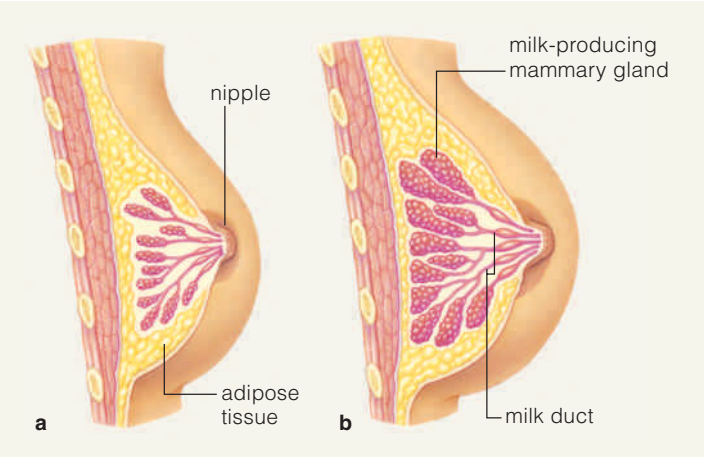


Figure 17.16 **Animated! Female breasts contain milk glands.** (**a**) The anatomy of the breast of a non-lactating woman. (**b**) Breast of a lactating woman.

Without the placenta to remove wastes, carbon dioxide builds up in the baby's blood. Together with other factors, including handling by medical personnel, this stimulates control centers in the brain, which respond by triggering inhalation—the newborn's crucial first breath.

As the infant's lungs begin to function, the bypass vessels of the fetal circulation begin to close, soon to shut completely. The fetal heart opening, the foramen ovale, normally closes slowly during the first year of life.

Most full-term pregnancies end in the birth of a healthy infant. Yet babies born prematurely—especially before about eight months of intrauterine life—can suffer complications because their organs have not developed to the point where they can function independently. Then, attempts to sustain the baby's life under conditions that will permit the necessary additional development may require a variety of advanced medical technologies. Even then, the majority of extremely premature infants do not survive.

Hormones also control milk production in a mother's mammary glands

Milk production provides an excellent example of how hormones may interact in the body. In this case, a total of four hormones are involved. During pregnancy, estrogen and progesterone stimulate the growth of mammary glands and ducts in the mother's breasts (Figure 17.16). For the first few days after birth, those glands produce colostrum, a pale fluid that is rich in proteins, antibodies, minerals, and vitamin A. Then prolactin secreted by the pituitary stimulates milk production, or **lactation**.

The "let-down" or flow of milk from a nursing mother's mammary glands is a reflex and an example of positive feedback (Figure 17.17). When a newborn nurses, mechanoreceptors in the nipple send nerve impulses to the hypothalamus, which in turn stimulates the mother's pituitary to release oxytocin, which causes the mother's breast tissues to contract. This forces milk into the ducts. This response continues as long as the baby suckles. Oxytocin also triggers contractions of uterine muscle that will help to "shrink" the uterus back to its normal size.

Take-Home Message

What are the stages of labor and how does lactation occur?

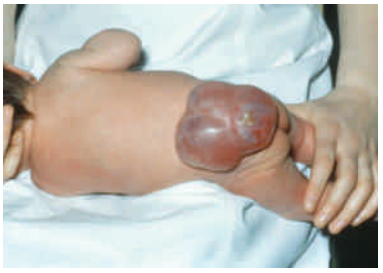
- The mother's cervix dilates during the first stage of labor. The baby is born during the second stage. In the third stage, contractions of the uterus expel the placenta.
- Lactation, or milk production, begins a few days after birth. It is stimulated by the hormone prolactin, which is released from the mother's pituitary and acts on her breast (mammary gland) tissues.
- Suckling triggers a reflex in which oxytocin from the pituitary acts to force milk into mammary ducts. The response continues as long as the infant suckles.

17.9 Potential Disorders of Early Development

- **From fertilization until birth, a woman's future child is at the mercy of her diet and lifestyle.**

Poor maternal nutrition puts a fetus at risk

A pregnant woman must nourish her unborn child as well as herself. In general, the same balanced diet that is good for her should also provide her developing baby with all the carbohydrates, lipids, and proteins it needs. Vitamins and minerals are a different story, however. Physicians recommend that a pregnant woman take supplemental vitamins and minerals, not only for her own benefit but also to meet the needs of her fetus. This is particularly true for the nutrient folic acid (folate), which is required for the neural tube to develop properly. If too little folic acid is available, a birth defect called **spina bifida** ("split spine") may develop, in which the neural tube doesn't close and separate from ectoderm. The infant may be born with part of its spinal cord exposed inside a cyst. Infection is a serious danger, and the resulting neurological problems can include poor bowel and bladder control. To prevent neural tube defects, folic acid now is added to wheat flour and other widely used foods.



An exposed spinal cord due to spina bifida

A pregnant woman must eat enough to gain between 20 and 35 pounds, on average. If she gains much less than that, she may be putting her fetus at risk. Infants who are severely underweight have more complications after delivery. As birth approaches, the growing fetus demands more and more nutrients from the mother's body. For

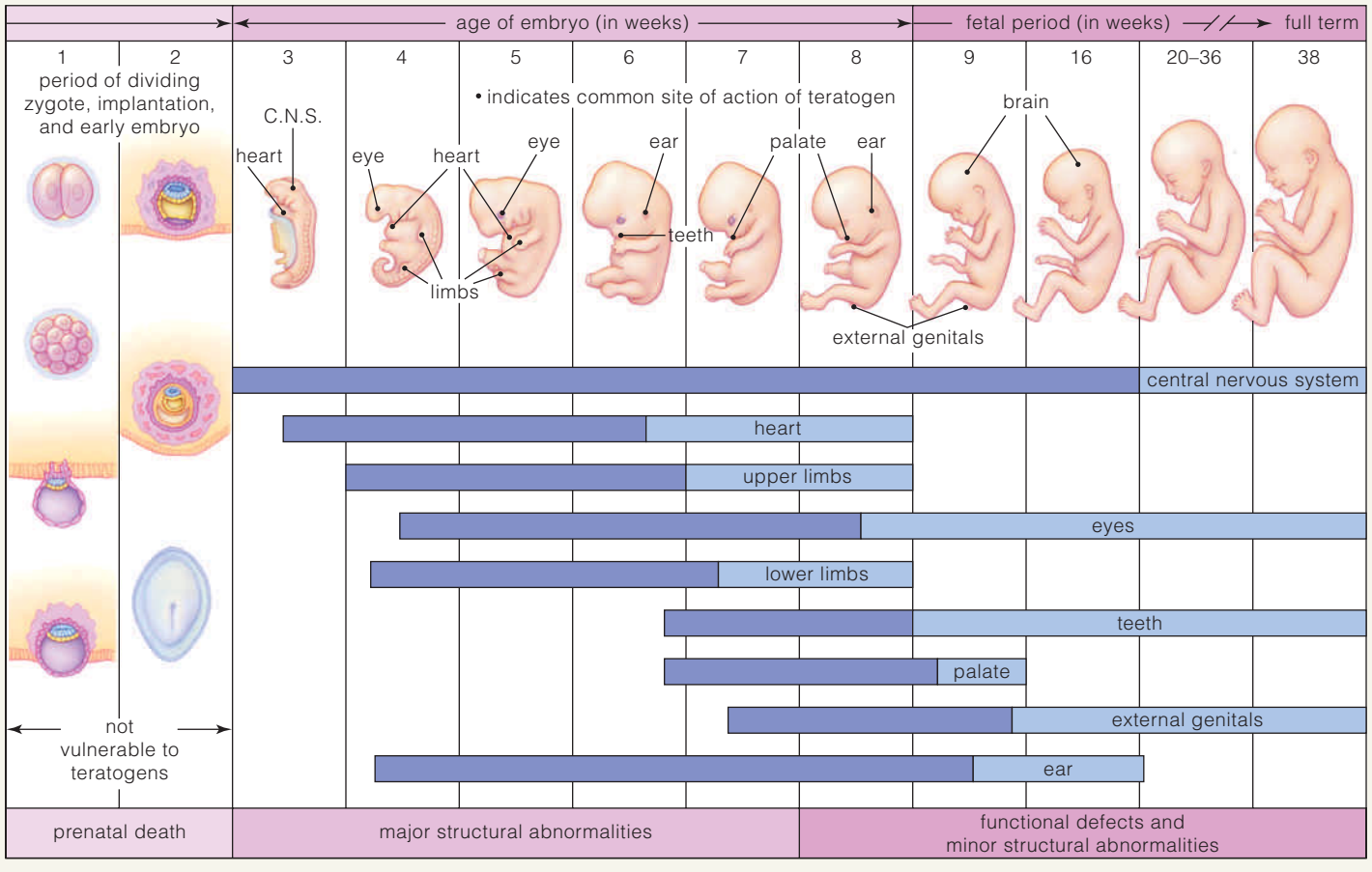


Figure 17.18 **Animated!** **Many factors can cause birth defects.** Light blue bars indicate periods when developing organs are most sensitive to damage from alcohol, viral infection, and so on. Numbers signify the week of development.

example, the brain grows the most in the weeks just before and after birth. Poor nutrition during that time, especially protein deficiency, can have repercussions on intelligence and other brain functions later in life.

Infections present serious risks

A pregnant woman's IgG antibodies cross the placenta. They can help protect her developing infant from all but the most severe bacterial infections. Other **teratogens**—agents that can cause birth defects—are more serious threats. Some viral diseases can be dangerous during the first six weeks of pregnancy, when the organs of a fetus are forming (Figure 17.18). For example, if a pregnant woman contracts **rubella** (German measles) during this time, there is a 50 percent chance that some organs of the embryo won't form properly. If she contracts the virus when the embryo's ears are forming, her newborn may be deaf. With time, the risk of damage diminishes, and getting vaccinated before pregnancy can eliminate it.

Drugs of all types may do harm

During its first trimester in the womb, an embryo is extremely sensitive to drugs the mother takes. In the 1960s many women using the tranquilizer thalidomide gave birth to infants with missing or deformed arms and legs. Although it wasn't known at the time, thalidomide alters the steps required for normal limbs to develop. When the connection became clear, thalidomide was withdrawn from the market (although it now has other medical uses).

Other commonly used tranquilizers, as well as some sedatives and barbiturates, may cause similar, although less severe, damage. Anti-acne drugs such as retinoic acid increase the risk of facial and cranial deformities. The antibiotic streptomycin causes hearing problems and may adversely affect the nervous system. A pregnant woman who uses the antibiotic tetracycline may have a child whose teeth are yellowed.

Like many other drugs, alcohol crosses the placenta and affects the fetus. *Fetal alcohol syndrome* (FAS) is a constellation of defects that can result from alcohol use by a pregnant woman. Tragically, FAS is one of the most common causes of mental retardation in the United States. Babies born with it typically have a smaller than normal brain and head, facial deformities, poor motor coordination, and, sometimes, heart defects (Figure 17.19). The symptoms can't be reversed, and FAS children never catch up physically or mentally. Between 60 and 70 percent of alcoholic women give birth to infants with FAS. Many doctors urge near or total abstinence from alcohol during pregnancy.

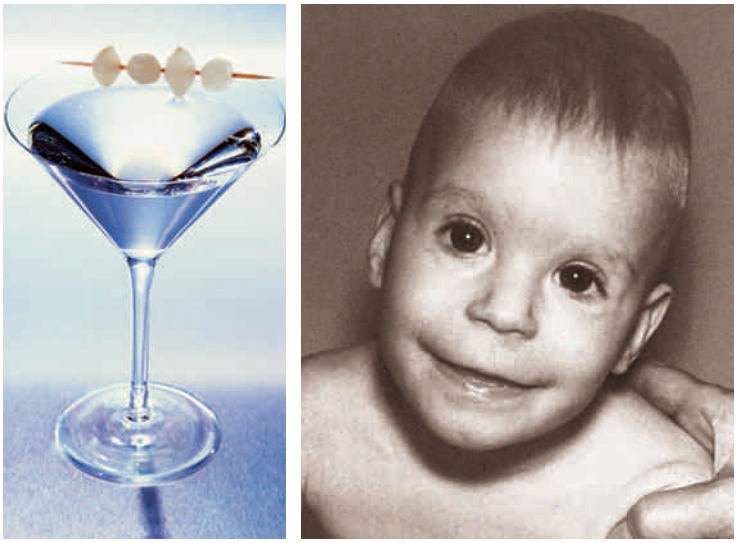


Figure 17.19 Fetal alcohol syndrome may cause mental retardation. Outward symptoms are low and prominent ears, poorly developed cheekbones, and a long, smooth upper lip. The child may have growth problems and abnormalities of the nervous system.

A pregnant woman who uses cocaine, especially crack, prevents her child's nervous system from developing normally. As a result, the child may be chronically irritable as well as abnormally small.

Research evidence suggests that tobacco smoke reduces the level of vitamin C in a pregnant woman's blood, and in that of her fetus as well. Cigarette smoke also harms the growth and development of a fetus in other ways. A pregnant woman who smokes daily will give birth to an underweight newborn even if her own weight, nutrition, and all other relevant variables are the same as those of pregnant nonsmokers. A pregnant smoker also has a greater risk of miscarriage, stillbirth, and premature delivery. A long-term study at Toronto's Hospital for Sick Children showed that toxins in tobacco build up even in the fetuses of nonsmokers who are exposed to secondhand smoke at home or work.

No one knows just how cigarette smoke damages a fetus. However, its demonstrated effects are additional evidence that the placenta cannot protect a developing fetus from every danger.

17.10 Prenatal Diagnosis: Detecting Birth Defects

A growing number of technologies now enable us to detect more than 100 genetic disorders before a child is born.

Chorionic villus sampling (CVS) uses tissue from the chorionic villi of the placenta. CVS can be used as early as the eighth week of pregnancy but it is tricky. Using ultrasound, the physician guides a tube through the vagina, past the cervix, and along the uterine wall, then removes a small sample of chorionic villus cells by suction. Results are available within days.

Amniocentesis is performed during the fourteenth to sixteenth weeks of pregnancy. It samples fluid from within the amnion, the sac that contains the fetus (Figure 17.20). The thin needle of a syringe is inserted through the mother's abdominal wall, into the amnion. The physician must take care that the needle doesn't puncture the fetus and that no infection occurs. Amniotic fluid contains sloughed fetal cells, and as the syringe withdraws fluid, some of those cells are included. They are then cultured and tested for genetic abnormalities.

Methods of embryo screening also are available. In *preimplantation diagnosis*, an embryo conceived by in vitro fertilization (Section 16.8) is analyzed for genetic defects using recombinant DNA technology. The testing occurs at the eight-cell stage (*left*), which by one view is a *pre*-pregnancy stage. Like unfertilized eggs discarded during monthly menstruation, the ball is not implanted in the uterus. Its cells all have the same genes and are not yet committed to giving rise to specialized cells of a heart, lungs, or other organs. Doctors take one of the undifferentiated cells and analyze its genes for suspected disorders. If the cell has no detectable genetic defects, the ball is inserted into the uterus. Embryo screening is designed to help parents who are at high risk of having children with a genetic birth defect. Even so, for some people it raises questions of morality.

It is now possible to see a live, developing fetus with the aid of an endoscope, a fiber-optic device. In *fetoscopy*, sound waves are pulsed across the mother's uterus. Images of parts of the fetus, umbilical cord, or placenta show up on a computer screen that is connected to the endoscope (Figure 17.21). A sample of fetal blood often is drawn at the same time in order to diagnose blood cell disorders such as sickle-cell anemia and hemophilia.

All three procedures pose some risk for the fetus, including infections, punctures, or miscarriage. With CVS there also is a slight chance the future child will have missing or underdeveloped fingers or toes.

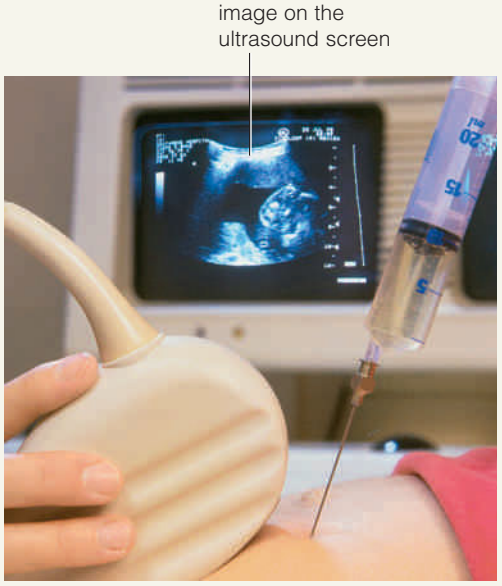


Figure 17.20 Animated! **Amniocentesis is a common prenatal diagnostic tool.**

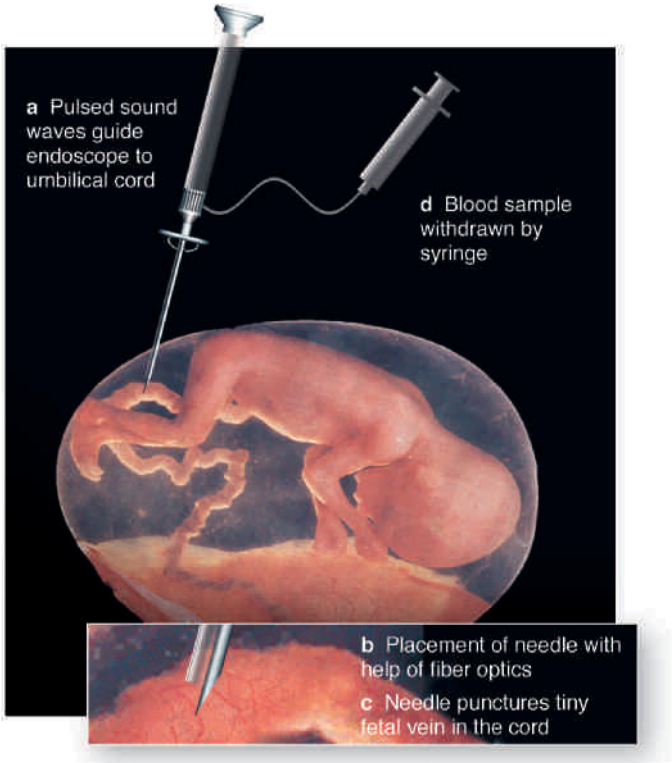


Figure 17.21 **Fetoscopy gives a direct view of a developing fetus in the womb.**

17.11 From Birth to Adulthood

- **After a child enters the world, a gene-dictated course of further growth and development leads to adulthood.**

There are many transitions from birth to adulthood

Table 17.3 summarizes the prenatal (before birth) and postnatal (after birth) stages of life. A newborn is called a *neonate*. During infancy, which lasts until about 15 months of age, the child's nervous and sensory systems mature rapidly, and a series of growth spurts makes its body longer. Figure 17.22 shows how body proportions change during childhood and adolescence. **Puberty** marks the arrival of sexual maturity as a person's reproductive organs begin to function. Sex hormones trigger the appearance of secondary sex characteristics, such as pubic and underarm hair, and behavior changes. A mix of hormones triggers another growth spurt at this time. Boys usually grow most rapidly between the ages of 12 and 15, whereas girls tend to grow most rapidly between the ages of 10 and 13. After several years, the influence of sex hormones causes the cartilaginous plates near the ends of long bones to harden into bone. Humans stop growing by their early twenties.

TABLE 17.3 Stages of Human Development

Prenatal Period		
1.	Zygote	Single cell resulting from fertilization
2.	Morula	Ball of cells produced by cleavage
3.	Blastocyst	Ball of cells with surface layer and inner cell mass
4.	Embryo	All developmental stages from 2 weeks after fertilization until end of eighth week
5.	Fetus	All developmental stages from the ninth week until birth (about 39 weeks after fertilization)
Postnatal Period		
6.	Newborn (neonate)	The first 2 weeks after birth
7.	Infancy	From 2 weeks to about 15 months after birth
8.	Childhood	From infancy to about 12 or 13 years
9.	Pubescence	Puberty, when secondary sexual traits develop; girls between 10 and 16 years, boys between 13 and 16 years
10.	Adolescence	From puberty until about 3 or 4 years later; physical, mental, emotional maturation occur
11.	Adulthood	Early adulthood (between 18 and 25 years); bone formation and growth completed. Changes proceed very slowly afterward.
12.	Old age	Aging culminates in general body deterioration

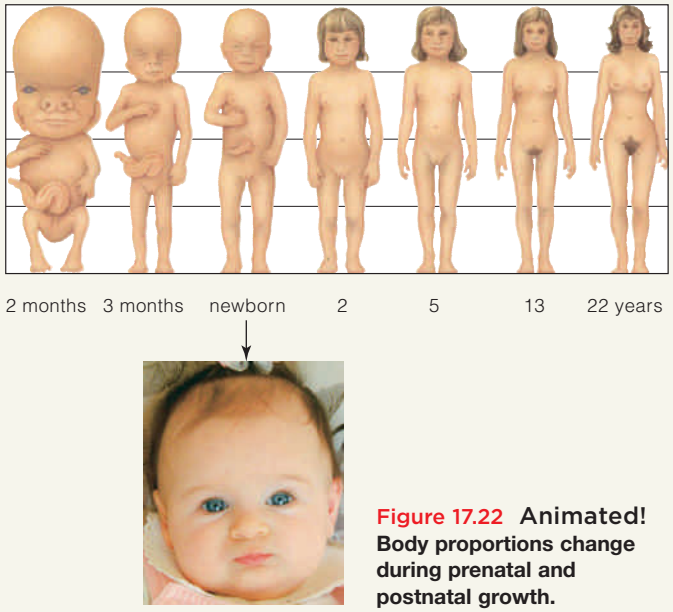


Figure 17.22 Animated! Body proportions change during prenatal and postnatal growth.

Adulthood is also a time of bodily change

Although in the United States the average life expectancy is 74 years for males and 79 years for females, we reach the peak of our physical potential in adolescence and early adulthood. A healthy diet, regular exercise, and other good lifestyle habits can help keep people vigorous for decades of adult life. Even so, after about age 40, body parts and their functioning begin to deteriorate. This proccess, called **senescence** or aging, is a natural part of the life cycle of all organisms that have highly specialized cells. We take a brief look at the possible causes and well-known effects of aging in the following sections.

Take-Home Message

What are post-birth stages of development?

- Following birth, development proceeds through childhood and adolescence, which includes the arrival of sexual maturity at puberty. Puberty is the gateway to the adult phase of life, including changes associated with aging.

17.12 Time's Toll: Everybody Ages

- **Time takes a toll on body tissues and organs. To some extent, our genes determine how long each of us will live.**

Genes may determine the maximum life span

Each species has a maximum life span. For example, we know the maximum is about 20 years for dogs and 12 weeks for butterflies. So far as we can document, no human has lived beyond 122 years. The consistency of life span within species is a sign that genes help govern aging.

One idea is that each type of cell, tissue, and organ is like a clock that ticks at its own genetically set pace. When researchers investigated this possibility, they grew normal human embryonic cells, all of which divided about 50 times, then died. In the body, most cells divide 80 or 90 times, at most. As discussed in Chapter 18, a cell copies its chromosomes before it divides. The ends of chromosomes are capped by numerous segments of DNA called *telomeres*. A bit of each telomere is lost each time a cell divides. The cell dies when only a nub remains.

Cancer cells, and cells in gonads that give rise to sperm and oocytes, make an enzyme that causes telomeres to lengthen. Apparently, that is why such cells can divide over and over, without dying.

Cumulative damage to DNA may also play a role in aging

A "cumulative assaults" hypothesis proposes that aging results from mounting damage to DNA combined with a decline in DNA's mechanisms of self-repair. Chapter 2 described how free radicals can damage DNA and other biological molecules. If changes in DNA aren't fixed, they may prevent cells from making needed enzymes and other proteins required for normal cell operations.

TABLE 17.4 Some Physiological Changes in Aging

Maximum Age	Lung Heart Rate	Muscle Capacity	Kidney Strength	Function
25	100%	100%	100%	100%
45	94%	82%	90%	88%
65	87%	62%	75%	78%
85	81%	50%	55%	69%

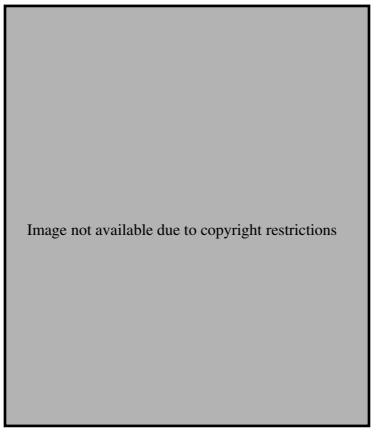
Note: Age 25 is the benchmark for maximal efficiency of physiological functions.

Ultimately, it's quite possible that aging involves processes in which genes, free radical damage, a decline in DNA repair mechanisms, and even other factors all come into play.

Visible changes occur in skin, muscles, and the skeleton

Aging is a gradual loss of vitality as cells, tissues, and organs function less and less efficiently. Starting at about age 40, all of us begin to see and feel the effects of aging-related changes.

Changes in structural proteins may contribute to many of the more obvious aging-related characteristics. Remember from Chapter 4 that many connective tissues contain large amounts of the protein collagen, and some also contain the flexible protein elastin. As we grow older, chemical changes make collagen molecules more rigid and reduce the amount of elastin in many tissues. For example, the elastin fibers that give skin its flexibility are slowly replaced with more rigid collagen. As a result, the skin becomes thinner and less elastic, so it sags and wrinkles. The skin also becomes drier as sweat and oil glands begin to break down and are not replaced.



As hair follicles die or become less active, there is a general loss of body hair. And as pigment-producing cells die and are not replaced, the remaining body hair begins to appear gray or white.

In general, aging muscles lose mass and strength The lost muscle tends to be replaced by fat and, with time, by collagen. Bone cells become less efficient at taking up calcium and generating new bone tissue, so the risk of osteoporosis rises. Osteoarthritis also is more common in older people. With the passing years, intervertebral disks gradually deteriorate, reducing the distance between vertebrae. This is why people tend to get shorter by about a centimeter every ten years from middle age onward. Staying physically active can help slow most of these changes.

Most other organ systems also decline

The heart, lungs, and kidneys also function less well with increasing age (Table 17.4). In the lungs, walls of alveoli break down, so there is less total respiratory surface available for gas exchange. If a person who does not have cardiovascular disease (which may cause an enlarged heart),

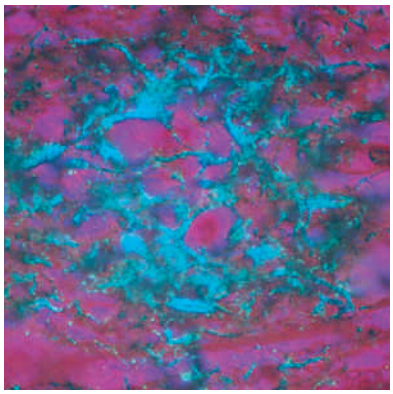


Figure 17.23 Beta amyloid plaques form in the brain tissue of Alzheimer's patients. The plaques are shown in *blue* in this image.

the heart muscle shrinks slightly and so its strength and blood-pumping ability decline. The decreased blood supply may be a factor in aging-related changes throughout the body. Blood transport is also affected by changes in aging blood vessels. Elastin fibers in blood vessel walls are replaced with connective tissue containing collagen or become hardened with calcium deposits, and so vessels become stiffer. Cholesterol plaques often cause further narrowing of arteries and veins (Section 7.8). This is why people often find that their resting blood pressure rises as they get older. However, as with the muscular and skeletal systems, lifestyle choices such as not smoking, eating a healthy diet, and getting regular exercise can help each of us maintain a vigorous respiratory and cardiovascular system well past middle age.

In the immune system, the total number of T cells falls and B cells become less active. Older people also are more likely to develop autoimmune diseases. It is possible that faltering DNA repair mechanisms no longer fix genetic changes that alter self-markers. This could provoke immune responses against the body's own cells.

In the digestive tract, aging mucus glands in linings of the stomach and intestines gradually break down, and the pancreas secretes fewer digestive enzymes. Although it is vital for older people to eat a healthy diet, we require fewer calories as we age. By age 50, your basal metabolic rate (BMR) will be only 80 to 85 percent of what it was in childhood and will keep declining about 3 percent every decade. This is why middle-aged people tend to gain weight unless they compensate by eating less, increasing their physical activity, or both.

Levels of most hormones stay steady throughout life. Sex hormones are exceptions, however. As Chapter 16 noted, falling levels of estrogens and progesterone trigger menopause in women. In older men, falling levels of testosterone reduce fertility. That said, men have fathered children into their 80s. Men and women both retain their capacity for sexual response well into old age.

Aging also alters the brain and senses

Even in a healthy person, brain neurons die throughout life, and as they do the brain shrinks slightly, losing about 10 percent of its mass after 80 years. Also, in most people who live to old age, tangled clumps of fibrils develop in the cytoplasm of many neuron cell bodies. These *neurofibrillary tangles* may disrupt normal cell operations, although why is not well understood. Clotlike plaques containing protein fragments called *beta amyloid* also develop between neurons.

In people who develop **Alzheimer's disease** (AD), the brain contains masses of neurofibrillary tangles and is riddled with beta amyloid plaques (Figure 17.23). Symptoms include progressive memory loss and disruptive changes to personality.

Some cases of AD are inherited. The increased risk is significant for people who inherit one version of a gene that codes for a protein called apolipoprotein E. Around 16 percent of the U.S. population has one or two copies of this gene. Those with two copies have a 90 percent chance of developing AD. Of the AD-related genes discovered thus far, most are associated with early-onset Alzheimer's, which develops before the age of 65.

Treatments for AD are limited, although drugs can temporarily help alleviate some symptoms or slow the progression of the disease.

After about age 60 even otherwise healthy people begin to have "senior moments," or difficulty with short-term memory. Perhaps because aging CNS neurons tend to lose some of their insulating myelin sheath, older neurons do not conduct action potentials as efficiently. In addition, neurotransmitters such as acetylcholine may be released more slowly. Such changes are why older people tend to move more slowly, have slower reflexes, and have more problems with muscle coordination.

Our sensory organs also become less efficient at detecting or responding to stimuli. The taste buds become less sensitive over time, and as Chapter 14 noted, people also tend to become farsighted as they grow older because the eye's lens loses elasticity and is altered in other ways that prevent it from properly focusing incoming light. Most people over 60 also have some hearing loss due to "worn out" sensory nerve cells in the ear.

Take-Home Message

How does aging affect the body?

- Virtually every body system undergoes aging-related declines in its structure and functioning.
- Aging may result from several factors, including an internal biological clock that ticks out the life spans of cells, and the accumulation of DNA damage.

IMPACTS, ISSUES

Male or Female? Body or Genes?

WHEN a child is born with ambiguous genitals, surgery can make him or her appear more normal, but it can harm nerves and impair sexual function. The best cosmetic result may require sex reassignment, as when a boy with a micropenis is surgically altered and reared as a female. On the other hand, avoiding surgery may lead to psychological trauma from having an unusual body.

How Would You Vote?

Should parents of a child who has unusual genitals wait and allow the child to choose or decline normalizing surgery? See CengageNOW for details, then vote online.

Summary

Section 17.1 The fertilization of an oocyte by a sperm launches several key stages in early development.

a. Cleavage, when the fertilized egg undergoes cell divisions that form the early multicellular embryo. The destiny of various cell lines is established in part by the portion of cytoplasm inherited at this time.

b. Gastrulation, when the organizational framework of the whole body is laid out. Endoderm, ectoderm, and mesoderm form; all the tissues of the adult body will develop from these three germ layers.

c. Cell differentiation, when cells come to have specific structures and functions.

d. Morphogenesis, during which tissues form and become organized into organs. Tissues and organs continue to mature as the fetus develops and even after birth.

- Use the animation and interaction on CengageNOW to track the stages in the formation of a hand.

Section 17.2 During the first week or so after fertilization, cell divisions and other changes transform the zygote into a multicellular blastocyst, which attaches to the mother's uterus during implantation. The blastocyst includes the inner cell mass, a small clump of cells from which the embryo develops.

Section 17.4 Gastrulation and morphogenesis shape the body's basic plan. A key step is the formation of the neural tube, the forerunner of the brain and spinal cord, from ectoderm. The skeleton and most muscles develop from blocks of cells called somites that arise from mesoderm. In morphogenesis sheets of cells fold and cells migrate to new locations in the developing embryo.

- Use the animation and interaction on CengageNOW to observe the early stages of human development.

Section 17.5 During implantation the inner cell mass is transformed into an embryonic disk. Some of its cells give rise to four extraembryonic membranes: the yolk sac, the allantois, the amnion, and the chorion. Table 17.5 summarizes their functions. The embryo and its mother exchange nutrients, gases, and wastes by way of the placenta, a spongy organ that is a combination of endometrium and extraembryonic membranes.

Section 17.6 The first eight weeks of development are the embryonic period; thereafter the developing individual is considered a fetus. By the ninth week of development, the fetus clearly looks human.

Section 17.7 During the last three months of gestation (the third trimester), the fetus grows rapidly and many organs mature. However, because the fetus exchanges gases and receives nourishment via its mother's bloodstream, its own circulatory system routes blood flowing to the lungs and liver through temporary blood vessels.

Section 17.8 Birth takes place approximately 39 weeks after fertilization. Labor advances through three stages; a baby is born at the end of stage two, and the afterbirth (placenta) is expelled in stage three. At birth, contractions of the uterus dilate expel the fetus and afterbirth. After delivery, nursing causes the secretion of hormones that stimulate lactation—the production and release of milk.

Section 17.9 The mother's nutrition and use of drugs including nicotinem alcohol, and therapeutic drugs may have serious harmful effects on her developing fetus.

Section 17.11 Human development can be divided into a prenatal period before birth, followed by the neonate (newborn) stage, childhood, adolescence, and adulthood. The process of aging is called senescence.

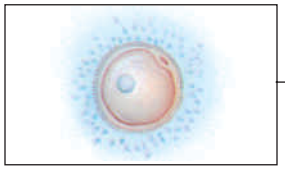
Section 17.12 As the body ages, changes occur in the structure and functional efficiency of many organ systems. These changes are due to multiple factors.

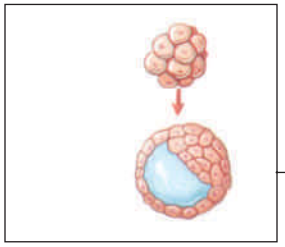
TABLE 17.5 Extraembryonic Membranes

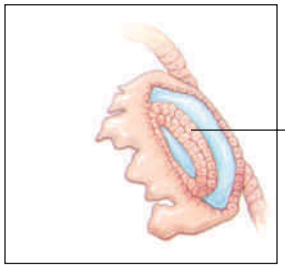
Membrane	Function
Yolk sac	Source of digestive tube; helps form blood cells and forerunners of gametes
Allantois	Source of umbilical blood vessels and vessels of the placenta
Amnion	Sac of fluid that protects the embryo and keeps it moist
Chorion	Forms part of the placenta; protects the embryo and the other extraembryonic membranes

Review Questions

1. Define and describe the main features of the following developmental stages: fertilization, cleavage, gastrulation, and organogenesis.
2. Label the following stages of early development:







3. Define cell differentiation and morphogenesis, two processes that are critical for development.
4. Summarize the development of an embryo and a fetus. When are body parts such as the heart, nervous system, and skeleton largely formed?

Self-Quiz *Answers in Appendix V*

1. Development cannot proceed properly unless each of the following processes is successfully completed before the next begins, starting with _____.
   a. gamete formation
   b. fertilization
   c. cleavage
   d. gastrulation
   e. organ formation
   f. growth, tissue specialization
2. During cleavage, the _____ is converted to a ball of cells, which in turn is transformed into the _____.
   a. zygote; blastocyst
   b. trophoblast; embryonic disk
   c. ovum; embryonic disk
   d. blastocyst; embryonic disk
3. In the week following implantation, cells of the _____ will give rise to the embryo.
   a. blastocyst
   b. trophoblast
   c. embryonic disk
   d. zygote
4. The developmental process called _____ produces the shape and structure of particular body regions.
5. _____ is the gene-guided process by which cells in different locations in the embryo become specialized.
   a. Implantation
   b. Neurulation
   c. Cell differentiation
   d. Morphogenesis
6. In a human zygote, the cell divisions of cleavage produce an embryonic stage known generally as a _____.
   a. zona pellucida
   b. gastrula
   c. blastocyst
   d. larva
7. Match each developmental stage with its description.
   ____ cleavage
   ____ gamete formation
   ____ organ formation
   ____ cell differentiation
   ____ gastrulation
   ____ fertilization
   a. egg and sperm mature in parents
   b. sperm, egg nuclei fuse
   c. germ layers form
   d. zygote becomes a ball of cells called a morula
   e. cells come to have specific structures and functions
   f. starts when germ layers split into subgroups of cells
8. Of the four extraembryonic membranes, only the _____ is not needed in order for an embryo to develop properly.
   a. yolk sac
   b. allantois
   c. amnion
   d. chorion
   e. This is a trick question, because all are needed.
9. Of the following, _____ cannot cross the placenta.
   a. alcohol
   b. the mother's antibodies
   c. antibiotics
   d. toxic substances in tobacco smoke
   e. all can cross the placenta

Critical Thinking

1. How accurate is the statement "A pregnant woman must do everything for two"? Give some specifics to support your answer.
2. A renowned developmental biologist, Lewis Wolpert, once observed that birth, death, and marriage are not the most important events in human life—rather, Wolpert said, the most important moment in life is gastrulation. Given the discussion in Section 17.1, what do you think he meant?
3. One of your best friends tells you that she and her husband think she might be pregnant. She feels she can wait until she's several months along before finding an obstetrician. You think she could use some medical advice sooner, and you suggest she discuss

her plans with a physician as soon as possible. What kinds of health issues might you be concerned about?

4. In an ectopic pregnancy, an embryo implants outside the mother's uterus, often in an oviduct (Figure 17.24). The complications of ectopic pregnancy are life-threatening for the mother, and in fact each year in the United States a few pregnant women die when their situation is not diagnosed in time. Tragically, the only option is to surgically remove the embryo, which was doomed from the beginning. Based on what you know about where an embryo normally develops, explain why an ectopic embryo could not have long survived.

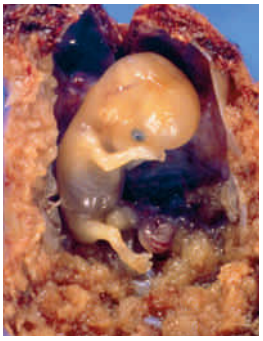


Figure 17.24 **In an ectopic or tubal pregnancy, the embryo impants outside the uterus.**

EXPLORE ON YOUR OWN

Housecats can carry the parasite that causes *toxoplasmosis*. In an otherwise healthy person the disease may only produce flulike symptoms, but it is dangerous for a pregnant woman and her fetus. A mother-to-be may suffer a miscarriage, and if the parasite infects a fetus it causes birth defects. An infected cat may not appear to be ill, but its feces will contain infectious cysts. This is why some physicians advise pregnant women to avoid contact with cats and not to clean sandboxes, take care of housecat "accidents," or empty a litterbox.

All that said, toxoplasmosis is not especially common—so is it something a cat-loving expectant mother should take seriously? To explore this health concern, research the kinds of birth defects caused by toxoplasmosis and find out what stance (if any) public health authorities in your community take on this issue. Is the disease more common in some regions or settings than in others? Can cat owners have their pets tested for the disease?

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Cell Reproduction

18

IMPACTS, ISSUES

Henrietta's Immortal Cells

BY the time you were born, cell division and other processes had given you a body of about a trillion cells. Even in an adult, many cells still divide, replacing damaged or worn-out ones.

In 1951, George and Margaret Gey of Johns Hopkins University were trying to develop a way to keep human cells dividing in the laboratory. An "immortal" cell line would help researchers study basic life processes as well as cancer and other diseases. It would be an alternative to experimenting directly on patients and possibly risking lives.

The Geys' lab assistant, Mary Kubicek, tried many times to establish a self-perpetuating line of human cancer cells. About to give up, she prepared one last culture and named them "HeLa" cells. The code name stood for the first two letters of the patient's first and last names, Henrietta Lacks.

Those cells began to divide. Four days later, there were so many HeLa cells that the researchers subdivided them into more culture tubes.

Sadly, cancer cells in the patient also were dividing rapidly. Six months after being diagnosed, the disease had spread throughout her body. Two months after that, Henrietta Lacks died. Yet some of her cells lived on in the Geys' laboratory as the first successful human cell culture. Today, several hundred major research projects use Henrietta's immortal cells.

Henrietta was only 31, a wife and the mother of four, when cancer killed her. Now, decades later, descendants of her cells are still dividing and helping people all over the world.

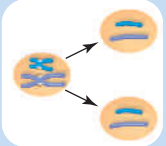
Learning about cell division helps us understand how each of us is put together in the image of our parents. Our study of this topic begins with the answers to three questions. First, what kind of information guides inheritance? Second, how is the information copied in a parent cell before being distributed into daughter cells? And third, what kinds of mechanisms actually parcel out the information to daughter cells?

KEY CONCEPTS

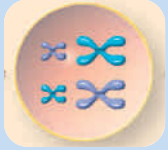
Basic Principles of Cell Division

Cells reproduce by duplicating their chromosomes and then dividing the chromosomes and cell cytoplasm among daughter cells. Sections 18.1–18.3

Mitosis: Body Growth and Repair



The body grows and tissues are repaired when cells divide by the mechanism called mitosis. This mechanism divides the nucleus so that each newly formed cell has the same number of chromosomes as the parent cell. Sections 18.4, 18.5, 18.10



Meiosis: Cells for Sexual Reproduction

Sperm and oocytes, the human gametes, form by the cell division mechanism of meiosis. Meiosis reduces the number of chromosomes so that each gamete has half the number of parent cell chromosomes. Sections 18.7–18.10

LINKS TO EARLIER CONCEPTS

- This chapter builds on what you have already learned about the cell nucleus and chromosomes (3.6) and explains how microtubules (3.9) assist in cell division.
- You will also learn more about how sperm and eggs form during the processes of spermatogenesis and oogenesis (16.2 and 16.4).
- By the end of this chapter you will have a fuller understanding of how the union of sperm and egg at fertilization (16.6) provides a zygote with the full set of parental chromosomes required for normal development.

How Would You Vote?

No one asked Henrietta Lacks's permission to use her cells. Her family did not find out about them until twenty-five years after she died. HeLa cells are still being sold worldwide. Should the family of Henrietta Lacks share in the profits? See CengageNOW for details, then vote online.

18.1 Dividing Cells Bridge Generations

- **The continuity of life depends on the ability of cells—and whole organisms—to faithfully reproduce themselves. Dividing cells are the bridge between these generations.**
- **Links to Life characteristics 1.1, the Cell nucleus 3.6, Formation of sperm and eggs 16.2, 16.4**

Division of the "parent" nucleus sorts DNA into a nucleus for each daughter cell

In biology, **reproduction** is when a parent cell produces a new generation of cells, or when parents produce a new individual. Reproduction is part of a **life cycle**, a recurring series of events in which individuals grow, develop, maintain themselves, and reproduce a new generation. The instructions for the human life cycle are encoded in our DNA, which we inherit from our parents. Reproduction begins with the division of single cells. It follows this basic rule: Each cell of a new generation must receive a copy of the parent cell's DNA. Otherwise the cell won't develop or function properly.

Each daughter cell also inherits some cytoplasm from the parent cell. The cytoplasm provides "start-up" machinery, such as enzymes and organelles, that will keep the new cell functioning until it has time to use its inherited DNA for growing and developing on its own.

A human cell has only one nucleus, so the cell can't just split in two when it divides. First, the nucleus must be divided in a way that parcels out DNA and packages it in two nuclei, one for each new cell. Depending on the kind of cell, the nucleus will be divided by *mitosis* or by *meiosis* (Table 18.1). Both mechanisms sort out and package DNA molecules into new nuclei for daughter cells.

TABLE 18.1 Overview of Mitosis and Meiosis

	Mitosis	Meiosis
Function	Growth, including repair and maintenance	Gamete production (sperm/eggs)
Occurs in	Somatic (body) cells	Germ cells in gonads (testes and ovaries)
Mechanism	Chromosomes are duplicated once, then the cytoplasm is divided	Chromosomes are duplicated twice, then the cytoplasm is divided
Outcome	Maintains the diploid chromosome number ($2n \rightarrow 2n$)	Halves the diploid chromosome number ($2n \rightarrow n$)
Effect	Two diploid daughter cells	Four haploid daughter cells

Mitosis (my-TOE-sis) is the division mechanism that divides the nucleus of a *somatic* (body) *cell*. The body grows, replaces worn-out or dead cells, and repairs tissues by way of mitosis.

In contrast to mitosis, **meiosis** (my-OH-sis) is the mechanism for dividing the nucleus of **germ cells**—the oogonia in ovaries and spermatogonia in testes (Chapter 16). In these cells, meiosis must take place before gametes (sperm and eggs) form. Accordingly, meiosis is the first stage in sexual reproduction.

Chromosomes are DNA "packages" in the cell nucleus

Both mitosis and meiosis divide a parent cell's DNA into new nuclei. To do this, mitosis and meiosis both must manipulate chromosomes—the DNA "packages" you first read about in Chapter 3. Each **chromosome** is one very long DNA molecule combined with protein. Each **gene** is a segment of DNA in a chromosome. Together, the DNA and protein are called **chromatin**. You will read more about the structure of chromosomes in Section 18.2.

Having two sets of chromosomes makes a cell diploid

You may remember from Section 16.1 that the sum of the chromosomes in cells of a given type is the **chromosome number**. Human DNA is carried on 23 chromosomes, but our somatic cells have two full sets of them—one set from each parent. Thus the chromosome number in all cells except germ cells is 46 (Figure 18.1*a*). A cell that has two of each type of chromosome is called a **diploid** cell. The shorthand $2n$ indicates that a cell is diploid. The n stands for the number of chromosomes in one full set.

When the nucleus of a diploid parent cell divides by mitosis, the result is two diploid daughter cells (Figure 18.2). One member of each chromosome pair is from the mother, and the other is from the father. Before a diploid cell divides, its chromosomes are duplicated, so it has four sets of chromosomes. Mitosis puts half of this doubled genetic material in each new cell, so each ends up with the diploid number of chromosomes.

In Figure 18.1*a*, there are 23 pairs of chromosomes. This is because each chromosome has been lined up with its partner from the other parent. Pairs 1 through 22 are **autosomes**: the two members of each pair are about the same length and both carry hereditary instructions for the same traits. Pair 23 consists of the **sex chromosomes**, which determine a person's biological sex. The two types of sex chromosomes are labeled X and Y. A female has two X chromosomes, while a male is XY.

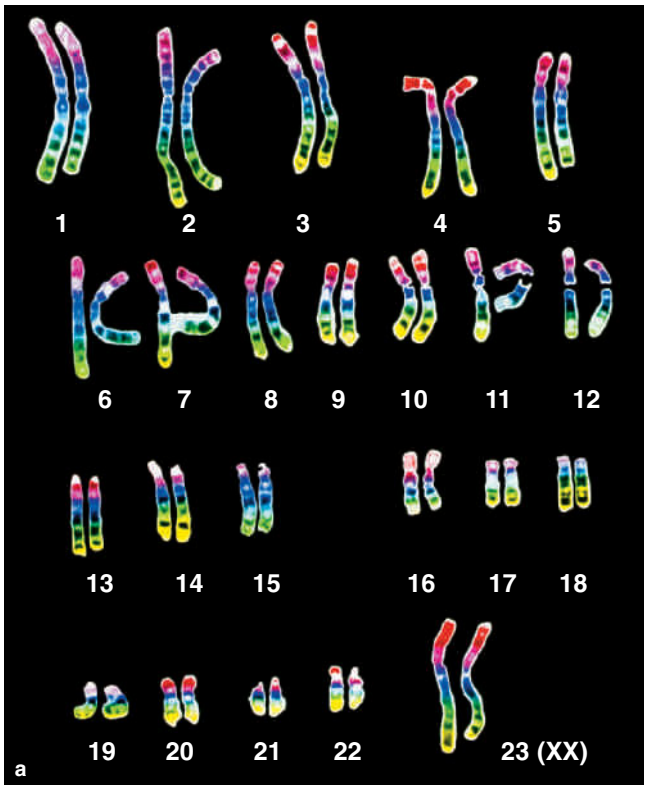


Figure 18.1 The usual chromosome number for human cells is forty-six. (**a**) Forty-six chromosomes from a human female. Each chromosome is duplicated. The presence of pairs of chromosomes (two of each type) tells you that they came from a diploid cell. One member of each pair contains genetic instructions inherited from the father. The other member contains instructions from the mother. (**b**) Close-up of a pair of homologous chromosomes from an animal cell.

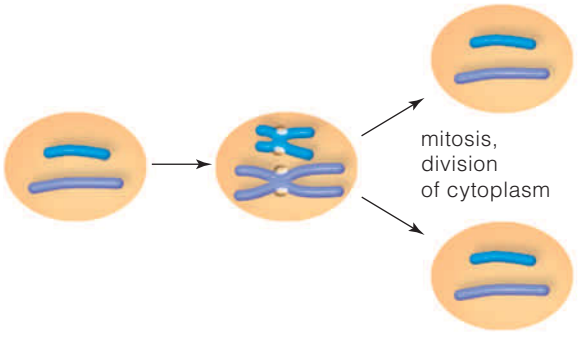
The paired corresponding chromosomes, one from each parent, are called **homologous chromosomes**, or simply *homologues* (from a Greek word meaning "to agree"). The X and Y sex chromosomes are considered homologues, even though they are of different size and form and for the most part they carry genes for different traits. Chapter 20 provides more information about both types of sex chromosomes.

Having only one set of chromosomes makes a cell haploid

Meiosis takes place in dividing germ cells in ovaries or testes. Remember from Chapter 16 that human germ cells are *spermatogonia* in males and *oogonia* in females. Spermatogonia and oogonia are diploid. However, unlike other body cells, they can give rise to haploid gametes—sperm or eggs—by way of meiosis.

A human sperm or oocyte typically contains just one set of 23 chromosomes, instead of 46 paired, homologous chromosomes. This is because meiosis is a **reductional division**. It halves the diploid number of chromosomes ($2n$) to a **haploid** number (n). And not just any half. Each haploid gamete ends up with one partner from each pair of homologous parent chromosomes.

With these basic concepts in mind, we now consider in more detail how cells divide. Chromosomes are central players in the story, so we begin in the next section by looking at how chromosomes are organized.



A Two of the chromosomes (unduplicated) in a parent cell at interphase

B The same two chromosomes, now duplicated, in that cell at interphase, prior to mitosis

C Two chromosomes (unduplicated) in the parent cell's daughter cells, which both start life in interphase

Figure 18.2 Mitosis maintains the diploid chromosome number from one generation to the next.

Take-Home Message

What are mitosis and meiosis, and what are their roles?

- Mitosis and meiosis are cell division mechanisms that sort chromosomes, and therefore DNA, into new nuclei for daughter cells.
- Mitosis occurs in dividing somatic cells. The chromosome number remains the same from one cell generation to the next. The body grows and tissues are repaired as cells divide by mitosis.
- Meiosis takes place in germ cells in the ovaries and testes. It is the mechanism that produces gametes.

18.2 A Brief Look at Chromosomes

- **A chromosome is nothing more than coiled loops of DNA and proteins.**
- **Links to the Cell nucleus 3.6, Cytoskeleton 3.19**

A chromosome undergoes changes in preparation for cell division

A chromosome consists of DNA and proteins that are attached to it. As Section 18.1 described, before a cell begins to divide by mitosis or meiosis, it duplicates its chromosomes. For much of the division process, each chromosome and its copy stay together. During this time they are called **sister chromatids** (Figure 18.3).

During the early stages of mitosis and meiosis, each duplicated chromosome coils back on itself again and again, into a highly condensed form. Figure 18.4*a* has an example of a duplicated human chromosome when it is most condensed. Figure 18.4*b* shows the deeper organization of a chromosome. Notice that the DNA loops around some proteins (called histones), forming beadlike structures. They in turn coil up into a long fiber.

As a cell nucleus starts to divide, the DNA coils tighten up even more to form the condensed chromosome. This "supercoiling" may help keep chromosomes from getting tangled up when they are moved and sorted into parcels for daughter cells.

When the coiling is complete, a chromosome has its typical size and shape. Each of its sister chromatids also has at least one "pinched in" region called a **centromere**. It will provide docking sites for microtubules that move chromosomes when a cell nucleus is dividing.

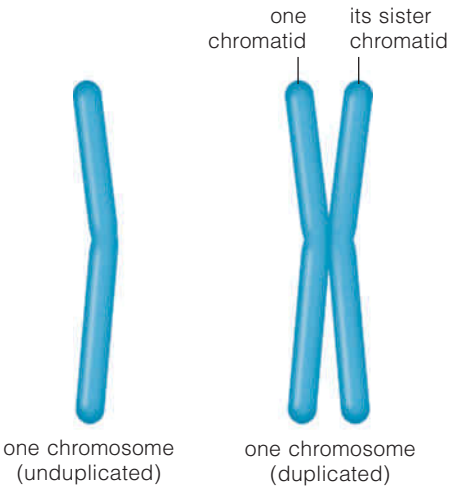


Figure 18.3 Chromosomes are duplicated before a cell divides. Each one becomes two sister chromatids.

Spindles attach to chromosomes and move them

In both mitosis and meiosis, chromosomes move into new positions with the help of a spindle. The **spindle** consists of two sets of microtubules extending from its two poles (Figure 18.5). These "poles" are centrioles, parts of a cell's cytoskeleton (Section 3.9). One set of microtubules overlaps the other set at the spindle's "equator," midway between its two poles. As you will read shortly, the spindle establishes where each sister chromatid will end up before a cell divides in two.

Take-Home Message

What happens to chromosomes before a cell divides?

- Chromosomes condense and are copied in cells that are ready to divide.
- When a cell's nucleus is about to divide, a spindle formed by microtubules attaches to the chromosomes and moves them into new positions.

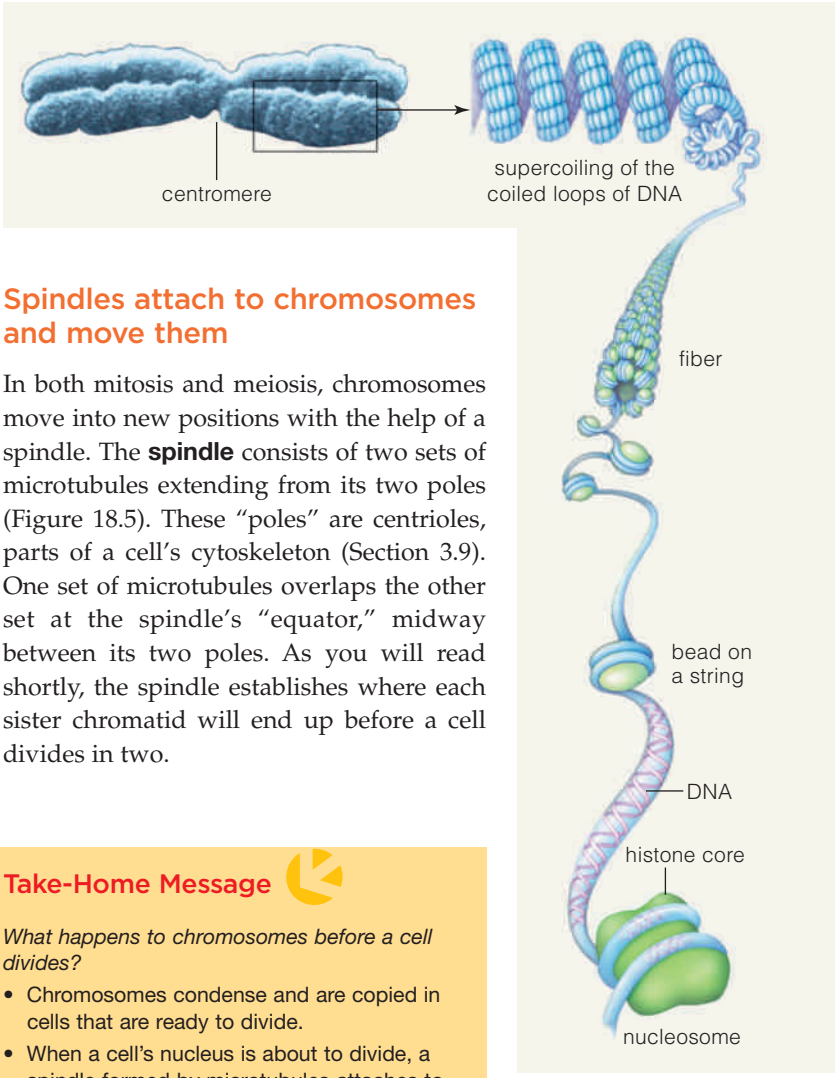


Figure 18.4 Animated! DNA in a chromosome is looped and coiled.

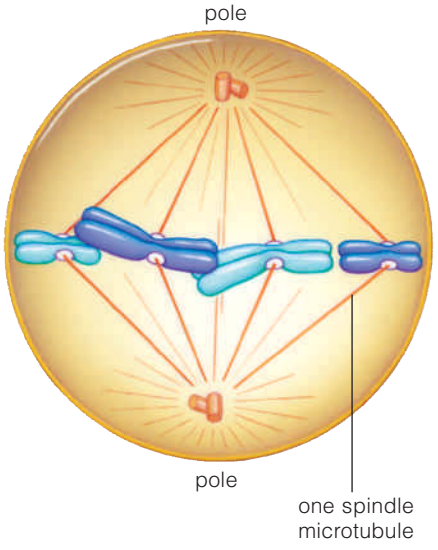


Figure 18.5 A spindle moves chromosomes in a dividing cell. The barrel-shaped structures are centrioles.

18.3 The Cell Cycle

- **Every time a new cell comes into being, a multistep cell cycle begins anew.**

The "lifetime" of a somatic cell is called the **cell cycle**. The cycle starts every time a new cell is produced, and it ends when the cell completes its own division. Mitosis is a part of the cycle, as sketched in Figure 18.6. Usually, the longest phase of the cell cycle is **interphase**. This phase has three parts in which a cell grows larger, more or less doubles the number of components in its cytoplasm, then copies its DNA. This copying process duplicates the chromosomes. The parts of the cell cycle are:

G1 The part of interphase when the cell grows

S The part of interphase when a cell's DNA is copied and its chromosomes are duplicated

G2 The part of interphase after chromosomes are duplicated, when other events prepare the cell to divide

M Mitosis, when chromosomes (duplicated DNA) are sorted into two sets and the cytoplasm divides

The length of the cell cycle varies depending on the type of cell involved. For instance, the cycle lasts twenty-five hours in epithelial cells in your stomach lining and eighteen hours in bone marrow cells. New red blood cells form and replace your worn-out ones at an average rate of 2 to 3 million each second.

Mitosis has four phases, called prophase, metaphase, anaphase, and telophase. We consider them next.

Take-Home Message

What are the phases of the cell cycle?

- A cell cycle begins at interphase, when a cell grows, doubles the components of its cytoplasm, and then copies its DNA, forming duplicates of its chromosomes.
- The cycle ends with mitosis, when the cell divides.

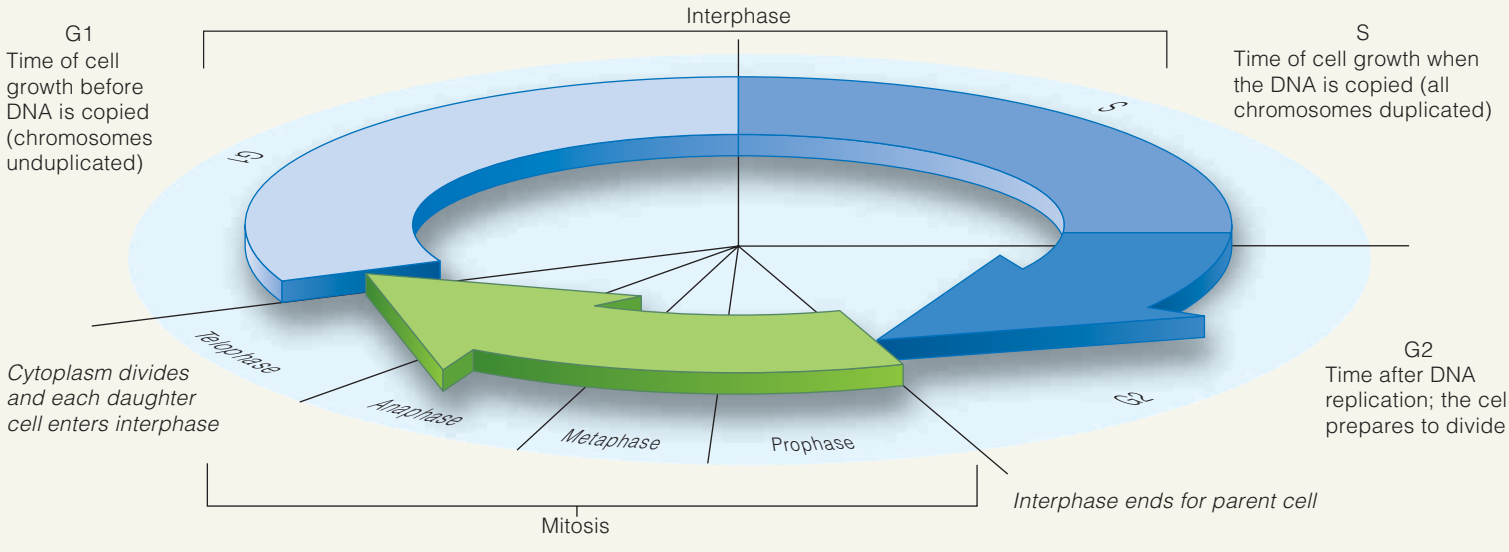


Figure 18.6 Animated! The cell cycle has two main stages, interphase and mitosis. The duration of each interval differs among cells.

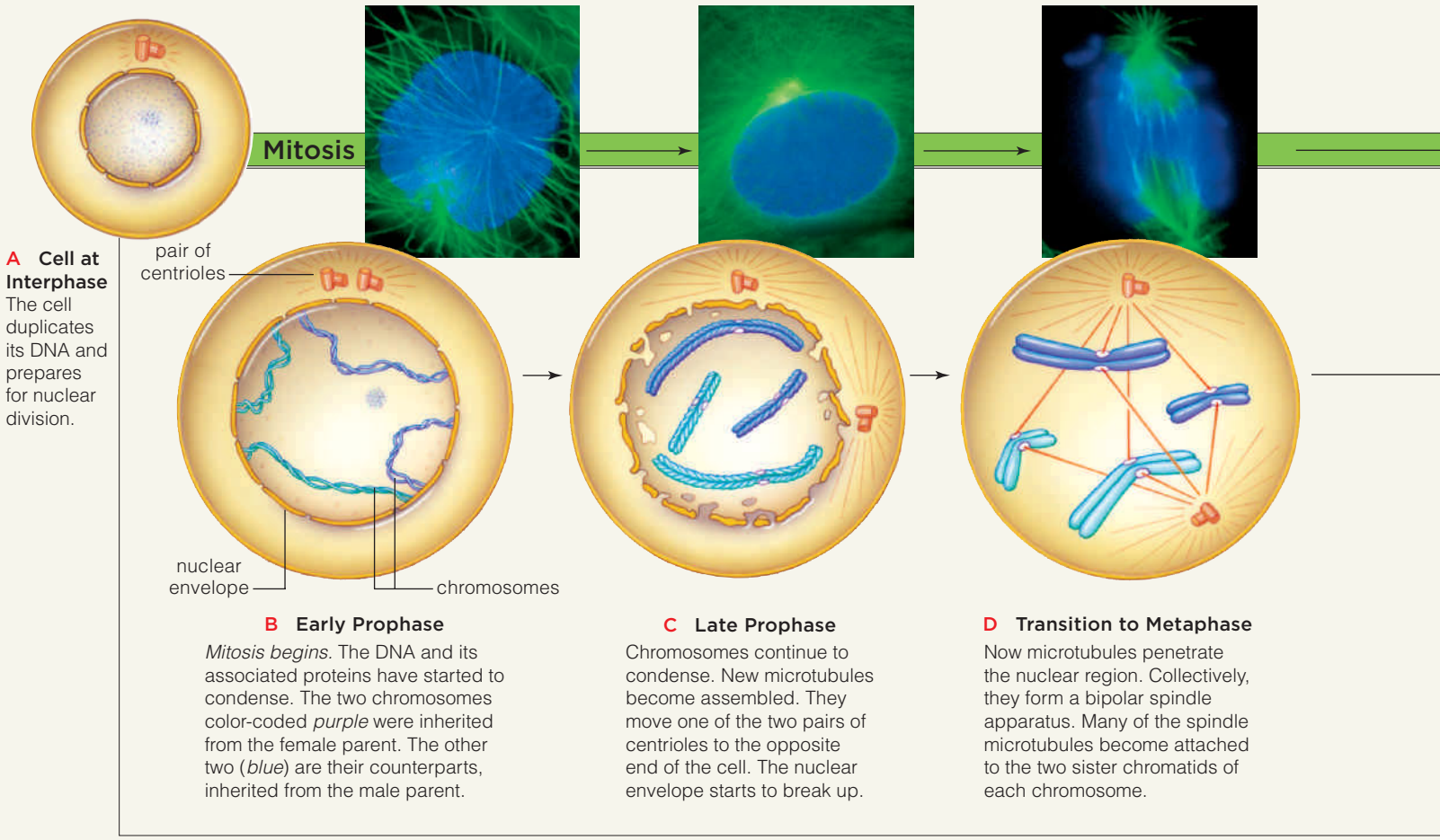


Figure 18.7 Animated! **Mitosis ensures that daughter cells will have the same chromosome number as the parent cell.** For clarity, the diagram shows only two pairs of chromosomes from a diploid (*2n*) animal cell.

18.4 The Four Stages of Mitosis

- **When interphase ends, a cell has stopped making new parts and its DNA has been replicated. Mitosis can begin.**
- **Links to the Cell nucleus 3.6, Microtubules 3.9**

The four stages of mitosis are **prophase**, **metaphase**, **anaphase**, and **telophase** (Figure 18.7).

Mitosis begins with prophase

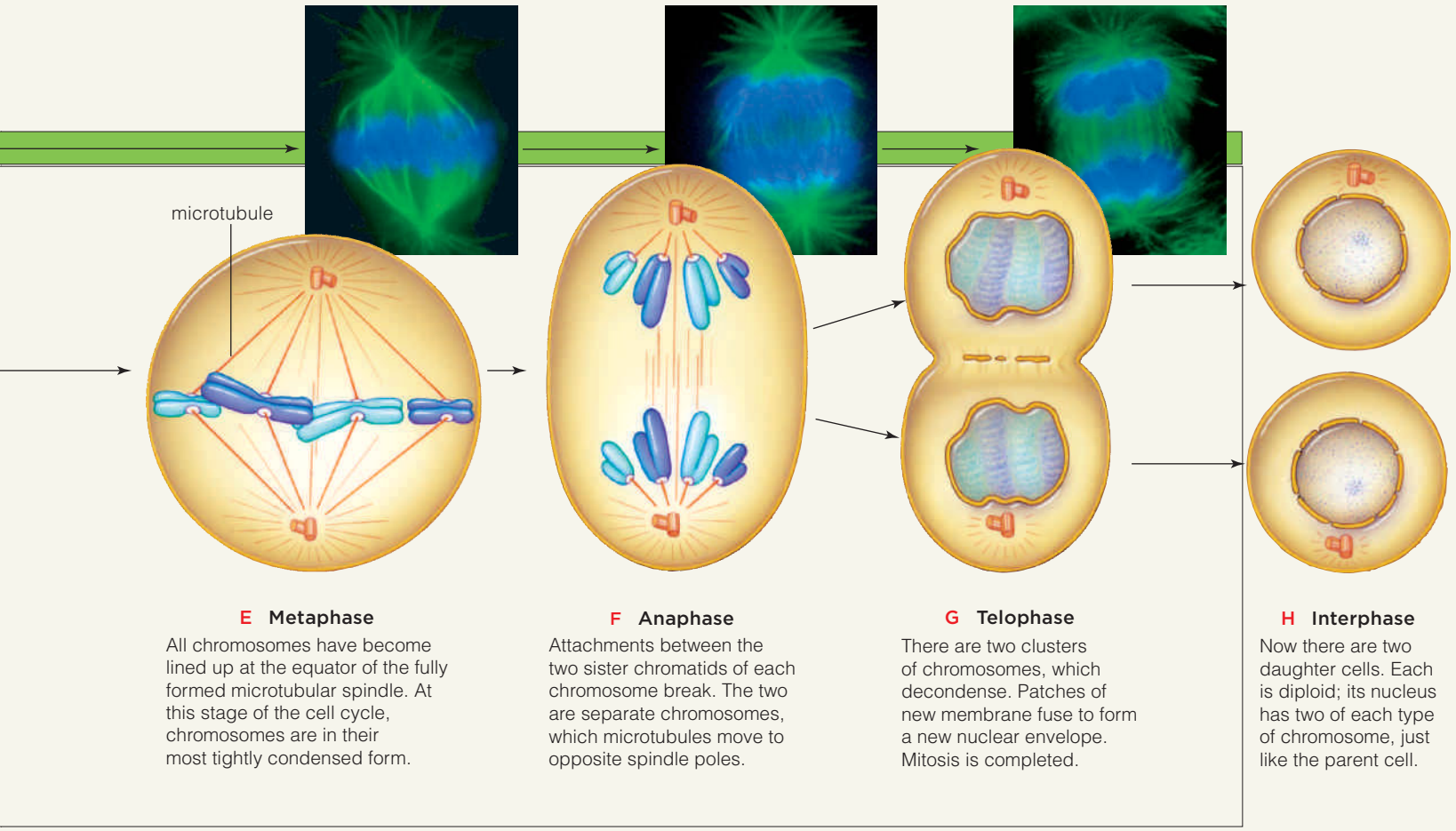
When prophase begins, a cell's chromosomes are thread-like. ("Mitosis" comes from the Greek *mitos*, for "thread.") During interphase each chromosome was duplicated, forming two sister chromatids joined at the centromere. The sister chromatids of each chromosome twist and fold into a more compact form. By the end of prophase, all chromosomes will be condensed into thick rod shapes.

Meanwhile, in the cytoplasm, most microtubules of the cell's cytoskeleton are breaking apart into their subunits (Section 3.9) and new microtubules are forming near the nucleus. The nuclear envelope physically prevents them from making contact with the chromosomes inside the nucleus, but not for long: The nuclear envelope starts to break up as prophase ends.

Many cells have two barrel-shaped centrioles. Each centriole was duplicated in interphase along with other components of the cytoplasm, so there are two pairs of them in prophase. Microtubules start moving one pair to the opposite pole of the developing spindle.

Next comes metaphase

A lot happens between prophase and metaphase—so much that this transitional period has its own name, "prometaphase." The nuclear envelope breaks apart, allowing the chromosomes in the nucleus to interact with microtubules extending toward them from the poles of the forming spindle. Cell biologists have watched this process occur. Microtubules from both poles harness each chromosome and start pulling on it. The two-way pulling tugs the



E Metaphase
All chromosomes have become lined up at the equator of the fully formed microtubular spindle. At this stage of the cell cycle, chromosomes are in their most tightly condensed form.

F Anaphase
Attachments between the two sister chromatids of each chromosome break. The two are separate chromosomes, which microtubules move to opposite spindle poles.

G Telophase
There are two clusters of chromosomes, which decondense. Patches of new membrane fuse to form a new nuclear envelope. Mitosis is completed.

H Interphase
Now there are two daughter cells. Each is diploid; its nucleus has two of each type of chromosome, just like the parent cell.

chromosome's two sister chromatids toward opposite poles. Meanwhile, overlapping spindle microtubules ratchet past each other and push the poles of the spindle apart. Soon the chromosomes reach the middle of the spindle.

When all the duplicated chromosomes are lined up midway between the poles of a spindle, we say the cell is in metaphase (*meta-* means midway between). This alignment sets the stage for anaphase, the next stage of mitosis.

Anaphase, then telophase follow

During anaphase, the sister chromatids of each chromosome separate from each other and move to opposite spindle poles. Two mechanisms produce this movement. First, the microtubules attached to the centromeres pull the chromosomes toward the poles. Second, the spindle elongates as overlapping microtubules continue to ratchet past each other and push the two spindle poles even farther apart. Once each chromatid is separated from its sister, it is an independent chromosome.

Telophase begins as soon the two clusters of chromosomes each arrive at a spindle pole. The chromosomes are no longer connected to microtubules, and they return to threadlike form. Bit by bit, a new nuclear envelope forms around each cluster, separating it from the cytoplasm. Now there are two new nuclei. Each new nucleus has the same chromosome number as the parent nucleus. Once two nuclei form, telophase is over—and so is mitosis.

Take-Home Message

What are the main events of mitosis?

- Before mitosis, each chromosome in a cell's nucleus is duplicated, so that it consists of two sister chromatids.
- Mitosis occurs in consecutive stages, called prophase, metaphase, anaphase, and telophase.
- A spindle of microtubules moves the sister chromatids of each chromosome apart, to opposite spindle poles. A new nuclear envelope forms around the two chromosome clusters. Both daughter nuclei have the same number of chromosomes as the parent cell's nucleus.

18.5 How the Cytoplasm Divides

- **After mitosis produces two new cell nuclei, each with a set of the parent cell's chromosomes, the parent cell's cytoplasm also must be divided between the two daughter cells.**

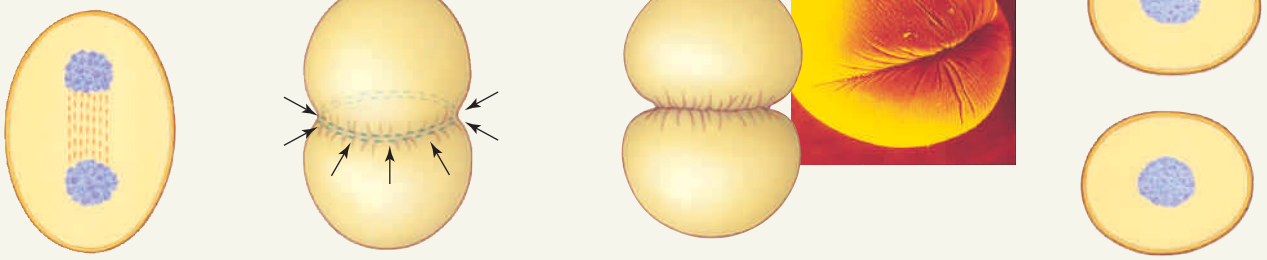
Division of the cytoplasm, or **cytokinesis**, usually begins toward the end of anaphase. By this time, the two sister chromatids of each chromosome have been separated and are independent chromosomes. In an animal cell, about midway between the cell's two poles, a patch of plasma membrane sinks inward, forming a **cleavage furrow**. Microfilaments made of the contractile protein actin steadily pull the plasma membrane inward all around the cell, until the cell is pinched in two (Figure 18.8). Now there are two new cells, each with a nucleus, cytoplasm, and a plasma membrane.

This concludes our tour of mitosis. Now we turn to meiosis, the nucleus-dividing mechanism that forms gametes. It is difficult not to be in awe of the astonishing precision with which both mitosis and meiosis take place.

Take-Home Message

What is cytokinesis?

- As mitosis ends, the mechanism of cytokinesis cuts the cytoplasm into two daughter cells, each with a daughter nucleus.



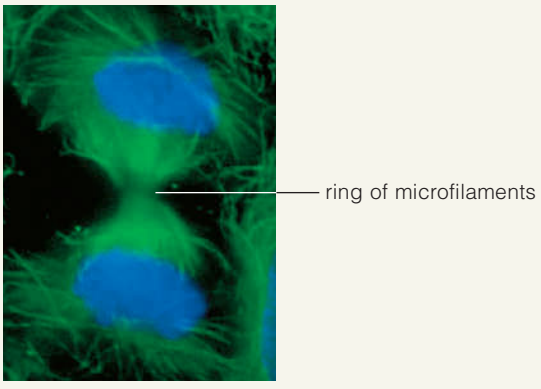
1 Mitosis is over, and the spindle is disassembling.

2 At the former spindle equator, a ring of microfilaments attached to the plasma membrane contracts.

3 As the microfilament ring shrinks in diameter, it pulls the cell surface inward.

4 Contractions continue; the cell is pinched in two.

a



b

Figure 18.8 Animated! Cytokinesis gives each new cell a share of the parent cell's cytoplasm. (**a**) Steps of cytokinesis in an animal cell. (**b**) The beltlike contracting ring of microfilaments inside a dividing animal cell that is undergoing cytokinesis.

18.6 Concerns and Controversies over Irradiation

What do a routine dental X-ray and an irradiated side of beef have in common? Both are examples of ways we use ionizing radiation. Like some other technologies, this one can be a double-edged sword and can even fuel serious controversy.

Irradiation effects on the body Ionizing radiation includes various potentially harmful types of electromagnetic energy—for instance, radio waves, visible light, microwaves, cosmic rays from outer space, and radioactive radon gas in rocks and soil. Forms that can harm living cells, including radon and X-rays, have enough energy to remove electrons from atoms and change them to positively charged ions (Section 2.4).

When ionizing radiation enters an organism, it may break apart chromosomes, alter genes, or both. If the chromosomes in an affected cell have been broken into fragments (Figure 18.9*a*), the spindle apparatus will not be able to harness and move the fragments when the cell divides. The cell or its descendants may then die. When ionizing radiation damage occurs in germ cells, the resulting gametes can carry damaged DNA. Therefore, an infant who inherits the DNA may have a genetic defect. If only somatic cells are affected, only the person exposed to the radiation will suffer damage.

When a person receives a sudden, large dose of ionizing radiation, it typically destroys cells of the immune system, epithelial cells of the skin and intestinal lining, and red blood cells, among other cell types. The results are serious infections, intestinal hemorrhages, anemia, and wounds that do not heal.

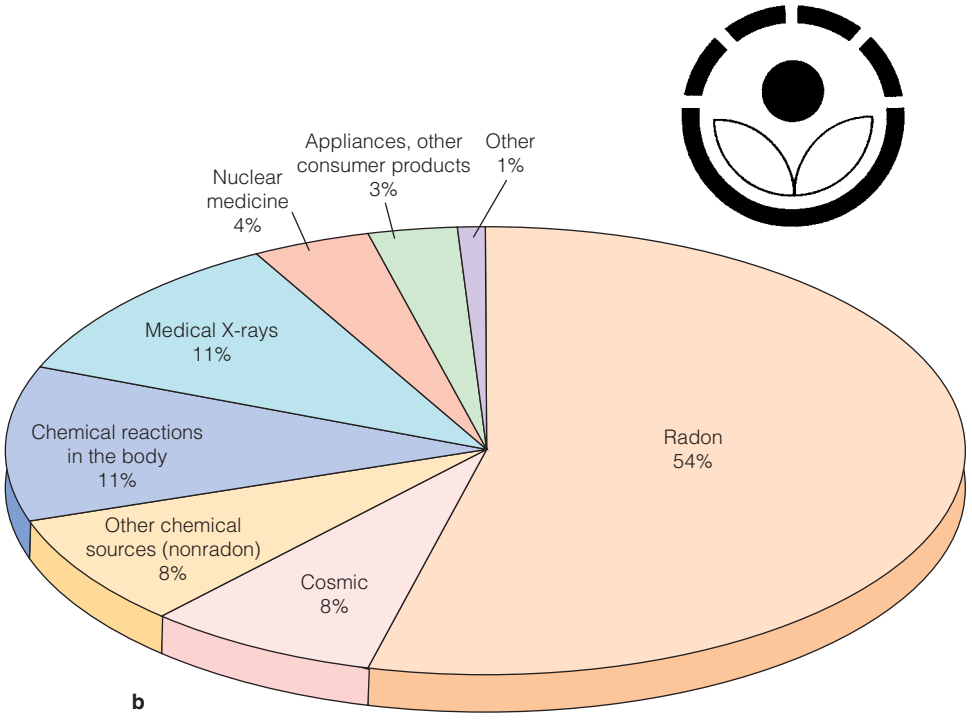
Small doses of ionizing radiation over a long period of time apparently cause less damage than the same total dosage given all at once. This may be due in part to the body's ability to repair damaged DNA. Even so, ionizing radiation is associated with miscarriages, eye cataracts, and various cancers (Chapter 22).

On the other hand, medical X-rays and diagnostic technologies such as magnetic resonance imaging (MRI) and PET scanning (Section 2.1) are valuable uses of ionizing radiation in health care. So is radiation therapy used in treating some cancers.

Irradiated food Just as living body cells can be damaged or killed by radiation, so can harmful bacteria, fungi, and other microorganisms. As a result, foods ranging from grains and potatoes to fruits, spices, beef, pork, and other meats may be irradiated. Irradiated food sold in the United States carries an identifying logo (Figure 18.9*b*).

Irradiated food is not radioactive, and some people are quite comfortable eating it because there is no scientific evidence that it presents a health hazard. In addition, irradiation limits spoilage, and proponents argue that it may reduce the incidence of food-borne illnesses. On the other hand, opponents worry that irradiation might promote the development of radiation-resistant microbes. Some also are concerned that irradiation may chemically change food in ways that could harm consumers. For the time being, there is no scientific evidence to support that fear.

a



b

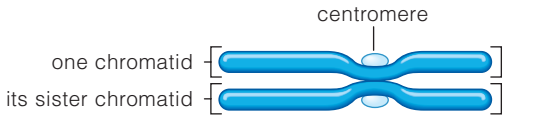
Figure 18.9 Ionizing radiation can break apart chromosomes. (**a**) Human chromosomes that have broken after being exposed to ionizing radiation (*arrows*). (**b**) The sources of radiation exposure for people in the United States. (far right) Logo required to be placed on irradiated food products in the United States.

18.7 Meiosis: The Beginnings of Eggs and Sperm

- **Meiosis divides the nuclei of germ cells in a way that halves the number of chromosomes in daughter cells. It is the first step toward the gametes required for sexual reproduction.**
- **Links to Sperm formation 16.2, Oocyte formation 16.4**

In meiosis the parent cell nucleus divides twice

Meiosis is like mitosis in some ways, even though the outcome is different. During interphase, a germ cell copies its DNA, forming duplicated chromosomes. As you learned in Section 18.2, each duplicated chromosome consists of two sister chromatids attached to one another:



one chromosome in the duplicated state

As in mitosis, a spindle moves chromosomes into the proper position for the formation of daughter nuclei. In meiosis, however, there are *two consecutive* divisions of the chromosomes. The result will be four haploid nuclei. There is no interphase between the two nuclear divisions, which we call meiosis I and meiosis II:

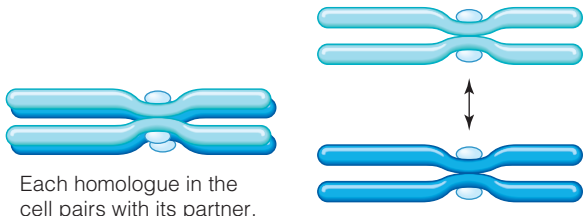
interphase (*DNA replication before meiosis I*)

MEIOSIS I
PROPHASE I
METAPHASE I
ANAPHASE I
TELOPHASE I

no interphase (*no DNA replication before meiosis II*)

MEIOSIS II
PROPHASE II
METAPHASE II
ANAPHASE II
TELOPHASE II

During meiosis I, each duplicated chromosome lines up with its partner, homologue to homologue. Then the two partners are moved apart:

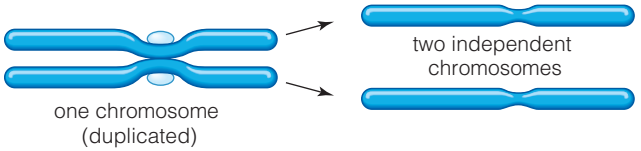


Each homologue in the cell pairs with its partner.

Then the partners separate.

The cytoplasm typically divides after each homologue is separated from its partner. The two daughter cells are haploid, with only one of each type of chromosome.

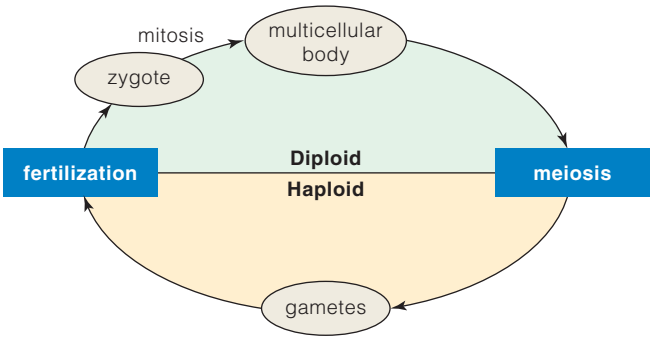
Later, during meiosis II, the two sister chromatids of each chromosome are separated from each other:



Each sister chromatid is now a separate chromosome. After the four nuclei form, the cytoplasm divides again. The result is four haploid cells that eventually may function in reproduction.

Meiosis leads to the formation of gametes

The human life cycle starts with meiosis. Next come the formation of gametes, fertilization, then growth of the new individual by way of mitosis:



In a male, meiosis and the formation of gametes are called **spermatogenesis** because the forthcoming gametes will be sperm (Figure 18.10). First, a diploid germ cell increases in size. The resulting large, immature cell (a primary spermatocyte) undergoes meiosis. The resulting four haploid spermatids then change in form, develop tails, and become sperm—mature male gametes.

In females, meiosis and gamete formation are called **oogenesis** (Figure 18.11). As you might expect, oogenesis differs from spermatogenesis in some important ways. For example, compared to a primary spermatocyte, many more components of the cytoplasm form in a primary oocyte, the female germ cell that undergoes meiosis. Also, in females the cells formed after meiosis are of different sizes and have different functions.

The early stages of oogenesis unfold in a developing female embryo. Recall from Chapter 16, however, that until a girl reaches puberty, her primary oocytes are arrested in prophase I. Then, each month, meiosis

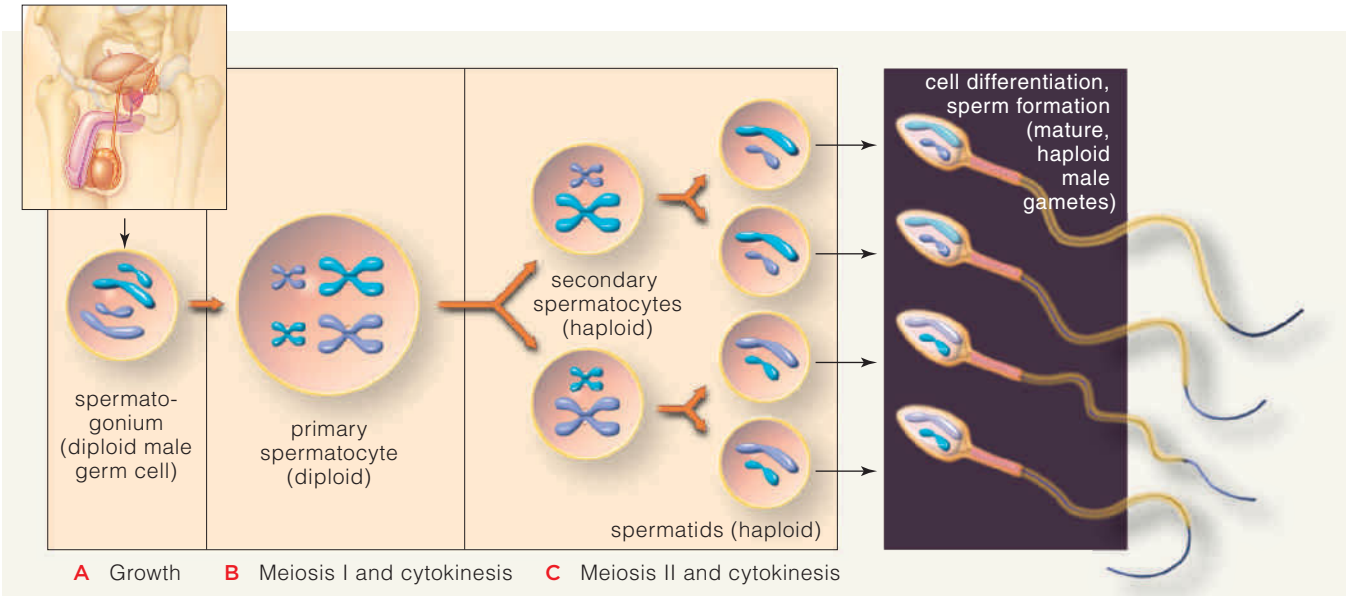


Figure 18.10 Animated! Spermatogenesis is the process that forms sperm.

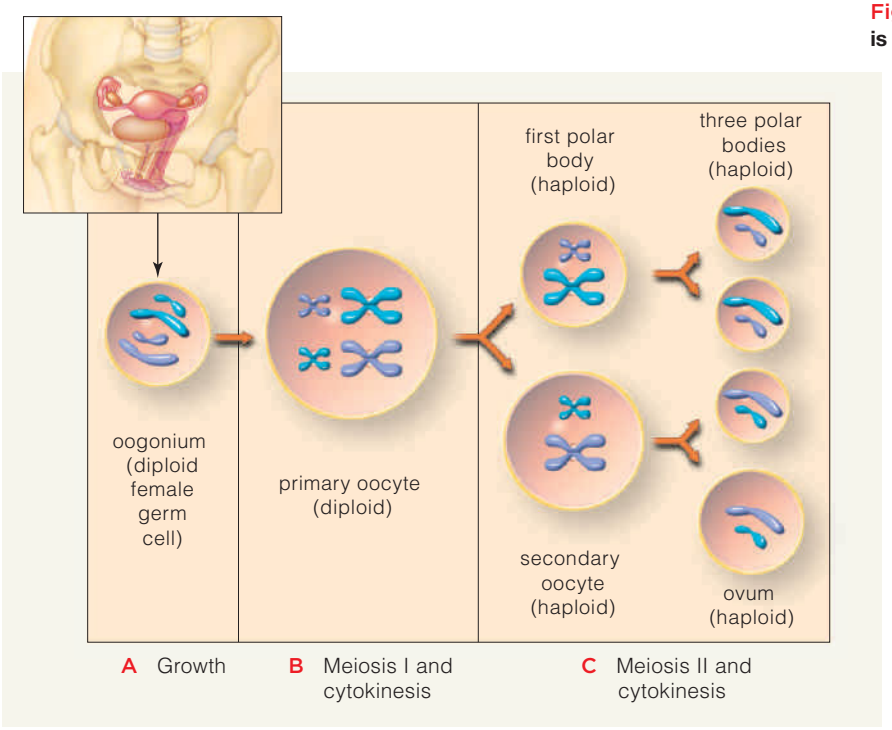


Figure 18.11 Animated! Oogenesis is the process that forms eggs. The diagram is not at the same scale as Figure 18.10. An egg becomes much larger than a sperm cell. It also is much larger than the polar bodies.

resumes in (usually) one oocyte that is ovulated. This cell, the secondary oocyte, receives nearly all the cytoplasm; the other, much smaller cell is a polar body. Both cells enter meiosis II, but the process is arrested again at metaphase II. If the secondary oocyte is fertilized, meiosis II continues. It results in one large cell and (often) three extremely small polar bodies. The polar bodies are "dumping grounds" for three sets of chromosomes so that the egg will end up with only the necessary haploid number. The large cell develops into the mature egg (ovum). Its cytoplasm contains components that will help guide the development of an embryo.

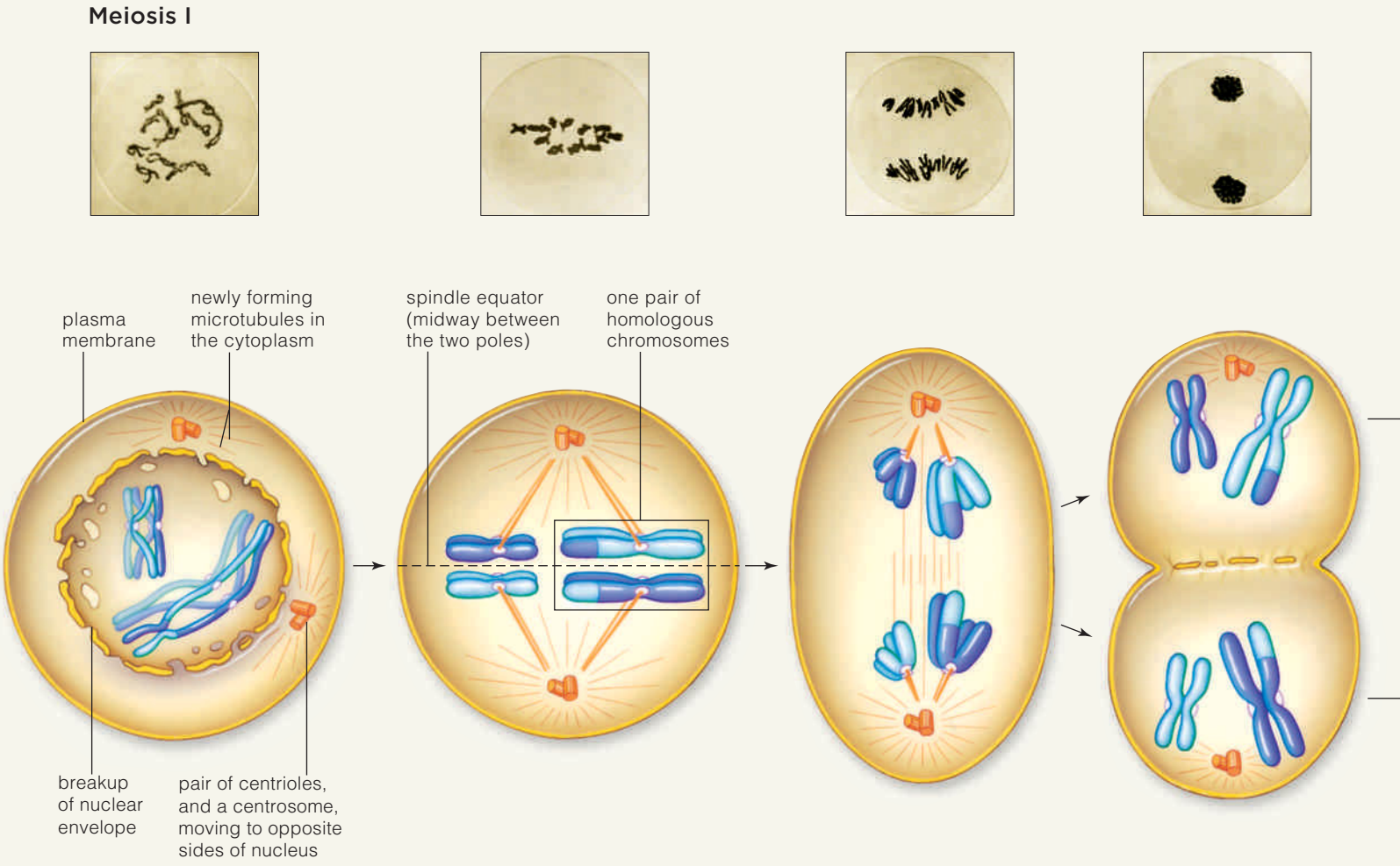
Oogenesis and spermatogenesis make gametes that are available for fertilization. As you may remember from Section 16.6, fertilization restores the diploid number of chromosomes in a zygote.

Take-Home Message

How does meiosis help form gametes?

- Meiosis reduces the parental chromosome number by half, to the haploid number.
- Meiosis is the first step in the formation of gametes (sperm and eggs) for sexual reproduction.
- In males, meiosis and gamete formation are called spermatogenesis. In females, these two processes are called oogenesis.

18.8 A Visual Tour of the Stages of Meiosis



A Prophase I

As prophase I begins, chromosomes become visible as threadlike forms. Each pairs with its homologue and usually swaps segments with it, as indicated by the breaks in color in the large chromosomes. Microtubules are forming a spindle. One pair is moved to the opposite side of the nuclear envelope, which is starting to break up.

B Metaphase I

Microtubules from one spindle pole have attached to one of each type of chromosome; microtubules from the other pole have attached to its homologue. By metaphase I, a tug-of-war between the two sets of microtubules has aligned all chromosomes midway between the poles.

C Anaphase I

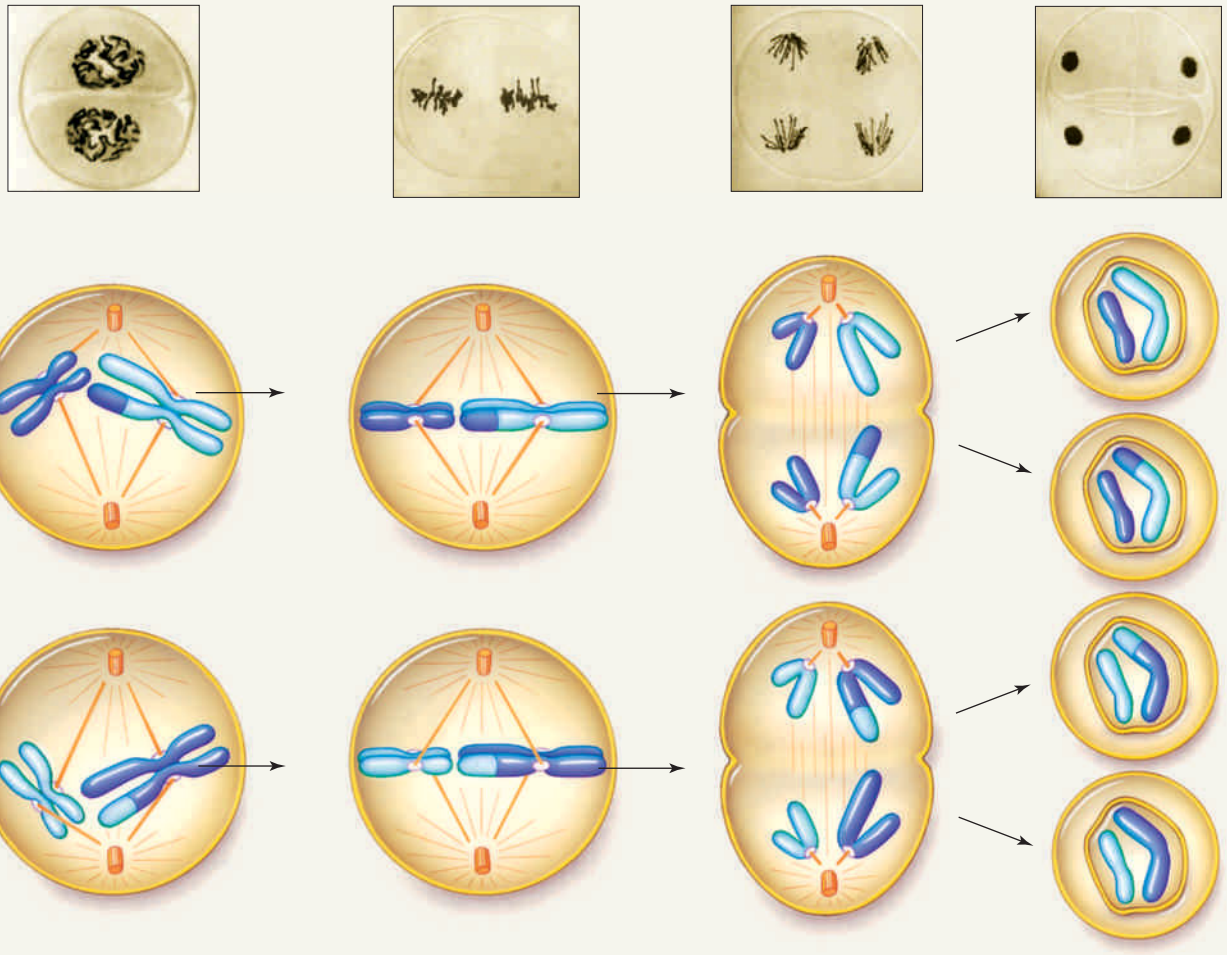
Microtubules attached to each chromosome shorten and move it toward a spindle pole. Other microtubules, which extend from the poles and overlap at the spindle equator, move past each other and push the two poles farther apart.

D Telophase I

One of each type of chromosome has now arrived at the spindle poles. The cytoplasm divides, forming two haploid cells. All chromosomes are still duplicated.

Figure 18.12 Animated! **Meiosis is the mechanism by which the parental number of chromosomes is reduced by half (to the haploid number) for forthcoming gametes.** Only two pairs of homologous chromosomes are shown. Maternal chromosomes are shaded *purple*, and paternal ones *blue*.

Meiosis I



There is no DNA replication between the two nuclear divisions.

E Prophase II

A new spindle forms in each haploid cell. Microtubules have moved the centrioles to opposite ends of each cell. One chromatid of each chromosome becomes attached to one spindle pole, and its sister chromatid becomes attached to the opposite pole.

F Metaphase II

Microtubules from both spindle poles have assembled and disassembled in a tug-of-war that ended at metaphase II, when all chromosomes are positioned midway between the poles.

G Anaphase II

The attachment between sister chromatids of each chromosome breaks. Each is now a separate chromosome but is still attached to microtubules, which move it toward a spindle pole. Other microtubules push the poles apart. A cluster of unduplicated chromosomes ends up near each pole. One of each type of chromosome is present in each cluster.

H Telophase II

Four nuclei form as a new nuclear envelope encloses each cluster of chromosomes. After the cytoplasm divides, each of the resulting daughter cells has a haploid (*n*) number of chromosomes.

18.9 How Meiosis Produces New Combinations of Genes

- **Events that happen during meiosis explain why no person is genetically identical to either parent.**

Pieces of chromosomes may be exchanged

We know that genes are responsible for body structures and their functions, and most humans have roughly the same anatomy and physiology. Yet no one ever looks, or has a body that operates, exactly like his or her parents. Most of the variations in humankind we take for granted result from changes to chromosomes that occurred during meiosis, when germ cells were forming sperm in a father's testes or eggs in a mother's ovaries.

Some genetic variations come about during prophase I of meiosis. This is a time when parts of the chromosomes in gonad germ cells are rearranged. Remember that germ cells contain sets of homologous chromosomes, one set that came originally from a person's mother and a corresponding set from the father. These homologues therefore can be called "maternal" and "paternal" chromosomes and they carry genes for the same traits. During meiosis I, the two pairs of sister chromatids (a maternal pair and a paternal pair) line up close together, as in Figure 18.13*a*. It is as if the two are stitched together along their length. (The X and Y chromosomes get "stitched" at one end only.) This close alignment favors **crossing over**. In a crossover, nonsister chromatids break at the same places along their length and exchange corresponding segments. The X-shaped areas shown in Figure 18.13*e* are crossovers. Each segment in the exchange includes one or more genes.

The exchange of chromosome pieces is called **genetic recombination**. It leads to variation in the details of inherited traits because a gene may have several chemical forms. For example, as Section 19.1 describes more fully,

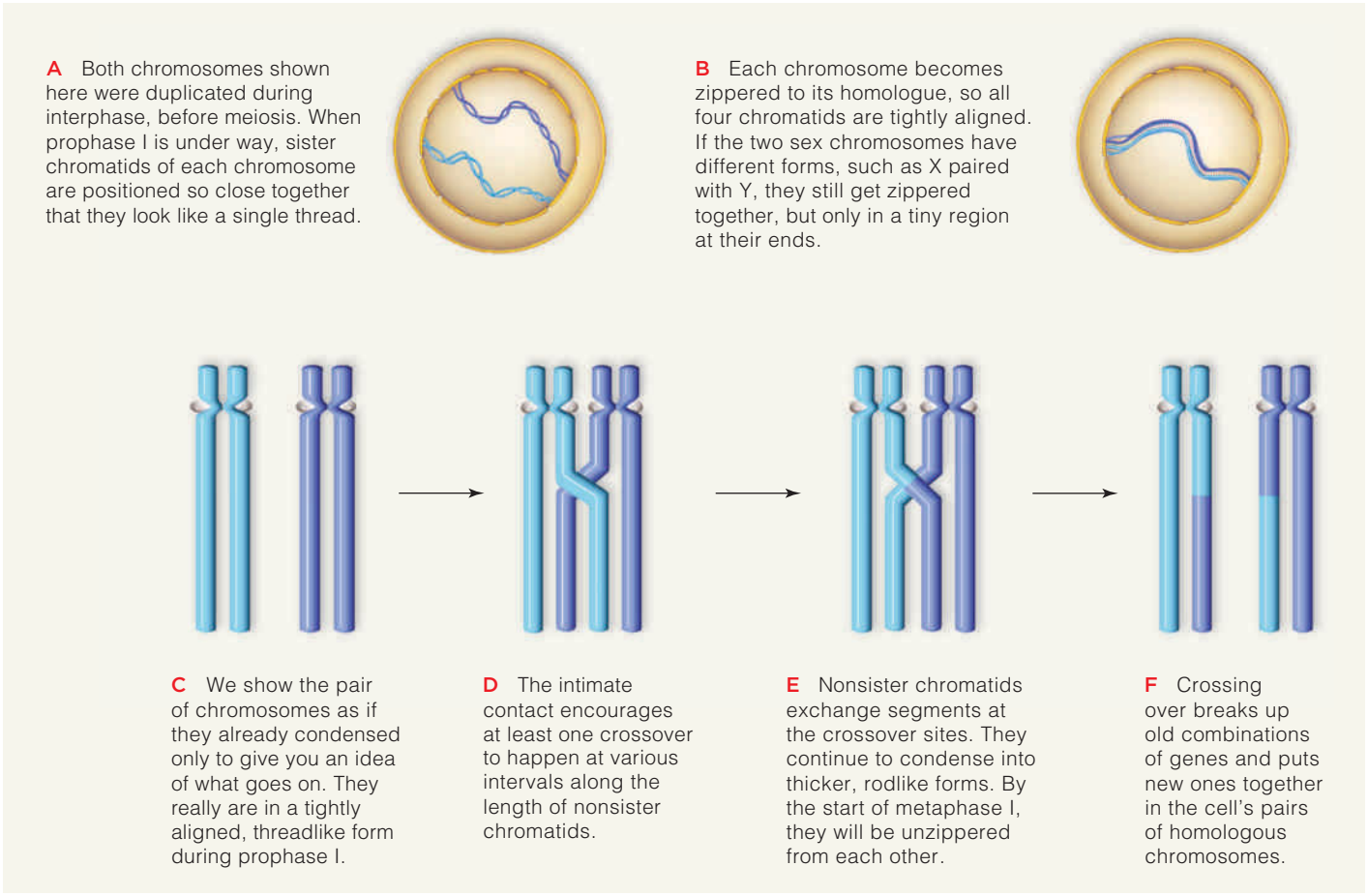


Figure 18.13 Animated! **During the first stage of meiosis, a process called crossing over may create new combinations of genes on the chromosomes in germ cells.** For clarity, this diagram of a cell shows only one pair of homologous chromosomes and one crossover. Here, the paternal chromosome is *blue* and its maternal homologue is *purple*.

the gene for earlobe shape has two forms (called alleles), one for attached earlobes and the other for detached earlobes. Often, particular forms of genes on one chromosome differ from corresponding ones on its homologue partner. When a crossover occurs between chromosomes in a germ cell, both suddenly have a slightly different version of their genes than they had before. If a "Mom" chromosome had the gene for attached earlobes and the "Dad" had the gene for detached earlobes, the situation may now be reversed.

Gametes also receive a random assortment of maternal and paternal chromosomes

As you know from looking at Figure 18.12 in Section 18.8, during metaphase I of meiosis the maternal and paternal chromosomes get lined up and tethered to the spindle in preparation for the formation of two new daughter cells. The chromosomes line up at random, making it highly unlikely that one daughter cell will receive only maternal chromosomes and the other will receive only paternal ones. In fact, odds are that there will always be a mix of maternal and paternal chromosomes in each cell that forms during meiosis. Figure 18.14 shows the possibilities when there are only three pairs of homologues. In this case, eight combinations (2^3) of maternal and paternal chromosomes are possible for the forthcoming gametes.

Of course, a human germ cell has a full 23 pairs of homologous chromosomes, not just three. So a grand total of 2^{23}, or 8,388,608, combinations of maternal and paternal chromosomes are possible every time meiosis in a germ cell produces a gamete! Are you beginning to see why striking mixes of traits can show up even in the same family?

During meiosis, each homologue normally is separated from its partner so that gametes receive only the required haploid set of chromosomes. This separation is called **disjunction**. As Chapter 20 describes, birth defects can result when this process does not occur as usual.

Take-Home Message

How does meiosis produce new combinations of genes in gametes?

- Crossing over of segments between a pair of homologous chromosomes creates new combinations of genes on the chromosomes.
- Meiosis moves maternal and paternal chromosomes into gametes at random. This random pattern creates new combinations of chromosomes in sperm and eggs, and children have varied combinations of their parents' traits.

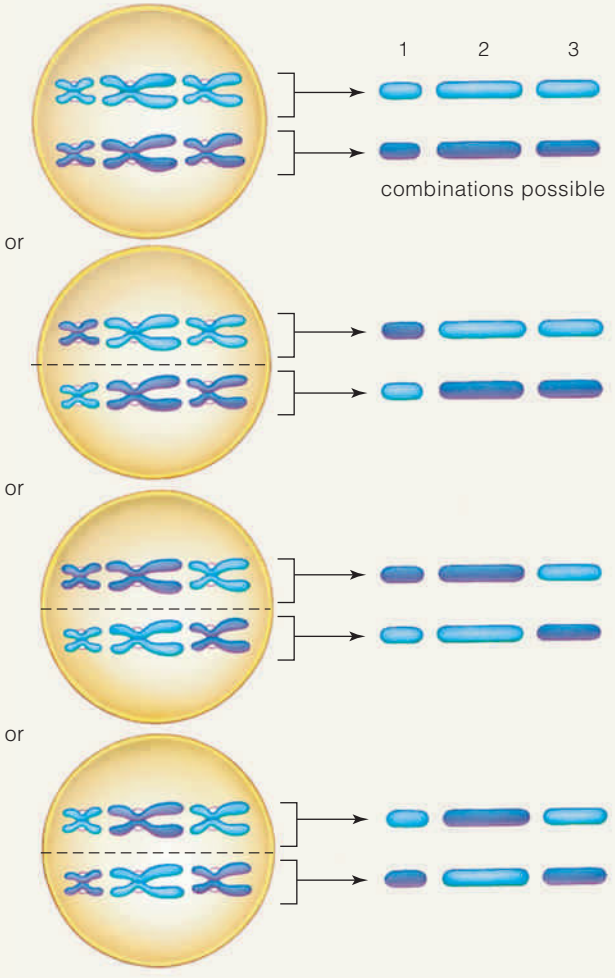


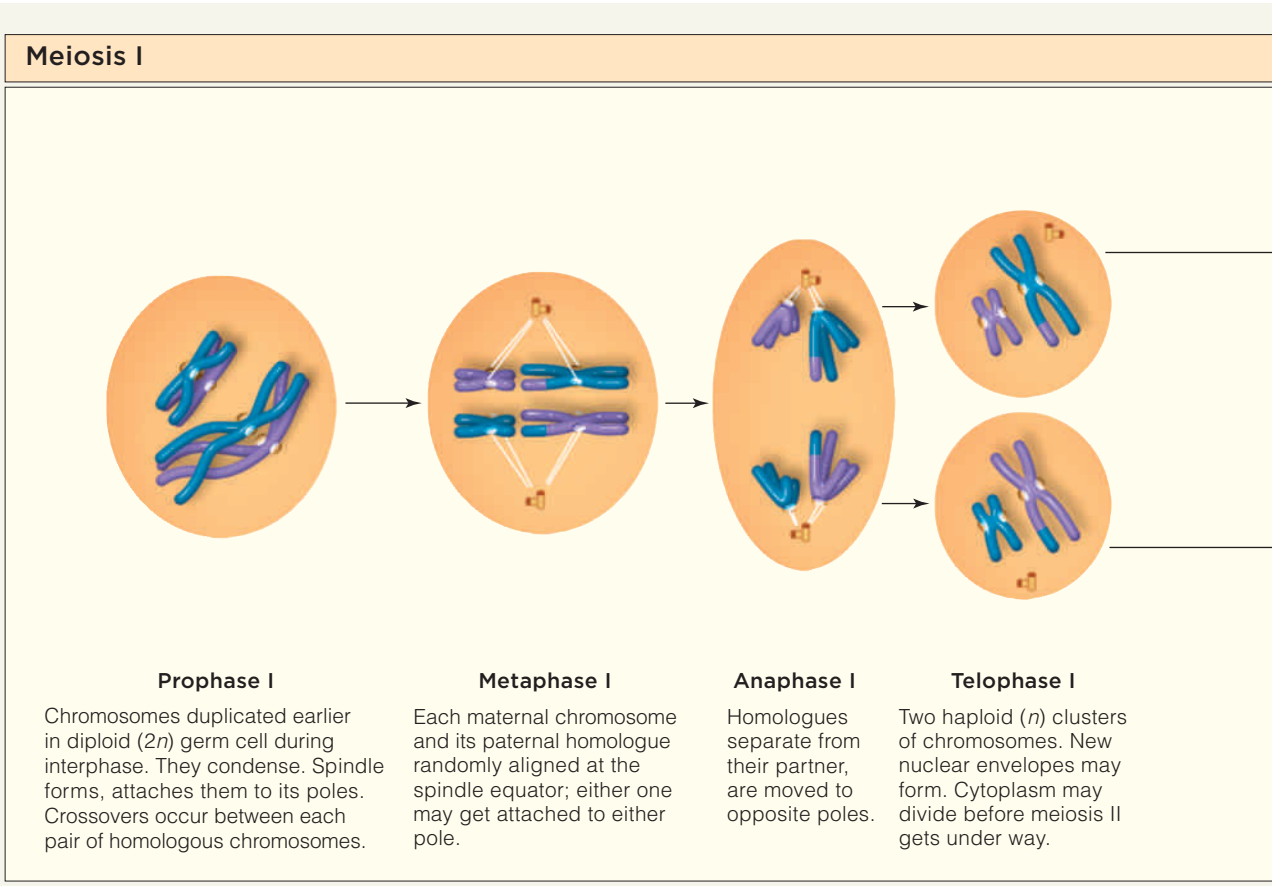
Figure 18.14 Animated! **Maternal and paternal chromosomes are assorted randomly into gametes.** The diagram shows possible outcomes of the random alignment of three pairs of homologous chromosomes at metaphase I of meiosis. Maternal chromosomes are *purple*; paternal ones *blue*.

18.10 Meiosis and Mitosis Compared

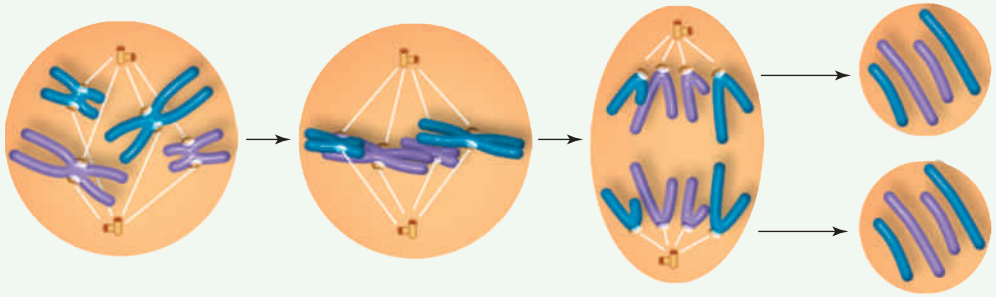
- **Miitosis occurs in somatic cells, while meiosis takes place in germ cells. The diagrams presented here summarize the similarities and key differences of these mechanisms.**

The end results of mitosis and meiosis differ in a crucial way (Figure 18.15). Mitosis produces genetically identical copies of a parent cell. Meiosis is an important source of genetic variation in the traits offspring will have.

Figure 18.15 Animated! **This diagram compares the similarities and differences between mitosis and meiosis.** As in other diagrams in this chapter, maternal chromosomes are *purple*, and paternal chromosomes are *blue*.



Mitosis



Prophase

Chromosomes duplicated earlier in diploid ($2n$) body cell, in interphase. They condense. A spindle forms; chromosomes attach to its poles.

Metaphase

All chromosomes aligned at the spindle equator.

Anaphase

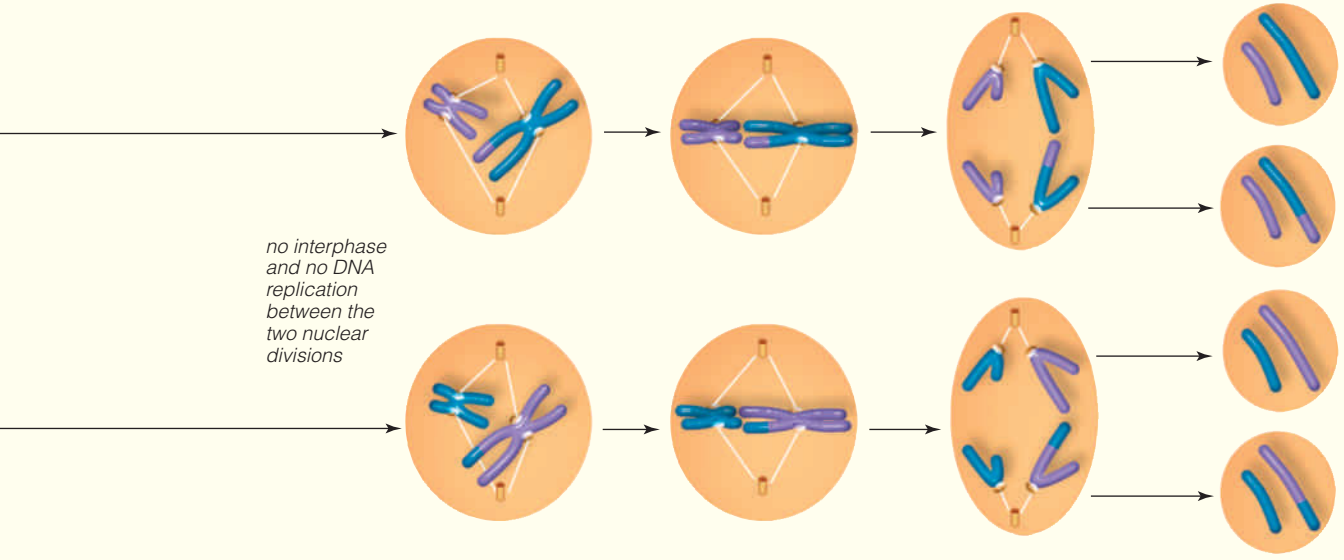
Sister chromatids of each chromosome moved to opposite spindle poles.

Telophase

Two diploid ($2n$) nuclei form. After the cytoplasm divides, there are two diploid body cells.

Meiosis II

no interphase and no DNA replication between the two nuclear divisions



Prophase II

All chromosomes still duplicated. New spindle forms in each nucleus, attaches chromosomes to spindle poles.

Metaphase II

All chromosomes aligned at the spindle equator.

Anaphase II

Sister chromatids of each chromosome moved to opposite spindle poles.

Telophase II

Four haploid (n) nuclei form. After the cytoplasm divides, haploid cells function as gametes or spores.

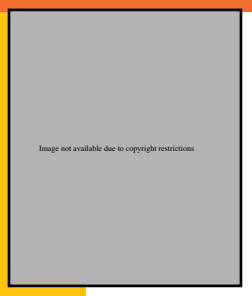
IMPACTS, ISSUES

Henrietta's Immortal Cells

HeLa cells divide aggressively and indefinitely. Since the 1970s they have been the foundation for decades of research on cancer and other health concerns. This information came as news to the family of Henrietta Lacks, who knew nothing of the use of their mother's cells for research for a quarter of a century.

How Would You Vote?

HeLa cells are sold all over the world by cell culture firms. Should the family of Henrietta Lacks (right) share in the profits of those sales? See CengageNOW for details, then vote online.



Summary

Section 18.1 In reproduction, a parent cell produces a new generation of cells, or parents produce a new individual. Reproduction is part of a life cycle, a recurring sequence in which individuals grow, develop, and reproduce. Each cell of a new generation must receive a copy of the parental DNA and enough cytoplasm to start up its own operation.

Human cells divide the cell nucleus by either mitosis or meiosis. Mitosis is the division mechanism in somatic cells—body cells that are not specialized to make gametes. It functions in growth and tissue repair. Meiosis divides the nucleus in germ cells, cells in the gonads that give rise to gametes.

A chromosome is a DNA molecule and its associated proteins. The sum of the chromosomes in a given cell type is the chromosome number. Human somatic cells have a diploid chromosome number of 46, or two copies of 23 types of chromosomes. Except for the sex chromosomes, pairs of homologous chromosomes are the same length and carry similar genes.

- Use the animation and interaction on CengageNOW to explore the structure of a chromosome.

Section 18.2 An unduplicated chromosome consists of one DNA molecule and proteins. A duplicated chromosome consists of two DNA molecules that are temporarily attached to each other as sister chromatids. When the nucleus divides, microtubules attach to a centromere on the paired chromatids. The microtubules are part of a spindle that moves chromosomes during nuclear division.

Section 18.3 The cell cycle begins when a new cell is produced and ends when that cell divides. The longest part of the cycle is interphase, which includes a growth stage (G1), when the cell roughly doubles the number of organelles and other components in its cytoplasm. In the S stage the cell's chromosomes are duplicated. There is also a final, short growth stage (G2). The duration of the cell cycle varies in different types of cells.

- Use the animation and interaction on CengageNOW to investigate the stages of the cell cycle.

Section 18.4 Mitosis maintains the diploid number of chromosomes in the two daughter nuclei (Figure 18.16). Division of the cytoplasm, called cytokinesis, occurs toward the end of mitosis or shortly afterward.

Section 18.5 Mitosis has four stages:

a. Prophase. Duplicated, threadlike chromosomes condense into rodlike structures; new microtubules start to assemble in organized arrays near the nucleus; they will form a spindle. The nuclear envelope disappears.

b. Metaphase. Spindle microtubules orient the sister chromatids of each chromosome toward opposite spindle poles. The chromosomes line up at the spindle equator.

c. Anaphase. Sister chromatids of each chromosome separate. Both are now independent chromosomes, and they move to opposite poles.

d. Telophase. Chromosomes become threadlike again and a new nuclear envelope forms around the two clusters of chromosomes. Mitosis is completed. Cytokinesis divides the cytoplasm; the result is two diploid cells.

- Use the animation and interaction on CengageNOW to explore what happens during each stage of mitosis.

Sections 18.7, 18.8 Meiosis reduces the total number of chromosomes in daughter cells. Two consecutive divisions of a germ cell cut the parental diploid chromosome number in half. Meiosis I distributes the pairs of homologous chromosomes. Meiosis II separates sister chromatids. The result, after cytokinesis, is four haploid cells (Figure 18.17).

- Use the animation and interaction on CengageNOW to explore what happens during each stage of meiosis, and learn how gametes form.

Section 18.9 Meiosis contributes to genetic variation. Crossing over during prophase I creates new combinations of genes in chromosomes. Random alignment of pairs of homologues at metaphase I results in new combinations of maternal and paternal traits.

- Use the animation and interaction on CengageNOW to learn more about how crossing over and other events during meiosis produce new combinations of genes on chromosomes.

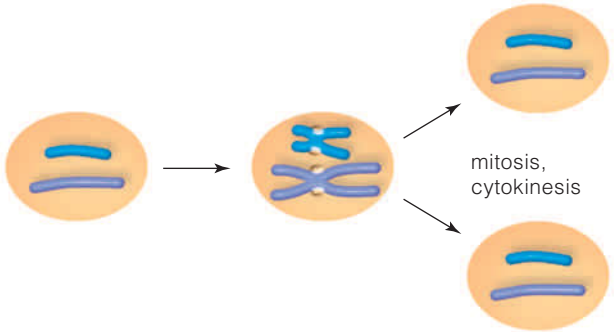


Figure 18.16 **Mitosis maintains the chromosome number of the parent cell.**

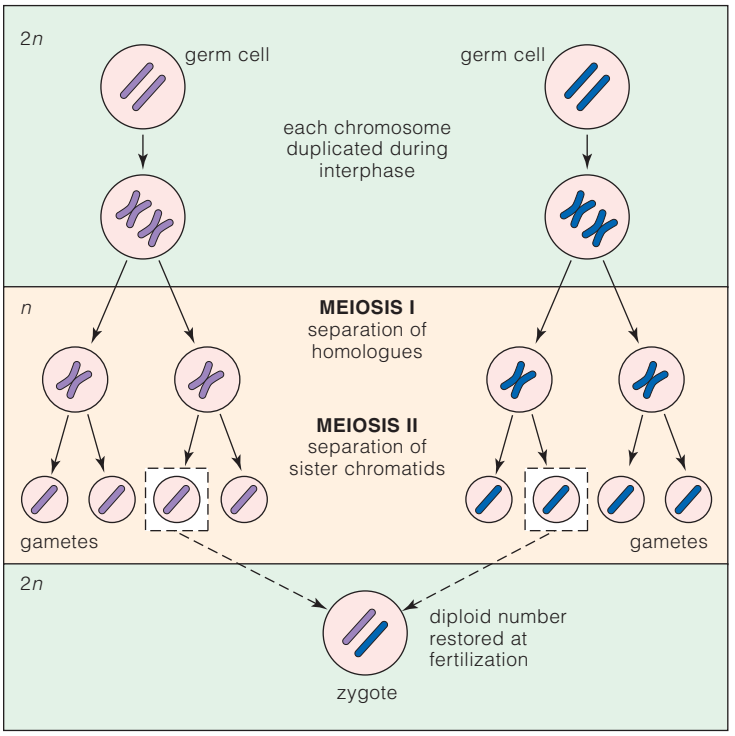


Figure 18.17 **Meiosis reduces the chromosome number by half.**

Review Questions

1. Define the two mechanisms by which chromosomes are allotted in dividing human cells. What is cytokinesis?
2. Define somatic cell and germ cell. Which type of cell can undergo mitosis?
3. What is a chromosome? What is the difference between a diploid cell and a haploid cell?
4. What are homologous chromosomes?
5. Name the four main stages of mitosis, and describe what happens in each stage.
6. In a paragraph, summarize the similarities and differences between mitosis and meiosis.

Self-Quiz *Answers in Appendix V*

1. DNA, packaged in chromosomes, is distributed to daughter cells by _____ or _____.
2. Each kind of organism contains a characteristic number of _____ in each cell; each of those structures is composed of a _____ molecule and proteins.
3. A pair of chromosomes that are similar in length and the traits they govern are called _____.
   a. diploid chromosomes
   b. mitotic chromosomes
   c. homologous chromosomes
   d. germ chromosomes
4. Somatic cells have a _____ number of chromosomes.
5. Interphase is the stage when _____.
   a. a cell ceases to function
   b. a germ cell forms its spindle
   c. a cell grows and duplicates its DNA
   d. mitosis takes place
6. After mitosis, each daughter cell contains genetic instructions that are _____ and _____ chromosome number of the parent cell.
   a. identical to the parent cell's; the same
   b. identical to the parent cell's; one-half the
   c. rearranged; the same
   d. rearranged; one-half the
7. All of the following are stages of mitosis *except* _____.
   a. prophase
   b. interphase
   c. metaphase
   d. anaphase
8. A duplicated chromosome has _____ chromatids.
   a. one b. two c. three d. four
9. Crossing over in meiosis _____.
   a. occurs between sperm DNA and egg DNA at fertilization
   b. leads to genetic recombination
   c. occurs only rarely
10. Because of the _____ alignment of homologous chromosomes during meiosis, gametes can end up with _____ mixes of maternal and paternal chromosomes.
    a. unvarying; different c. random; duplicate
    b. unvarying; duplicate d. random; different

11. Match stage of mitosis with the following key events.

____metaphase	a. sister chromatids separate and move to opposite poles
____prophase	b. chromosomes condense and a microtubular spindle forms
____telophase	c. chromosomes decondense, daughter nuclei re-form
____anaphase	d. chromosomes line up at a spindle equator

Critical Thinking

1. Normally you can't inherit both copies of a homologous chromosome from the same parent. Why? Assuming that no crossing over has occurred, how likely is it that one of your non-sex chromosomes is an exact copy of the same chromosome your maternal grandmother had? Explain your answer.
2. Suppose you have a way of measuring the amount of DNA in a single cell during the cell cycle. You first measure the amount during the G1 phase. At what points during the remainder of the cycle would you predict changes in the amount of DNA per cell?
3. Adam's maternal and paternal chromosomes have alternate forms of a gene that influences whether a person is right-handed or left-handed. One form says "right" and its partner says "left." Visualize one of his germ cells, in which chromosomes are being duplicated prior to meiosis. Visualize what happens to the chromosomes during anaphase I and II. (It might help to use toothpicks as models of the sister chromatids of each chromosome.) What fraction of Adam's sperm will carry the gene for right-handedness? For left-handedness?
4. Fresh out of college, Maria has her first job teaching school. When she goes for a pre-employment chest X-ray required by the school district, the technician places a lead-lined apron over her abdomen but not over any other part of Maria's body. The apron prevents electromagnetic radiation from penetrating into the protected body area. What cells is the lead shield designed to protect, and why?

EXPLORE ON YOUR OWN

Section 16.4 explains that oogenesis begins when a female is still a developing embryo.

In the immature eggs (primary oocytes) of a female embryo, meiosis I begins, but is arrested in prophase I. Meiosis I won't resume until the female undergoes puberty. From then until menopause, just before an egg is ovulated, it will undergo the remaining stages of meiosis I. As the egg is traveling down an oviduct, meiosis II begins. This stage also is arrested, in metaphase II. Only if the egg is fertilized will all the stages of meiosis finally be completed (Figure 18.18).

Knowing this sequence, you can calculate fairly accurately how long it took for the egg that helped make you to pass through all the stages of meiosis. You only need to know the month and year your mother was born and the month and year you were conceived (or born). As a starting point, remember that a female's primary oocytes form during the third month of embryonic development, about 6 months before birth. If you have siblings, do the same calculation for them.

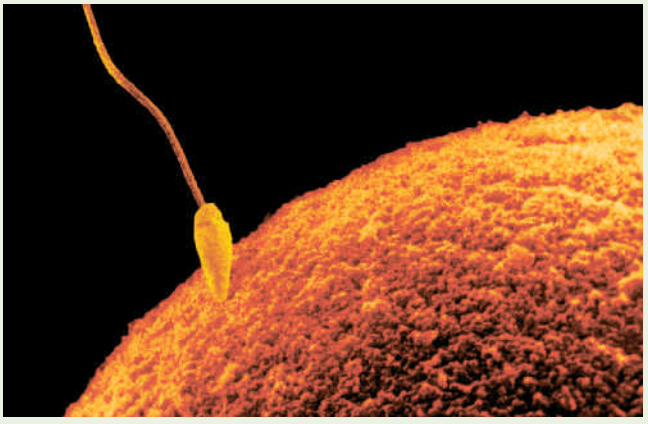


Figure 18.18 **This photograph shows an egg with a sperm that will penetrate and fertilize it—marking the end of meiosis in the egg and the beginning of bodily growth by mitosis.**

Introduction to Genetics

19

IMPACTS, ISSUES

The Color of Skin

HUMAN skin color can range from very pale to to very dark brown, sometimes in a single family. As Chapter 4 described, skin color comes from the pigment melanin made in skin cells called melanocytes. Some human traits are governed by single genes, but not this one. Geneticists have identified more than 100 genes that directly or indirectly influence the amount and chemical makeup of the melanin in an individual's skin cells—and therefore what the skin's natural shade will be.

This complex genetic picture explains why there is so much variety in human skin color. It also explains why Kian and Remee, the little girls shown at left, can have such different skin and hair colors even though they are fraternal twins. The girls' parents both are of mixed African and European descent, and each carries skin color genes common in both groups. As you will read in this chapter, chance determined the exact combinations of skin color genes each sister inherited.

With this chapter we begin to explore the topics of genes and the basic principles that govern inheritance. As you read, you will gain a much fuller understanding of the genetic events that ultimately gave you all your biological traits.

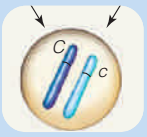
LINKS TO EARLIER CONCEPTS

- Your reading in this chapter will flesh out the concept of inheritance introduced at the beginning of this textbook (1.1).
- You will also draw on what you have learned about diploid and haploid sets of chromosomes (18.1) and how gametes form during meiosis (18.7).

How Would You Vote?

Traditionally, humans have been assigned to race categories based on physical attributes such as skin color, which have a genetic basis. Are twins such as Kian and Remee of different races? See CengageNOW for details, then vote online.

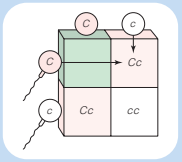
KEY CONCEPTS



Genes and Inheritance

Genes are segments of DNA that code for Inherited traits. Genes have different forms called alleles. A gamete carries one copy of each gene. Sections 19.1, 19.2

Probability Rules



Chance determines which sperm will fertilize which egg. This means that rules of probability apply to the inheritance of traits coded by a single gene. Section 19.3

Sorting Genes into Gametes

The paired copies of a gene on one chromosome are sorted into gametes independently of genes on other chromosomes. Section 19.4

Gene Effects

Genetic traits are not always predictable. Examples are traits determined by more than one gene, and instances in which one gene affects several traits. Sections 19.5, 19.6

19.1 Basic Concepts of Heredity

- **Genes provide the instructions for all human traits, including physical features and how body parts function. Each person inherits a particular mix of maternal and paternal genes.**
- **Link to Reproduction and the chromosome number 18.1**

Having read Chapter 18, you already know a bit about chromosomes. The following list and Figure 19.1 explain some basic concepts about the genes chromosomes carry.

1. **Genes** are units of information about specific traits and are passed from parents to offspring. Today we know that humans have about 21,500 genes, and that genes are chemical instructions for building proteins. Each gene has a specific location, or **locus**, on a given chromosome.
2. Diploid cells have two copies of each gene, on pairs of homologous chromosomes.
3. All copies of a gene deal with the same trait, but their information about it may vary a little due to chemical differences between them. Each version of the gene is called an **allele**. Contrasting alleles produce much of the variation we see in traits, such as whether a person has attached or detached earlobes (Figure 19.2).
4. If the two copies of a gene are identical alleles, this is a **homozygous condition** (*homo:* same; *zygo:* joined together). If the two allele copies are different, this is a **heterozygous condition** (*hetero:* different).
5. An allele is **dominant** when its effect on a trait masks that of any **recessive** allele paired with it. A dominant allele is represented by an uppercase letter, a recessive one by a lowercase (for instance, *A* and *a* or *C* and *c*).
6. Someone who is *homozygous dominant* has a pair of dominant alleles (*AA*) for the trait being studied. A *homozygous recessive* individual has a pair of recessive alleles (*aa*). A *heterozygous* person has a pair of nonidentical alleles (*Aa*).
7. The alleles a person inherits are his or her **genotype**. Observable functional or physical traits, such as attached earlobes, are the **phenotype** (Table 19.1).

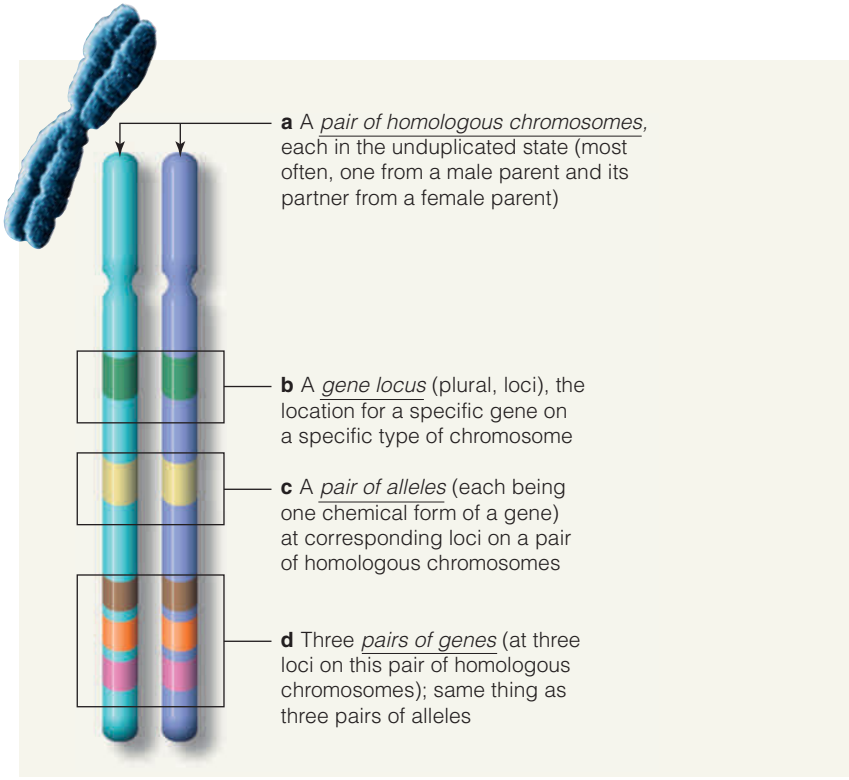


Figure 19.1 Animated! This diagram illustrates a few basic genetic terms.

Figure 19.2 Many genetic traits have dominant and recessive forms. (**a**) Actor Tom Cruise has attached earlobes. (**b**) Actress Joan Chen's are detached. The detached version is dominant. So are the alleles for long eyelashes and flat feet, among other human traits.

TABLE 19.1 Genotype and Phenotype Compared

Genotype	Described as	Phenotype
EE	homozygous dominant	detached ear lobe
Ee	heterozygous (one of each allele; dominant form of trait observed)	detached ear lobe
ee	homozygous recessive	attached earlobe

Take-Home Message

What are genes?

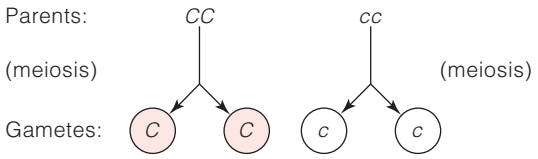
- Genes are units of information about traits.
- Different versions of a gene are called alleles.
- A person inherits two copies of each gene, one on each member of a pair of homologous chromosomes.
- If the two inherited alleles of a gene are identical, we say the person is homozygous for the trait. If the two are different, the person is heterozygous for the trait.

19.2 One Chromosome, One Copy of a Gene

- **We inherit pairs of genes (alleles) on pairs of chromosomes, but a gamete receives only one gene from each pair.**
- **Links to Stages of meiosis 18.7, 18.8**

For geneticists working with nonhuman organisms, a "monohybrid" experiment (*mono-* means one) is one way to learn more about the genotypes of their test subjects. In this kind of experiment, the two parents have different alleles for the gene being studied. Although a scientist can't ethically do genetic experiments on human beings, monohybrid matings do occur naturally and they show patterns of inheritance at work.

Consider, for example, the "dimple" in actor Viggo Mortenson's chin, a trait called a chin fissure (Figure 19.3). The configuration of a person's chin is governed by a gene that has two allele forms. One allele, which calls for a chin fissure (actually an indentation in the skin), is dominant when it is present. We can use *C* to represent this allele. The recessive allele, which codes for a smooth chin, is *c*. The diagram below shows the genotypes gametes can have when one parent is homozygous for the *C* form of the gene and has a chin fissure, and the other is homozygous for the *c* form and has a smooth chin. The *CC* parent's gonads make only *C* gametes while the *cc* parent makes only *c* gametes:



Each gamete gets only one allele for the trait because each gamete has only one copy of each chromosome. This process was described in Section 18.7, and Figure 19.4 will remind you how it works. To summarize what the diagram shows, when meiosis separates homologous chromosomes—as it must do to reduce the diploid number of chromosomes to the haploid number—the pairs of alleles on those chromosomes also are separated and each one ends up in a different gamete. This separation of gamete pairs is called **segregation**.

Take-Home Message

Why does each gamete have only one copy of each gene?

- The two copies of each gene in a diploid organism separate (segregate) from each other during meiosis in germ cells. Each copy ends up in a different gamete. As a result, each gamete contains only one copy of each gene.

Figure 19.3 The trait called a chin fissure arises from one allele of a gene. (**a**) Actor Viggo Mortensen received a gene that influences this trait from each of his parents. At least one of those genes was dominant. (**b**) What Mr. Mortensen's chin might have looked like if he had inherited identical alleles for "no chin fissure" instead.

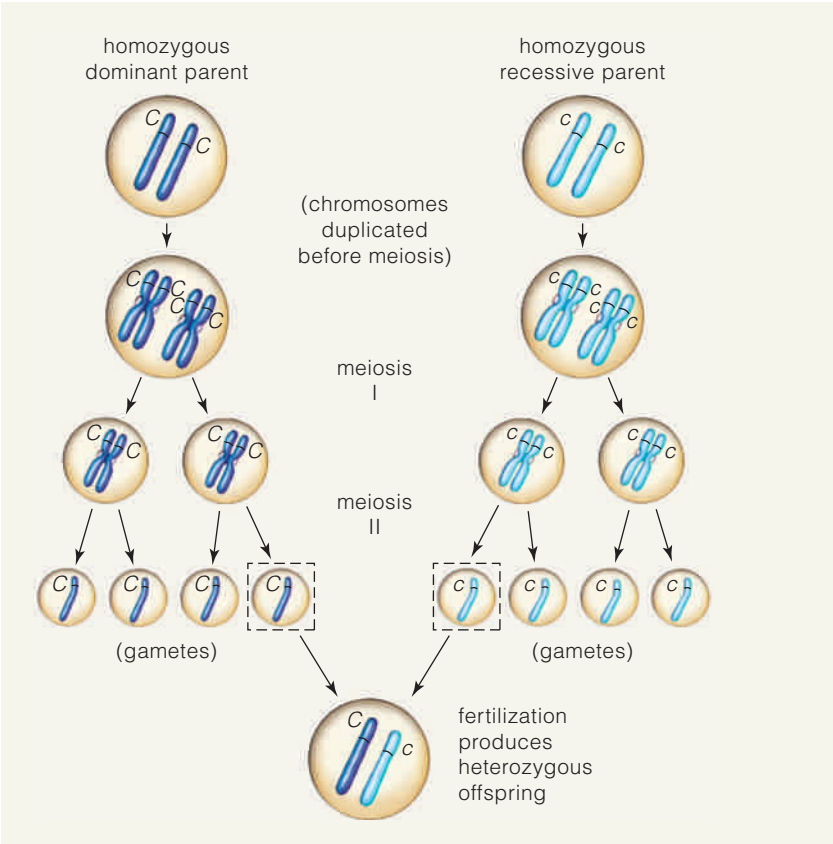


Figure 19.4 Animated! Each pair of gene alleles is separated and the two alleles end up in different gametes. Due to this segregation, two parents that are each homozygous for a different version of a trait will have only offspring who are heterozygous for that trait.

19.3 Genetic Tools: Testcrosses and Probability

- **When potential parents are concerned about passing a harmful trait to a child, genetic counselors must try to predict the likely outcome of the mating.**

Geneticists and genetic counselors are very concerned about **probability**—a measure of the chance that some particular outcome will occur. Probability is a factor in the inheritance of single-gene traits. A bit like a lottery, that chance depends on the number of possible outcomes.

To begin to get a feel for how probability works, let's again use the chin fissure trait as our example. Each child will inherit a pair of differing alleles for the trait, one from each homozygous parent. The children will thus each be heterozygous for the chin genotype, or *Cc*. Because *C* is dominant, each child will have a chin fissure.

Suppose now that one of the *Cc* children grows up and has a family with another *Cc* person. Because half of each parent's gametes (sperm or eggs) are *C* and half are *c* (due to segregation at meiosis), four outcomes are possible every time a sperm fertilizes an egg:

Possible event:	Probable outcome:	
sperm *C* unites with egg *C*	1/4 *CC* offspring	chin fissure
sperm *C* unites with egg *c*	1/4 *Cc* (or 1/2 *Cc*)	chin fissure
sperm *C* unites with egg *c*	1/4 *Cc* (or 1/2 *Cc*)	chin fissure
sperm *c* unites with egg *c*	1/4 *cc*	smooth chin

A Punnett square can be used to predict the result of a genetic cross

Figure 19.5 shows how to construct a **Punnett square**—a grid for determining the probable outcome of genetic crosses. In the current example, there is a 75 percent chance (three our of four) that a child from a cross between two *Cc* parents will have at least one dominant *C* allele and a chin fissure. When the first generation parents are homozygous for different alleles (*CC* and *cc*), this probable ratio turns up (in theory) in the second generation (Figure 19.6).

The rules of probability apply to crosses because fertilization is a chance event. It is expressed as a number between zero and one that expresses the likelihood of a particular event. For example, an event with a probability of one will always occur and an event with a probability of zero will never occur. As you might guess, an event that has a probability of one-half (or 50 percent) is likely to occur in about half of all situations (Figure 19.7).

Having a chin fissure doesn't affect a person's health. However, a fair number of genetic disorders, including cystic fibrosis and sickle-cell anemia, result from single-gene defects and so follow the laws of probability. Chapter 20 looks more closely at genetic disorders. For the moment, two ideas are important:

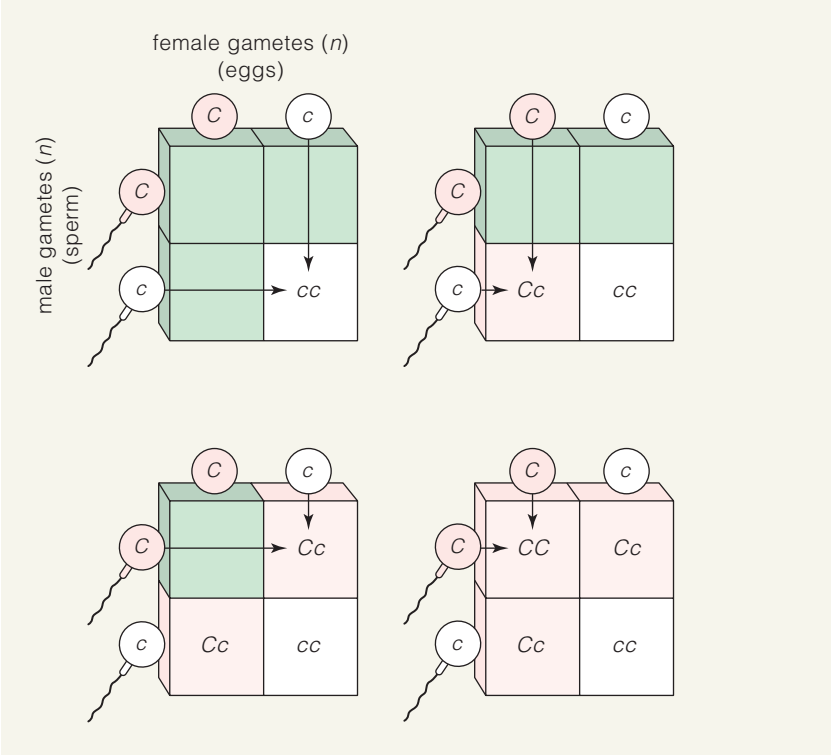


Figure 19.5 Animated! Making a Punnett square is one way to determine the likely outcome of a genetic cross. Here the cross is between two heterozygous individuals. Circles are gametes. Letters represent gene alleles. Genotypes of the resulting offspring are inside the squares.

1. The most probable outcome doesn't have to occur. For instance, it's common to see families in which the parents have produced a string of boys or girls when probability says that parents with two or more children will have equal numbers of girls and boys. Predicted ratios usually only turn up with a large number of events. You can test this for yourself by flipping a coin. Probability predicts that heads and tails should each come up about half the time, but you may have to flip the coin a hundred times to end up with a ratio close to 1:1.
2. In a given genetic situation, *probability doesn't change*. The chance that a certain genotype will occur—say, a baby with cystic fibrosis—is the same for every child no matter how many children a couple has. Based on the parents' genotypes, if the probability that a child will inherit a given genotype is one in four, then each child of those parents has a one-in-four (25 percent) chance of inheriting the genotype. If the parents have three children without the trait, the fourth child still has only a one-in-four chance of inheriting it.

A testcross also can reveal genotypes

Until the advent of high-tech genetic analysis, a **testcross** was used to learn the genotype of a (nonhuman) organism. In this method, an individual with an unknown genotype is crossed with an individual that is homozygous recessive for the trait being studied (say, it is *aa*). Then the phenotypes of the offspring are observed.

If all offspring have a dominant form of the trait, the "mystery" parent's genotype must include at least one dominant allele (the parent must be *Aa* or *AA*). If some offspring have the dominant phenotype and some have the recessive one, then the parent with the unknown genotype must be a heterozygote, or *Aa*.

Similar situations can shed light on the genotype of a human parent. Suppose that a woman has smooth cheeks and her husband has dimpled cheeks. "No dimples" is a recessive trait, so the woman is *dd*. If a child is born with no dimples, then the father must be a heterozygote for this trait, with a genotype of *Dd*. That is the only way he could himself have dimples and also father a *dd* child. If, on the other hand, the child has dimples, the father can be either *DD* or *Dd*. If he is *Dd*, the probability that he will have a dimpled child is 1/2, a 50–50 chance every time. If he were *DD*, every child of his would have dimples.

Take-Home Message

How does probability affect inheritance?

- Probability applies to the inheritance of single-gene traits.
- If the genotypes of parents are known, it is possible to establish a potential child's chances for inheriting a particular genotype and thus for having a particular phenotype (trait).
- Observing traits in offspring also can help reveal the genotypes of parents.

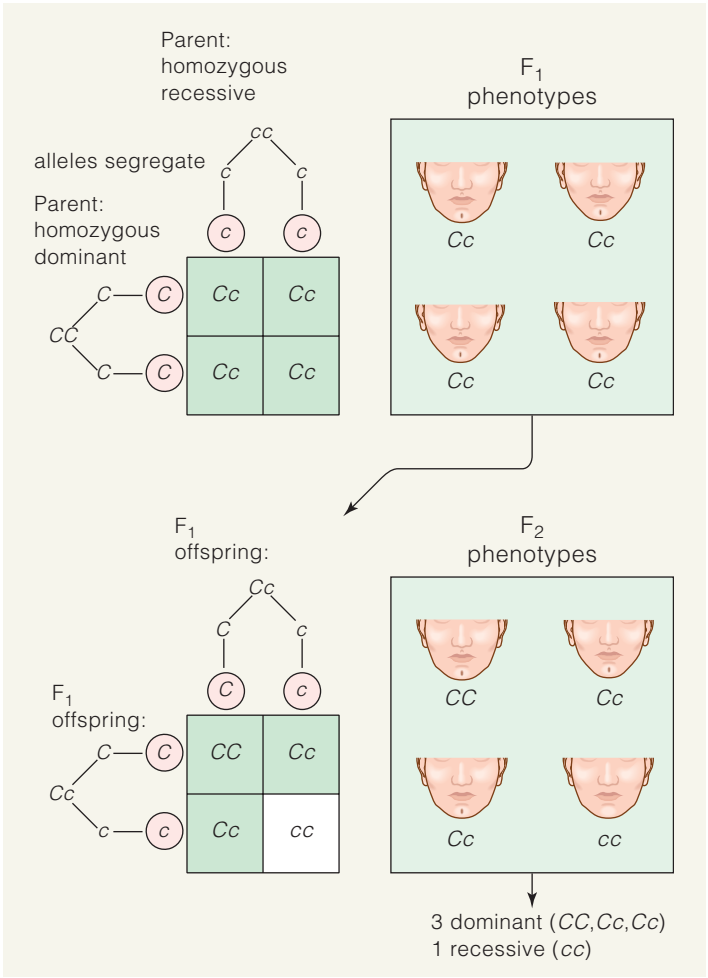


Figure 19.6 Animated! **A different set of genetic results is possible in the second generation after a monohybrid mating.** Notice that the dominant-to-recessive ratio is 3:1 for the second generation of offspring.

How to Calculate Probability

Step 1. Actual genotypes of parental gametes

In the cross *Cc* × *Cc*, gametes have a 50–50 chance of receiving either allele (*C* or *c*) from each parent. Said another way, the probability that a particular sperm or egg will be *C* is 1/2, and the probability that it will be *c* is also 1/2:

probability of *C*: 1/2

probability of *c*: 1/2

Step 2. Probable genotypes of offspring

Offspring receive one allele from each parent. Three different combinations of alleles are possible in this cross. To figure the probability that a child will receive a particular allele combination, simply multiply the probabilities of the individual alleles:

probability of *CC*: 1/2 × 1/2 = 1/4

probability of *Cc*: 1/2 × 1/2 = 1/4

probability of *cC*: 1/2 × 1/2 = 1/4 } 1/2

probability of *cc*: 1/2 × 1/2 = 1/4

Step 3. Probable phenotypes

Chin fissure: (*CC*,*Cc*,*cC*) 1/4 + 1/4 + 1/4 = 3/4

Smooth chin: (*cc*) 1/4

Figure 19.7 **Simple multiplication lets you figure the probability that a child will inherit alleles for a particular phenotype.**

19.4 How Genes for Different Traits Are Sorted into Gametes

- **When we consider more than one trait, we see that the gene for each trait is inherited independently of the gene for other traits.**
- **Links to Meiosis 18.8, Crossing over 18.9**

Section 19.2 explained how segregation separates the pairs of gene alleles for a single trait so that only one allele of each pair ends up in forming sperm or eggs. It also is important to understand how people inherit genes for different traits. Among other uses, such knowledge can help explain the genetic basis for some disorders. For example, is someone who inherits the faulty gene that causes hemophilia likely to also have a gene for color blindness? As you will read later on, the answer in that case is yes, because sometimes certain genes on the same chromosome are closely linked. Crossing over doesn't often separate them, so in general they are inherited together. Otherwise, however, we inherit each of our traits independently of all others.

The reason most traits are inherited independently is a mechanism called **independent assortment** that occurs during meiosis. As you can see in Figure 19.8, there are two ways the two members of each pair of homologous parent chromosomes can line up before the pairs become separated. Exactly how each lines up is a random process. This means that a given chromosome and its genes may end up in any of eight gametes—and the same rule applies to all the parent chromosomes. As a result, meiosis can yield gametes having all the possible combinations of parental genes. Adding to this the fact that which sperm fertilizes which egg is random makes it easy to understand why we see so much variety in the mix of traits we humans have.

To get an idea of how independent assortment works, let's look at a case in which two traits, the chin fissure and cheek dimples, are inherited. As with earlier examples, there are two contrasting alleles of each gene, one dominant and one recessive. The dominant alleles are *C* for a chin fissure and *D* for cheek dimples and *c* and *d* for recessive forms of the genes. Let's also say that both parents are heterozygous for both traits. That is, they are both *CcDd*. As a result, they can each produce equal proportions of four types of gametes:

1/4 *CD* 1/4 *Cd* 1/4 *cD* 1/4 *cd*

A Punnet square can show the probabilities that a child will inherit a particular combination of single-gene traits

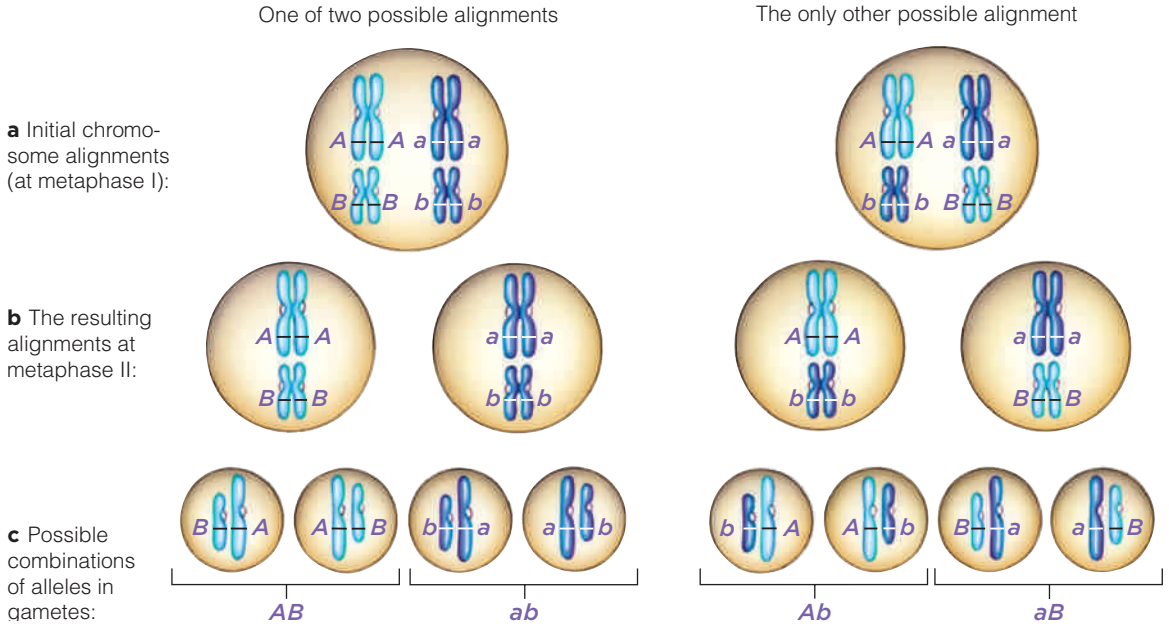


Figure 19.8 **In independent assortment chromosomes and the genes they carry are moved at random into forming gametes.**

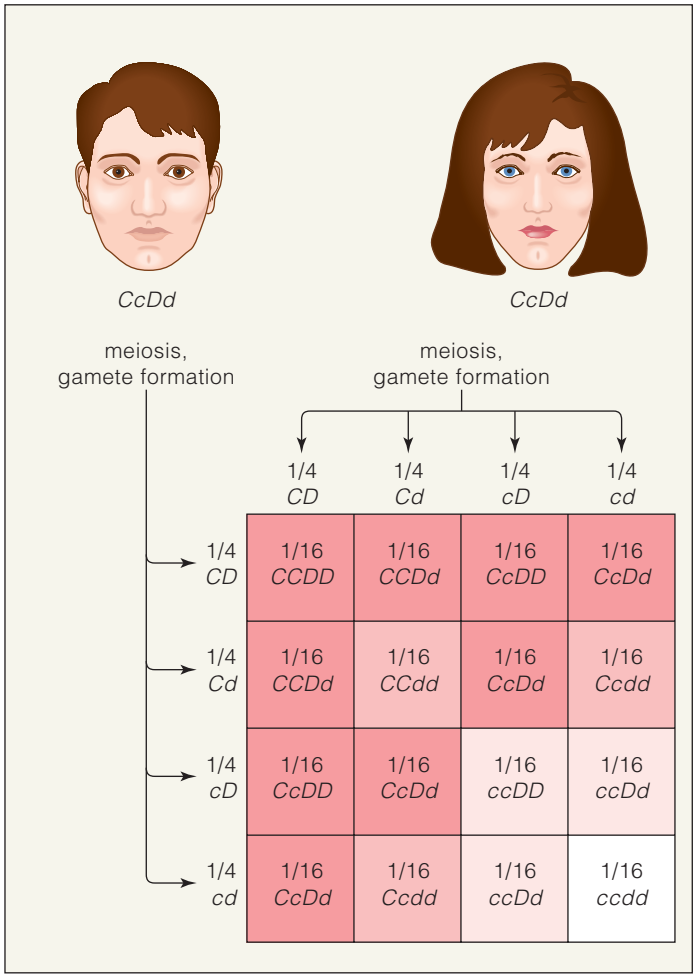


Figure 19.9 Animated! Tracking two traits shows the results of independent assortment. Both parents are heterozygous for both genes. Rules of probability predict that certain combinations of phenotypes among offspring of this type of cross occur in a 9:3:3:1 ratio, on average.

Probability in a Mating Where Both Parents Are Heterozygous at Two Loci

A dihybrid cross considers two traits. If both parents are heterozygous for both traits, a dihybrid cross produces the following 9:3:3:1 phenotype ratio (Figure 20.9):

9/16 or 9 chin fissure, dimples

3/16 or 3 chin fissure, no dimples

3/16 or 3 smooth chin, dimples

1/16 or 1 smooth chin, no dimples

Individually, these phenotypes have the following probabilities:

probability of chin fissure (12 of 16) = 3/4
probability of dimples (12 of 16) = 3/4
probability of smooth chin (4 of 16) = 1/4
probability of no dimples (4 of 16) = 1/4

To figure the probability that a child will show a particular *combination* of phenotypes, multiply the probabilities of the individual phenotypes in each possible combination:

Trait combination		Probability
Chin fissure, dimples	3/4 × 3/4	9/16
Chin fissure, no dimples	3/4 × 1/4	3/16
Smooth chin, dimples	1/4 × 3/4	3/16
Smooth chin, no dimples	1/4 × 1/4	1/16

Figure 19.10 Probability rules apply to independent assortment.

(Figure 19.9). Simple multiplication (four kinds of sperm times four kinds of eggs) tells us that sixteen different gamete unions are possible when each parent is heterozygous for the two genes in question. Notice that when such individuals mate, there are nine possible ways for gametes to unite that produce a chin fissure and dimples, three for a chin fissure and no dimples, three for a smooth chin and dimples, and one for a smooth chin and no dimples. The probability of any one child having a chin fissure and dimples is 9/16; a chin fissure and no dimples, 3/16; a smooth chin and dimples, 3/16; and a smooth chin and no dimples, 1/16.

Figure 19.10 shows how to calculate the probability that a child will inherit genes for a particular set of two traits on different chromosomes.

Take-Home Message

How are genes for different traits sorted into gametes?

- Usually, the two members of each pair of homologous chromosomes are assorted into gametes independently of how other chromosome pairs are sorted. This inheritance pattern is called independent assortment.
- As a result of independent assortment, the individual gene alleles on chromosomes also are sorted into gametes without regard to which other genes the gamete may get.
- As a result of independent assortment, the probability is high that gametes (sperm and eggs) will carry every possible combination of parental genes.

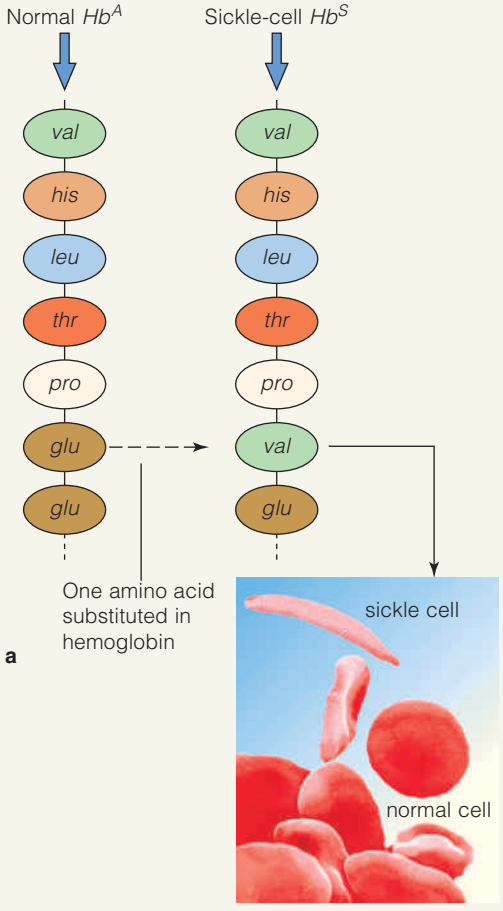
19.5 Single Genes, Varying Effects

- **Some traits have clearly dominant and recessive forms. For most traits, however, the story is not so simple.**
- **Links to Red blood cells 8.1, ABO blood groups 8.4**

Section 19.1 noted that genes are chemical instructions for building proteins. A gene is "expressed" when its instructions are carried out and the cell makes the protein. In some cases, the expression of a gene leads to a single phenotype, or observable trait. Usually, however, the genetic underpinning of traits is more complicated.

One gene may affect several traits

Expression of a gene at just a single locus (location) on a chromosome may affect two or more traits in positive or negative ways. This wide-ranging effect of a single gene is called **pleiotropy** (ply-AH-trow-pee, after the Greek *pleio-*, meaning "more," and *-tropic*, meaning "to change"). Much of what researchers have learned about how genes function has come from studies of genetic diseases. An example is **sickle-cell anemia**, which was introduced in the discussion of malaria in Chapter 8. This disabling and painful disease arises when a person is homozygous for a



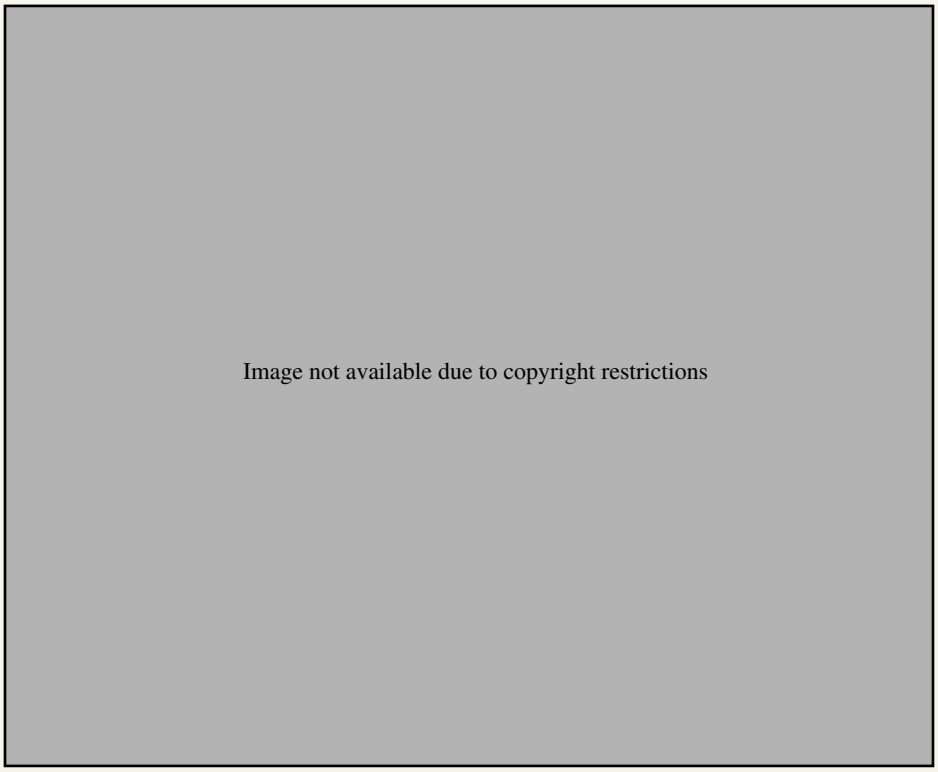


Figure 19.11 Animated! **A single genetic change leads to the many physical effects of sickle-cell anemia.** Part (**a**) shows how an incorrect amino acid has been substituted in the chain of amino acids making up the hemoglobin protein. The inset shows how the shape of a sickled red blood cell differs from that of a normal red blood cells. (

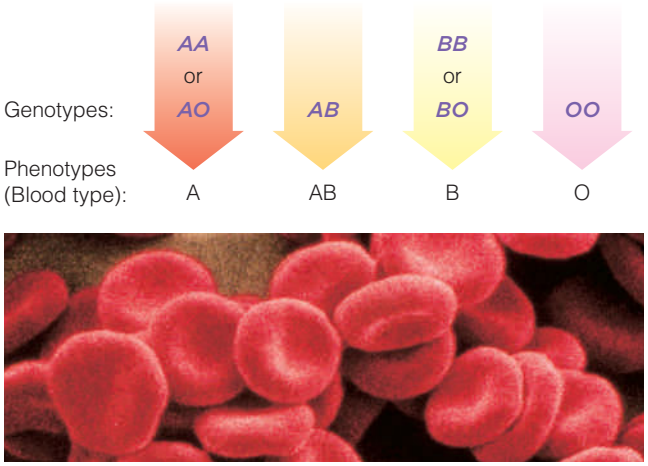


Figure 19.12 **There are several possible allele combinations for ABO blood types.**

recessive allele. The normal allele, Hb^A, has instructions for building normal hemoglobin, the oxygen-transporting protein in red blood cells. When a person inherits two copies of the recessive mutant allele, Hb^S, he or she develops sickle-cell anemia.

Section 8.7 described how red blood cells, which normally are biconcave disks, take on a sickle shape when the oxygen content of blood falls below a certain level. The sickled cells clump in blood capillaries and can rupture. The flow of blood can be so disrupted that the person's oxygen-deprived tissues are severely damaged (Figure 19.11). Homozygotes for the mutated hemoglobin gene (Hb^S/Hb^S) often die relatively young. Heterozygotes (Hb^A/Hb^S), on the other hand, have *sickle-cell trait*. They generally have few symptoms because the one Hb^A allele provides enough normal hemoglobin to prevent red blood cells from sickling.

During a crisis, sickle-cell anemia patients may receive blood transfusions, oxygen, antibiotics, and painkilling drugs. There is evidence that the food additive butyrate can reactivate "dormant" genes responsible for fetal hemoglobin, an efficient oxygen carrier that normally is produced only before birth. For this reason, some states require hospitals to screen newborn infants for sickle-cell anemia so that appropriate action can begin right away.

In codominance, more than one allele of a gene is expressed

As you now know, people who are heterozygous for a trait have two contrasting alleles for that trait. Usually, one is dominat and one is recessive. In some cases, however, *both* alleles are expressed. We see a classic example of this **codominance** in people who are heterozygotes for alleles that confer A and B blood types (Figure 19.12). Remember from Section 8.4 that the alleles you carry for the *ABO* gene determines your blood type. The gene's "job" is to provide instructions for making an enzyme that helps build a polysaccharide (a sugar) on the surface of red blood cells. Each *ABO* allele provides slightly different instructions for building the sugar. The sugar in turn gives each person's red blood cells their particular chemical identity—which we call blood type.

Two *ABO* alleles, *IA* and *IB*, are codominant when paired with each other. Someone who inherits them has type AB blood. A third allele, *O*, is recessive. When paired with either *IA* or *IB*, the *O*'s effect is masked. A person who has it plus an *IA* allele has type A blood, while someone who has it paired with the *IB* allele has type B blood. Someone who inherits two *O*s has type O blood. A gene that has three or more alleles is called a **multiple allele system**. There are many such human genes.

Take-Home Message

What are some ways a single gene may have several effects?

- One gene may affect two or more traits, a phenomenon called pleiotropy. The effects may not be simultaneous, but may have repercussions over time as one altered trait changes another trait and so on, as in sickle-cell anemia.
- In some cases contrasting alleles for a trait are codominant—that is, both are expressed.
- Some genes have more than two alleles. These multiple allele systems include the alleles for the ABO blood group.

19.6 Other Gene Effects and Interactions

- **Many phenotypes, such as eye color, can't be predicted with certainty. Biologists have uncovered several underlying causes for these variations.**

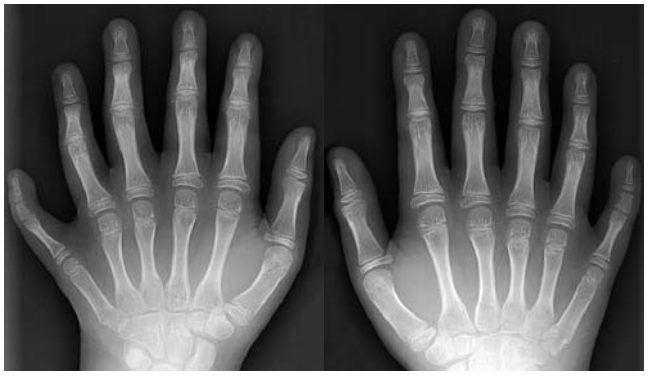
A gene or multiple allele system may have an all-or-nothing effect on a trait. Either you have dimples or Type A blood or you don't. But in other cases, the expression of a gene varies due to gene interactions or nongenetic factors in the environment.

The term **penetrance** refers to the probability that someone who inherits an allele will have the phenotype associated with it. For example, the recessive allele that causes cystic fibrosis is completely penetrant. A full 100 percent of people who are homozygous for it develop CF. The dominant allele for having extra fingers or toes (called *polydactyly*) is incompletely penetrant. Some people who inherit it have the usual ten digits, while others have more (Figure 19.13). *Campodactyly* is caused by the abnormal attachment of muscles to bones of the little finger. Some people who inherit the allele for it have a stiff, bent little finger on both hands. Others have a bent pinkie on one hand only. When an allele can produce a range of phenotypes, its expression is said to be "variable." The campodactyly allele also is incompletely penetrant. In some people who inherit it, the trait doesn't show up.

Polygenic traits come from several genes combined

Polygenic traits result from the combined expression of several genes. For example, like skin color, eye color is the cumulative result of many genes involved in the stepwise production and distribution of melanin. Black eyes have abundant melanin in the iris. Dark-brown eyes have less melanin, and light-brown or hazel eyes have still less (Figure 19.14). Green, gray, and blue eyes don't have green, gray, or blue pigments. Instead, they have so little melanin that we readily see blue wavelengths of light being reflected from the iris. Hair color probably also results from the interactions of several genes. This explains our real-world observation that there is lots of natural variation in human hair color.

For many polygenic traits a population as a whole may show **continuous variation**. That is, its members show a range of continuous, rather than incremental, differences in some trait. Continuous variation is especially evident in



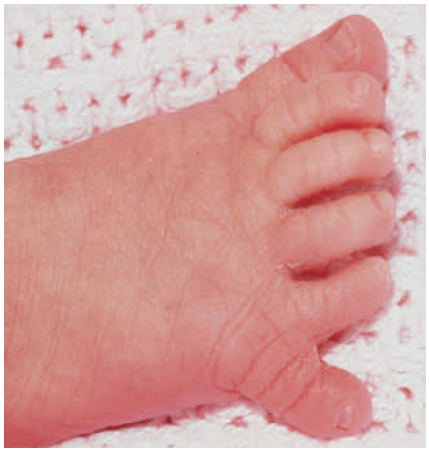


Figure 19.13 People with polydactyly have extra digits on their hands or feet. Usually the extra digits are duplicates. These X-rays reveal two "middle" fingers on each hand. The photograph shows the same pattern with a baby's toes.

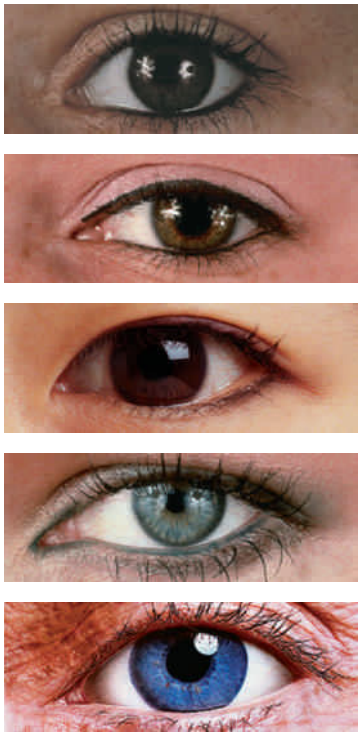
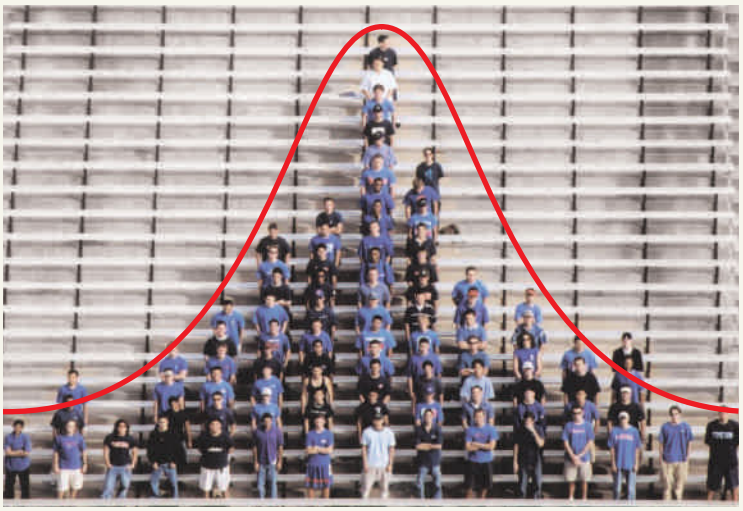


Figure 19.14 Eye color is just one of many human polygenic traits. Alleles of more than one gene interact to produce and deposit melanin, the pigment that helps color the eye's iris (and skin, too).



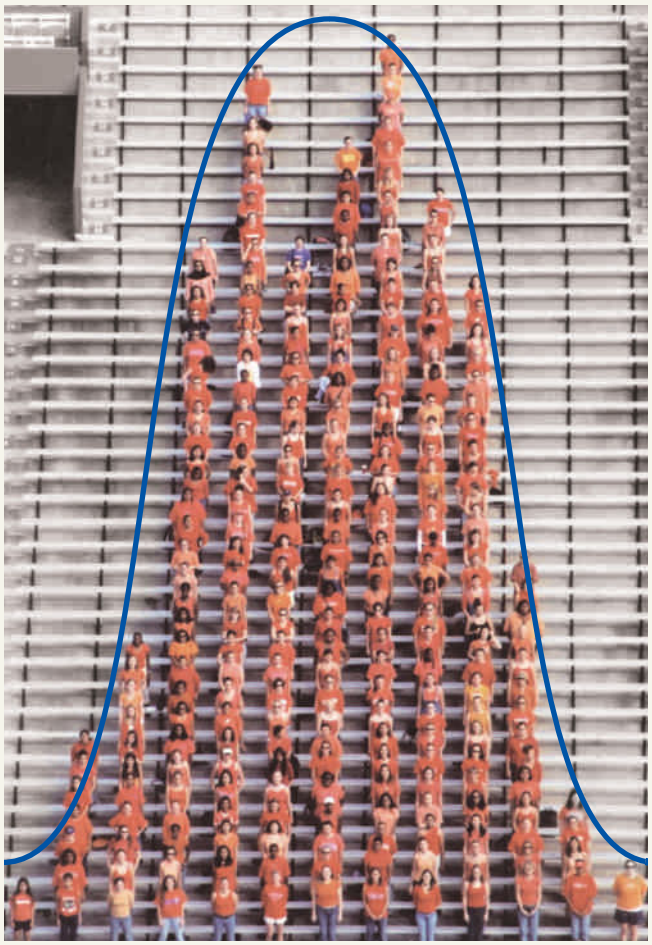


Figure 19.15 Animated! **Organized by height, these biology students (males, left; females, right) demonstrate continuous variation.** Height is also a multifactorial trait because it is influenced by more than one gene as well as by environmental factors.

traits that are easily measurable, such as height (Figure 19.15). Height is also a **multifactorial trait**. This term applies to complex phenotypes that are shaped by more than one gene and also by some aspect of the individual's environment.

The environment can affect phenotypes

There are many examples of human traits in which the environment can help determine the exact phenotype we observe. As just described, a person's adult height is programmed to a great extent by genes, but diet also may play a role. If a young child's diet is deficient in protein, or a disease or injury prevents the normal release of growth hormone, then the person will be shorter than his or her genetical potential would allow. Tanning darkens the natural color of a person's skin, a change that may become permanent in extreme cases.

Many of us inherit genetic predispositions for certain conditions, such as some cancers, obesity, hypertension, even alcoholism and depression. Today a great deal of scientific research is aimed at discovering the degree to which genes and environmental factors contribute to developing one of these health problems. Because it can be quite difficult to sort out these issues, many of the "good lifestyle choices" you hear so much about these days—from not smoking to eating a healthy diet and reducing stress—are recommendations for ways each of us can limit the chances a harmful gene or genes will be expressed.

Take-Home Message

What are some causes for variation we see in phenotypes?

- Gene expression may vary in several ways, so that the resulting trait (phenotype) is unpredictable.
- Examples include alleles that are incompletely penetrant and polygenic traits that result from the combined expression of two or more genes.
- With complex, multifactorial traits, the phenotype is shaped by more than one gene as well as by environmental factors.

IMPACTS, ISSUES

The Color of Skin

A PERSON of mixed ethnicity may produce gametes that have different mixes of alleles for dark and light skin. It is fairly rare that one of those gametes contains all of the alleles for dark skin, or all of the alleles for light skin, but it happens, as with twins Kian and Remee.

How Would You Vote?

Physical attributes such as skin color, which have a genetic basis, are often used to define race. Are twins such as Kian and Remee of different races? See CengageNOW for details, then vote online.

Summary

Section 19.1 Genes are specific units of inheritance that are passed to offspring. Each gene has a specific location on a chromosome. Chromosomes come in pairs, so each person has two copies of each gene. The copies are called alleles, and they may or may not be identical.

Someone who is homozygous for a trait (such as *AA*) has two identical alleles for the trait. Having two different alleles (*Aa*) is a heterozygous condition. Alleles (and traits) may be dominant (*A*) or recessive (*a*).

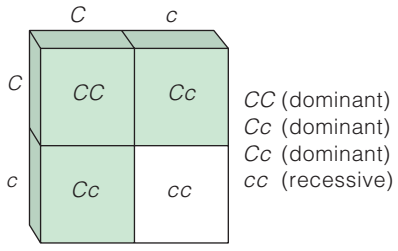
The term *genotype* refers to the particular alleles an individual has. *Phenotype* is the term used to refer to an individual's actual observable traits.

- Use the animation and interaction on CengageNOW to learn how Gregor Mendel, the "father" of modern genetics, crossed garden pea plants and to review the definitions of important genetic terms.

Section 19.2 As diploid organisms, humans have two copies (alleles) of each gene, one on each of the two chromosomes of a homologous pair. The two copies of each gene segregate from each other during meiosis, so each gamete formed ends up with one gene or the other.

- Use the animation and interaction on CengageNOW to learn more about the segregation of gene alleles.

Section 19.3 A Punnett square is a grid for figuring the probable outcome of a genetic cross. Probability expresses the likelihood of a particular event. Matings between two heterozygous individuals (*Cc* × *Cc*) produce the following combinations of alleles in offspring:



This results in a probability of 3/4 that any one child will have the dominant phenotype and 1/4 that the child will have the recessive phenotype.

A testcross is a tool in which the phenotypes of offspring are interpreted to identify a parent's genotype. For ethical reasons testcrosses are not used with humans.

Section 19.4 The members of each pair of homologous chromosomes sort into gametes independently of how the members of other chromosome pairs sort. Therefore, the genes on the chromosomes also sort into gametes independently. A mating between two heterozygous parents results in the following probable phenotypes:

CcDd × *CcDd*

9 dominant for both traits
3 dominant for *C*, recessive for *d*
3 dominant for *D*, recessive for *c*
1 recessive for both traits

Thus in this situation, sixteen genotypes and four phenotypes are possible.

- Use the animation and interaction on CengageNOW to learn more about how independent assortment works.

Section 19.5 In cases of pleiotropy, a single gene can influence many seemingly unrelated traits (as in sickle-cell anemia). In codominance, two contrasting alleles of a gene are both expressed. *ABO* blood types provide an example: people who are type AB have codominant alleles for type A and type B blood. Someone who has two copies of the *O* allele has type O blood. A gene that has three or more alleles is called a multiple allele system.

- Use the animation and interaction on CengageNOW to explore some patterns of inheritance that do not follow classical genetic rules.

Section 19.6 Various factors can influence the expression of genes. Penetrance refers to the probability that someone who inherits an allele will have the phenotype associated with it. Polygenic traits, such as eye color and height, are due to the expression of several genes. For polygenic traits we may see continuous variation in populations. In multifactorial inheritance the phenotype associated with a polygenic trait can be influenced by nongenetic environmental factors.

- Use the animation and interaction on CengageNOW to see how environmental factors can affect genetic traits. You can also plot the continuous distribution for height for a group of students.

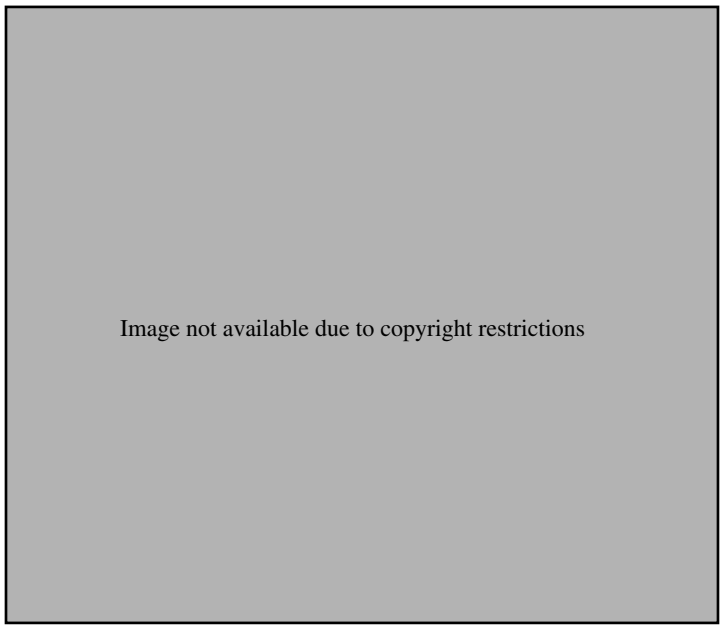
Review Questions

1. Define the difference between: (a) gene and allele, (b) dominant allele and recessive allele, (c) homozygote and heterozygote, and (d) genotype and phenotype.
2. State the theory of segregation. Does segregation occur during mitosis or during meiosis?
3. Distinguish between monohybrid and dihybrid crosses. What is a testcross, and why is it useful in genetic analysis?
4. What is independent assortment? Does independent assortment occur during mitosis or during meiosis?

Self-Quiz *Answers in Appendix V*

1. Alleles are _____.
   a. alternate forms of a gene
   b. different molecular forms of a chromosome
   c. always homozygous
   d. always heterozygous
2. A heterozygote has _____.
   a. only one of the various forms of a gene
   b. a pair of identical alleles
   c. a pair of contrasting alleles
   d. a haploid condition, in genetic terms
3. The observable traits of an organism are its _____.
   a. phenotype
   b. pedigree
   c. genotype
   d. multiple allele system
4. Offspring of a monohybrid cross *AA* × *aa* are _____.
   a. all *AA*
   b. all *aa*
   c. all *Aa*
   d. 1/2 *AA* and 1/2 *aa*
   e. none of the above
5. Second-generation offspring from a cross between two homozygotes are the _____.
   a. F_1 generation
   b. F_2 generation
   c. hybrid generation
   d. none of the above
6. Assuming complete dominance, offspring of the cross *Aa* × *Aa* will show a phenotypic ratio of _____.
   a. 1:2:1
   b. 1:1:1
   c. 9:1
   d. 3:1
7. Which statement best fits the principle of segregation?
   a. Units of heredity are transmitted to offspring.
   b. Two genes of a pair separate from each other during meiosis.
   c. Members of a population become segregated.
   d. A segregating pair of genes is sorted out into gametes independently of how gene pairs located on other chromosomes are sorted out.
8. Dihybrid crosses of heterozygotes (*AaBb* × *AaBb*) lead to F_2 offspring with phenotypic ratios close to _____.
   a. 1:2:1
   b. 1:1:1:1
   c. 3:1
   d. 9:3:3:1
9. Match each genetic term appropriately.

____dihybrid cross	a. *AA* × *aa*
____monohybrid cross	b. *Aa*
____homozygous condition	c. *AABB* × *aabb*
____heterozygous condition	d. *aa*



Critical Thinking

1. One gene has alleles *A* and *a*. Another has alleles *B* and *b*. For each genotype listed, what type(s) of gametes can be produced? (Assume independent assortment occurs.)
   a. *AABB*
   b. *AaBB*
   c. *Aabb*
   d. *AaBb*
2. Still referring to Problem 1, what will be the possible genotypes of offspring from the following matings? With what frequency will each genotype show up?
   a. *AABB* × *aaBB*
   b. *AaBB* × *AABb*
   c. *AaBb* × *aabb*
   d. *AaBb* × *AaBb*
3. A gene on one chromosome governs a trait involving tongue movement. If you have a dominant allele of that gene, you can curl the sides of your tongue upward (Figure 19.16). If you are homozygous for recessive alleles of the gene, you cannot roll your tongue. A gene on a different chromosome controls whether your earlobes are attached or detached. People with detached earlobes have at least one dominant allele of the gene. Because these two genes are on different chromosomes, they assort independently. Suppose a tongue-rolling woman with detached earlobes marries a man who has attached earlobes and can't roll his tongue. Their first child has attached earlobes and can't roll its tongue.
   a. What are the genotypes of the mother, father, and child?
   b. What is the probability that a second child will have detached earlobes and won't be a tongue-roller?
4. Go back to Problem 1, and assume you now study a third gene having alleles *C* and *c*. For each genotype listed, what type(s) of gametes can be produced?
   a. *AABBCC*
   b. *AaBBcc*
   c. *AaBBCc*
   d. *AaBbCc*

5. When you decide to breed your Labrador retriever Molly and sell the puppies, you discover that two of Molly's four siblings have developed a hip disorder that is traceable to the action of a single recessive allele. Molly herself shows no sign of the disorder. If you breed Molly to a male Labrador that does not carry the recessive allele, can you assure a purchaser that the puppies will also be free of the condition? Explain your answer.

6. The ABO blood system has been used to settle cases of disputed paternity. Suppose, as a geneticist, you must testify during a case in which the mother has type A blood, the child has type O blood, and the alleged father has type B blood. How would you respond to the following statements?
   a. *Man's attorney*: "The mother has type A blood, so the child's type O blood must have come from the father. Because my client has type B blood, he could not be the father."
   b. *Mother's attorney*: "Further tests prove this man is heterozygous, so he must be the father."

7. Soon after a couple marries, tests show that both the man and the woman are heterozygotes for the recessive allele that causes sickling of red blood cells; they are both Hb^A/Hb^S. What is the probability that any of their children will have sickle-cell trait? Sickle-cell anemia?

8. A man is homozygous dominant for 10 different genes that assort independently. How many genotypically different types of sperm could he produce? A woman is homozygous recessive for 8 of these genes and is heterozygous for the other 2. How many genotypically different types of eggs could she produce? What can you conclude about the relationship between the number of different gametes possible and the number of heterozygous and homozygous gene pairs that are present?

9. As is the case with the mutated hemoglobin gene that causes sickle-cell anemia, certain dominant alleles are crucial to normal functioning (or development). Some are so vital that when the mutant recessive alleles are homozygous, the combination is lethal and death results before birth or early in life. However, such recessive alleles can be passed on by heterozygotes (*Ll*). In many cases, these are not phenotypically different from homozygous normals (*LL*). If two heterozygote parents mate (*Ll* × *Ll*), what is the probability that any of the children will be heterozygous?

10. Bill and Marie each have flat feet, long eyelashes, and "achoo syndrome" (chronic sneezing). All are dominant traits. The genes for these traits each have two alleles, which we can designate as follows:

	Dominant	*Recessive*
Foot arch	*A*	*a*
Sneezing	*S*	*s*
Eyelash length	*E*	*e*

Bill is heterozygous for each trait. Marie is homozygous for all of them. What is Bill's genotype? What is Marie's genotype? If they have four children, what is the probability that each child will have the same phenotype as the parents? What is the probability that a child will have short lashes, high arches, and no achoo syndrome?

11. You decide to breed a pair of guinea pigs, one black and one white. In guinea pigs, black fur is caused by a dominant allele (*B*) and white is due to homozygosity for a recessive allele (*b*) at the same locus. Your guinea pigs have 7 offspring, 4 black and 3 white. What are the genotypes of the parents? Why is there a 1:1 ratio in this cross?

EXPLORE ON YOUR OWN

Identical twins have identical genes and look alike. In addition, they have many behaviors in common. Are these parallels coincidence, clever hoaxes, or evidence that aspects of behavior are inherited characteristics, like hair and eye color? Although the question is intriguing, clear answers have proven difficult to come by.

There is strong evidence that some basic behaviors, such as smiling to indicate pleasure and the crying of an infant when it is hungry, are genetically programmed. Scientists have also begun to look for links between genes and alcoholism, some types of mental illness, violent behavior, and even sexual orientation. Such studies raise controversial social issues. So far their greatest impact has been to point out how little we know about the biological basis of human behavior. To learn more about these efforts and find links to some other fascinating and reputable human genetics websites, visit the Personality Research website at www.personalityresearch.org.

Chromosomes and Human Genetics 20

IMPACTS, ISSUES

Menacing Genes

CYSTIC fibrosis (CF) is a fatal genetic disorder. Its cause has been traced to a gene on chromosome 7 that provides the instructions for building a plasma membrane protein called CFTR. The protein helps chloride and water move into and out of exocrine cells, which secrete mucus or sweat. Many different mutations of the gene can make the CFTR protein abnormal. Cystic fibrosis results when a child inherits a faulty CFTR gene from both parents.

More than 10 million people in the United States have a dominant, normal copy of the CFTR gene and one recessive, abnormal copy. They thus are carriers, but most don't know it.

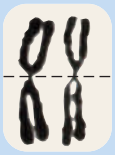
In cystic fibrosis, dry, thickened mucus clogs the airways and makes it hard to breathe. You may remember from Chapter 10 how ciliated cells lining the airways sweep out material that becomes trapped in mucus there. In people with CF, bacteria grow in the mucus and infections develop.

Although antibiotics can help control the lung infections, each day patients like the young woman at left must undergo physiotherapy that includes thumping on the chest and back to loosen the mucus so it can be expelled. In most cases the lungs eventually fail. CF patients rarely live beyond 30.

Hundreds of thousands of expectant parents have been screened for CF. In some early cases the results were not interpreted properly and a few couples may have unwittingly opted to abort normal fetuses.

Thinking about the power and challenges of genetic testing is an appropriate introduction to our topic in this chapter—the links between chromosomes and inheritance, including the causes of many common inherited diseases. The more we learn about how our genes operate in health and disease, the more we all will be dealing with issues related to the proper use of that knowledge.

KEY CONCEPTS

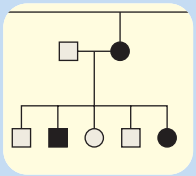


Chromosomes and Genes

Humans have two types of chromosomes, autosomes and sex chromosomes. Each of the chromosomes carries genes. Each gene is located at a particular place on a specific chromosome. Sections 20.1–20.3

Patterns of Inheritance

Studies of genetic disorders can reveal how traits in general are inherited. Some disease traits arise from dominant or recessive alleles on an autosome or sex chromosome. Sections 20.4–20.6



Changes in Chromosomes

Many genetic disorders arise from rare changes in the number or structure of chromosomes. Such changes can cause harmful or lethal effects. Sections 20.8, 20.9

LINKS TO EARLIER CONCEPTS

- In this chapter you will learn more about the concept of homologous chromosomes (19.1).
- You will also gain a more complete understanding of how exchanges of chromosome segments (crossing over) during meiosis creates new combinations of parent genes in sperm and eggs (18.9).
- You will expand your knowledge of how human chromosomes carry genetic information (19.2), and you will see some additional examples of how basic patterns of inheritance operate in humans (19.3).

How Would You Vote?

Do we as a society want to encourage women to give birth only to offspring who will not develop serious gene-based medical problems? See CengageNOW for details, then vote online.

20.1 A Review of Genes and Chromosomes

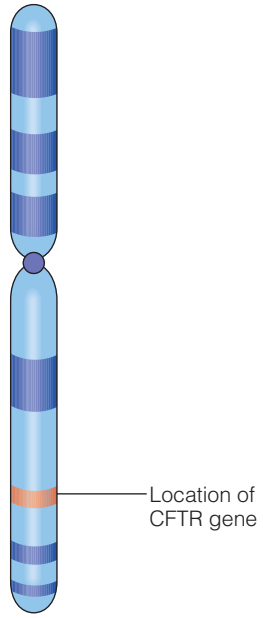
- **Chapters 18 and 19 provided general information about chromosomes and what happens to them during meiosis. We can correlate this information with some common patterns of heredity.**
- **Links to Chromosome structure 18.1, Meiosis 18.7–18.9, Concepts of heredity 19.1**

Understanding inheritance starts with gene–chromosome connections

Chapters 18 and 19 discussed how chromosomes carry genes, and outlined basic "rules" for how genes are passed from one generation to another. To recap some of what you have learned up to this point:

1. Each gene has a particular location (its **locus**) on a specific chromosome.
2. A diploid cell ($2n$) has pairs of homologous chromosomes, one from the mother and one from the father. Except for the sex chromosomes (X and Y), the chromosomes of each pair are alike in length, shape, and the genes they include.
3. During meiosis in germ cells, homologous chromosomes line up together, then later separate from each other. While they are lined up, they may exchange corresponding segments. This exchange of segments and their genes is called crossing over.
4. A given gene may have two or more alleles, but a diploid cell can have only two of them, one on each member of a pair of homologous chromosomes.
5. In general, each gene on a chromosome is sorted into gametes independently of the chromosome's other genes. Geneticists call this process independent assortment.

The concept of independent assortment helps explain why even close relatives have such a varied mix of genetic traits. Geneticists could not help noticing, however, that some traits often seemed to go together. It turns out that there are exceptions to the "rule" of independent assortment, and they result in some traits often being inherited together.



Human chromosome 7

Figure 20.2 The gene for cystic fibrosis has been mapped to human chromosome 7.

Some traits often are inherited together because their genes are physically linked

Although most genes on a chromosome do sort into gametes independently, others are physically connected. When the distance between two genes is short, we say there is close *linkage* between them. Closely linked genes nearly always end up in the same gamete. On the other hand, when two genes on a chromosome are far apart, it is more likely that crossing over will break up the linkage. Those genes are less likely to stay together as gametes form (Figure 20.1). The patterns in which genes are distributed into gametes are so regular they can be used to map the positions of the genes on a chromosome. The simple map of human chromosome 7 in Figure 20.2 shows the location of the cystic fibrosis gene (CFTR).

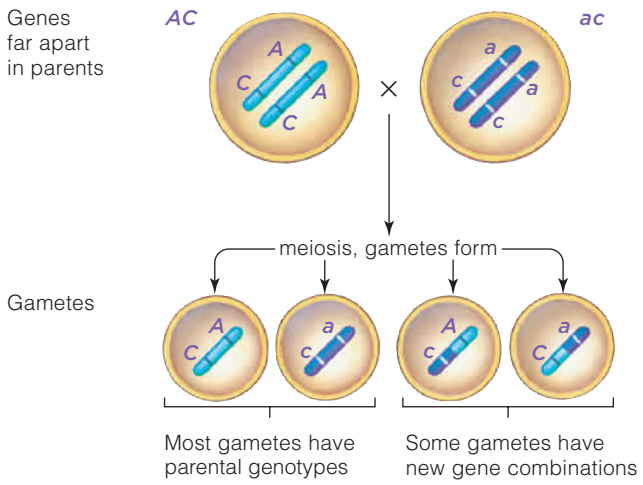


Figure 20.1 Closely linked genes tend to stay together when meiosis sorts genes into gametes.

Take-Home Message

How does gene linkage affect inheritance?

- Major patterns of inheritance reflect factors such as gene linkage, in which the physical distance of genes on a chromosome influences whether the genes move into the same or different gametes.

20.2 Picturing Chromosomes with Karyotypes

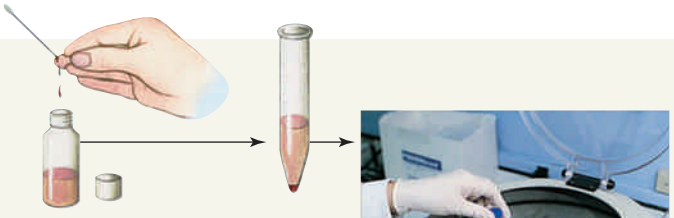
A diagram called a **karyotype** can help answer questions about a person's chromosomes. Chromosomes are the most condensed and easiest to identify at the phase of mitosis called metaphase (Section 18.10).

A technician who wants to make a karyotype doesn't assume that it will be possible to find a body cell that is dividing. Instead, cells are cultured in the laboratory along with chemicals that stimulate the cells to grow and to divide by mitosis. Blood cells are often used for this purpose.

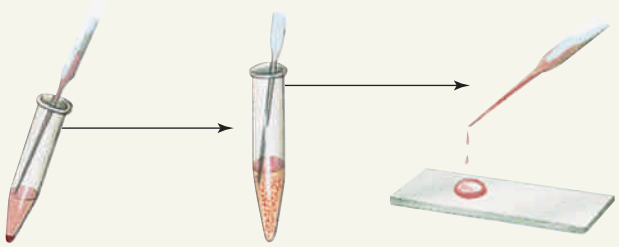
Once the cell culture is established, a chemical called colchicine is added to stop mitosis at metaphase. After the colchicine treatment, the "soup" of cultured cells is placed into glass tubes that are whirled in a centrifuge. The spinning force moves the cells to the bottom of the test tubes.

Next the cells are transferred to a saline (salt-water) solution. They swell (by osmosis) and separate, as do the metaphase chromosomes. At this point the cells are placed on a microscope slide, "fixed" (stabilized by air-drying or some other method), and stained so that they are easy to see.

The chromosomes are photographed through the microscope, and the image is enlarged. Then the photograph is cut apart, one chromosome at a time. The cutouts are arranged in order, essentially from largest to smallest (Figure 20.3). The sex chromosomes are placed last. All pairs of homologous chromosomes are aligned horizontally, by their centromeres. Figure 20.3*f* shows a karyotype diagram prepared this way.



a Add cells from a small blood sample to a medium that has a chemical stimulator for mitosis. Add colchicine to arrest mitosis at metaphase. Transfer culture to a centrifuge. (This motor-driven rotary device spins test tubes at high speed. Tube contents respond to the centrifugal force according to their mass, density, and shape.)

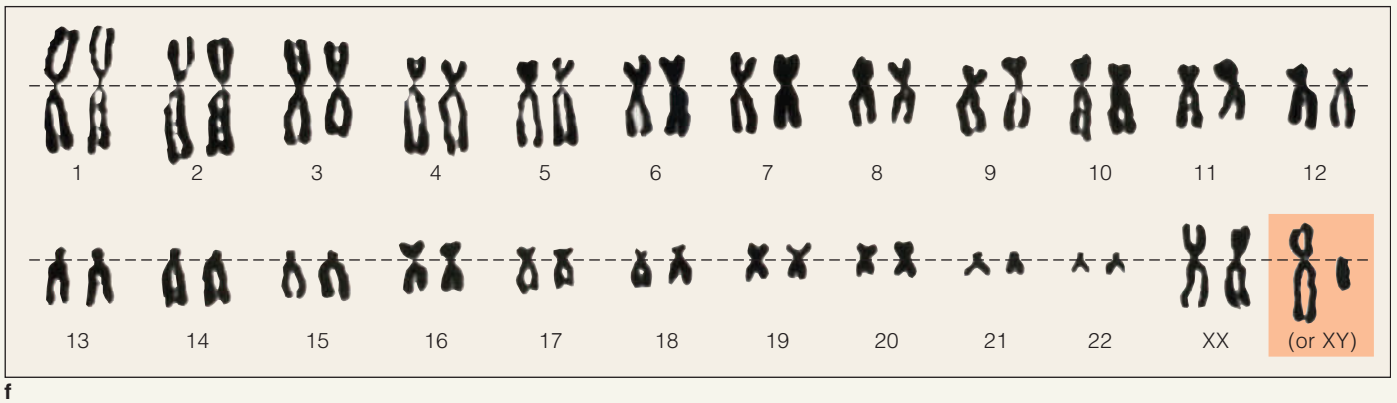


b Centrifugation forces cells to bottom of tube. Draw off culture medium. Add a dilute saline solution to tube. Add a fixative.

c Prepare and stain cells for microscopy.

d Put cells on a microscope slide. Observe.

e Photograph one cell through microscope. Enlarge image of its chromosomes. Cut the image apart. Arrange chromosomes as a set.



f

Figure 20.3 Animated! A karyotype gives a portrait of the chromosomes in a cell. The diagrams show how to prepare a karyotype (**a**–**e**). (**f**) A human karyotype. Human somatic cells have twenty-two pairs of autosomes and one pair of sex chromosomes (XX or XY). These are metaphase chromosomes from a female; and each has been duplicated. In the orange box at the far right are the two sex chromosomes (XY) of a male.

20.3 The Sex Chromosomes

- **Sex chromosomes carry genes associated with sexual traits.**
- **Links to the Formation of sperm and eggs 16.2, 16.4**

Gender is a question of X or Y

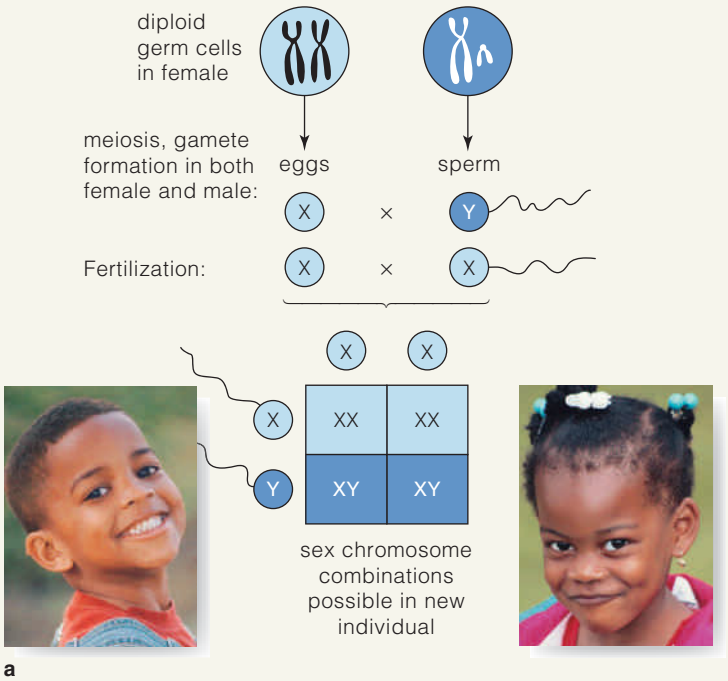
It has been said that "men are from Mars, women are from Venus." While that topic goes far beyond biology class, there *are* biological differences between the sexes. You probably already know that the **X chromosome** is the female sex chromosome and the **Y chromosome** is the male sex chromosome. A female's diploid cells each have two X chromosomes, so females are said to be XX. A male's diploid cells each have one X chromosome and one Y, so males are said to be XY. Each X chromosome carries 2,062 genes, but a Y chromosome is much smaller and carries only about 330 genes.

Despite their differences, the X and Y chromosomes can be joined together briefly in a small region along their length. This allows the X and Y to function as homologues during meiosis.

A mother's egg always carries an X chromosome, so the father's sperm determines a baby's gender. If an X-bearing sperm fertilizes an egg, the embryo will be XX and develop into a female. On the other hand, if the sperm has a Y chromosome, the embryo will be XY and develop into a male (Figure 20.4*a*).

The genes on a Y chromosome include the master gene for male sex determination, which has been dubbed *SRY*. When the gene is expressed, testes form in the embryo (Figure 20.4*b*). When that gene is "missing" because no Y chromosome is present, ovaries form, and the developing embryo is female.

Although the X chromosome has some genes associated with sexual traits, such as the distribution of body fat, most of its genes deal with nonsexual traits such as blood clotting. Males have one X chromosome, so these genes can be expressed in males as well as in females. The genes on X and Y chromosomes are sometimes called **X-linked genes** and **Y-linked genes**, respectively.



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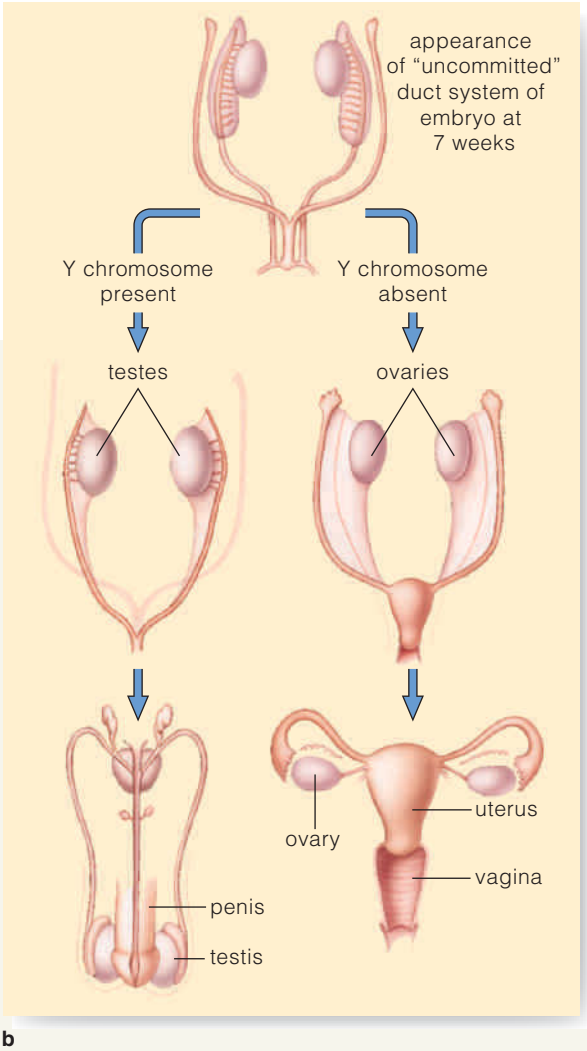
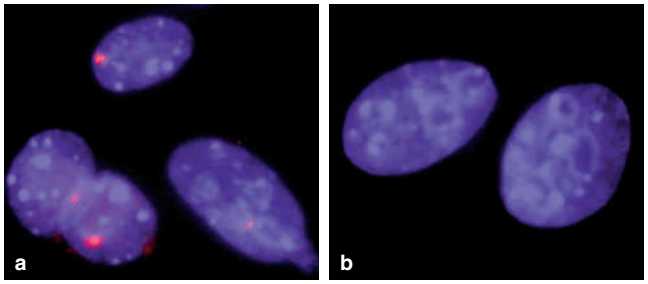


b

Figure 20.4 Animated! The father's sperm determines whether a baby will be male or female. (**a**) Males transmit their Y chromosome to sons but not daughters. Males get their X chromosome from their mother. (**b**) The duct system in the early embryo that develops into a male or a female reproductive system.

In females, one X is inactivated

Since females have two X chromosomes and males have only one, do females have twice as many X-linked genes and therefore a double dose of their gene products? Not really, because a compensating mechanism called **X inactivation** occurs in females. Apparently, most or all of the genes on one of a female's X chromosomes are turned off soon after the first cleavages of the zygote. In a given cell, either of the two X chromosomes can be inactivated. The inactivated X is condensed into a **Barr body** (Figure 20.5*a* and 20.5*b*). From then on, the same X chromosome will be inactivated in all the descendants of the cell. After X inactivation takes place, the embryo continues to develop. Typically, a female's body has patches of tissue where the genes of the maternal X chromosome are expressed, and other patches where the genes of the paternal X chromosome are expressed.



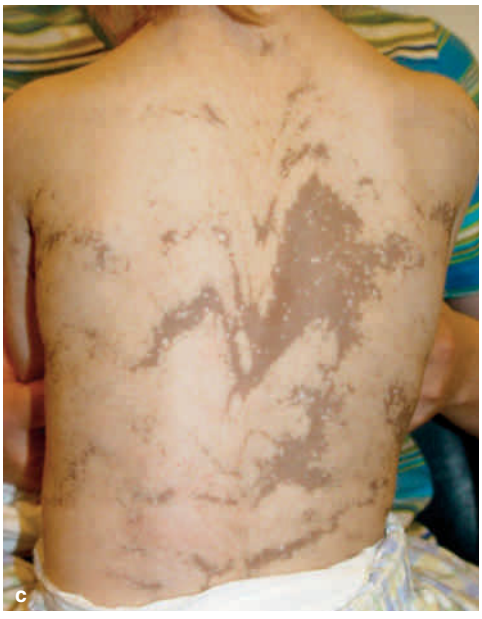


Figure 20.5 X inactivation halts the functioning of one of a female's two X chromosomes. (**a**) Light micrographs show Barr bodies (condensed X chromosomes) in the nuclei of several cells. (**b**) The X chromosome in cells of males is not condensed this way. (**c**) A "mosaic" tissue effect that shows up in females who have incontinentia pigmenti. In darker patches of this girl's skin, the mutated X chromosome is active.

Some females have a mutation that makes the mosaic tissues visible (Figure 20.5*c*). For example, *incontinentia pigmenti* is an X-linked disorder that affects the skin, teeth, nails, and hair. In females who are heterozygous for the trait (one X chromosome has the mutation and the other X is normal), mosaic tissue shows up as lighter and darker patches of skin.

Some genes are expressed differently in males and females

You may have noticed that many more men than women have pattern baldness (*right*). This common form of hair loss in men is an example of a *sex-influenced* trait. Such traits appear much more often in one sex than in the other, or else the phenotype differs depending on whether the person is male or female. Genes for sex-influenced traits are on autosomes, not on sex chromosomes. The gene allele that causes pattern baldness acts like a dominant gene in males but behaves like a recessive gene in females. That is, a male needs only to inherit one copy in order to become bald. A woman will develop pattern baldness only if she has two copies of the allele, and usually much later in life than a male who has the allele. The difference is due to differences in the effects of male sex hormones in females and males.

Secondary sexual characeristics such as the growth of a man's beard and the development of a woman's breasts are governed by *sex-limited* genes. Both males and females inherit the same genes (on the X chromosome), but only the genes appropriate to a person's gender are turned on when a youngster reaches puberty. Sex hormones once again are the "switch."

Take-Home Message

What are the characteristics and functions of sex hormones?

- The two human sex chromosomes, X and Y, differ in their size, shape, and the kinds of genes they carry.
- A person's sex is determined by the father's sperm, which can carry either an X chromosome or a Y chromosome. XY embryos develop as males, and XX embryos as females.
- In females, one of the two X chromosomes is inactivated soon after embryonic development begins.
- Sex-influenced traits are governed by genes on autosomes but are expressed differently in males and females.

20.4 Human Genetic Analysis

- **In some cases prospective parents can assess their risk of conceiving a child with an inherited disorder. A first step can be to construct a genetic family history.**
- **Links to Chromosomes 18.1, Dominant and recessive conditions 19.1**

A pedigree shows genetic connections

In nonhuman organisms, geneticists use experimental crosses to do genetic analysis. Since we can't experiment with humans, however, a basic tool is a genetic family history called a **pedigree chart**. The chart tracks several generations of a family, showing who exhibited the trait being investigated. The example shown in Figure 20.6 includes definitions of some of the symbols used.

When analyzing a pedigree, geneticists use their knowledge of probability and of basic inheritance patterns, which may yield clues to a trait's genetic basis. For instance, they might figure out that the allele that causes a disorder is dominant or recessive or that it is located on an autosome or a sex chromosome. Pedigrees often are used to identify those at risk of transmitting or developing the trait in question—including any children that a couple may have. Some inheritance patterns are clues to past events (Figure 20.7)

Gathering numerous family pedigrees increases the numerical base for analysis. Figure 20.8 shows a series of pedigrees for **Huntington disease**, in which the nervous system progressively degenerates. Genetic researcher Nancy Wexler constructed the pedigrees for a huge extended family in Venezuela that includes more than 10,000 people.

Someone who is heterozygous for a recessive disease trait can be designated as a *carrier*. A carrier shows the

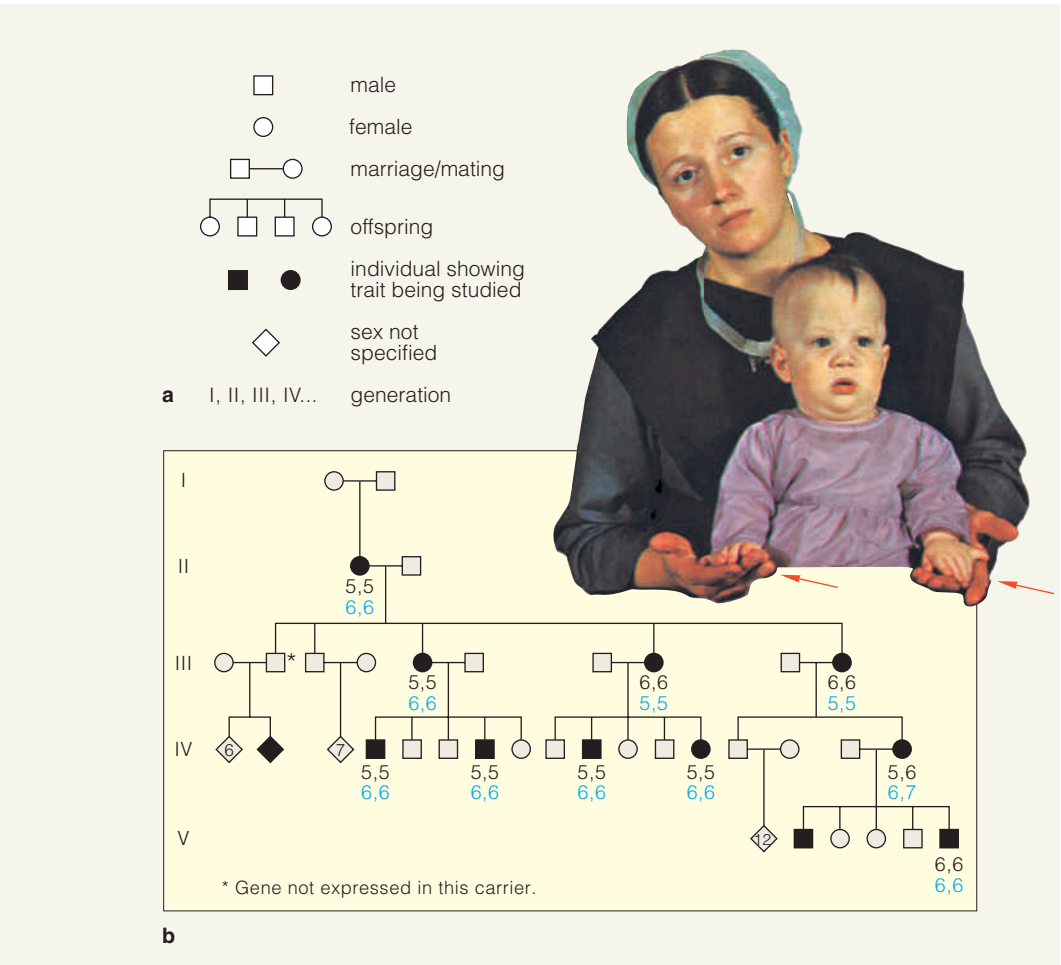
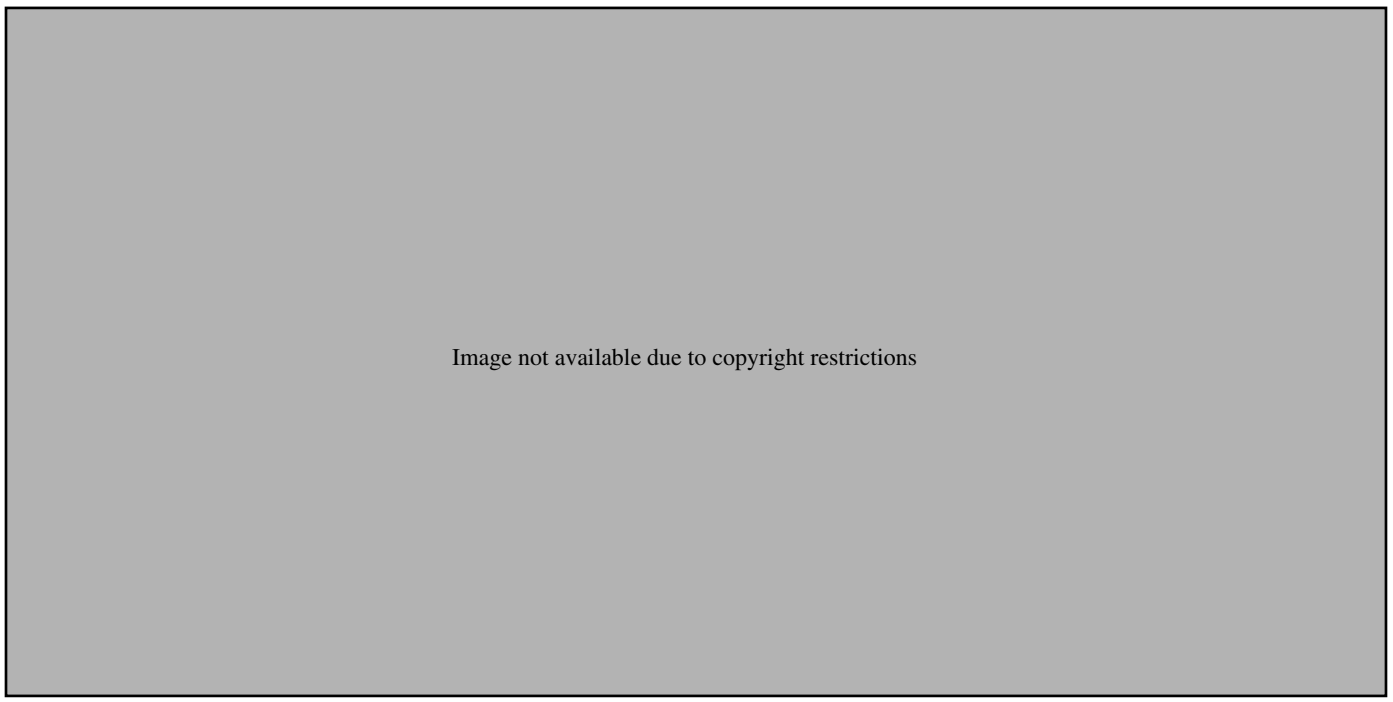


Figure 20.6 Animated! A pedigree is the family history of a genetic trait. (**a**) Here you see some symbols used in constructing pedigree diagrams. (**b**) A pedigree for polydactyly, in which affected people have extra fingers, extra toes, or both. As described in Section 19.6, expression of the gene governing polydactyly can vary. Here, *black* numerals designate the number of fingers on each hand. *Blue* ones designate the number of toes on each foot.

Figure 20.7 Are you related to the great warrior Ghengis Khan? Eight percent of the men in Central Asia carry nearly identical Y chromosomes. This discovery implies that they are all descended from a common ancestor. If so, then some 16 million males living between northeastern China and Afghanistan—close to 1 of every 200 men alive today—may be descended from the warlord and notorious womanizer Genghis Khan. In time his offspring ruled an empire that stretched from China all the way to central Europe.



dominant phenotype (no disease symptoms) but still can produce sperm or eggs with the recessive allele and potentially pass it on to a child. If both parents are carriers for a disorder, a child has a 25 percent chance of being homozygous for the harmful recessive allele.

In thinking about genetics, it's good to keep in mind the difference between an abnormality and a disorder. A **genetic abnormality** is simply deviation from the average, such as having six toes on each foot instead of five. A **genetic disorder** causes mild to severe medical problems. A **syndrome** is a set of symptoms that usually occur together and characterize a disorder.

Each of us carries an average of three to eight harmful recessive alleles. Why don't alleles that cause severe disorders simply disappear from human populations? There are several reasons. For example, new gene alleles can come about by way of mutation, as described in Section 20.8. Also, in heterozygotes, a recessive allele is paired with a normal dominant one that prevents the recessive phenotype from showing up. However, the recessive allele still can be transmitted to offspring.

It is not uncommon for some genetic disorders to be described as diseases (for example, Huntington disease and cystic fibrosis), but in other situations the terms are not interchangeable. For instance, a person's genes may increase her or his susceptibility or weaken the response to infection by a virus, bacterium, or some other pathogen. Strictly speaking, however, the resulting illness isn't a genetic disease. A common example is a genetic predisposition to develop allergies or asthma that runs in some families.

Genetic analysis may predict disorders

Some prospective parents suspect that they are likely to produce a severely afflicted child. Their first child, a close relative, or they themselves may have a genetic disorder, and they wonder how likely it is that future children also will be affected. Psychologists, geneticists, and other specialists may be called in to provide answers.

A common first step is determining the genotype of each parent. Family pedigrees can aid the diagnosis. For disorders that follow one of the basic inheritance patterns described in Chapter 19, it's possible to predict the chances a given child will be affected. But not all follow basic patterns. And those that do can be influenced by other factors, some identifiable, others not. Even when the extent of risk has been determined with confidence, prospective parents must understand that the risk is the same for *each* pregnancy. If a pregnancy has one chance in four of producing a child with a genetic disorder, the same odds apply to every subsequent pregnancy.

Take-Home Message

What kind of information can a genetic pedigree provide?

- For many genes, pedigree analysis may reveal basic inheritance patterns that provide information about the probability the genes may be transmitted to children.
- A genetic abnormality is an uncommon version of an inherited trait.
- A genetic disorder is an inherited condition that produces mild to severe health problems.

20.5 Inheritance of Genes on Autosomes

- **Research on genetic disorders and abnormalities has revealed patterns in the way dominant and recessive genes on autosomes are inherited.**
- **Links to Blood cholesterol 7.8, Basal nuclei and Parkinson's disease 13.12, Basic heredity concepts and probability 19.1, 19.3**

Inherited recessive traits on autosomes cause a variety of disorders

For some traits, inheritance patterns reveal two clues that point to a recessive allele on an autosome. *First*, if both parents are heterozygous, any child of theirs will have a 50 percent chance of being heterozygous and a 25 percent chance of being homozygous recessive (Figure 20.9). *Second*, if both parents are homozygous recessive, any child of theirs will be too.

Cystic fibrosis, which you read about in the chapter introduction, is an **autosomal recessive** condition. So is **phenylketonuria** (PKU), which results from abnormal buildup of the amino acid phenylalanine. Affected people are homozygous for a recessive allele that fails to provide instructions for an enzyme that is needed to convert phenylalanine to another amino acid, tyrosine. Excess phenylalanine builds up and may be used by cells to make phenylpyruvic acid. At high levels, phenylpyruvic acid can cause mental retardation. Fortunately, a diet low in phenylalanine will prevent PKU symptoms. Many diet soft drinks and other products are sweetened with aspartame, which contains phenylalanine. They must carry a warning label so people with PKU can avoid using them.

In some autosomal recessive disorders, the defective gene product is an enzyme needed to metabolize lipids. Infants born with **Tay-Sachs disease** lack hexosaminidase A, which is an enzyme required for the metabolism of sphingolipids, a type of lipid that is especially abundant in the plasma membrane of cells in nerves and the brain. Affected babies seem normal at birth, but over time they lose motor functions and also become deaf, blind, and mentally retarded. Most die in early childhood.

Tay-Sachs disease is most common among children of eastern European Jewish descent. Biochemical tests before conception can determine whether either member of a couple carries the recessive allele.

Some disorders are due to dominant genes

Other kinds of clues indicate that an **autosomal dominant** allele is responsible for a trait. First, the trait usually appears in each generation because the dominant allele generally is expressed even in heterozygotes. Second, if one parent is heterozygous and the other is homozygous for the normal, recessive allele, there is a 50 percent chance that any child of theirs will be heterozygous (Figure 20.10). A few dominant alleles that cause severe genetic disorders persist in populations. Some result from spontaneous mutations. In other cases, expression of a dominant allele may not prevent reproduction, or affected people have children before the disorder's symptoms become severe.

Huntington disease (Section 20.4) is a prime example of an autosomal dominant disorder that does not cause

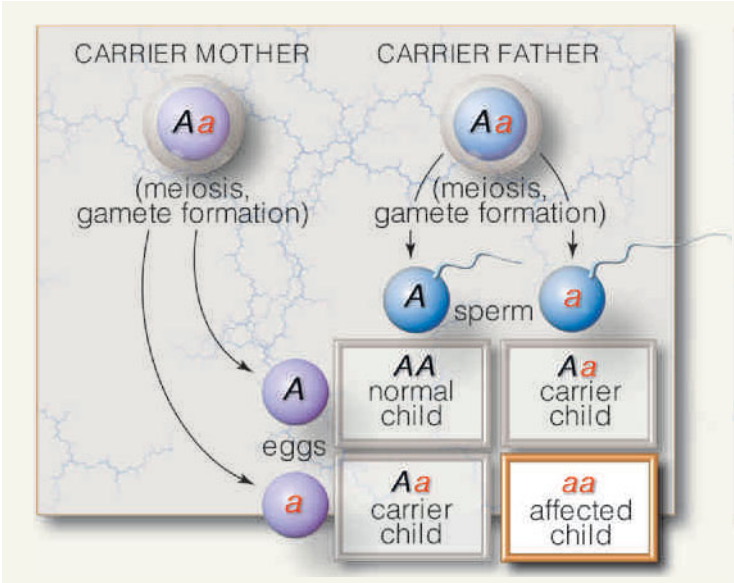


Figure 20.9 Animated! This is a typical pattern for autosomal recessive inheritance. In this case both parents are heterozygous carriers of the recessive allele (*red*).

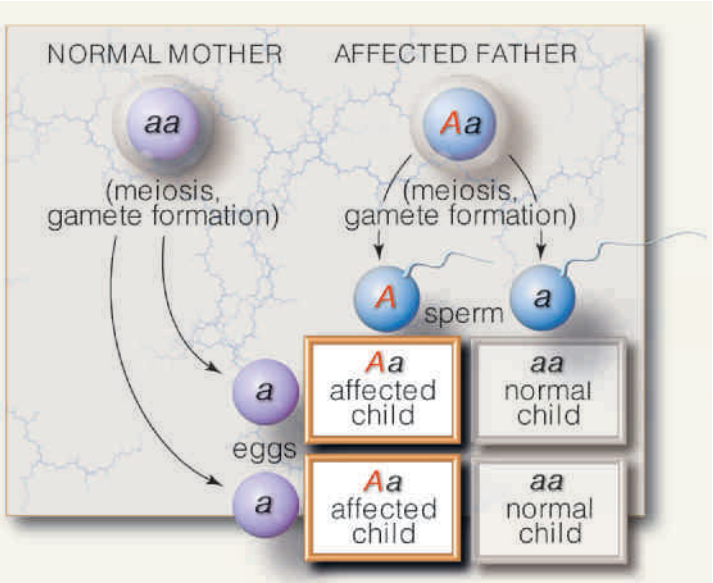


Figure 20.10 Animated! This is a pattern for autosomal dominant inheritance. Here the phenotype for the dominant allele (*red*) is expressed in the carriers.

Figure 20.11 Animated! About 1 in 5,000 humans have Marfan syndrome, an autosomal dominant condition. This photograph shows promising basketball star Haris Charalambous, who died suddenly when his aorta burst during warmup exercises at the University of Toledo in 2006. He was 21. Charalambous was very tall and lanky, with long arms and legs, traits that are highly valued in professional athletes such as basketball players. These traits are also associated with Marfan syndrome. Like many other people, Charalambous did not know he had Marfan syndrome.

symptoms until well into adulthood. In about half the cases, symptoms emerge after age 30, when the person may already have had children (so the allele may be passed on). Homozygotes for the Huntington allele die as embryos, so affected adults are always heterozygous. Today testing can reveal the disease-causing allele, which is on chromosome 4. Unfortunately, because of the nature of the Huntington defect, there is no cure. Some at-risk people opt not to have the diagnostic test, and many don't have children to avoid passing on the disorder.

Marfan syndrome (Figure 20.11) is another autosomal dominant condition. The responsible allele codes for a defective form of the protein fibrillin, which is found in connective tissue. The abnormal protein has a variety of effects, including disrupting both the structure and the function of smooth muscle cells in the wall of the aorta, the large vessel that carries blood away from the heart. Over time the wall thins and weakens, and it can rupture suddenly during strenuous exercise. Marfan syndrome affects 1 in 10,000 people throughout the world. Until recent medical advances, it killed most affected people before they reached age 50.

Figure 20.12 These three men are affected by achondroplasia. One (center) has a big audience: Actor Verne Troyer, also known as Mini Me in the Austin Powers series of spy movies. Troyer stands two feet, eight inches tall.

Another example, **achondroplasia**, also affects about 1 in 10,000 people. Homozygous dominant infants usually are stillborn. Heterozygotes can reproduce, but while they are young and their limb bones are forming, the cartilage elements of those bones cannot form properly. For that reason, at maturity affected people have abnormally short arms and legs (Figure 20.12). Adults with achondroplasia don't grow taller than about 4 feet, 4 inches. In many cases, the dominant allele has no other effects.

About 1 person in 500 is heterozygous for a dominant autosomal allele that causes a condition called **familial hypercholesterolemia**. This allele leads to dangerously elevated blood cholesterol because it fails to encode the normal number of cell receptors for LDLs (low-density lipoproteins). You may remember from Chapter 7 that LDLs bind cholesterol in the blood, the first step in removing it from the body. A person who is homozygous for the allele may develop severe cholesterol-related heart disease as a child. Affected people usually die in their 20s or 30s.

Take-Home Message

What are the basic inheritance patterns of traits carried on autosomes?

- If both parents are heterozygous carriers of a recessive allele, there is a 25 percent chance that a child of theirs will be homozygous for the trait and exhibit the recessive phenotype.
- A dominant trait may appear in each generation, because the dominant allele is expressed even in heterozygotes.

20.6 Inheritance of Genes on the X Chromosome

- **Genes on the X chromosome also are inherited according to predictable patterns.**
- **Links to Muscle contraction 6.3, Blood clotting 8.7, Eye disorders 14.10**

Some disorders are recessive X-linked traits

When a recessive allele on an X chromosome causes a trait, two clues often point to this source. First, many more males than females are affected. This is because a recessive allele can be masked in females, who may inherit a dominant allele on their other X chromosome. It cannot be masked in males, who have only one X chromosome (Figure 20.13). Second, only a daughter can inherit the recessive allele from an affected father, because his sons will receive a copy of his Y chromosome, not the X.

Two forms of the bleeding disorder **hemophilia** are X-linked recessive traits. The most common one, hemophilia A, is caused by a mutation in the gene for the blood-clotting protein called factor VIII (Section 8.7). A male with a recessive allele on his X chromosome is always affected, and he risks death from anything that causes bleeding, even a bruise. The blood of a heterozygous female clots normally, because the normal gene on her normal X chromosome makes enough factor VIII. (Hemophilia B, which involves clotting factor IX, has similar symptoms.)

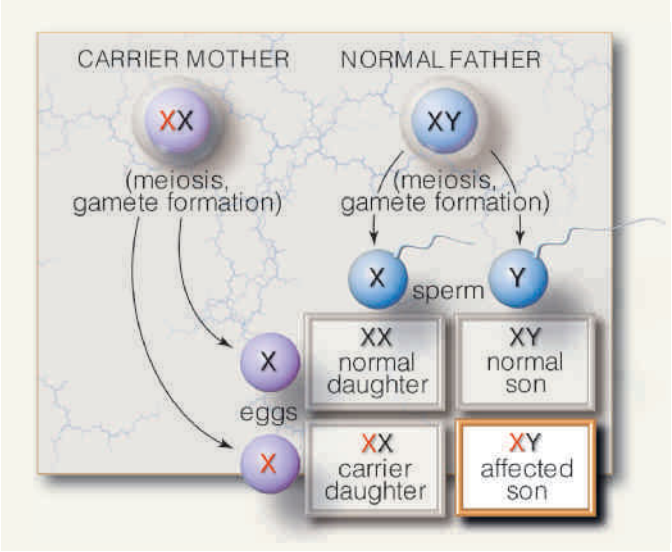
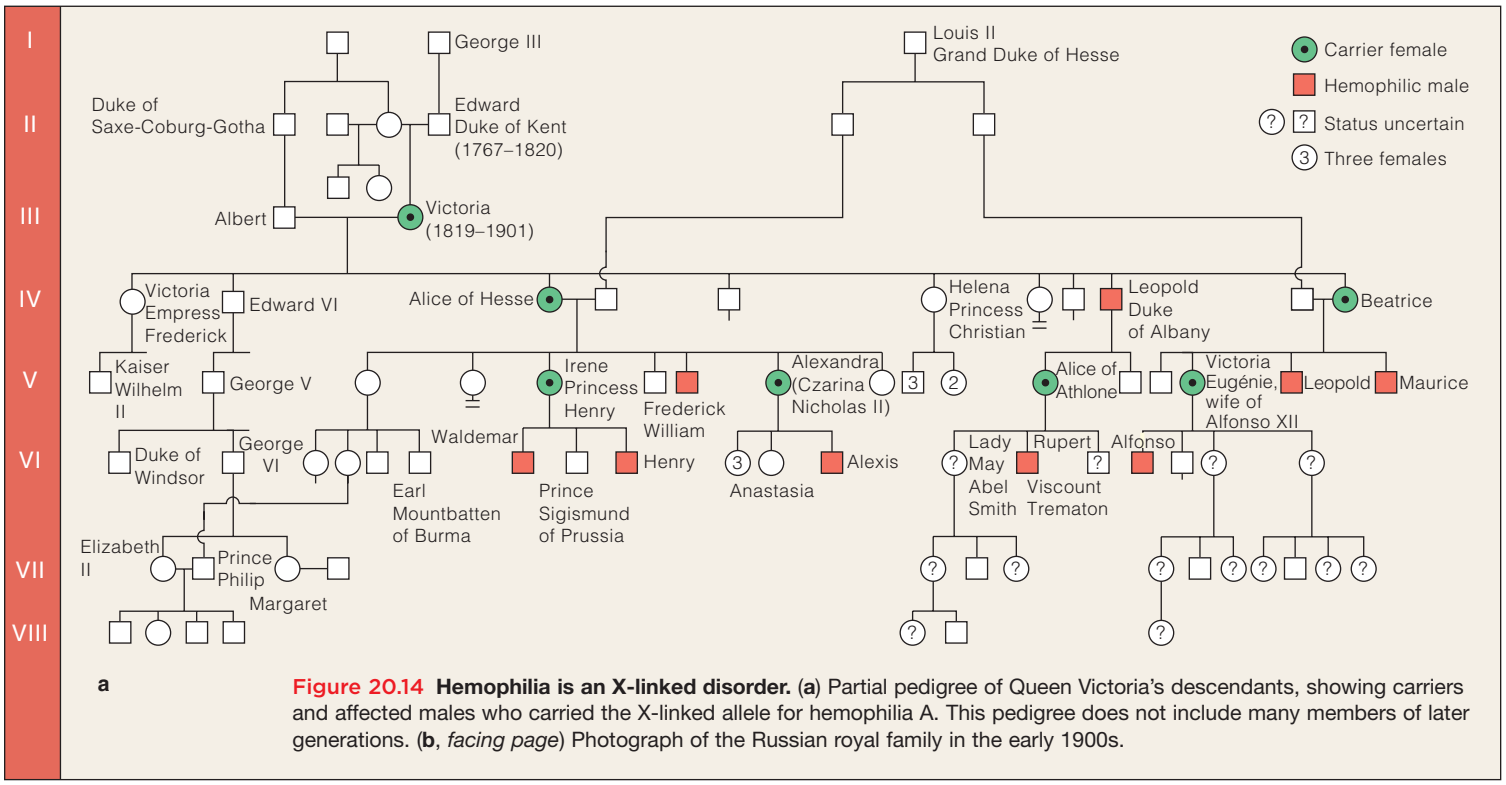


Figure 20.13 Animated! Here is one pattern for X-linked inheritance. It shows the outcomes possible when the mother carries a recessive allele on one of her X chromosomes (*red*).

Hemophilia A affects about 1 in 7,000 males. Among nineteenth-century European royal families, however, the frequency was unusually high because close relatives often married. Queen Victoria of England and two of her daughters were carriers. In a pedigree developed some years ago, more than 15 of her 69 descendants at that time were affected males or female carriers (Figure 20.14).



a

Figure 20.14 Hemophilia is an X-linked disorder. (**a**) Partial pedigree of Queen Victoria's descendants, showing carriers and affected males who carried the X-linked allele for hemophilia A. This pedigree does not include many members of later generations. (**b**, *facing page*) Photograph of the Russian royal family in the early 1900s.

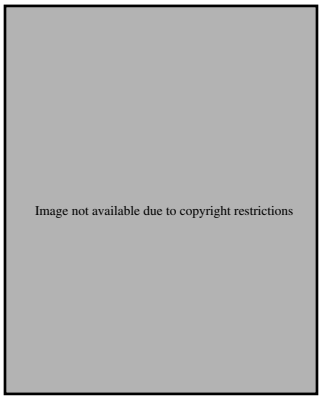
You may recall from Chapter 6 that diseases lumped under "muscular dystrophy" involve progressive wasting of muscle tissue. **Duchenne muscular dystrophy (DMD)** is X-linked. It affects 1 in 3,500 males, usually in childhood. As muscles degenerate, affected boys become weak and unable to walk. They usually die by age 20 from cardiac or respiratory failure. The gene that is mutated in DMD normally encodes the protein dystrophin, which gives structural support to muscle fibers. In DMD, muscle fibers lack dystrophin, so they can't withstand the physical stress of contraction and break down. In time the whole muscle is destroyed.

Red/green color blindness is an X-linked recessive trait. About 8 percent of males in the United States have this condition. It arises from mutation of an allele that codes for the protein opsin, which binds visual pigments in cone cells of the retina. Females also can have red/green color blindness, but this occurs rarely because a girl must inherit the recessive allele from both parents. The genes for opsin and blood clotting factor VIII are closely linked, so often hemophilia and red/green color blindness are inherited together.

Some X-linked abnormalities are quite rare

The **faulty enamel trait** is one of a few known examples of a trait caused by a dominant mutant allele that is X-linked. With this disorder, the hard, thick enamel coating that normally protects teeth fails to develop properly (Figure 20.15).

b The Russian royal family members. All are believed to have been executed near the end of the Russian Revolution. They were recently exhumed from their hidden graves, but DNA fingerprinting indicated that the remains of Alexis and one daughter, Anastasia, were not among them. The search has continued for other graves where the two missing children might have been buried.



On rare occasions, someone whose sex chromosomes are XY develops as a female. The result is **testicular feminizing syndrome**, or "androgen insensitivity." This is the condition that affected Santhi Soundarajan, the champion athlete featured in the introduction to Chapter 17. As you may remember, in Santhi and others with this syndrome, a gene mutation on the X chromosome produces defective receptors for male sex hormones (androgens), including testosterone. Normally, cells in the testes and other male reproductive organs bind one or more of the hormones and then develop further. With defective receptors, however, they can't bind the hormones. As a result, the embryo develops externally as a female but has no uterus or ovaries.

Many factors complicate genetic analysis

This chapter's examples of autosomal and X-linked traits give a general idea of the clues that geneticists look for. Genetic analysis is usually a difficult task, however. These days few people have large families, so it may be necessary to pool several pedigrees. Typically the geneticist will make detailed analyses of clinical data and keep abreast of current research, in part because more than one gene may be responsible for a given phenotype. For example, we know of dozens of conditions that can arise from a mutated gene on an autosome or from a mutated gene on the X chromosome. Also, some genes on autosomes are dominant in males but recessive in females—so they may initially appear to be due to X-linked recessive inheritance, even though they are not.

Take-Home Message

What are some inheritance patterns for the X chromosome?

- A trait that shows up most often in males and that a son can inherit only from his mother is most likely passed on through X-linked recessive inheritance.
- A few rare mutant traits are passed to offspring via X-linked dominant inheritance. A heterozygous mother will pass the allele to half her offspring. An affected father will pass the allele only to his daughters.

20.7 Custom Cures

Everybody's different. And thanks to our genes, so is every *body*. Because each of us has our own personal mix of alleles—the varying chemical forms of genes—we also may respond differently to therapeutic drugs. A new field of study called *pharmacogenetics* aims to pinpoint genetic variations that influence how individuals respond to medications. The idea is to allow physicians to custom-prescribe the drugs that will be safest and most effective for each patient.

All medicines work for some people, but none is a perfect fit for all. Blood pressure drugs are an example. There are more than 100 different ones, partly because there are many individual differences in how well each one controls high blood pressure. The medication and dose that work well for one patient may be only modestly effective for another, or may cause dangerous or unpleasant side effects for someone else. Figuring out the best course often is a matter of trial and error.

How can we take the guesswork out of prescribing drugs? A first step is identifying the genes that control common reactions to various drugs. That research is happening now (Figure 20.16). The technology for rapid, low-cost genetic screening is becoming widely available. With these tools, a physician could order a genetic profile for a patient and use it to select the best medicine to deal with that person's illness.

Pharmacogenetics promises to improve patient care by allowing doctors to tailor treatments to their patients' genes. As medical treatment moves in this direction, it will be important to have safeguards in place to protect the privacy of patients' genetic records.

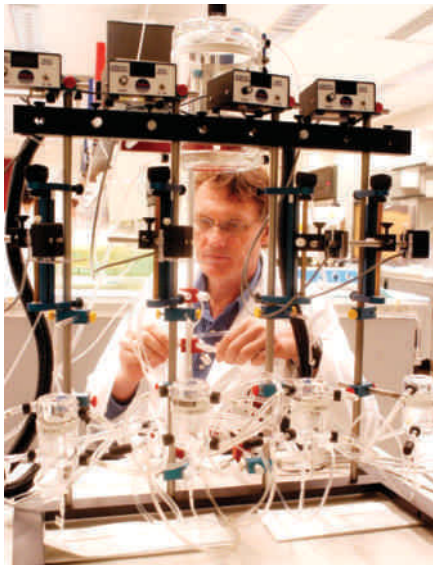


Figure 20.16
Dr. Stephen Liggett is a researcher in the field of pharmacogenetics. He is studying genes that control how patients respond to asthma drugs.

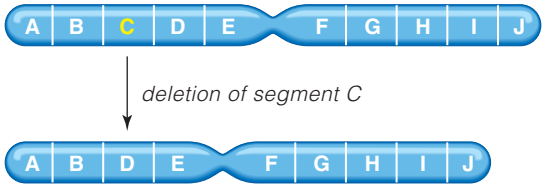
20.8 Changes in a Chromosome or Its Genes

- **The structure of a chromosome isn't "written in stone." It can change in a variety of ways.**

You may recall that DNA in chromosomes consists of various types of nucleotides linked by chemical bonds (Section 2.13). A **gene mutation** is a change in one or more of the nucleotides that make up a gene. Mutations can arise in several ways that we will discuss in detail in Chapter 21. In this section we are concerned with changes in the structure of whole chromosomes. During meiosis, pieces of chromosomes can be deleted, duplicated, or moved around in other ways. The result often is harmful.

Various changes in a chromosome's structure may cause a genetic disorder

A chromosome region may be deleted spontaneously, or by a virus, irradiation, chemical assaults, or some other environmental factor:



Any part of a chromosome can be lost. Wherever such a **deletion** happens, it permanently removes one or more of the chromosome's genes. The loss of a gene can lead to

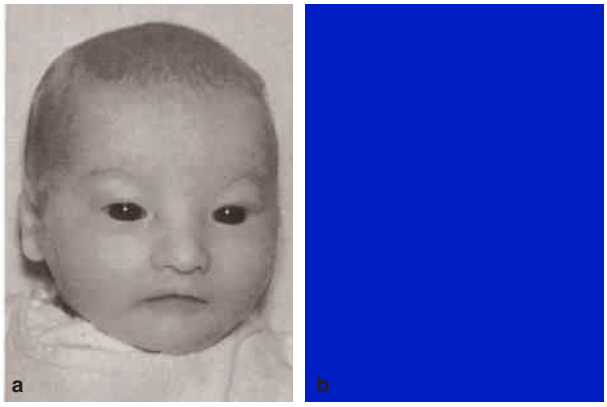


Figure 20.17 **This baby boy developed cri-du-chat syndrome.** Having ears low on the head relative to the eyes (**a**) is a typical sign of the disorder. (**b**) The same boy four years later.

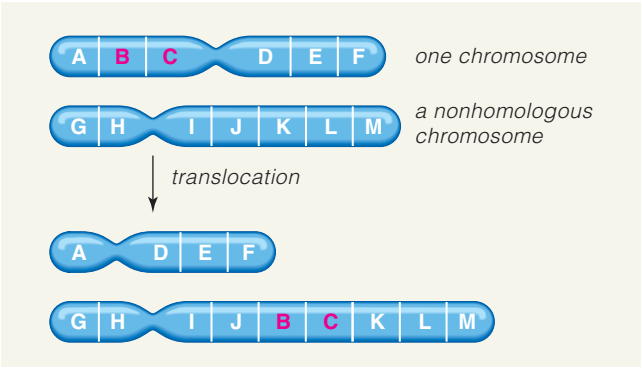


Figure 20.18 Animated! **A translocation is one kind of chromosome change.**

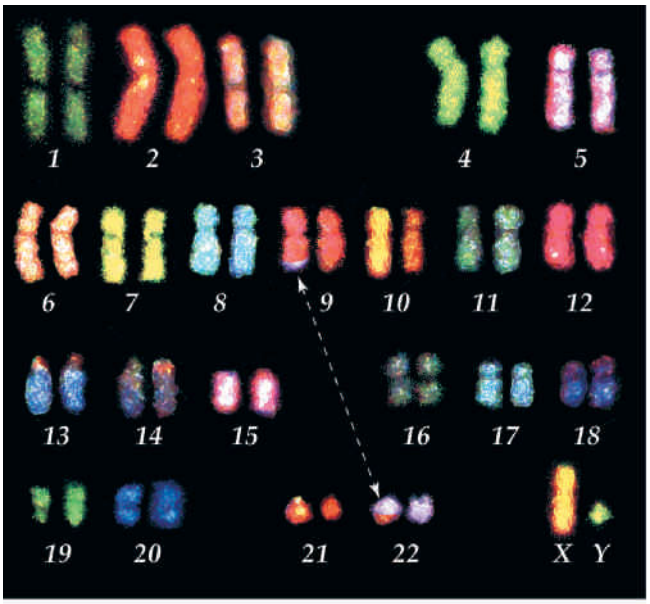


Figure 20.19 A karyotype may reveal damage to a chromosome. This is a spectral karyotype of the forty-six chromosomes in a human diploid cell. The arrow indicates the bit of chromosome 22 fused to the Philadelphia chromosome (chromosome number 9) before it was altered.

serious problems. For example, one deletion from human chromosome 5 leads to abnormal mental development and an abnormally shaped larynx. When an affected infant cries, the sounds produced resemble meowing—hence the name of the disorder, **cri-du-chat** (French, meaning "cat cry"). Figure 20.17 shows an affected child.

Given that humans have diploid cells, it might seem logical that genes on the affected chromosome's homologue would make up for the loss. In fact, this often happens if a segment deleted from one chromosome is present—and normal—on the homologous chromosome. However, if the remaining, homologous segment is abnormal or carries a harmful recessive allele, nothing will mask its effects.

Even normal chromosomes contain the changes called **duplications**, which are gene sequences that are repeated. Often the same gene sequence is repeated thousands of times. You might guess that so much duplicate DNA would be harmful, but no genetic disorder has yet been linked to duplication.

Another kind of chromosome change is called a **translocation**. Here, part of one chromosome exchanges places with a corresponding part of another chromosome that is *not* its homologous partner (Figure 20.18). This sort of change to a chromosome's structure is virtually sure to be harmful. For instance, in some people a region of chromosome 8 has been translocated to chromosome 14—and the result can be several rare types of cancer. The disease develops because genes in that region are no longer properly regulated, a topic that you will read more about in Chapter 22.

Patients who have a chronic type of leukemia (a blood cell cancer) have an abnormally long chromosome 9—called the Philadelphia chromosome after the city where it was discovered. The extra length is actually a piece of chromosome 22. By chance, both chromosomes break in a stem cell in bone marrow. Then, each broken piece reattaches to the *wrong* chromosome—and a gene located at the end of chromosome 9 becomes fused with a gene in chromosome 22 (Figure 20.19). Instructions from this altered gene lead to the synthesis of an abnormal protein. In some way that researchers do not yet understand, that protein promotes the runaway multiplication of white blood cells.

In the next section we will look at some genetic effects that can arise when a gamete or new embryo receives an abnormal number of chromosomes—either too few or too many.

Take-Home Message

How can changes in a chromosome's structure cause a disorder?

- Genetic disorders can be due to mutations on genes on chromosomes or from changes in the structure of one or more chromosomes.
- A viral infection, radiation, and other factors can delete some part of a chromosome. Sometimes the genes of a normal segment on the affected chromosome's homologue can make up for the loss.
- In a duplication, a gene sequence is repeated in a chromosome.
- In a translocation, part of a chromosome is moved to a nonhomologous chromosome.

20.9 Changes in Chromosome Number

- **Several kinds of events can increase or decrease the number of chromosomes in gametes.**

Sometimes gametes—and, later on, embryos—end up with the wrong chromosome number. The effects range from minor physical ones to deadly disruption of body function. More often, an affected fetus is miscarried, or spontaneously aborted before birth.

About half of fertilized eggs have a lethal condition called *aneuploidy* (AN-yoo-ploy-dee). In this situation, the embryo doesn't have an exact multiple of the normal haploid set of 23 chromosomes. A *polyploid* embryo has three, four, or more sets of the normal haploid set of 23 chromosomes. All but 1 percent of human polyploids die before birth, and the rare newborns die soon afterward.

Chromosome numbers can change during mitosis or meiosis or even at fertilization. For instance, a cell cycle might advance through DNA duplication and mitosis; then for some reason it stops before the dividing cell's cytoplasm divides. The cell then is polyploid—it has four of each type of chromosome.

Nondisjunction is a common cause of abnormal numbers of autosomes

In **nondisjunction**, one or more pairs of chromosomes fail to separate during mitosis or meiosis. Here again, some or all of the resulting cells end up with too many or too few chromosomes (Figure 20.20).

If fertilization involves a gamete that has an extra chromosome ($n + 1$), the result will be **trisomy**: the new individual will have three of one type of chromosome ($2n + 1$). If the gamete is missing a chromosome, then the result is **monosomy** ($2n - 1$). Most changes in the number of autosomes arise through nondisjunction when meiosis is forming gametes. About 1 in every 1,000 children is born with trisomy 21—three copies of chromosome 21.

A person with trisomy 21 will have **Down syndrome** (Figure 20.21). Symptoms vary, but most affected people are mentally retarded. About 40 percent develop heart defects. Because of abnormal skeletal development, older children have shortened body parts, loose joints, and poorly aligned hip, finger, and toe bones. Their muscles and muscle reflexes are weak, and their motor functions develop slowly. With special training, though, people with Down syndrome often engage in normal activities.

For women, the incidence of nondisjunction increases with age. The probability that a woman will conceive an embryo with Down syndrome rises steeply after age 35. Yet 80 percent of trisomic 21 infants are born to younger mothers. This statistic reflects the fact that between the ages of 18 and 35 women are the most fertile, so more babies are born to mothers in this age range.

Nondisjunction also can change the number of sex chromosomes

Most sex chromosome abnormalities come about as a result of nondisjunction as gametes are forming. Let's look at a few of the resulting phenotypes.

Turner syndrome and XXX females About 1 in every 5,000 newborns has **Turner syndrome**, in which a nondisjunction has reduced the chromosome number to 45 (Figure 20.22*a*). Most people with Turner syndrome are missing an X chromosome (in most cases, the one that would have come from the father), and the condition is

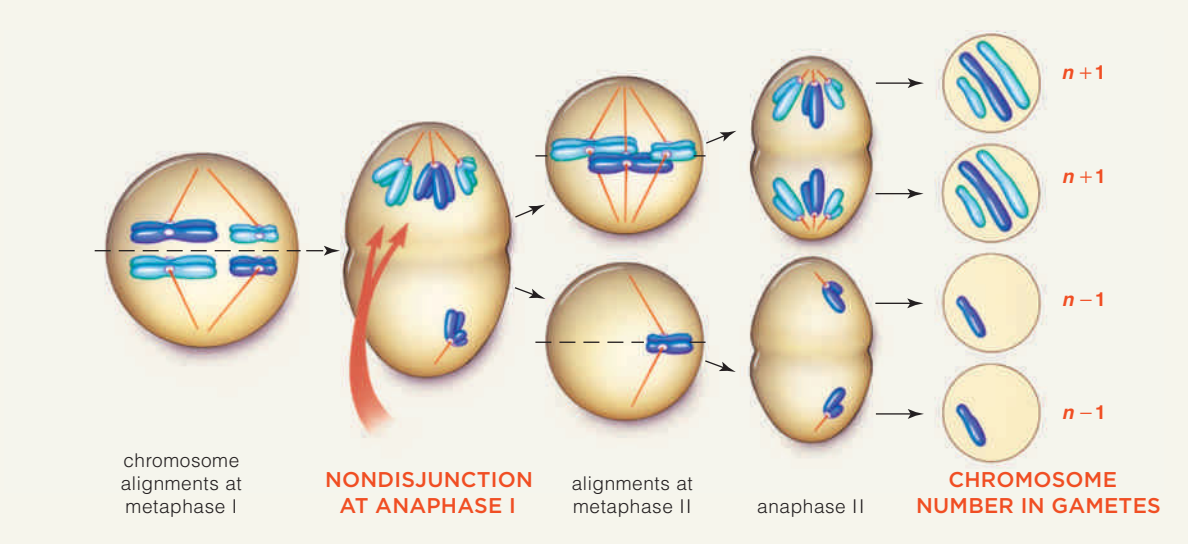


Figure 20.20 Animated! **In nondisjunction, chromosomes don't separate properly during meiosis.** In this example, chromosomes fail to separate during anaphase I of meiosis and so there is a change in the chromosome number in gametes that form.

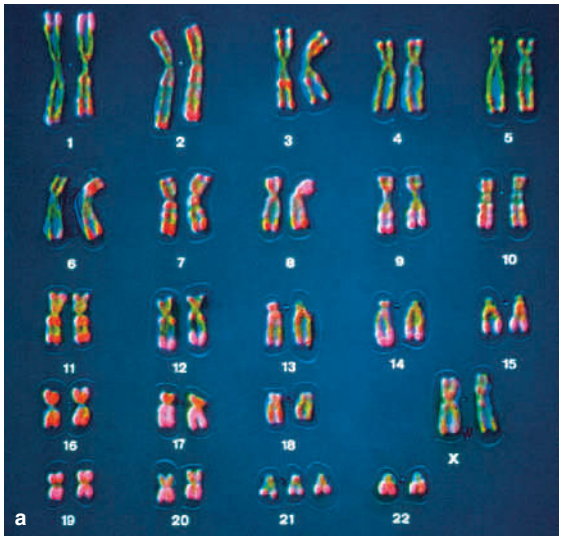


Figure 20.21 In Down syndrome there are three copies of chromosome 21. (**a**) In this karyotype of a girl with Down syndrome, note the extra copy of chromosome 21. (**b**) A boy with Down syndrome.

symbolized as XO. Turner syndrome occurs less often than other sex chromosome abnormalities, probably because most XO embryos are miscarried early in the pregnancy. Affected people are female and have a webbed neck and other phenotypic abnormalities. Their ovaries don't function, they are sterile, and secondary sexual traits don't develop at puberty. People who have Turner syndrome often age prematurely and have shortened life expectancies.

Roughly 1 in 1,000 females has three X chromosomes. Two of these X chromosomes are condensed to Barr bodies, and most XXX females develop normally.

Klinefelter syndrome In **Klinefelter syndrome**, nondisjunction produces the genotype XXY (Figure 20.22). This sex chromosome abnormality occurs in about 1 in 500 males. XXY males have low fertility and many have some mental retardation. They have abnormally small testes, sparse body hair, and may develop enlarged breasts. Testosterone injections can reverse some aspects of the phenotype.

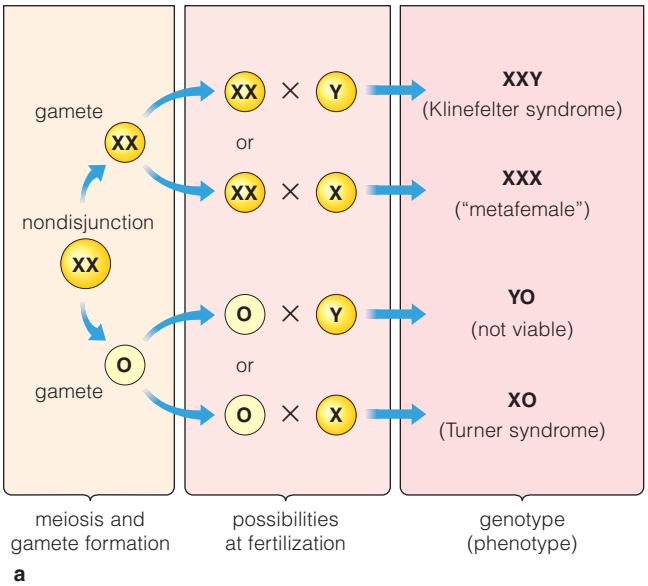


Figure 20.22 Genetic disorders can result from nondisjunction of X chromosomes followed by fertilization by normal sperm. (**a**) The chart shows the progression to both Klinefelter and Turner synromes. (**b**) The photograph shows a man with Klinefelter syndrome (left), along with his fiancee, whose son also has the syndrome.

XYY condition About 1 in every 1,000 males has one X and two Y chromosomes, a condition due to nondisjunction of duplicated Y chromosomes during meiosis. XYY males tend to be taller than average, but otherwise they have a normal male phenotype.

Take-Home Message

How can an abnormal chromosome number arise?

- Most changes in the number of chromosomes arise due to nondisjunction during meiosis and the formation of gametes.

IMPACTS, ISSUES

Menacing Genes

TODAY advanced prenatal testing methods allow expectant parents to learn the nature of a wide variety of a developing embryo's traits. When the results reveal a genetic disorder, some parents decide to end the pregnancy but others opt to continue, knowing they and their child will have to face the health consequences of the child's likely disorder.

How Would You Vote?

Do we as a society want to encourage women to give birth only to offspring who will not develop serious gene-based medical problems? See CengageNOW for details, then vote online.

Summary

Section 20.1 A gene has a specific location on a specific chromosome. The genes on a chromosome are physically linked. Those that are closest together usually end up in the same gamete.

Autosomes are the same in males and females. They are roughly the same in size and shape and carry genes for the same traits. Sex chromosomes (X and Y) differ from each other in size, shape, and the genes they carry.

- Use the animation and interaction on CengageNOW to learn how to create a karyotype.

Section 20.3 A person's gender is determined by the father's sperm, which can have either an X or a Y chromosome. Males have an XY genotype, females are XX. Genes on the X and Y chromosomes are X-linked and Y-linked, respectively. In a female, X inactivation shuts down the expression of genes carried on one of her X chromosomes.

- Use the animation and interaction on CengageNOW to see how a developing embryo's gender is determined.

Section 20.4 A pedigree chart can help establish inheritance patterns and track genetic abnormalities through several generations of a family. Table 20.1 lists some common genetic disorders.

- Use the animation and interaction on CengageNOW to learn more about making a human pedigree.

Section 20.5 Genetic disorders provide information about patterns of gene inheritance. In disorders that involve autosomal recessive inheritance, a person who is homozygous for a recessive allele has the recessive phenotype. Heterozygotes generally have no symptoms.

In autosomal dominant inheritance, a dominant allele usually is expressed to some degree.

- Use the animation and interaction on CengageNOW to learn more about autosomal inheritance.

Sections 20.6, 20.7 Many genetic disorders are X-linked—the mutated gene occurs on the X chromosome. Males, who inherit only one X chromosome, typically are affected. Sex-influenced traits, such as pattern baldness, appear more frequently in one sex. They may reflect the varying influences of sex hormones.

- Use the animation and interaction on CengageNOW to investigate X-linked inheritance.

Section 20.8 A chromosome's structure can be changed by deletions, duplications, or translocations. Such changes usually lead to harmful changes in traits.

Section 20.9 Chromosome number can be altered by nondisjunction, in which one or more pairs of chromosomes do not separate during meiosis or mitosis. In trisomy, a new individual inherits an extra copy of one type of chromosome. If one copy of a given chromosome is missing, the condition is called monosomy.

Review Questions

1. How do X and Y chromosomes differ?
2. What is a "carrier" of a genetic trait?
3. What evidence indicates that a trait is coded by a dominant allele on an autosome?
4. Explain the difference between an X-linked trait and a sex-influenced trait.
5. Explain what nondisjunction is, and give two examples of phenotypes that can result from it.

Self-Quiz *Answers in Appendix V*

1. _____ segregate during _____.
   a. Homologues; mitosis
   b. Genes on one chromosome; meiosis
   c. Homologues; meiosis
   d. Genes on one chromosome; mitosis

2. The alleles of a gene on homologous chromosomes end up in separate _____.
   a. body cells
   b. gametes
   c. nonhomologous chromosomes
   d. offspring
   e. both b and d are possible

3. Genes on the same chromosome tend to stay together during _____ and end up in the same _____.
   a. mitosis; body cell
   b. mitosis; gamete
   c. meiosis; body cell
   d. meiosis; gamete
   e. both a and d

TABLE 11.1 Examples of Human Genetic Disorders and Genetic Abnormalities

Disorder or Abnormality	Main Symptoms
Autosomal recessive inheritance	
Albinism	Absence of pigmentation
Hereditary methemoglob inemia	Blue skin coloration
Cystic fibrosis	Abnormal glandular secretions leading to tissue, organ damage
Ellis–van Creveld syndrome	Dwarfism, heart defects, polydactyly
Fanconi anemia	Physical abnormalities, bone marrow failure
Galactosemia	Brain, liver, eye damage
Phenylketonuria (PKU)	Mental impairment
Sickle-cell anemia	Adverse pleiotropic effects on organs throughout body
Autosomal dominant inheritance	
Achondroplasia	One form of dwarfism
Camptodactyly	Rigid, bent fingers
Familial hypercholesterolemia	High cholesterol levels in blood; eventually clogged arteries
Huntington's disease	Nervous system degenerates progressively, irreversibly
Marfan syndrome	Abnormal or no connective tissue
Polydactyly	Extra fingers, toes, or both
Progeria	Drastic premature aging
Neurofibromatosis	Tumors of nervous system, skin

Disorder or Abnormality	Main Symptoms
X-linked recessive inheritance	
Androgen insensitivity syndrome	XY individual but having some female traits; sterility
Red–green color blindness	Inability to distinguish among some or all shades of red and green
Fragile X syndrome	Mental impairment
Hemophilia	Impaired blood clotting ability
Muscular dystrophies	Progressive loss of muscle function
X-linked anhidrotic dysplasia	Mosaic skin (patches with or without sweat glands); other effects
Changes in chromosome structure	
Chronic myelogenous leukemia (CML)	Overproduction of white blood cells in bone marrow; organ malfunctions
Cri-du-chat syndrome	Mental impairment; abnormally shaped larynx
Changes in chromosome number	
Down syndrome	Mental impairment; heart defects
Turner syndrome (XO)	Sterility; abnormal ovaries, abnormal sexual traits
Klinefelter syndrome	Sterility; mild mental impairment
XXX syndrome	Minimal abnormalities
XYY condition	Mild mental impairment or no effect

4. The probability of a crossover occurring between two genes on the same chromosome _____.
a. is unrelated to the distance between them
b. increases the closer they are
c. increases the farther apart they are
d. zero

5. A chromosome's structure can be altered by _____.
a. deletions
b. duplications
c. translocations
d. all of the above

6. Nondisjunction can be caused by _____.
a. crossing over in meiosis
b. segregation in meiosis
c. failure of chromosomes to separate during meiosis
d. multiple independent assortments

7. A gamete affected by nondisjunction could have _____.
a. a change from the normal chromosome number
b. one extra or one missing chromosome
c. the potential for a genetic disorder
d. all of the above

8. Genetic disorders can be caused by _____.
a. gene mutations
b. changes in chromosome structure
c. changes in chromosome number
d. all of the above

9. A person who is a carrier for a genetic trait _____.
a. is heterozygous for a dominant trait
b. is heterozygous for a recessive trait
c. is homozygous for a recessive trait
d. could be either a or b but not c

10. Match the following chromosome terms appropriately.

____crossing over	a. a chemical change in DNA that may affect genotype and phenotype
____deletion	
____nondisjunction	
____translocation	b. movement of a chromosome segment to a nonhomologous chromosome
____gene mutation	c. disrupts gene linkages during meiosis
	d. causes gametes to have abnormal chromosome numbers
	e. loss of a chromosome segment

Critical Thinking

1. If a couple has six boys, what is the probability that a seventh child will be a girl?
2. Human sex chromosomes are XX for females and XY for males.
   a. From which parent does a male inherit his X chromosome?
   b. With respect to an X-linked gene, how many different types of gametes can a male produce?
   c. If a female is homozygous for an X-linked allele, how many different types of gametes can she produce with respect to this allele?
   d. If a female is heterozygous for an X-linked allele, how many different types of gametes can she produce with respect to this allele?
3. As described in this chapter, people with Down syndrome have an extra copy of chromosome 21, for a total of 47 chromosomes in their body cells. However, in a few cases of Down syndrome, 46 chromosomes are present. This total includes two normal-looking chromosomes 21, one normal chromosome 14, and a longer-than-normal chromosome 14. Interpret this observation. How can these individuals have 46 chromosomes?
4. If a trait appears only in males, is this good evidence that the trait is due to a Y-linked allele? Explain why you answered as you did.
5. A woman unaffected by hemophilia A whose father had hemophilia A marries a man who also has hemophilia A. If their first child is a boy, what is the probability he will have the disorder?
6. Among people of European descent, about 4 percent have the allele for cystic fibrosis. Yet only about 1 in 2,500 people actually has the disorder. What is the most likely reason for this finding?
7. The young woman shown below has albinism—very pale skin, white hair, and pale blue eyes. This phenotype, typically caused by a recessive allele, is due to the absence of melanin, which imparts color to the skin, hair, and eyes. Suppose a person with albinism marries a person with typical pigmentation and they have one child with albinism and three with typical pigmentation. What is the genotype of the parent with typical pigmentation? Why is the ratio of this couple's offspring 3:1?

EXPLORE ON YOUR OWN

Several mutant genes are known to be associated with neurobiological disorders (NBDs) such as schizophrenia, which affects 1 of every 100 people worldwide. Schizophrenia is characterized by delusions, hallucinations, disorganized speech, and abnormal social behavior. Another facet of schizophrenia and other NBDs (such as bipolar disorder) is that affected people often are exceptionally creative. One example is John Nash (Figure 20.23*a*), the brilliant mathematician and Nobel Prize winner whose battle with schizophrenia was portrayed in the film *A Beautiful Mind*. Another was the writer Virginia Woolf (Figure 20.23*b*), who committed suicide after a long mental breakdown.

Evidence suggests to some researchers that a number of other highly creative, distinguished historical figures, possibly including Abraham Lincoln, suffered from some type of NBD. To explore this topic further, do an Internet search and make a list of ten well-known people from the past who may have had an NBD. What behaviors or other characteristics have been cited to support the hypothesis that each individual was affected by an NBD?

Figure 20.23 **Some highly creative people have suffered from a genetic neural disorder.** Two famous cases are (**a**) mathematician John Nash and (**b**) writer Virginia Woolf.

DNA, Genes, and Biotechnology

21

IMPACTS, ISSUES

Golden Rice, or "Frankenfood"?

GENETICALLY modified, or "GM" food is a hot topic these days. In the United States, it is probably impossible to avoid such foods—a whopping 38 percent of soybeans and 25 percent of corn crops are engineered to withstand weedkillers or make their own pesticides. For years, the corn and soybeans have been used in breakfast cereals, soy sauce, vegetable oils, beer, soft drinks, and lots of other food products. They also are fed to farm animals.

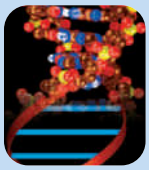
Golden Rice

In Europe, public resistance to genetically modified food is strong. Many people speak out against what the tabloids call "Frankenfoods." Protesters like those pictured at left often rip up crops. Worries abound that such foods may be more toxic, less nutritious, and promote antibiotic resistance.

On the other hand, biotechnologists envision a new "green revolution" in which GM food plants can help feed the hungry and improve nutrition. For example, about 140 million children under the age of six suffer blindness and and other serious health problems due to a vitamin A deficiency. The deficiency can be corrected by eating one cup a day of a special gold-tinted rice that has been genetically engineered to contain beta carotene, a pigment formed in some plants that is a precursor (preliminary compound) for the formation of vitamin A. As it happens, rice is a cheap, staple food in many parts of the world where poor people suffer the most from vitamin A deficiency. For them Golden Rice might make the difference between relative good health and a life of misery.

This chapter discusses DNA and how our cells use it to make the proteins all of us need to survive. We will also look at examples of how that knowledge is being applied in biotechnology.

KEY CONCEPTS



Genetic Instructions in DNA

DNA consists of two strands of nucleotides twisted into a double helix. When a cell copies its DNA, a "parent" strand is joined to a new, complementary strand. A gene is a sequence of nucleotides in DNA. **Sections 21.1, 21.2**

Making Proteins

Genes are the genetic code for proteins. Cells build proteins in two steps. First, an mRNA molecule is transcribed from DNA. Then mRNA is translated into a string of amino acids, the primary structure of proteins. **Sections 21.3–21.6**

Engineering and Exploring Genes

Biotechnology is a tool for changing genes and studying their effects. Practical applications include gene therapy, DNA fingerprinting, and studying the human genome. **Sections 21.7–21.12**

LINKS TO EARLIER CONCEPTS

- This chapter draws on what you know about DNA and RNA (2.13) and how a string of amino acids forms the primary structure of a protein (2.11).
- The chapter's discussion of how DNA is copied will deepen your understanding of events in the cell cycle, before chromosomes are duplicated and assorted into new cells (18.3, 18.4, 18.7).
- Here you will learn more about RNA's role in making proteins. You will also gain a fuller understanding of the key role a cell's ribosomes (3.6) play in protein synthesis.

How Would You Vote?

Genetically modified (GM) food plants are a $50 billion a year industry in the United States alone. In addition to helping feed the hungry, such crops have higher yields, may help hold down food production costs, and reduce the use of polluting agricultural chemicals. Despite these benefits, some people want all GM foods banned on the grounds that they may pose unforeseen dangers to human health and the environment. Would you support such a ban? See CengageNOW for details, then vote online.

21.1 DNA: A Double Helix

- **DNA is built of nucleotides—the subunits of the biological molecules called nucleic acids. DNA nucleotides are arranged to form a double helix.**
- **Links to Nucleic acids 2.13, Genes 19.1**

DNA is built of four kinds of nucleotides

As you know from Chapter 18, a chromosome consists of a DNA molecule and proteins. A molecule of DNA, in turn, is built from four kinds of **nucleotides**, the building blocks of nucleic acids (Figure 21.1).

A DNA nucleotide is built of a five-carbon sugar (deoxyribose), a phosphate group, and one of these four nitrogen-containing bases:

adenine	guanine	thymine	cytosine
A	G	T	C

Many researchers were in the race to discover DNA's structure, but James Watson and Francis Crick were the first to realize that DNA consists of two strands of nucleotides twisted into a double helix. Nucleotides in a strand are linked together, like boxcars in a train, by strong covalent bonds. Weaker hydrogen bonds link the bases of one strand with bases of the other. The two strands run in opposite directions, as shown in Figure 21.2.

Chemical "rules" determine which nucleotide bases in DNA can pair up

The bases in the four DNA nucleotides have different shapes, and different sites where hydrogen bonds can form. These factors determine which bases can pair up. Adenine pairs with thymine, and guanine pairs with cytosine. Therefore, two kinds of **base pairs** occur in DNA: A—T and G—C. In a double-stranded DNA molecule, the amount of adenine equals the amount of thymine, and the amount of guanine equals the amount of cytosine.

While base pairs must form as we've just described—A with T and G with C—the nucleotides can line up in any order. For example, these are just three possibilities of the pattern one might find in DNA:

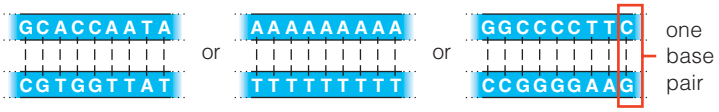
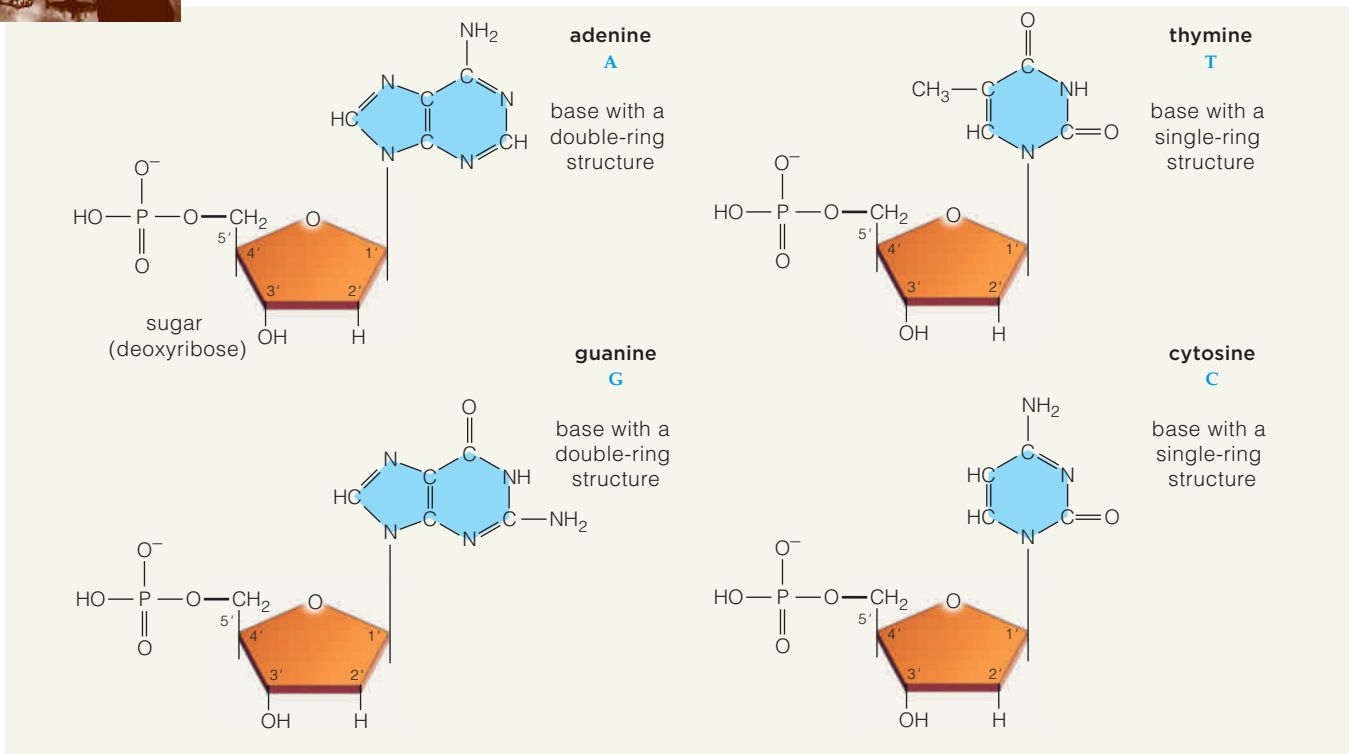


Figure 21.1 Animated! There are four kinds of nucleotides in DNA. Here the five-carbon sugars are *orange*. Each one has a phosphate group attached to its ring structure (below, on the left). Small numerals on the structural formulas identify the carbon atoms where various parts of the molecule are attached. The photograph shows James Watson (left) and Francis Crick, who figured out the structure of DNA.



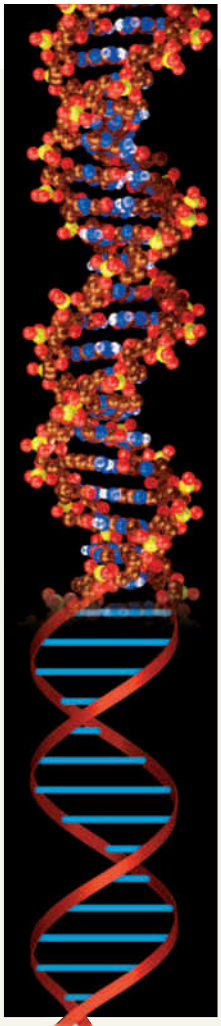
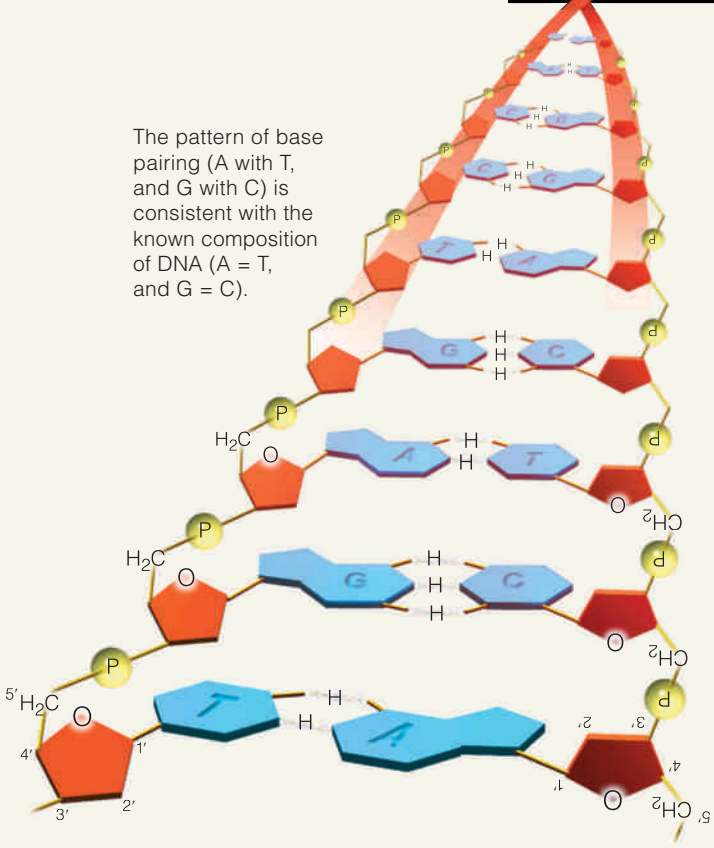


Figure 21.2 Animated!
This diagram shows how nucleotide bases are arranged in the DNA double helix. Three different models are combined here. Notice that the two sugar–phosphate backbones run in opposite directions. It may help to think of the sugar units of one strand as being upside down. By comparing the numerals used to identify each carbon atom of the deoxyribose molecule (1′, 2′, 3′, and so on), you can see that the strands run in opposing directions.



The pattern of base pairing (A with T, and G with C) is consistent with the known composition of DNA (A = T, and G = C).

Image not available due to copyright restrictions

A gene is a sequence of nucleotides

As you already know, genes are the units of heredity. Chemically, a **gene** is a sequence of nucleotides in a DNA molecule. The **nucleotide sequence** of each gene codes for a specific polypeptide chain. Polypeptide chains, remember, are the basic structural units of proteins. We'll see how they form later on. Figure 21.3 shows one way researchers can visualize small fragments of DNA.

Table 21.1 summarizes the main concepts of DNA structure we have discussed thus far. With these in mind, we now turn to a key feature of each DNA molecule—how it can be copied, or replicated, so that the information it contains is faithfully passed on to new generations.

TABLE 21.1 A DNA Summary

Nucleotide	Building blocks of nucleic acids; composed of phosphate and a nitrogen-containing base (A, G, T, or C)
Base pair	Two bases (A + T or G + C) held together by hydrogen bonds
Gene	A sequence of nucleotides in a DNA molecule

Take-Home Message

What are the parts of a DNA molecule?

- In a DNA molecule two strands of nucleotides are held together at their bases by hydrogen bonds. The two strands run in opposite directions and twist into a double helix.
- DNA's nucleotides are built of the sugar deoxyribose, a phosphate group, and one of the nitrogen-containing bases adenine (A), guanine (G), thymine (T), and cytosine (C).
- In a DNA molecule, two kinds of base pairs occur: A—T and G—C.
- Chemically, a gene is a sequence of nucleotides in DNA.

21.2 Passing on Genetic Instructions

- **Each DNA molecule must be faithfully copied so parents may pass on their traits to offspring.**
- **Links to DNA repair 17.12, Genes on chromosomes 20.1, the Cell cycle 18.3**

How is a DNA molecule duplicated?

Chapter 19 mentioned that DNA must be copied before a cell divides. This process is called **DNA replication**.

Enzymes easily break the hydrogen bonds between the two nucleotide strands of a DNA molecule. When enzymes and other proteins act on the molecule, one strand unwinds from the other and exposes stretches of its nucleotide bases. Cells contain stockpiles of free nucleotides that can pair with the exposed bases (A with T and G with C), and they are linked by hydrogen bonds. Each parent strand remains intact while a new strand is assembled on it, nucleotide by nucleotide.

As replication occurs, the newly formed double-stranded molecule twists back into a double helix. One strand is from the starting molecule, so *that* strand is said to be conserved. Only the second strand has been freshly synthesized—so each DNA molecule is really half new and half "old." The DNA replication mechanism is thus called **semiconservative replication** (Figure 21.4).

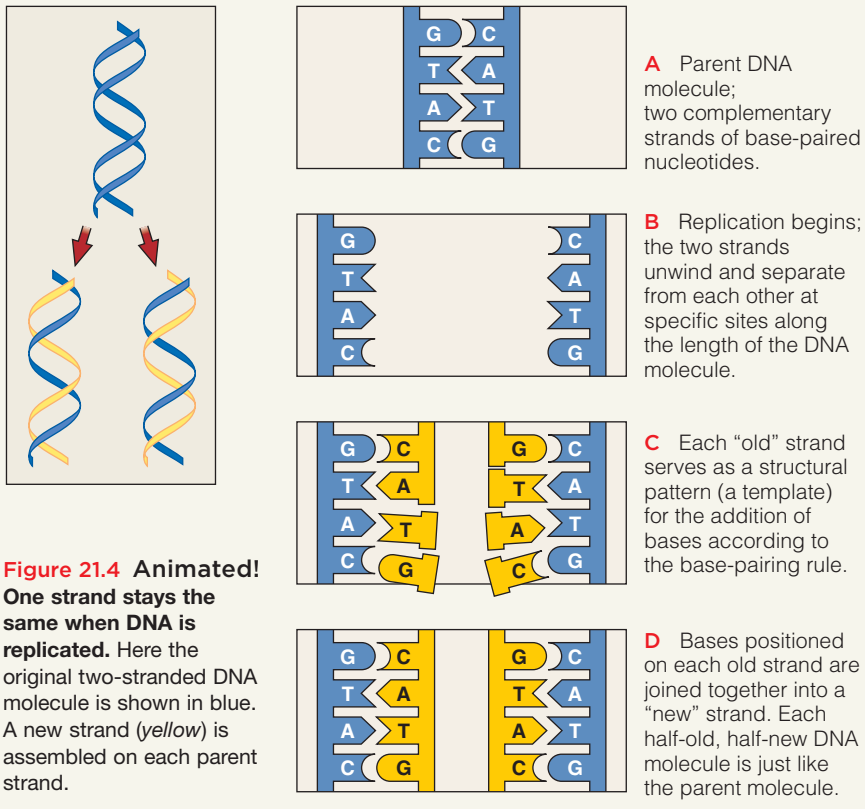


Figure 21.4 Animated! One strand stays the same when DNA is replicated. Here the original two-stranded DNA molecule is shown in blue. A new strand (*yellow*) is assembled on each parent strand.

During replication, enzymes called *DNA polymerases* and other proteins unwind the DNA molecule, keep the two unwound strands separated, and assemble and seal a new strand on each one. DNA polymerases also link the individual nucleotides on a parent strand.

Mistakes and damage in DNA can be repaired

DNA polymerases and other enzymes also act in **DNA repair**. There are many opportunities for problems to occur in a cell's DNA. For example, DNA is copied very rapidly—between ten and twenty nucleotides per second are added at a replication site. Every time a cell replicates its store of DNA before dividing, at least 3 billion nucleotides must be assembled properly. It's no wonder, then, that mistakes are made. It has been estimated that a human cell must repair breaks in a strand of its DNA up to 2 million times every hour! Luckily, if an error takes place during replication, enzymes may detect and correct the problem, restoring the proper DNA sequence. When an error is not fixed, the result is a mutation.

Previous chapters have noted that DNA is vulnerable to damage from certain chemicals, ionizing radiation, and ultraviolet light (as in sunlight or the rays of tanning lamps). One type of damage is the formation of *thymine dimers*. UV light causes two neighboring thymine bases to become linked (forming a dimer; Figure 21.5*a*). The new structure distorts the affected DNA molecule in a way that prevents effective DNA repair. A thymine dimer can lead to the genetic disorder called **xeroderma pigmentosum** (Figure 21.5*b*), in which radiation damage to DNA cannot be fixed.

As Chapter 22 discusses, unrepaired gene mutations are thought to be the underlying cause of a high percentage of cancers. For example, patients with xeroderma pigmentosum are at high risk for lethal skin cancer.

A mutation is a change in the sequence of a gene's nucleotides

Every so often, genes do change. Sometimes one base gets substituted for another in the nucleotide sequence. At other times, an extra base is inserted into the sequence or a base is deleted from it. These kinds of small-scale changes in the nucleotide sequence of genes are **gene mutations**.

Figure 21.6 shows two common kinds of gene mutations. Figure 21.6*b* diagrams a **base-pair substitution**, in which the wrong nucleotide is paired with an exposed base while DNA is being replicated. Proofreading enzymes may fix the error. But if they don't, a mutation will be established in the DNA in the next round of replication. As a result of this mutation, one amino acid might replace another during protein synthesis. This is what has happened in people who have sickle-cell anemia (Section 19.5). Figure 21.6*c* shows a **deletion**, in which a base has been lost.

In an **expansion mutation**, a nucleotide sequence is repeated over and over, sometimes many hundreds of times. Expansion mutations cause several genetic disorders, including Huntington disease and **fragile X syndrome** (Figure 21.7*a*), in which the brain does not develop properly.

Mutations also can result when segments of DNA called **transposable elements** move around. These bits of DNA can move from one location to another in the same DNA molecule or in a different one. The DNA of a human diploid cell typically contains hundreds of thousands of copies of one transposable element (called Alu). When it is inserted in a particular location, a genetic disorder called **neurofibromatosis** results (Figure 21.7*b*).

While mutations can occur in the DNA at any time in in any cell, they are inherited only when they take place in germ cells that give rise to gametes. Whether a mutation turns out to be harmful, neutral, or beneficial depends on a variety of factors, including how the resulting protein affects body functions.

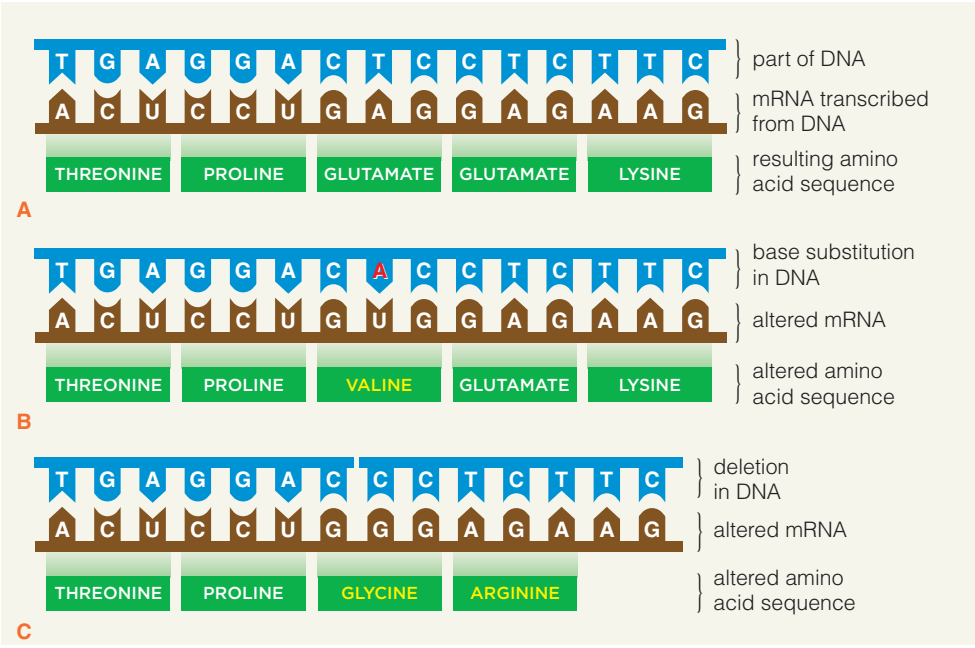
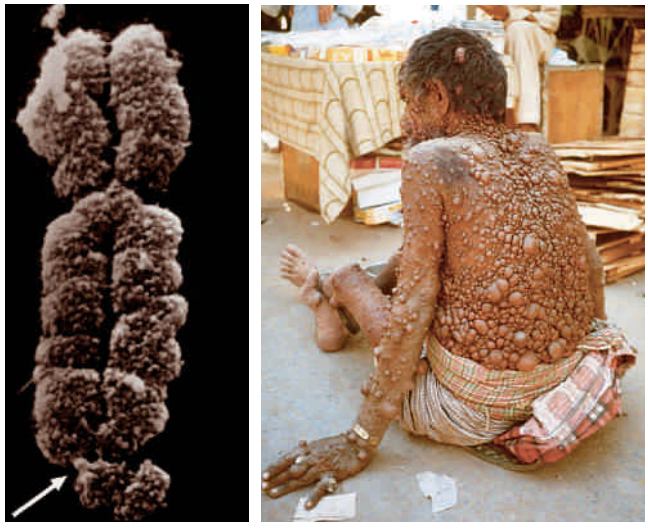


Figure 21.6 Animated! There are several types of gene mutations. (**a**) Part of a gene (*blue*), the mRNA (*brown*), and the specified amino acid sequence. (**b**) A base-pair substitution. (**c**) A deletion in DNA.



a b

Figure 21.7 Gene mutations cause numerous disorders. (**a**) A human chromosome showing the constriction that occurs with fragile X syndrome (*arrow*). (**b**) Soft skin tumors of a person with neurofibromatosis.

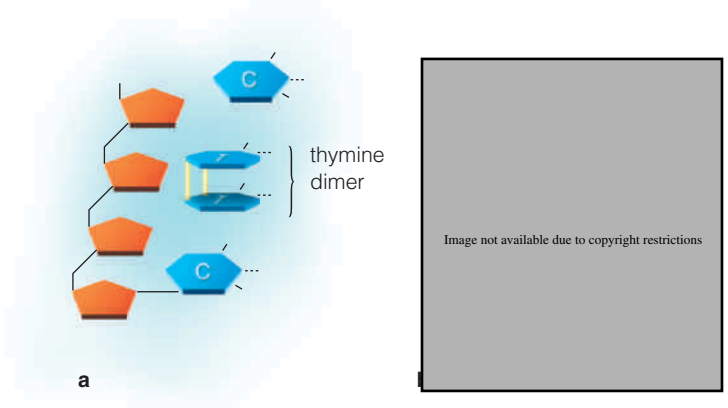


Figure 21.5 DNA damage can cause thymine dimers, which in turn may cause genetic disorders. (**a**) In this sketch, note the covalent bonds that have formed between two thymines. The two nucleotides to which the thymines belong form an abnormal structure that may interfere with replication of the DNA molecule.

Take-Home Message

How is DNA replicated?

- DNA replication is semiconservative. After the double helix unwinds, each parent strand stays intact and enzymes assemble a new, complementary strand on it.
- Enzymes involved in replication also may repair damage in DNA.
- A gene mutation is a change in one or more bases in the nucleotide sequence of DNA.
- A mutation may be harmful, neutral, or beneficial depending on how it affects body structures and functions.

21.3 DNA into RNA: The First Step in Making Proteins

- **Two processes, called transcription and translation, convert the information in DNA into proteins.**
- **Link to Primary protein structure 2.11**

The path from genes to proteins involves two processes, transcription and translation. In both, molecules of ribonucleic acid, or **RNA**, have major roles. Most often, RNA consists of a single strand. Structurally, it is much like a strand of DNA. Its nucleotides each consist of a sugar (ribose), a phosphate group, and a nitrogen-containing base. However, its bases are adenine, cytosine, guanine, and **uracil**, not thymine. Table 21.2 summarizes these differences.

	DNA	RNA
Sugar:	deoxyribose	ribose
Bases:	adenine, cytosine, guanine, thymine	adenine, cytosine, guanine, uracil

Like the thymine in DNA, the uracil in RNA base-pairs with adenine.

In **transcription**, molecules of RNA are assembled on DNA templates in the nucleus. In **translation**, which you'll read about in Section 21.6, RNA molecules move from the nucleus into the cytoplasm, where they in turn become templates for assembling polypeptide chains. When translation is complete, one or more polypeptide chains are folded into protein molecules. Said another way, DNA guides the synthesis of RNA, then RNA guides the synthesis of proteins.

TABLE 21.2 DNA and RNA

	DNA	RNA
Sugar	Deoxyribose	Ribose
Bases	Adenine, cytosine guanine, thymine	Adenine, cytosine, guanine, uracil

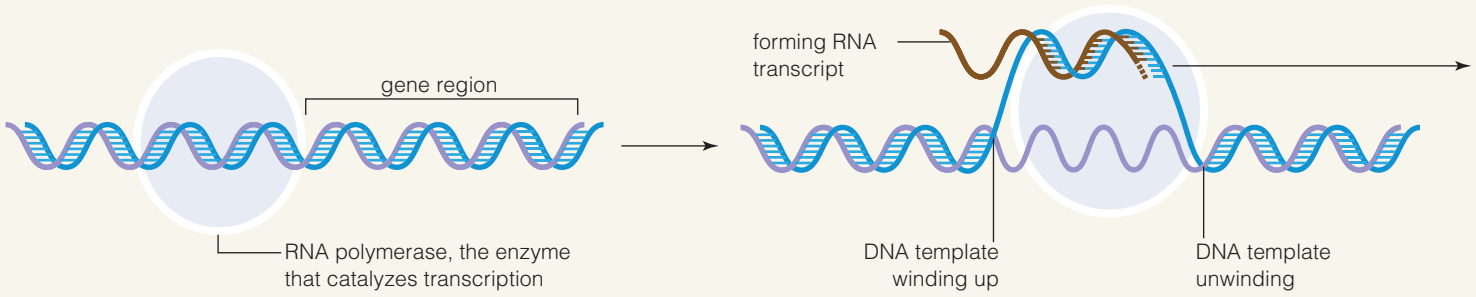
Genes are transcribed into three types of RNA:

ribosomal RNA (rRNA) — a nucleic acid chain that combines with certain proteins to form a ribosome, a structure on which a polypeptide chain is assembled

messenger RNA (mRNA) — a linear sequence of nucleotides that carries protein-building instructions; this "code" is delivered to the ribosome for translation into a polypeptide chain

transfer RNA (tRNA) — another nucleic acid chain that can pick up a specific amino acid and pair with an mRNA code word for that amino acid

An important point to remember is that only mRNA eventually is translated into a protein. The other two types of RNA operate in the process of translation.



A RNA polymerase binds to a promoter in the DNA. The binding positions the polymerase near a gene in the DNA.

In most cases, the nucleotide sequence of the gene occurs on only one of the two strands of DNA. Only the complementary strand will be translated into RNA.

B The polymerase begins to move along the DNA and unwind it. As it does, it links RNA nucleotides into a strand of RNA in the order specified by the base sequence of the DNA.

The DNA double helix winds up again after the polymerase passes. The structure of the "opened" DNA molecule at the transcription site is called a transcription bubble, due to its appearance.

Figure 21.8 Animated! In transcription, an mRNA molecule is assembled on a DNA template. The sketch in (**a**) shows a gene in part of a DNA double helix. The base sequence of one of the two nucleotide strands is used as the template. (**b–d**) Transcribing that gene results in a molecule of mRNA.

In transcription, DNA is decoded into RNA

In transcription, a strand of RNA is assembled on a DNA template according to the base-pairing rules:

base pairing in DNA replication

base pairing in transcription

Transcription takes place in the cell nucleus, but it is not the same as DNA replication. Only the gene serves as the template, not the whole DNA strand, and the enzymes involved are **RNA polymerases**. Also, transcription makes a single-stranded molecule, not one with two strands.

Transcription starts at a "promoter," a sequence of bases that signals the start of a gene. As transcription starts, a nucleotide "cap" is added to the beginning of the mRNA for protection. This capped end (designated 5′) is also where the mRNA will bind to a ribosome when the time comes for translation.

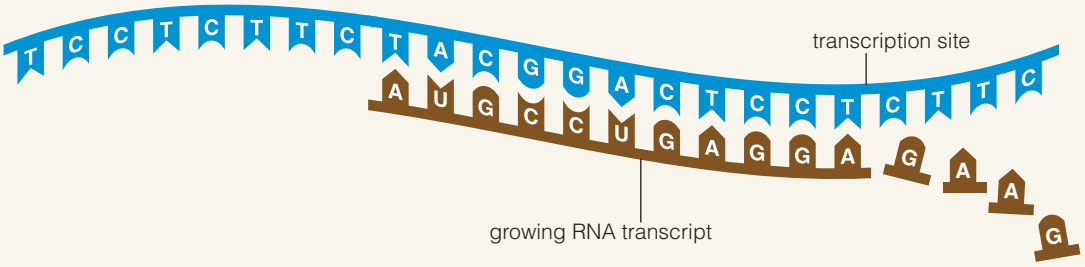
As RNA polymerase moves along the DNA, it joins nucleotides together (Figure 21.8). When it reaches a termination sequence of bases, the RNA strand called a transcript, is released, but it is not yet finished. It must be modified before its protein-building instructions can be used. For example, when many human genes are transcribed, this "pre-mRNA" contains sections called **introns**—in some cases including as many as 100,000 nucleotides! Introns may be a sort of genetic gibberish. Researchers have not discovered any that code for proteins.

All new mRNA transcripts also contain regions called **exons**. Unlike introns, exons are the nucleotide sequences that carry DNA's protein-building instructions. Before an mRNA leaves the nucleus, its introns are snipped out and its exons are spliced together. Now the mRNA is ready to enter the cell cytoplasm and be translated into a protein.

Gene transcription can be turned on or off

Most cells of your body carry the same genes. Many of those genes carry instructions for making proteins that are essential to any cell's structure and functioning. Yet each type of cell also uses a small subset of genes in specialized ways. For example, every cell carries the genes for hemoglobin, but only the precursors of red blood cells activate those genes. Each cell determines which genes are active and which gene products appear, when, and in what amounts. Some genes might be switched on and off throughout a person's life. Others might be turned on only in certain cells and only at certain times.

Genes are regulated by molecules that interact with DNA, RNA, or other substances. For example, **regulatory proteins** speed up or halt transcription. Some also may bind with noncoding DNA sequences and in this way trigger or shut down the transcription of a neighboring gene. This is how steroid hormones, such as cortisol, estrogen, and testosterone, act (Section 15.2).



C The base sequence of the new RNA strand is complementary to the base sequence of its DNA template—the gene.

D At the end of the gene region, the last stretch of the new transcript unwinds and detaches from the DNA template.

Take-Home Message

What is gene transcription?

- Protein synthesis has two steps, transcription and translation.
- In transcription, a sequence of bases in one strand of a DNA molecule is the template for assembling a strand of RNA. The RNA strand is built according to base-pairing rules. Before leaving the nucleus, new RNA transcripts are modified into their final form.
- Genes are turned on or off in different ways to produce specialized cell structures or functions.

21.4 The Genetic Code

- **The sequence of nucleotides in an mRNA molecule is like a string of three-letter protein-building "words."**
- **Link to Primary structure of proteins 2.11**

Codons are mRNA "words" for building proteins

Each "word" in the mRNA instructions for building a protein is a set of three nucleotide bases that are "read" by enzymes. These base triplets are called **codons**. There are sixty-four kinds of codons (Figure 21.9*a*). Together they are the **genetic code**—a cell's basic instructions for making proteins. Figure 21.9*b* shows how the order of different codons in an mRNA molecule determines the order of amino acids that are assembled into a protein.

Most of the twenty kinds of amino acids can be "ordered up" by more than one **start codon**. (For example, glutamate corresponds to the code words GAA *or* GAG.) The codon AUG also establishes the "reading frame" for translation. That is, ribosomes start their "three-bases-at-a-time" selections at an AUG that is the start signal in an mRNA strand. Three different **stop codons** (UAA, UAG, and UGA) can signal ribosomes to stop adding amino acids to the growing chain.

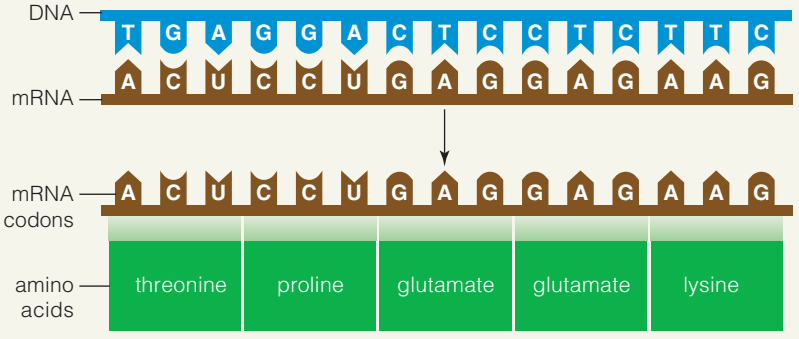
Take-Home Message

What is the genetic code?

- The genetic code is a set of sixty-four different groups of three mRNA nucleotide bases called codons.
- A cell's protein-making machinery "reads" codons, which specify different amino acids.

first base	second base U	second base C	second base A	second base G	third base
U	UUU phe	UCU ser	UAU tyr	UGU cys	U
	UUC phe	UCC ser	UAC tyr	UGC cys	C
	UUA leu	UCA ser	UAA STOP	UGA STOP	A
	UUG leu	UCG ser	UAG STOP	UGG trp	G
C	CUU leu	CCU pro	CAU his	CGU arg	U
	CUC leu	CCC pro	CAC his	CGC arg	C
	CUA leu	CCA pro	CAA gln	CGA arg	A
	CUG leu	CCG pro	CAG gln	CGG arg	G
A	AUU ile	ACU thr	AAU asn	AGU ser	U
	AUC ile	ACC thr	AAC asn	AGC ser	C
	AUA ile	ACA thr	AAA lys	AGA arg	A
	AUG met	ACG thr	AAG lys	AGG arg	G
G	GUU val	GCU ala	GAU asp	GGU gly	U
	GUC val	GCC ala	GAC asp	GGC gly	C
	GUA val	GCA ala	GAA glu	GGA gly	A
	GUG val	GCG ala	GAG glu	GGG gly	G

A



B

Figure 21.9 Animated! The genetic code consists of mRNA "words" called codons. **(a)** The codons in mRNA are nucleotide bases, "read" in blocks of three. Sixty-one of these base triplets correspond to specific amino acids. Three more are signals that stop translation.

The left column of the diagram shows the first of the three nucleotides in each mRNA codon. The middle columns show the second nucleotide. The right column shows the third. Reading from left to right, for instance, the triplet U G G corresponds to tryptophan. Both U U U and U U C correspond to phenylalanine.

(b) How genetic information is converted into a protein. First, a DNA strand is transcribed into mRNA. Notice how the mRNA's nucleotide sequence is complementary to the gene sequence in the DNA. Each mRNA codon called for one amino acid in a growing protein (polypeptide chain).

21.5 tRNA and rRNA

tRNA translates the genetic code

A cell's cytoplasm contains amino acids and tRNA molecules. Each tRNA has a "hook" site where it can attach to a specific amino acid. As shown in Figure 21.10, a tRNA also has an **anticodon**, a nucleotide triplet that can base-pair with codons. When a series of tRNAs bind to a series of codons, the matching up of codons and anticodons automatically lines up the amino acids attached to tRNAs in the order specified by mRNA.

A cell has more than sixty kinds of codons but fewer kinds of tRNAs. The needed match-ups occur anyway. Remember that by the base-pairing rules, adenine pairs with uracil, and cytosine with guanine. However, for codon–anticodon interactions, the rules loosen up for the third base. For example, only two tRNAs are needed to hook onto the codons CCU, CCC, CCA, and CCG, which all have instructions for making the amino acid proline.

rRNAs are ribosome building blocks

Gene by gene, mRNAs carry protein building instructions from the DNA in a cell's nucleus to the cytoplasm where amino acids are. In the cytoplasm, a cell's tRNAs come into contact with mRNAs at binding sites on the surfaces of ribosomes. Each ribosome has two subunits (Figure 21.11). The subunits are built in the nucleus from rRNA and proteins; then are shipped to the cytoplasm. There they will combine into ribosomes during translation, as described in the next section.

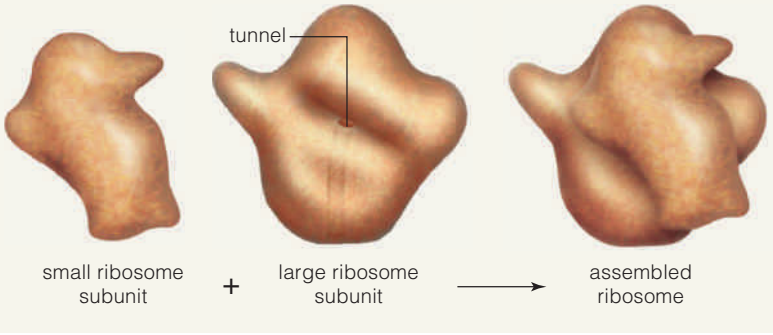


Figure 21.11 Animated! Ribosomes consist of small and large subunits formed by rRNA. Chains of amino acids—the primary structure of proteins, called polypeptide chains—are assembled on part of the small subunit. Newly forming chains move through a tunnel in the large subunit.

Take-Home Message

How do rRNAs and tRNAs help build proteins?

- The different tRNA anticodons bind specific codons in mRNA. In this way amino acids line up in the order specified by mRNA. Thus tRNAs translate mRNA into a corresponding sequence of amino acids.
- mRNAs carry protein-building instructions from a cell's DNA to its cytoplasm. rRNAs are subunits that combine into ribosomes.
- Amino acids are assembled into the linear sequence that is a protein's primary structure.

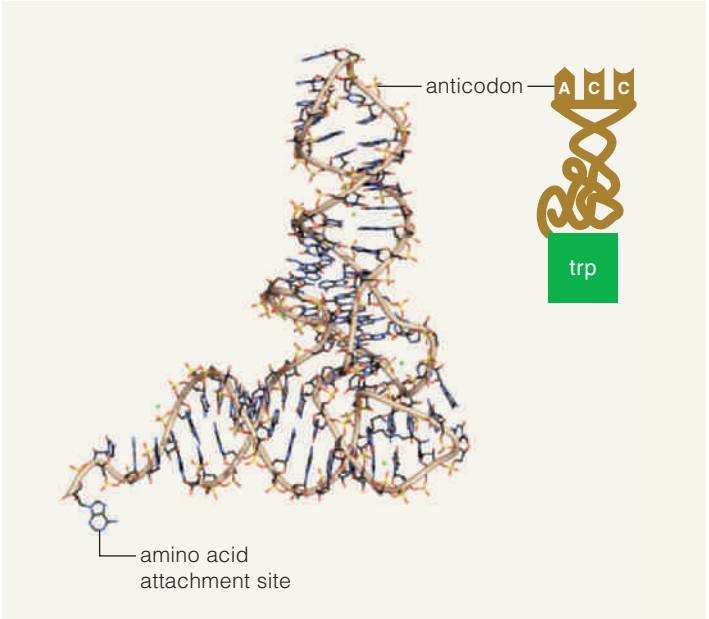


Figure 21.10 Animated! Amino acids "hook up" with tRNAs. Models of a tRNA that carries the amino acid tryptophan. Each tRNA's anticodon is complementary to an mRNA codon. Each also carries the amino acid that is specified by the codon.

21.6 The Three Stages of Translation

- **The protein-building instructions carried by mRNAs are translated into proteins. This process occurs ribosomes in the cytoplasm.**
- **Links to Protein primary structure 2.11, Ribosomes 3.6**

The translation phase of protein synthesis has three stages: initiation, elongation, and termination. Here you will read about the basics of this process.

To begin *initiation*, a tRNA that can start transcription is loaded onto a ribosome subunit. This initiator tRNA binds with the small ribosome subunit. AUG, the start codon for the mRNA transcript, matches up with this tRNA's anticodon. The AUG also binds with the small subunit. Next, a large ribosome subunit binds with the small subunit. When joined together in this way, the three elements form an initiation complex (Figure 21.12*a*, 21.12*b*). Now the next stage can begin.

In the *elongation* stage of translation, a polypeptide chain forms as the mRNA strand passes between the ribosome subunits, like a thread moving through the eye of a needle. Some proteins in the ribosome are enzymes. They join amino acids together in the sequence dictated by the codon sequence in the mRNA molecule. Figure 21.12*c*–21.12*e* shows that a peptide bond forms between the most recently attached amino acid and the next amino acid being delivered to the ribosome. (Section 2.11 explains how a peptide bond forms.)

During the last stage of translation, *termination*, a stop codon in the mRNA moves onto the ribosome platform. No tRNA has a corresponding anticodon, so translation stops. Enzymes then detach the mRNA *and* the new chain from the ribosome (Figure 21.12*f*).

Some cells, such as unfertilized oocytes, may have to be ready to make many copies of different proteins very quickly. As "preparation," they stockpile transcribed mRNA in their cytoplasm. In cells that are already rapidly using or secreting proteins (such as endocrine cells that are making hormones), *polysomes* are often present. A polysome is a cluster of ribosomes, all translating the same mRNA transcript at the same time. The transcript threads through all of them, one after another.

Many newly forming polypeptide chains carry out their functions in the cytoplasm. Others have a "shipping label," a special sequence of amino acids. The label allows them to enter the rough ER of the endomembrane system (Section 3.6). There they are modified into their final form before being shipped to their ultimate destinations inside or outside the cell.

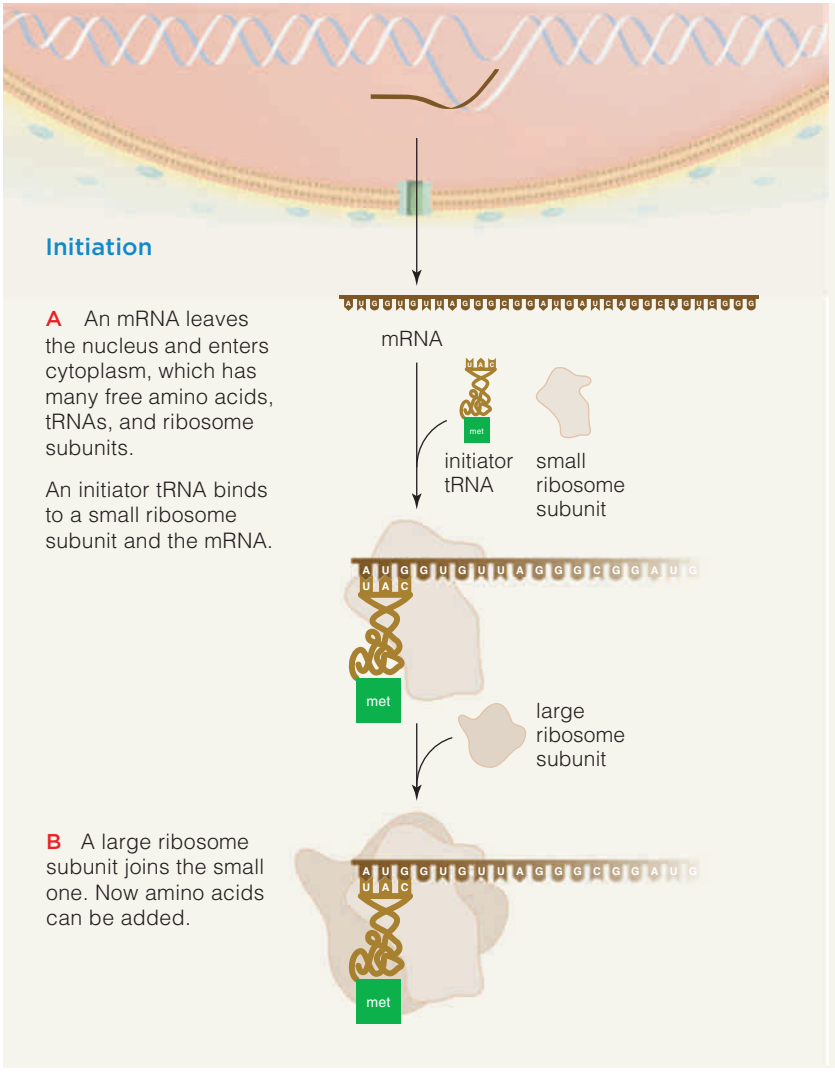


Figure 21.12 Animated! Translation is the second step of protein synthesis.

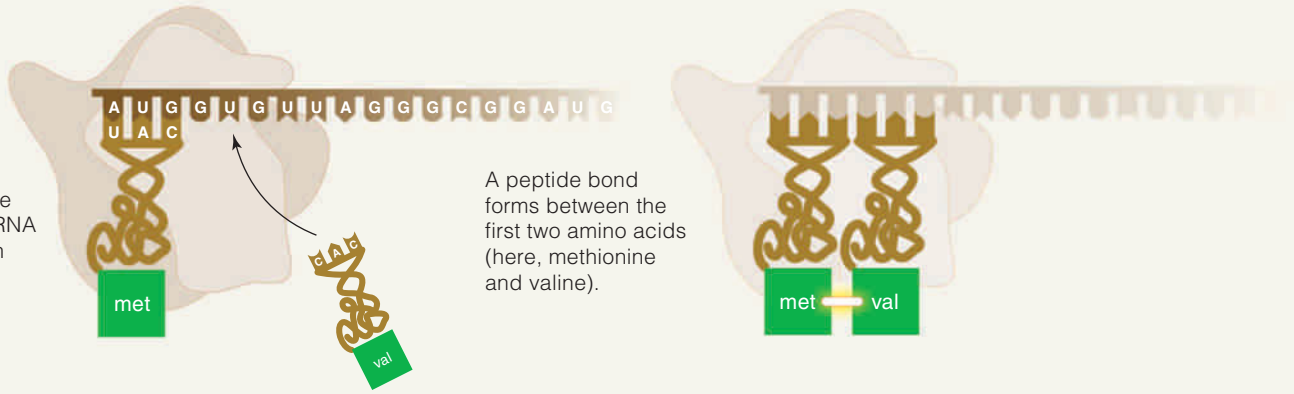
Take-Home Message

What are the three stages of translation?

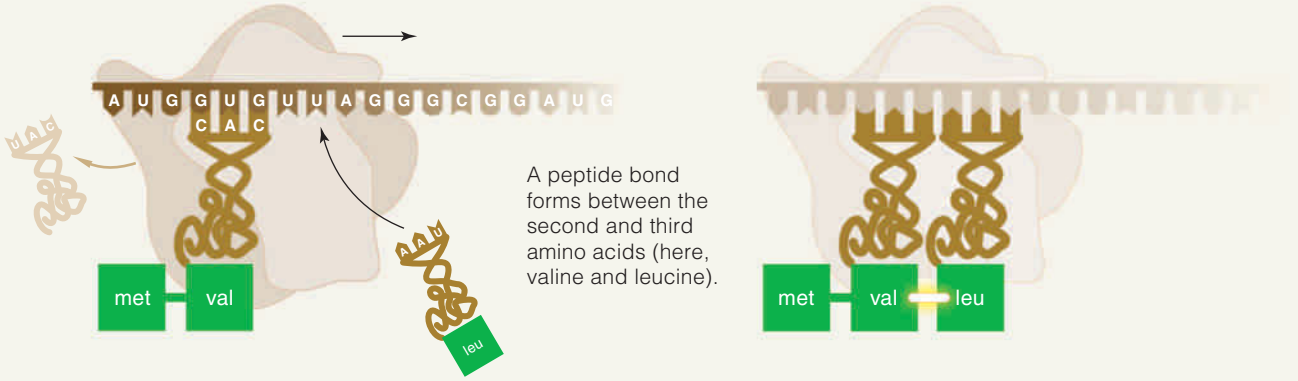
- Translation begins when a small ribosome unit and an initiator tRNA both arrive at an mRNA's start codon and a large ribosome subunit binds to them.
- tRNAs deliver amino acids to the ribosome in the order dictated by the sequence of mRNA codons. A chain of amino acids (a polypeptide chain) grows as peptide bonds form between the amino acids.
- Translation ends when a stop codon triggers events that cause the chain and the mRNA to detach from the ribosome.

Elongation

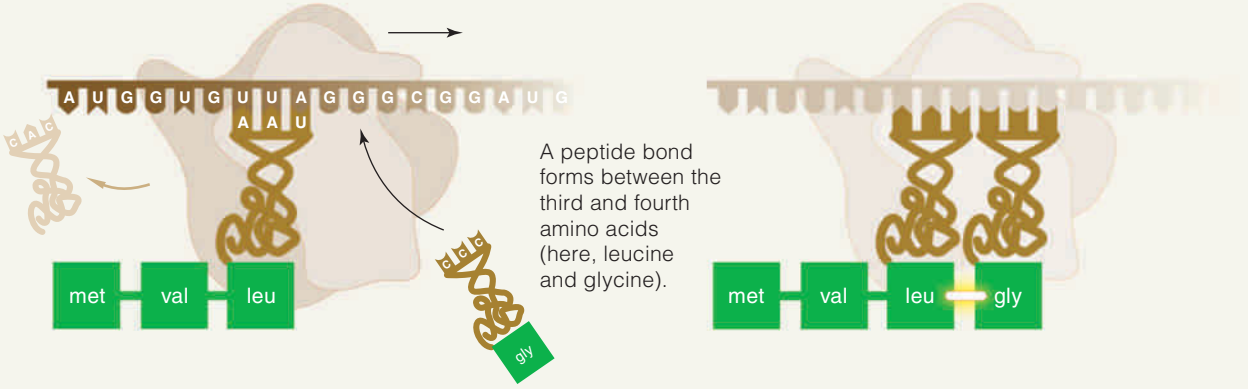
C An initiator tRNA carries the amino acid methionine, so the first amino acid of the new polypeptide chain will be methionine. A second tRNA binds the second codon of the mRNA (here, that codon is GUG, so the tRNA that binds carries the amino acid valine).



D The first tRNA is released and the ribosome moves to the next codon in the mRNA. A third tRNA binds to the third codon of the mRNA (here, that codon is UUA, so the tRNA carries the amino acid leucine).

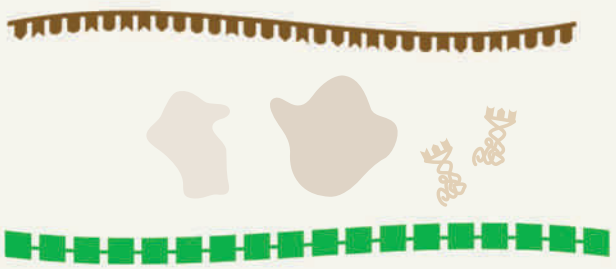


E The second tRNA is released and the ribosome moves to the next codon. A fourth tRNA binds the fourth mRNA codon (here, that codon is GGG, so the tRNA carries the amino acid glycine).



Termination

F Steps **d** and **e** are repeated over and over until the ribosome comes to a stop codon in the mRNA. The mRNA and the new polypeptide chain are released from the ribosome. The two ribosome subunits separate from each other. Translation is now complete. Either the chain will join the pool of proteins in the cytoplasm or it will enter rough ER of the endomembrane system (Section 3.7).



21.7 Tools for Engineering Genes

- **Nature has conducted countless genetic experiments through mutation and other events. We humans now can use advanced technology to change genetic traits.**
- **Link to Cell division 18.1**

Today researchers use **recombinant DNA technology** to create genetic changes. They can cut and splice DNA from different species, then insert the modified molecules into bacteria or other types of cells that can replicate genetic material and divide. The cells copy the foreign DNA along with their own. Copying soon produces large quantities of **recombinant DNA** molecules. This technology also is the basis of **genetic engineering**, in which genes are modified and inserted back into the original organism or into a different one.

Enzymes and plasmids from bacteria are basic tools

Recombinant DNA technology depends on the genetic workings of bacteria. Many bacteria have small circular molecules of "extra" DNA called **plasmids**, which contain a few genes. The bacterium's replication enzymes can copy plasmid DNA. Bacteria also have *restriction enzymes*—enzymes that can detect and cut apart specific short sequences of bases in DNA. Today, plasmids and restriction enzymes are basic parts of a tool kit for doing genetic recombination in the laboratory.

Many restriction enzymes make staggered cuts that leave single-stranded "tails" on the end of DNA fragments. Depending on the molecule being cut, the fragments may be long enough to be useful for studying the organization of a genome. A **genome** is all the DNA in a haploid set of a species' chromosomes.

DNA fragments with staggered cuts have so-called "sticky" ends. This means that a restriction fragment's single-stranded tail can base-pair with a complementary tail of any other DNA fragment or molecule cut by the same restriction enzyme. If you mix together some DNA fragments cut by the same restriction enzyme, the sticky ends of fragments that have complementary base sequences will base-pair and form a recombinant DNA molecule. Then another enzyme seals the nicks.

Using the necessary enzymes, it's possible to splice foreign DNA into bacterial plasmids. The result is called a **DNA clone**, because when a bacterium copies a plasmid, it makes many identical, "cloned" copies of it.

A DNA clone carries foreign DNA into a host cell that can divide rapidly (such as a bacterium or a yeast cell).

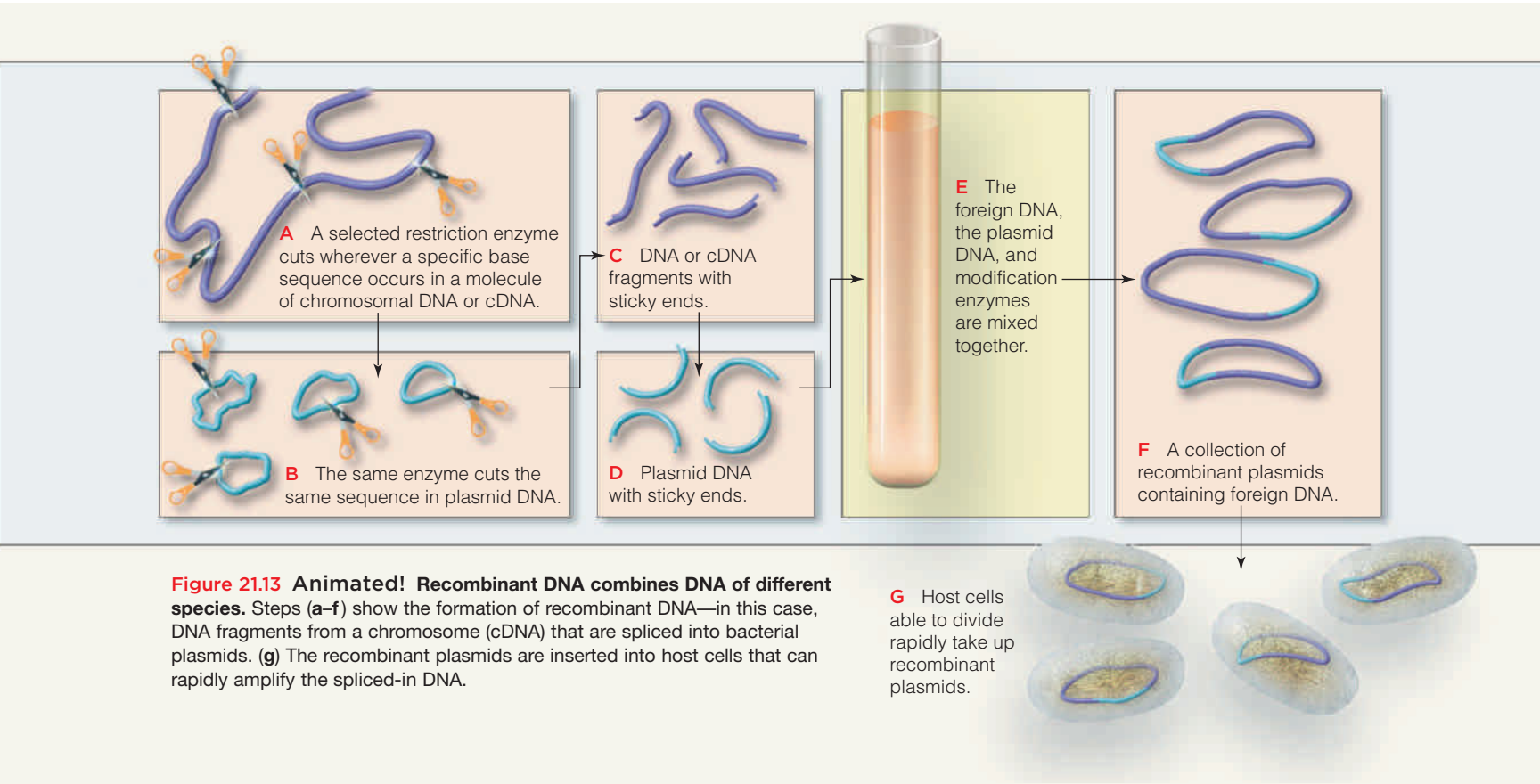
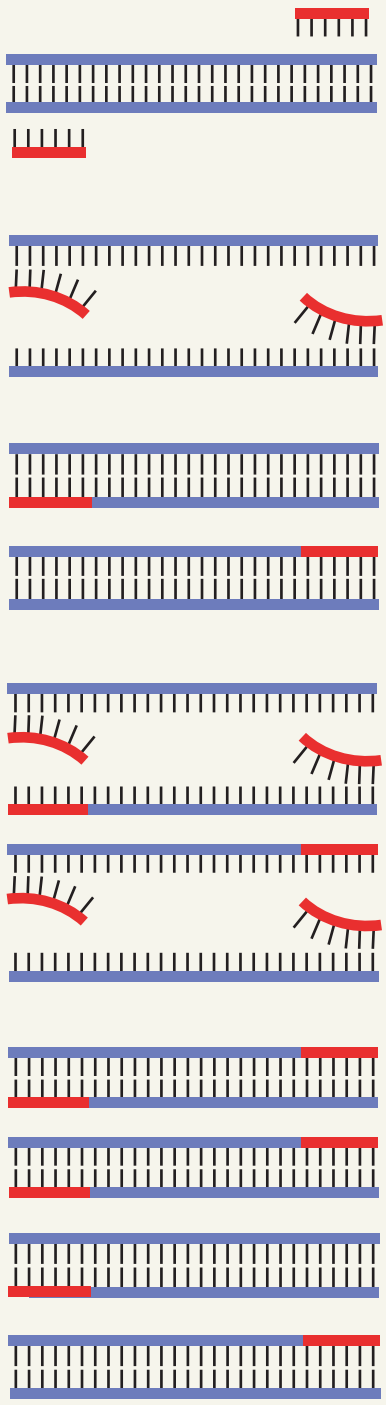


Figure 21.13 Animated! Recombinant DNA combines DNA of different species. Steps (**a**–**f**) show the formation of recombinant DNA—in this case, DNA fragments from a chromosome (cDNA) that are spliced into bacterial plasmids. (**g**) The recombinant plasmids are inserted into host cells that can rapidly amplify the spliced-in DNA.

Figure 21.14 Animated! PCR makes quick work of copying DNA. The above photograph shows rows of PCR systems that are copying human DNA. Right: The steps of the polymerase chain reaction (PCR).



A DNA (*blue*) is mixed with primers (*red*), nucleotides, and heat-tolerant DNA polymerase.

B When the mixture is heated, DNA strands separate. When it is cooled, some primers bond to the template DNA.

C DNA polymerase uses the primers to begin synthesis, and complementary strands of DNA form. The first round of PCR is now complete.

D The mixture is heated again, and all of the DNA separates into single strands. When the mixture is cooled, some of the primers bond to the DNA.

E DNA polymerase uses the primers to begin DNA synthesis, and complementary strands of DNA form. The second round of PCR is complete.

Each round can double the number of DNA molecules. After 30 rounds, the mixture contains huge numbers of DNA fragments, all copies of the starting DNA.

This can be the start of a cloning "factory"—a population of rapidly dividing descendants, all with identical copies of the foreign DNA (Figure 21.13). As they divide they make much more of, or amplify, the foreign DNA.

PCR is a super-fast way to copy DNA

The **polymerase chain reaction**, or **PCR**, is an even faster way to copy DNA. These reactions occur in test tubes, and primers get them started.

A **primer** is a manmade, short nucleotide sequence that base-pairs with any complementary sequences in DNA. The workhorses of DNA replication—the DNA polymerases—chemically recognize primers as start tags. Following a computer program, machines make a primer one step at a time.

PCR also uses a DNA polymerase that is not destroyed at the high temperatures that are required to unwind a DNA double helix. (Such high temperatures will denature and destroy the activity of most DNA polymerases.)

In the lab, primers, the polymerase, DNA from an organism, and nucleotides are all mixed together. Next, the mixture is exposed to precise temperature cycles. During each temperature cycle, the two strands of all the DNA molecules in the mixture unwind from each other.

Primers line up on exposed nucleotides at the targeted site according to base-pairing rules (Figure 21.14). Each round of reactions doubles the number of DNA molecules amplified from the target site. For example, if there are 10 such molecules in the test tube, there soon will be 20, then 40, 80, 160, 320, and so on. Very soon there will be billions of copies of a target piece of DNA.

PCR can amplify samples that contain tiny amounts of DNA, and it is used in laboratories all over the world. As you'll read shortly, it can copy DNA from even a single hair follicle or a drop of blood left at a crime scene.

Take-Home Message

What is recombinant DNA?

- Recombinant DNA is a molecule that combines the DNA from different species. It can be inserted into bacteria or other rapidly dividing cells that can make multiple, identical copies of the DNA of interest.
- PCR is a rapid method of amplifying DNA in test tubes.

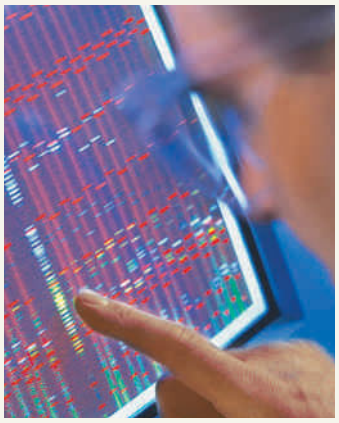
21.8 "Sequencing" DNA

- **DNA sequencing provides useful information about genes, including their size, location on chromosomes, and the order of their nucleotides.**

To study how a particular gene functions, what kind of mutations occur in it, and how it interacts with other genes, it is extremely useful to have information such as where the gene is on its chromosome, its size—how many nucleotides are in it—and the order of the nucleotides. **DNA sequencing** provides this sort of information. Today researchers use powerful supercomputers to "sequence" DNA with tremendous speed.

The sequencing method uses standard and modified versions of the four nucleotides—A, T, G, and C. Each modified version has been attached to another molecule that fluoresces (lights up) a preselected color during the sequencing process. Before the reactions, all the nucleotides are mixed with millions of copies of the DNA for which the sequence is to be determined, along with a primer and DNA polymerase. Next the DNA is separated into single strands and a series of chemical steps produce a "soup" containing millions of copies of DNA fragments, each one tagged with a fluorescing molecule. Additional processing produces fragments in which each nucleotide in the "mystery" base sequence fluoresces. After several more steps the computer program interprets the information from all the "marked" nucleotides in the sample and assembles the original DNA's sequence (Figure 21.15).

DNA sequencing is a major tool in the new field of **genomics**, the study of genomes. We will now look at the promise and challenges of the multinational effort called the Human Genome Project.



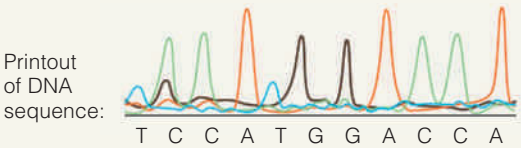


Figure 21.15 Animated! The printout from a DNA sequencing machine matches colors with DNA nucleotides.

Take-Home Message

What is DNA sequencing?

- DNA sequencing is a method for determining the order of nucleotides in a DNA fragment.
- The study of whole genomes, called genomics, uses the information from DNA sequencing, among other tools.

21.9 Mapping the Human Genome

- **The Human Genome Project is providing valuable insights into the genetic basis of many disorders and diseases.**

Thanks to the DNA sequencing of the **Human Genome Project**, we now know that the human genome consists of about 3.2 billion nucleotide bases—As, Ts, Gs, and Cs. The bases are subdivided into roughly 21,500 genes, which provide all the instructions needed to build and operate the body.

Genome mapping provides basic biological information

Knowing the order of the nucleotides in our DNA gives us key basic knowledge about our genome. One surprising discovery is that only about 1.5 percent of human DNA is devoted to the protein-coding parts of our genes, the exons. The rest is noncoding DNA, and over half of it appears to be repeated sequences of various types (such as the Alu repeat mentioned in Section 21.2). We cannot assume that all noncoding DNA is "junk DNA," so one of the challenges biologists now face is figuring out the roles of noncoding gene regions (Figure 21.16).

It turns out that our DNA also is sprinkled with SNPs ("snips"). Each SNP (for *s*ingle *n*ucleotide *p*olymorphism) is a change in one nucleotide in a sequence. It appears there are around 1.4 million SNPs in the human genome. Many result in different gene alleles—the different versions of a gene that encode slightly different traits.

Figure 21.16 Supercomputers are used in human genome research. These gene-sequencing computers are at Celera Genomics in Maryland. The map of the human genome will have many applications, including more efficiently designed drugs and better understanding of genetic disorders.

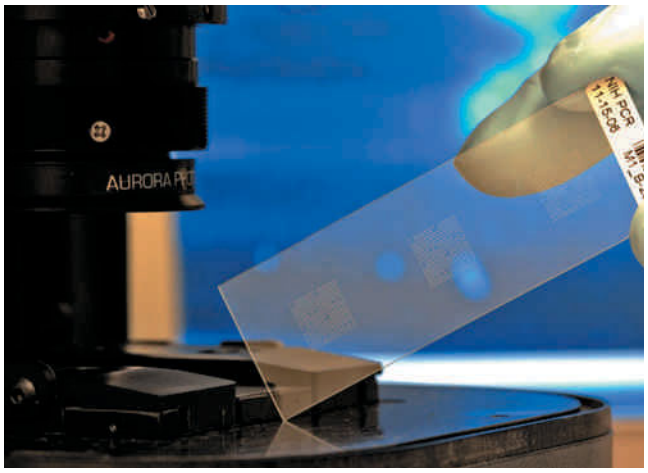


Figure 21.17 **DNA chips, like those stamped on this glass plate, can be used to analyze thousands of genes at once.**

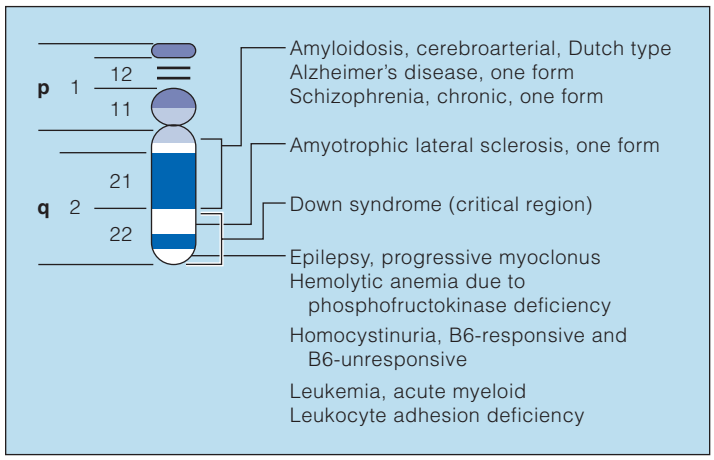


Figure 21.18 **A map of human chromosome 21 shows genes correlated with several diseases.** The upper arm of the chromosome is marked p and the lower arm q. In this case, each arm has a single region, labeled 1 and 2, respectively. In other chromosomes, each arm may have two or more regions. Stains used in chromosome analysis produce a series of bands, indicated by the small numbers to the left of each arm. A combination of letters and numbers indicates the chromosome region where a given gene is found; for instance, the gene for one form of amyotrophic lateral sclerosis (ALS) is 21q2.22. A total of 225 genes have been mapped to this chromosome.

DNA chips help identify mutations and diagnose diseases

Unraveling the human genome has extremely important implications for human biology and medicine. One new tool is the **DNA chip**, a microscopic array (microarray) of thousands of DNA sequences that are stamped onto a small glass plate (Figure 21.17). The chips can quickly pinpoint which genes are being expressed in a tissue, including tissues such as cancerous tumors. DNA chips are already being used to pinpoint mutations, diagnose genetic diseases, and test how drugs or other therapies affect the functioning of genes.

As new genes are identified, biologists are exploring the roles of proteins they encode. We already know how having a particular allele can set the course of diseases such as sickle-cell anemia and forms of breast cancer. Soon it will be possible to apply the deeper understanding of human genes to many more health concerns. For instance, a simple blood test might be able to provide a complete genetic profile of a person's inborn predisposition to heart disease, asthma, diabetes, and certain cancers. Armed with your profile, your doctor might be able to diagnose and treat problems earlier and more effectively. Drugs could be customized for various genetic situations, as described in Section 20.7.

Mapping shows where genes are located

As already noted, genome sequencing can identify where specific genes are located on chromosomes. For instance, we know that genes on chromosome 21 are responsible for early-onset Alzheimer's disease, some forms of epilepsy, and one type of **amyotrophic lateral sclerosis**, or ALS, a disease that destroys motor neurons (Figure 21.18). More than 60 disorders have been mapped to chromosome 14. In 2002, a consortium of public and private laboratories began a $100 million effort to correlate disorders with individual genetic differences. Appendix VI at the end of this book shows maps for all 23 human chromosomes.

Along with the promise of genome sequencing come serious cautions. There is the possibility that genetic profiling could lead to discrimination against people seeking employment or insurance, based solely on their genetic makeup. New issues could arise in the genetic screening of embryos, already a major ethical concern to some. Clearly, a challenging genetic future awaits us.

Take-Home Message

What is the Human Genome Project?

- The Human Genome Project has determined the sequence of nucleotides in the human genome. The project now is mapping the locations of specific genes on chromosomes.

21.10 Some Applications of Biotechnology

- **Practical applications of biotechnology are coming along almost as fast as the leaps in our understanding of human genetics. They include genetic fixes for diseases and using DNA as a personal identifier.**
- **Link to Inheritance of genes on autosomes 20.5**

Researchers are exploring gene therapy

There are 15,500 known human genetic disorders. Some, such as cystic fibrosis and hemophilia, develop when one single gene mutates, producing a malfunctioning protein. Many cancers arise the same way. **Gene therapy** aims to replace mutated genes with normal ones that will encode functional proteins, or to insert genes that restore normal controls over gene activity. Scientists around the world are exploring these possibilities.

Genes can be inserted two ways

The size of a gene (how many base pairs it has) helps determine how it might be inserted into a host cell. Smaller genes can be carried into animal cells by a *vector* such as a virus. Larger genes must enter a host cell some other way.

In *transformation*, cells grown in the laboratory are exposed to DNA that contains a gene of interest, and some of the foreign DNA may become integrated into the host cell's genome. Exposing the host cells to a weak electric current seems to help. Even so, sometimes only one cell in 10 million takes up a new gene.

In *transfection*, a gene is inserted into a virus (often, a retrovirus). The first step is to remove from the virus its genetic instructions that would allow it to replicate and cause disease. In their place goes the gene to be transferred. Next, the virus is allowed to infect target cells (Figure 21.19). Once the virus is inside the host cell, the desired foreign DNA usually becomes integrated into the host cell's DNA.

Transfection can be used only with genes that are expressed in the tissues into which the new DNA will be inserted. In addition, many introduced genes turn off within a few days or weeks. And a few patients have died from complications of the procedure, which raises serious safety questions.

Gene therapy results have been mixed

The first federally approved gene therapy test on humans began in the early 1990s. It aimed to replace a defective gene that causes one type of **severe combined immune deficiency**, called SCID-X1. In this disorder, stem cells in the affected person's bone marrow fail to make the immune system's infection-fighting lymphocytes (Section 9.1). Affected children (sometimes called "bubble babies") must live in germ-free isolation tents. Several years ago, a retrovirus was used to insert copies of a normal allele into stem cells taken from the bone marrow of eleven children with the disorder. Then the genetically modified stem cells were infused back into the marrow, which began to produce lymphocytes. Some months later, seven of the treated children, including the boy shown in Figure 21.20, left their isolation tents. Their immune systems had kicked in. Since that early success, however, several of the children have developed leukemia.

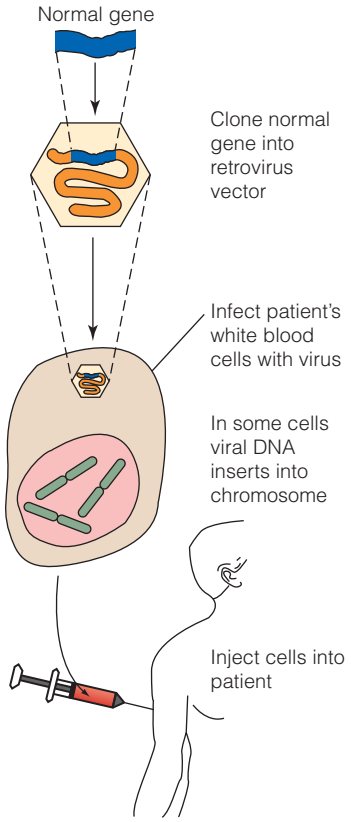


Figure 21.19 This diagram shows one gene therapy method. Here, white blood cells are removed from a patient with a genetic disorder. Next, a retrovirus is used as a vector to insert a normal gene into the DNA. After the normal gene begins to produce its protein, the cells are placed back into the patient. If enough of the normal protein is present in the patient, the disorder's symptoms diminish. Because the genetically altered blood cells live but a few months, however, the procedure must be repeated regularly.

Cystic fibrosis has been another target. The idea is to introduce normal copies of the defective CFTR gene into cells of the respiratory system, using a viral vector in a nasal spray. In the trials thus far, only about 5 percent of affected cells have taken up the normal gene. One major problem has been that the retrovirus vectors used are not effective enough at delivering the new genes to cells that need them.

To date, gene therapy has been most successful in treating cancer. Trials have targeted malignant melanoma, leukemia, a fast-growing form of lung cancer, and cancers of the brain, ovaries, and other organs. In some approaches, tumor cells are first removed from a patient and grown in the laboratory. Genes for an interleukin (which helps activate T cells of the immune system) are then introduced

Figure 21.20 Gene therapy helped this boy born with SCID-X1. His immune system did not develop properly, so his body couldn't fight infections. A gene transfer freed him from life in an isolation tent. However, it also may have increased his risk of developing leukemia.

into the cells, and the cells are returned to the body. In theory, interleukins produced by the tumor cells may act as "suicide tags" that stimulate T cells to recognize cancerous cells and attack them. An exciting variation on this theme involves structures called "lipoplexes," laboratory-made packets in which a plasmid is encased in a lipid coat that helps it gain entry into a cell. The plasmid carries a gene encoding a protein marker that can trigger an immune system attack on cancer cells. Several dozen melanoma patients have been treated with lipoplex therapy, with encouraging results.

At present, gene therapy is still experimental, costly, and available to only a few. It will probably be years before it is widely used for treating and curing disease.

Genetic analysis also is used to read DNA fingerprints

Each of us has a unique set of fingerprints. Likewise, no two people (other than identical twins) have exactly the same sequence of bases in their DNA. Thus each of us also has a **DNA fingerprint**—a unique set of certain DNA fragments that we have inherited from our parents. DNA fingerprints are very accurate—so accurate, in fact, that they can easily distinguish between tissues taken from full siblings.

How does DNA fingerprinting work? More than 99 percent of human DNA is exactly the same in all people, regardless of race and gender. Thus DNA fingerprinting focuses only on the part that tends to differ from one person to the next. Throughout the human genome are short regions of repeated DNA that are very different from person to person. Each person has a unique combination of repeats.

Forensic scientists use DNA fingerprinting to identify criminals and crime victims from the DNA in blood, semen, or bits of tissue left at a crime scene. Figure 21.21 shows DNA fingerprints that were analyzed in an effort to identify the perpetrator of a rape. See how different the DNA fingerprints are—and how only one exactly matches the pattern from the crime scene?

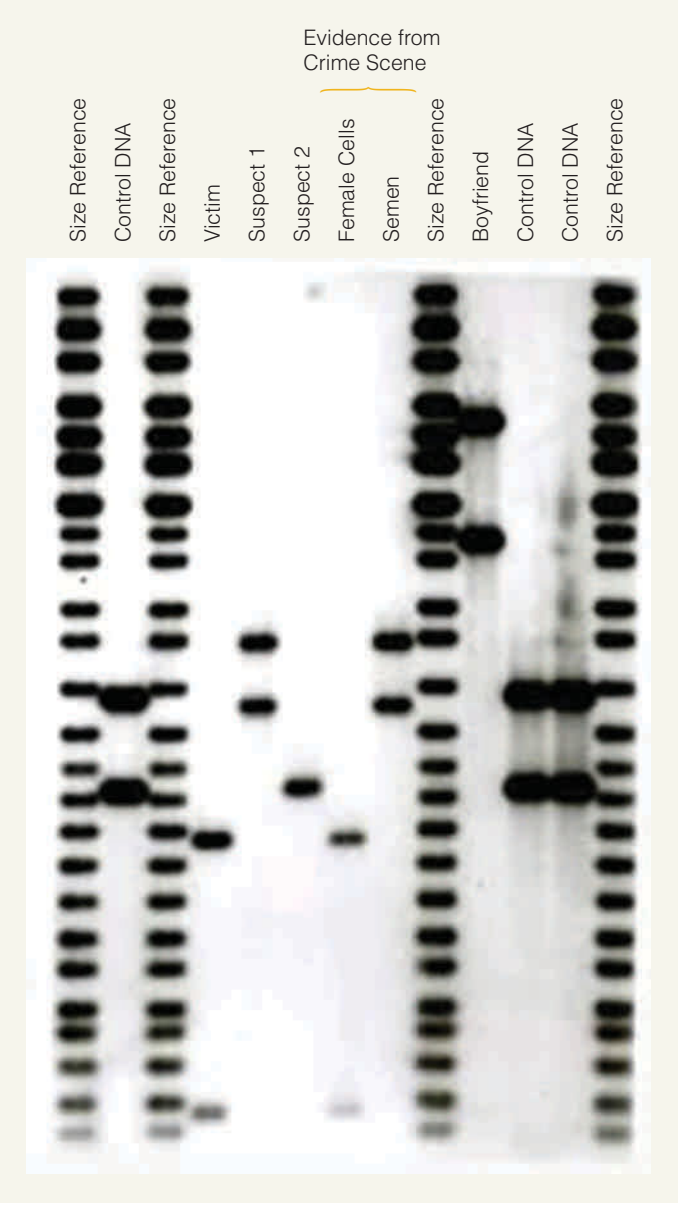


Figure 21.21 Animated! These DNA fingerprints compare DNA gathered during the investigation of a sexual assault. The assay compared DNA from the victim and from the semen of two suspects and the victim's boyfriend. Three control samples were included to confirm that the test procedure was working correctly.

The variation in DNA repeats also can be detected as *restriction fragment length polymorphisms*, or **RFLPs** ("riff-lips"). These are DNA fragments of different sizes that have been cut out of DNA by restriction enzymes.

Take-Home Message

What are some applications of biotechnology?

- In gene therapy, one or more normal genes are inserted into body cells to correct a genetic defect or enhance the activity of specific genes.
- DNA fingerprinting is another application of biotechnology.

21.11 Engineering Bacteria, Animals, and Plants

- **Any genetically engineered organism that carries one or more foreign genes is transgenic.**

Bacteria were the first organisms to be bioengineered. Plasmids in modified bacteria can carry a range of human genes, which are expressed to produce large quantities of useful human proteins. Many of these proteins, such as human growth hormone, once were available only in tiny amounts and were costly because they had to be chemically extracted from endocrine tissues. Other human proteins produced today by bacteria include insulin and interferons.

Many types of animal cells can be "micro-injected" with foreign DNA. For instance, when researchers introduced the gene for human growth hormone into mice, the result was the "super mouse" shown in Figure 21.22*a*. Recombinant DNA technology also has been used to transfer human and cow growth hormones into pigs, which then grow much faster. Transgenic goats (Figure 21.22*b*) produce CFTR protein (used to treat cystic fibrosis), as well as drugs that prevent dangerous blood clots. These and other medically useful engineered proteins show up in the goats' milk.

People with hemophilia A now can obtain the needed blood-clotting factor VIII from a drug that is produced by hamster ovary cells in which genes for human factor VIII have been inserted. Factor VIII produced in this way eliminates the need to obtain it from human blood, and thus the risk of transmitting blood-borne diseases.

Plants have been intriguing genetic engineers for a long time. Researchers now routinely grow crop plants and many other plant species from cells cultured in the laboratory. They use a variety of methods to pinpoint genes that confer useful traits, such as resistance to salt, a pathogen, or an herbicide (Figure 21.22*c*). Later, whole plants with the trait can be grown from the cultured cells.

Take-Home Message

What are some current applications of genetic engineering?

- Applications of genetic engineering include efforts to develop transgenic animals or animal cells capable of producing medically useful substances.
- Genetically engineered plants have a variety of traits, such as resistance to disease and herbicides.

Figure 21.22 These are just a few of the organisms with new traits bestowed by genetic engineering. (**a**) Mouse littermates. The larger mouse grew from a fertilized egg into which the gene for human growth hormone had been inserted. (**b**) Myra, a goat transgenic for human antithrombin III, an anticlotting factor. (**c**) Aspen seedlings genetically altered for a higher ratio of cellulose, compared to the control plant at left. Wood from such trees might make it easier to manufacture paper and some clean-burning fuels, such as ethanol. The altered trees also grew 25–30 percent faster than unaltered ones. (**d**) The chart lists some USDA-approved crop plants.

USDA-Approved Crop Plant	Modified Trait
Tomato, potato, corn, rice, sugar beet; canola bean; cotton, flax croplands	Resistance to weed-killing herbicides used in agriculture
Potato, squash, papaya	More resistance to harmful viruses, bacteria, and fungi
Tomato	Delayed ripening; easier to ship, with less bruising
Corn, chicory	Plants cannot interbreed with wild stocks

d

21.12 Issues for a Biotechnological Society

Many people believe that genetic technologies are a double-edged sword: they can be used for good or ill. Some say that no matter what the species of organism, DNA should never be altered—even though natural mutations change DNA all the time. Cloning, or making a genetic copy of a cell or organism, has become another issue. Geneticists have become increasingly expert in applying this technology, from the cloned bacteria used in recombinant DNA technology to embryos cloned to obtain stem cells and cloned adult animals.

Figure 21.23 Cloned cats and other animals are a modern-day reality. The owner of Tahini, a Bengal cat (above) founded Genetic Savings and Clone, a biotechnology company. The two kittens at right are exact clones of Tahini. As they grow older their eye color will become exactly like Tahini's.

Cloning of bacteria, plants, and nonhuman animals raises concerns

There are pros and cons associated with many current uses of biotechnology. For instance, most recombinant bacteria or viruses are altered in ways that will prevent them from reproducing outside a laboratory. In theory, though, transgenic bacteria or viruses could mutate and possibly become new pathogens in the process. On the other hand, genetically engineered "oil-eating" bacteria have been used to help clean up oil spills, an example of *bioremediation*.

The chapter introduction mentioned some objections to bioengineered plants. Critics also point out that such plants could escape from test plots and become "superweeds" that are resistant to herbicides and other controls. It is also possible that crop plants with engineered insect resistance could trigger the evolution of new, even worse pests. Although experts deem many, even most, of these possibilities to be unlikely, there are documented cases of engineered plant genes turning up in wild plants.

Controversy swirls over cloning

Scientists have achieved considerable success in cloning embryos and whole animals of several species. The 1997 cloning of a fully grown sheep named Dolly has been followed by a string of similar experiments that have produced clones of rabbits, pigs, mules, cattle, goats, and other animals, including cats (Figure 21.23). Uses for adult animal clones range from saving endangered species from extinction to cloning livestock with desirable traits to "replacing" a beloved pet that has died.

To make a clone of an adult animal, the nucleus of an unfertilized egg cell is removed and replaced with the nucleus from some type of adult cell. An embryo then may develop from the cell. In theory, the embryo can become a source of stem cells (Chapter 4), or it may grow into an adult. Either way, the clone contains only the DNA of the original adult cell.

To date many clones have developed serious health problems and have aged much more rapidly than usual. This happens when the substituted adult nucleus does not revert to an embryonic state (when a cell is not yet differentiated for its final function in the body). Getting a nucleus to "reprogram" in this way is tricky and often is not successful.

Even so, efforts are under way in many laboratories to perfect methods for making cloned embryos as well as healthy adult animal clones. Such embryos might be used for **therapeutic cloning**—that is, as a source of embryonic stem cells that can be used to grow replacement human tissues and organs. Some companies have announced plans for **reproductive cloning**—creating a cloned embryo that can be implanted in a woman's uterus and allowed to develop into a baby. So-called germline engineering would take the technology a step further by altering the cloned embryo's genetic makeup in some desired way before implanting it.

We humans have been doing genetic experiments for centuries by manipulating matings to create modern crop plants and new breeds of animals. Going forward, the real issue will be how to bring about beneficial changes without doing harm.

IMPACTS, ISSUES

Golden Rice, or "Frankenfood"?

GENETICALLY modified (GM) food plants can help feed the hungry, improve crop yields, and offer enhanced nutrition, among other benefits. Even so, some people object to GM foods because they are "unnatural" and may pose unforeseen dangers to human health and the environment.

How Would You Vote?

Currently, there are no regulations on the use of GM foods. Would you support government restrictions, or even a ban? See CengageNOW for details, then vote online.

Summary

Section 21.1 A gene is a sequence of nucleotide bases in DNA. These bases are adenine, thymine, guanine, and cytosine (A, T, G, and C). The nucleotide sequence of most genes codes for the sequence of amino acids in a protein (polypeptide chain).

Section 21.2 A DNA molecule consists of two strands of nucleotides twisted together in a double helix. DNA is copied (duplicated) by semiconservative replication. One strand in each new DNA molecule is new and one is from the parent molecule. DNA polymerases and other enzymes unwind the existing DNA molecule, keep the strands apart, and assemble a new strand on each one.

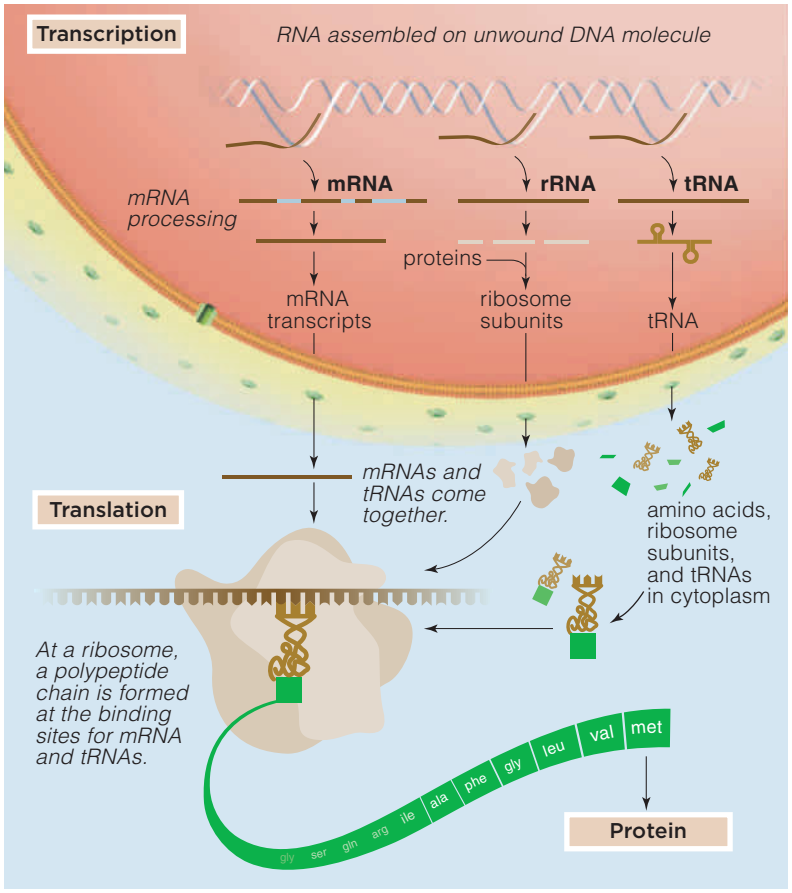


Figure 21.24 Animated! This diagram is a summary of transcription and translation, the two steps leading to protein synthesis in cells. DNA is transcribed into RNA in the nucleus. RNA is translated into proteins in the cytoplasm.

A gene mutation is a change in the DNA nucleotide sequence. Mutations may be harmful, neutral, or helpful. Mutations in germ cells (cells that produce gametes) can be passed to the next generation.

- Use the animation and interaction on CengageNOW to investigate the effects of a gene mutation.

Section 21.3 Converting genetic information into a protein requires steps called transcription and translation (Figure 21.24). In transcription, DNA instructions guide the formation of RNA from nucleotides in the cell. The double-stranded DNA is unwound at a gene region, then RNA polymerases use the exposed bases as a template to build a corresponding strand of RNA. Base-pairing rules govern which bases pair up. In RNA, guanine pairs with cytosine, and uracil (not thymine) pairs with adenine.

DNA encodes three kinds of RNA molecules. Messenger RNA (mRNA) carries instructions for building proteins. Ribosomal RNA (rRNA) forms the subunits of ribosomes, the structures on which amino acids are assembled into polypeptide chains. Different kinds of transfer RNA (tRNA) pick up amino acids and deliver them to ribosomes in the order specified by mRNAs.

A new mRNA transcript consists of introns (nucleotide sequences that do not code for proteins) and exons. Exons are the mRNA sequences that carry protein-building instructions. Regulatory proteins stimulate or suppress gene transcription and so control gene activity.

- Use the animation and interaction on CengageNOW to learn how genes are transcribed and how these transcripts are processed.

Section 21.4 In translation, RNAs link amino acids in the sequence required to produce a specific polypeptide chain.

Translation follows the genetic code, a set of sixty-four base triplets—nucleotide bases that ribosome proteins "read" three at a time.

A base triplet in an mRNA molecule is a codon. A given combination of codons specifies the amino acid sequence of a polypeptide chain.

- Use the animation and interaction on CengageNOW to explore the genetic code.

Section 21.5 Translation has three stages. In initiation, a small ribosome subunit and an initiator tRNA bind with an mRNA transcript and move along it until they reach an

AUG start codon. The small subunit binds with a large ribosome subunit.

In elongation, tRNAs deliver amino acids to the ribosome. Their anticodons base-pair with mRNA codons. The amino acids are joined (by peptide bonds) to form a new polypeptide chain.

In chain termination, an mRNA stop codon moves onto the ribosome; then the polypeptide chain and mRNA detach from the ribosome.

- Use the animation and interaction on CengageNOW to observe the translation of mRNA.

Section 21.6 Recombinant DNA technology is the foundation for genetic engineering. Restriction enzymes are used to cut DNA molecules into fragments, which are inserted into a cloning vector (such as a plasmid) and then multiplied in rapidly dividing cells.

A DNA clone is a foreign DNA sequence that has been introduced and amplified in dividing cells. DNA sequences also can be amplified in test tubes by the polymerase chain reaction.

The genome of a species is all the DNA in a haploid set of chromosomes. The human genome, including our species' 21,500 genes, consists of about 3.2 billion nucleotides. Some tools of recombinant DNA technology can be used to identify genes in the genome.

- Use the animation and interaction on CengageNOW to explore tools used to make recombinant DNA and learn how researchers isolate and copy genes.

Sections 21.7, 21.8 Automated DNA sequencing can quickly determine the sequence of nucleotides in segments of DNA—and, accordingly, in genes. The human genome has been sequenced, and researchers are identifying genes responsible for a variety of traits and genetic disorders.

- Use the animation and interaction on CengageNOW to investigate DNA sequencing and observe the process of DNA fingerprinting.

Sections 21.9–21.11 Recombinant DNA technology and genetic engineering have enormous potential for research and applications in medicine, agriculture, and industry. Both also may pose ecological and social risks.

Review Questions

1. Why is DNA replication called "semiconservative"?
2. Name one kind of mutation that produces an altered protein. What determines whether the altered protein will have beneficial, neutral, or harmful effects?
3. How are the polypeptide chains of proteins that are specified by DNA assembled?
4. How does RNA differ from DNA?
5. Name the three classes of RNA and describe their functions.
6. Distinguish between a codon and an anticodon.
7. Describe the three steps of translation.
8. What is a restriction enzyme?
9. What is a "gene sequence"?

Self-Quiz *Answers in Appendix V*

1. Nucleotide bases, read _____ at a time, serve as the "code words" of genes.
2. DNA contains genes that are transcribed into _____.
   a. proteins
   b. mRNAs
   c. rRNAs
   d. tRNAs
   e. b, c, and d
3. mRNA is produced by _____.
   a. replication
   b. duplication
   c. transcription
   d. translation
4. _____ carries coded instructions for an amino acid sequence to the ribosome.
   a. DNA
   b. rRNA
   c. mRNA
   d. tRNA
5. tRNA _____.
   a. delivers amino acids to ribosomes
   b. picks up genetic messages from rRNA
   c. synthesizes mRNA
   d. all of the above
6. An anticodon pairs with the bases of _____.
   a. mRNA codons
   b. DNA codons
   c. tRNA anticodons
   d. amino acids
7. The loading of mRNA onto the small ribosomal subunit occurs during _____.
   a. initiation of transcription
   b. transcript processing
   c. translation
   d. chain elongation
8. Use the genetic code (Figure 21.9) to translate the mRNA sequence AUGCGCACCUCAGGAUGAGAU. (Human reading frames start with AUG.) Which amino acid sequence is being specified?
   a. meth-arg-thr-ser-gly-stop-asp . . .
   b. meth-arg-thr-ser-gly . . .
   c. meth-arg-tyr-ser-gly-stop-asp . . .
   d. none of the above
9. Match the terms related to protein building.

_____ alters genetic instructions	a. initiation, elongation, termination
_____ codon	b. conversion of genetic messages into polypeptide chains
_____ transcription	c. base triplet for an amino acid
_____ translation	d. RNA synthesis
_____ stages of transcription, translation	e. mutation

10. Rejoined cut DNA fragments from different organisms are best known as _____.
    a. cloned genes
    b. mapped genes
    c. recombinant DNA
    d. conjugated DNA

11. The polymerase chain reaction _____.
    a. is a natural reaction in bacterial DNA
    b. cuts DNA into fragments
    c. amplifies DNA sequences in test tubes
    d. inserts foreign DNA into bacterial DNA

Critical Thinking

1. Which mutation would be more harmful: a mutation in DNA or one in mRNA? Explain your answer.
2. Jimmie's Produce put out a bin of tomatoes having beautiful red color and looking "just right" in terms of ripeness. A sign above the bin identified them as genetically modified produce. Most shoppers selected unmodified tomatoes in the neighboring bin, even though those tomatoes were pale pink and hard as rocks. Which ones would you pick? Why?
3. Previous chapters have discussed various types of cloning, including the cloning of stem cells and of embryos. Dolly, the sheep shown in Figure 21.25*a*, grew from a cloned cell. Is cloning the same as genetic engineering? Explain your answer.
4. Scientists at Oregon Health Sciences University produced the first transgenic primate by inserting a jellyfish gene into a fertilized egg of a rhesus monkey. The gene encodes a bioluminescent protein that fluoresces green. The egg was implanted in a surrogate monkey's uterus, where it developed into a male that was named ANDi (Figure 21.25*b*).

The long-term goal of this gene transfer project is not to make glowing-green monkeys. It is the transfer of human genes into primates whose genomes are most like ours. Transgenic primates could then be studied to gain insight into genetic disorders, which might lead to the development of cures.

However, something more controversial is at stake. Will the time come when foreign genes can be inserted into human embryos? Would it be ethical to transfer a chimpanzee or monkey gene into a human embryo to cure a genetic defect or to bestow immunity against a potentially fatal disease such as AIDS?

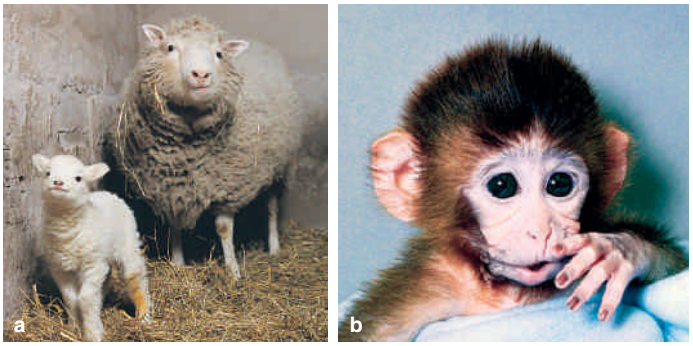


Figure 21.25 Animated! Transgenic animals have become important research subjects. (**a**) The cloned sheep Dolly with her first lamb. The lamb was conceived the old-fashioned way. (**b**) ANDi, the first transgenic primate. His cells have a jellyfish gene for bioluminescence, so he literally glows in the dark.

EXPLORE ON YOUR OWN

Thomas Jefferson (Figure 21.26) was the third president of the United States and the main author of the Declaration of Independence. The proprietor of a Virginia plantation, Mr. Jefferson owned African-American slaves, including a woman named Sally Hemings who eventually bore five children, including several sons. In 1998, writing in the prestigious scientific journal *Nature*, British researchers cited genetic analysis purportedly showing that a modern male descendant of Hemings had the same Y chromosome as males descended from the Jefferson family. Some in the media reported it as solid genetic evidence supporting an old rumor that Thomas Jefferson had fathered at least one of his slave's sons. Other researchers and historians soon pointed out that there was no way the study could present conclusive findings, and eventually the original researchers agreed. Despite this admission, tales of the "scientifically proven" intimate relationship between Jefferson and Hemings are still part of popular lore.

Numerous websites explore this story and the larger issue of ethical guidelines for such "biohistory." To learn more, go to www.tjheritage.org, which provides links to discussions of problems and issues this incident raised.

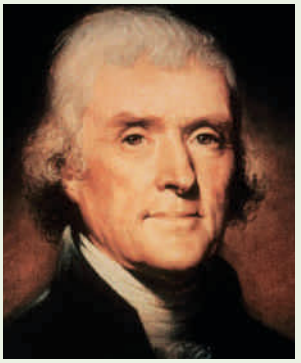


Figure 21.26 Controversial research has attempted to prove that Thomas Jefferson, shown here, fathered at least one of his slave's sons.

Genes and Disease: Cancer

22

IMPACTS, ISSUES

Between You and Eternity

CANCER strikes one in three people in the United States and kills one in four. According to the American Cancer Society, there are about 1,500 cancer deaths every day, over half a million each year. Overall cancer strikes more males than females, but the pattern varies depending on the type of cancer involved. Take breast cancer, for example. Each year more than 200,000 women in the United States are diagnosed with the disease. About 5 to 10 percent of them have a gene mutation that greatly increases their risk of developing breast cancer. There are two of these "breast cancer susceptibility genes," called BRCA1 and BRCA2.

Robin Shoulla (left) inherited the predisposition for breast cancer and was diagnosed with the disease when she was just seventeen years old. She had a radical mastectomy, an operation that removes the affected breast, all lymph nodes under the arm, and the underlying skeletal muscle. Today she is a cancer survivor with a career, husband, and children.

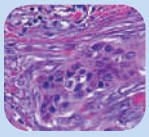
Some healthy women who carry BRCA1 or BRCA2 choose to have both their breasts removed before cancer can strike. The surgery, called preventive (or prophylactic) mastectomy, is also an option for women who have had cancer in one breast, or who have a strong family history of the disease. Most women who have a preventive mastectomy report no major negative aftereffects.

Intensive research is rapidly increasing our understanding of and ability to treat many kinds of cancer, including those of the breast, ovary, colon, and skin. Most cancers are treatable, and many are curable if the disease is discovered early.

LINKS TO EARLIER CONCEPTS

- In cancer, normal controls over cell division are lost. Hence this chapter draws on what you have learned about the structure of normal cells (3.2) and the cell cycle (18.3).
- Because cancer also involves genetic changes, our discussion here relates to what you have read about gene mutations and how cells repair damaged DNA (21.2).
- You will read about links between cancer and operations of the immune system (9.1, 9.7, 9.8, 9.9) and the DNA-damaging effects of ionizing radiation (18.6).

KEY CONCEPTS



Cancer: Uncontrolled Cell Division

Cancer cells are abnormal in both structure and function. Cancer develops when gene changes remove the normal controls over cell division. Sections 22.1–22.4

Diagnosis and Screening

Cancer is diagnosed by biopsy and other tools. Early detection increases the chances of successful treatment. Section 22.5

Treatment and Prevention

Cancer treatments may include surgery, chemotherapy, radiation, and immunotherapy. Lifestyle decisions that promote health can limit a person's risk of developing cancer. Section 22.6

How Would You Vote?

Some young women with an elevated genetic risk of developing breast cancer have chosen to have their breasts removed (radical mastectomy) even before cancer develops. Should this major surgery be restricted to the treatment of actual breast cancers? See CengageNOW for details, then vote online.

22.1 The Characteristics of Cancer

- **As genes switch on and off, they determine when and how fast the cell will grow and divide, when it will stop dividing, and even when it will die. Cancer can result when controls over cell division are lost.**
- **Links to Cell structure 3.2, Cell differentiation 17.1, Mutations in DNA 21.2**

Some tumors are cancer, others are not

If cells in a tissue overgrow—an abnormal enlargement called **hyperplasia**—the result is a defined mass of tissue called a **tumor**. Technically, a tumor is a *neoplasm*, which means "new growth."

A tumor may not be "cancer." As Figure 23.1*a* shows, the cells of a *benign* tumor are often enclosed by a capsule of connective tissue, and inside the capsule they are organized in an orderly way. They also tend to grow slowly and to be well differentiated (structurally specialized for a particular function), much like normal cells of the same tissue (Section 17.1). Benign tumors usually stay put in the body, push aside but don't invade surrounding tissue, and generally can be easily removed by surgery. Benign tumors *can* threaten health, as when they occur in the brain. Nearly everyone has at least several of the benign tumors we call *moles*. Most of us also have or have had some other type of benign neoplasm, such as a cyst. A *malignant* growth, by contrast, is potentially harmful. Table 22.1 compares the main features of malignant and benign tumors, and Figure 22.2 shows the outward differences between a harmless mole and a malignant melanoma, the most dangerous skin cancer.

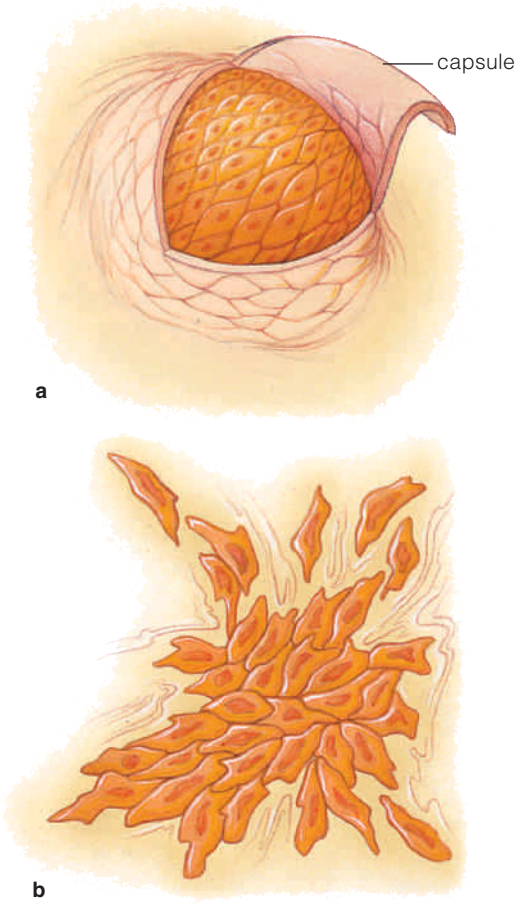
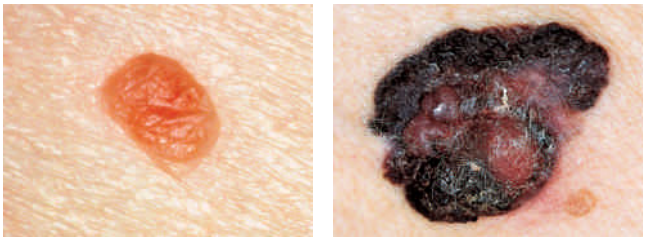


Figure 22.1 Cancer cells are abnormal in their growth and appearance. (**a**) Sketch of a benign tumor. Cells appear nearly normal, and connective tissue encapsulates the tumor. (**b**) A cancerous neoplasm. Due to the abnormal growth of cancer cells, the tumor is a disorganized heap of cells. Some of the cells may break off and invade surrounding tissues, a process called metastasis.

TABLE 22.1 Main Features of Benign and Malignant Tumors

	Malignant Tumor	Benign Tumor
Rate of growth	Rapid	Slow
Nature of growth	Invades surrounding tissue	Expands in the same tissue
Spread	Metastasizes via the bloodstream and the lymphatic system	Does not spread
Cell differentiation	Usually poor	Nearly normal



a Benign mole **b** Melanoma

Figure 22.2 Normal moles are common examples of benign growths. (**a**) Harmless moles, like this one, are all one color, symmetrical, and have a smooth edge. Malignant melanomas (**b**) are asymmetrical (they look blobby), have a ragged edge, and often have differently colored areas. A "mole" with these characteristics is suspicious and should be evaluated right away by a doctor.

Dysplasia ("bad form") is an *abnormal* change in the sizes, shapes, and organization of cells in a tissue. Such change is often an early step toward **cancer**. Under the microscope, the edges of a cancerous tumor usually look ragged (Figure 22.1*b*), and its cells form a disorganized clump. Most cancer cells also have characteristics that enable them to behave differently from normal cells.

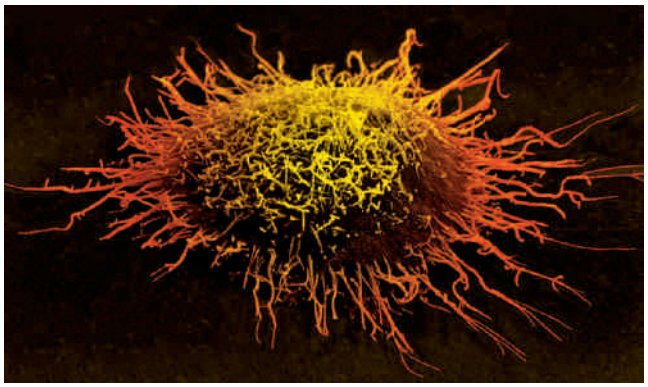


Figure 22.3 **This cervical cancer cell has the threadlike "false feet" that are a common feature of cancerous cells.**

A cancer cell's structure is abnormal

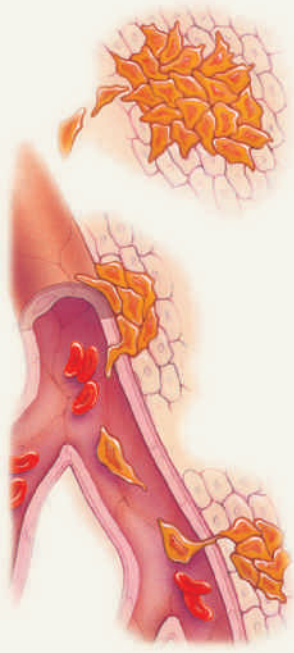
Cancer is the result of a series of mutations in a cell's genes, as you will read in Section 22.2. One effect of these changes is that a cancer cell's structure is abnormal. Often, the nucleus is much larger than usual and there is much less cytoplasm. Cancer cells also often do not have the structural specializations of healthy cells in mature body tissues. As a general rule, the less specialized cancer cells are, the more likely they are to break away from the primary tumor and spread the disease.

When a normal cell is transformed into a cancerous one, more changes take place. The cytoskeleton shrinks, becomes disorganized, or both. Proteins that are part of the plasma membrane are lost or altered, and new, different ones appear. These changes are passed on to the cell's descendants: When a transformed cell divides, its daughter cells are cancerous cells too.

Cancer cells also do not divide normally

Contrary to popular belief, cancer cells don't necessarily divide more rapidly than normal cells do, but they do increase in number faster. This is because the death of normal cells usually closely balances the production of new ones by mitosis. In a cancerous tumor, however, at any given moment more cells are dividing than are dying. As this runaway cell division continues, the cancer cells do not respond to crowding, as normal cells do. A normal cell stops dividing once it comes into contact with another cell, so the arrangement of cells in a tissue remains orderly. By contrast, a cancer cell keeps on dividing. Therefore, cancer cells pile up in a disorganized heap. This is why cancer tumors are often lumpy.

Cancer cells also do not stay well connected physically to the cells next to them in a tissue, and they may form extensions (pseudopodia, "false feet") that enable them to move about (Figure 22.3). These extensions allow cancer cells to break away from the parent tumor and invade other tissues, including the lymphatic and circulatory systems (Figure 22.4). The spread of cancer is called **metastasis**. It is what makes a cancer malignant.



A Cancer cells break away from their home tissue.

B The metastasizing cells become attached to the wall of a blood vessel or lymph vessel. They secrete enzymes that break down part of the wall. Then they enter the vessel.

C Cancer cells creep or tumble along inside blood vessels, then leave the bloodstream the same way they got in. They start new tumors in new tissues.

Figure 22.4 **Animated!** **Cancer spreads step-by-step.**

Some kinds of cancer cells produce the hormone HCG, human chorionic gonadotropin. (Recall from Chapter 17 that HCG maintains the uterus lining when a pregnancy begins.) The presence of HCG in the blood can serve as a red flag that a cancer exists somewhere in a person's body.

Some cancer cells produce a chemical that stimulates cell division, and the cells themselves have receptors for that chemical. Cancer cells also secrete a growth factor called angiogenin that encourages new blood vessels to grow around the tumor. The blood vessels can "feed" the tumor with the large supply of nutrients and oxygen it needs to continue growing. Cancer researchers are working to develop drugs that essentially starve tumors to death by blocking the effects of angiogenin.

Take-Home Message

What are the characteristics of cancer?

- Cancer cells have genetic mutations that remove normal controls over cell division. The cells are abnormal in both their structure and their function.
- Cancer cells often are not well specialized (differentiated). They can break away from a primary tumor, invade surrounding tissue, and metastasize to other areas of the body.

22.2 Cancer, a Genetic Disease

- **Cancer is genetic disease that develops in a predictable sequence of steps.**
- **Links to Cell-mediated immunity 9.7, Immunotherapy 9.9, Corticosteroids 15.7, the Cell cycle 18.3, Radiation 18.6**

Cancer is basically a genetic disease. It nearly always develops through a series of steps in which genetic changes remove normal controls over cell division. The transformation of a normal cell into a cancer cell is called **carcinogenesis** (Figures 22.5 and 22.6).

Cancer usually involves several genes

As a rule, the beginning of cancer involves two main types of genes. **Proto-oncogenes** (*proto* "before" and *onco*,

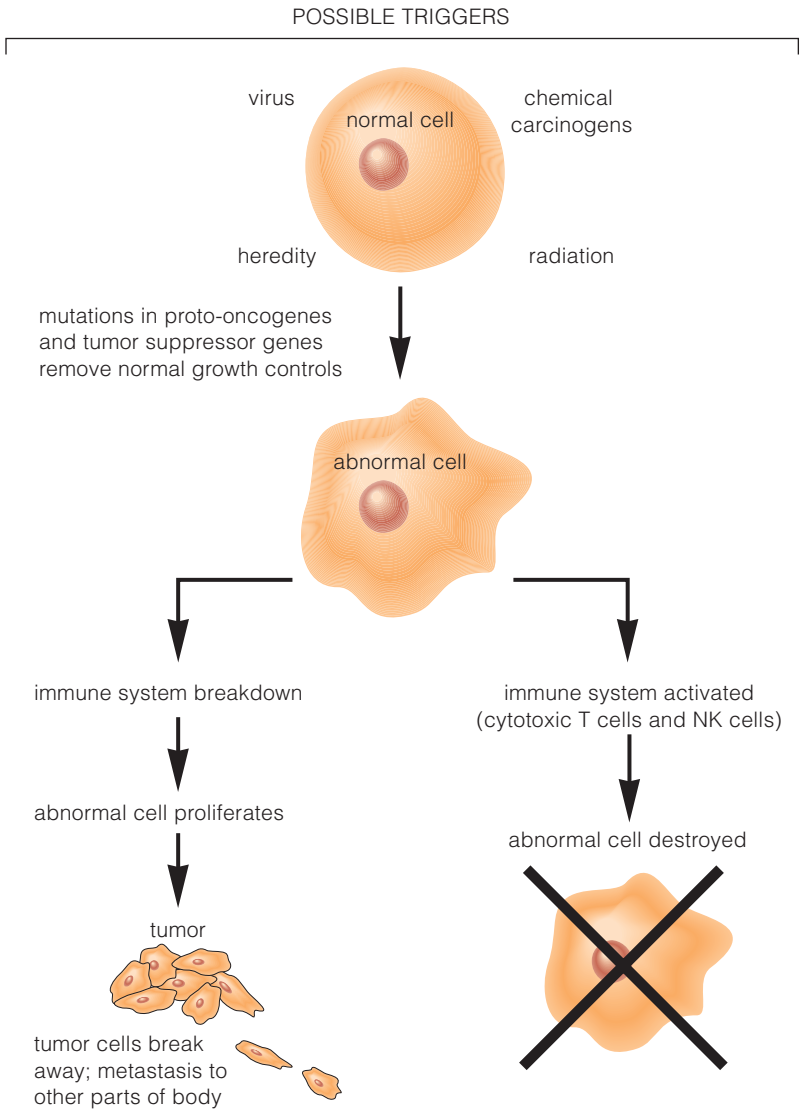


Figure 22.5 **Carcinogenesis occurs in predictable steps.**

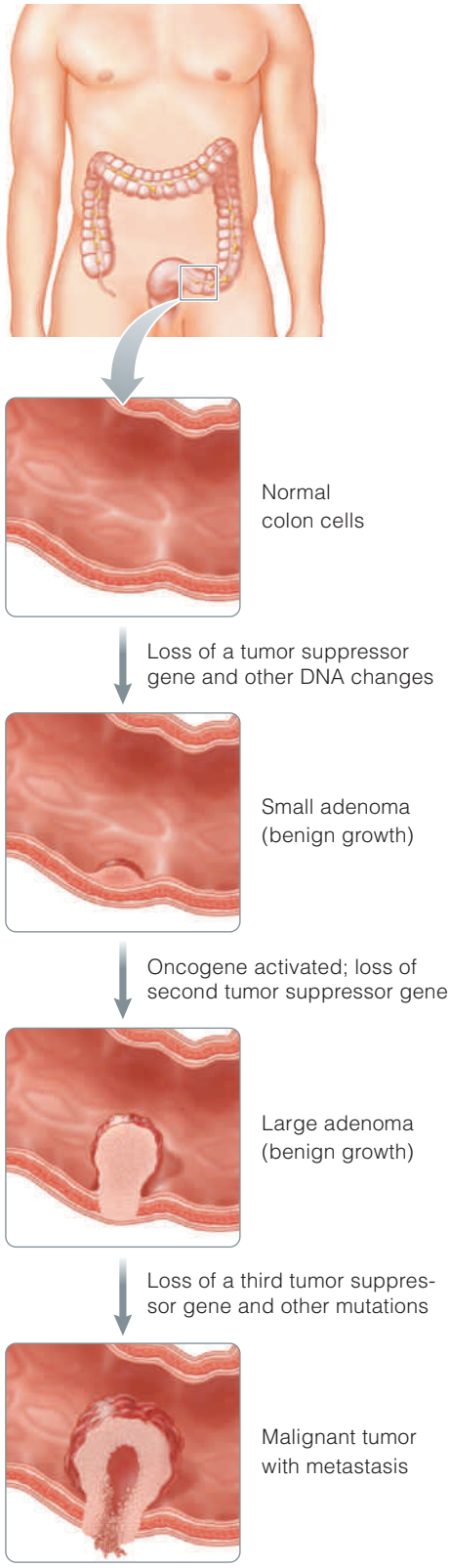
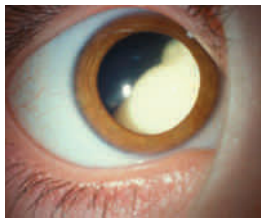


Figure 22.6 **A common type of colorectal cancer may develop by these steps.**

"mass") are genes in normal cells. They code for proteins that stimulate cell division in some way. If something alters a proto-oncogene or the way its protein-making instructions are read out, it may be converted into an **oncogene**—a gene that does not respond to the control signals that regulate cell division.

By itself, an oncogene does not cause malignant cancer. That usually requires mutations in several other genes, including at least one **tumor suppressor gene**. These are genes that can halt cell growth and division, preventing cancers from developing. They also may prevent oncogenes from being expressed.

Scientists are beginning to understand how some tumor suppressor genes operate. For example, we know that the childhood eye cancer **retinoblastoma** (*right*) is likely to develop when a child has only one functional copy of a tumor suppressor gene on chromosome 13. The two genes associated with a predisposition to breast cancer, BRCA1 and BRCA2, also are tumor suppressor genes. As the chapter introduction noted, women who inherit mutant forms of these genes are at high risk of developing breast cancer.



Retinoblastoma

Research has revealed a lot about a tumor suppressor gene called p53. This gene codes for a regulatory protein that stops cell division when cells are stressed or damaged. When p53 mutates, the controls turn off. Then an affected cell may begin runaway division. Even worse, a mutated p53 gene's faulty protein may turn on an oncogene. Half or more of cancers involve a mutated or missing p53 gene.

Other factors also may lead to cancer

Inherited susceptibility to cancer Heredity plays a major role in about 5 percent of cancers, including cases of familial breast cancer, colorectal cancer, and lung cancer. If a mutation in a germ cell or a gamete (sperm or egg) alters a proto-oncogene or tumor suppressor gene, the defect can be passed on from parent to child. An affected person may be more likely to develop cancer if later mutations occur in other proto-oncogenes, in tumor suppressor genes, or in genes that control aspects of cell metabolism and responses to hormones.

Viruses Viruses cause some cancers. For example, a viral infection may switch on a proto-oncogene when the viral DNA is inserted at a certain location in the host cell's DNA. Other viruses carry oncogenes as part of their genetic material and insert them into the host's DNA.

Chemical carcinogens There are thousands of known **carcinogens**, cancer-causing substances that can lead to a mutation in DNA. The list includes many chemicals that are by-products of industrial activities, such as asbestos, vinyl chloride, and benzene. The list also includes hydrocarbons in cigarette smoke and on the charred surfaces of barbecued meats, and substances in dyes and pesticides. Some of the first carcinogens to be identified were substances in fireplace soot, which caused many cases of scrotum cancer in chimney sweeps. Some plants and fungi also produce carcinogens. Aflatoxin, which is produced by a fungus that attacks stored grain, peanuts, and other seeds, causes liver cancer. For this reason, some authorities advise against eating unprocessed peanut butter.

Radiation Section 18.6 noted that radiation can cause cancer-related mutations in DNA. Common sources include ultraviolet radiation from sunlight and tanning lamps, medical and dental X rays, and some radioactive materials used to diagnose diseases. Other sources are radon gas in soil and water, background radiation from cosmic rays, and the gamma rays emitted from nuclear reactors and radioactive wastes. Sun exposure is probably the greatest radiation risk factor for most people.

Breakdowns in immunity When a normal cell turns cancerous, altered proteins at its surface function like foreign antigens—the "nonself" tags that mark a cell for destruction by cytotoxic T cells and natural killer cells. A healthy immune system can detect and destroy some types of cancer cells, but this protection deteriorates as a person ages. This is why the risk of cancer rises with age.

A person's cancer risk may rise whenever the immune system is suppressed for a long time. In addition to factors such as infection by HIV, anxiety and severe depression can suppress immunity. So can some therapeutic drugs, such as the corticosteroids discussed in Section 15.7.

Finally, for various reasons, the cells of a growing cancer may not trigger an immune response. When this happens, the immune system is "blind" to the cancer threat.

Take-Home Message

How does cancer develop?

- Oncogenes have a major role in changing a normal cell to a cancerous one. Proto-oncogenes may become oncogenes if there is a change in their structure or how they are expressed.
- The development of cancer typically also requires the absence or mutation of at least one tumor suppressor gene.

22.3 Cancer Risk from Environmental Chemicals

According to the American Cancer Society, factors in our environment lead to about half of all cancers. This statistic includes exposure to UV light and radiation, and it also includes agricultural and industrial chemicals. How are people exposed to these chemicals? And how dangerous are they? Let's begin with the first question.

Government statistics indicate that about 40 percent of the food in American supermarkets contains detectable residues of one or more of the active ingredients in commonly used pesticides. The residues are especially likely to be found in tomatoes, grapes, apples, lettuce, oranges, potatoes, beef, and dairy products. Imported crops, such as fruits, vegetables, and coffee beans, can also carry significant pesticide residues—sometimes including pesticides, such as DDT, that are banned in the United States. The pesticide category includes roughly 600 chemicals used as fungicides, insecticides, and herbicides, which are used alone or in combination.

Avoiding exposure to pesticides is difficult. Although residues of some pesticides can be removed from the surfaces of fruits and vegetables by washing, it can be difficult to avoid coming into contact with pesticides used in community spraying programs to control mosquitoes and other pests, or used to eradicate animal and plant pests on golf courses and along roadsides. We have more control over chemicals we use in gardens and on lawns (Figure 22.7).

Agricultural chemicals are not the only potential threats to human health. Industrial chemicals also have been linked to cancer. In one way or another, the industrial chemicals in Table 22.2 all can cause carcinogenic mutations in DNA.

Biochemist Bruce Ames developed a test that could be used to assess the ability of chemicals to cause mutations. This Ames test uses *Salmonella* bacteria as the "guinea pigs," because chemicals that cause mutations in bacterial DNA may also have the same effect on human DNA. After extensive experimentation, Ames arrived at some interesting conclusions. First, he found that more than 80 percent of known cancer-causing chemicals do cause mutations. However, Ames testing at many different laboratories has not revealed a "cancer epidemic" caused by synthetic chemicals.

Ames's findings do not mean we should carelessly expose ourselves to environmental chemicals. The National Academy of Sciences has warned that the active ingredients in 90 percent of all fungicides, 60 percent of all herbicides, and 30 percent of all insecticides used in the United States have the potential to cause cancer in humans. At the same time, responsible scientists recognize that it is virtually impossible to determine that a certain level of a specific chemical caused a particular cancer or some other harmful effect. Given these facts, it seems wise to be cautious and limit our exposure to the potential carcinogens in an increasingly chemical world.

Figure 22.7 Home garden chemicals are just one way people can come into contact with carcinogenic substances.

TABLE 22.2 Some Industrial Chemicals Linked to Cancer

Chemical/Substance	Type of Cancer
Benzene	Leukemias
Vinyl chloride	Liver, various connective tissues
Various solvents	Bladder, nasal epithelium
Ether	Lung
Asbestos	Lung, epithelial linings of body cavities
Arsenic	Lung, skin
Radioisotopes	Leukemias
Nickel	Lung, nasal epithelium
Chromium	Lung
Hydrocarbons in soot, tar smoke	Skin, lung

22.4 Some Major Types of Cancer

- **In general, a cancer is named according to the type of tissue in which it first forms.**

Although there are dozens of specific types of cancer, they can be sorted into more general categories based on the tissue where the primary (first) cancer develops.

For example, cancers of connective tissues such as muscle and bone are **sarcomas**. Types of **carcinomas** arise from cells in epithelium, including cells of the skin and the epithelial linings of internal organs. **Lymphomas** are cancers of lymphoid tissues in organs such as lymph nodes, and cancers arising in blood-forming regions—mainly stem cells in bone marrow—are **leukemias**. **Gliomas** develop in glial cells of the brain.

Scientists use Latin prefixes to indicate the particular tissue or organ where cancer develops (Figure 22.8). For example, the prefix *adeno-* refers to gland cells. A woman whose breast cancer develops in milk ducts will therefore be diagnosed with an adenocarcinoma of the breast.

Previous chapters have discussed examples of cancers that strike major body systems. Figure 22.9 summarizes American Cancer Society statistics on where the most common types of cancer form.

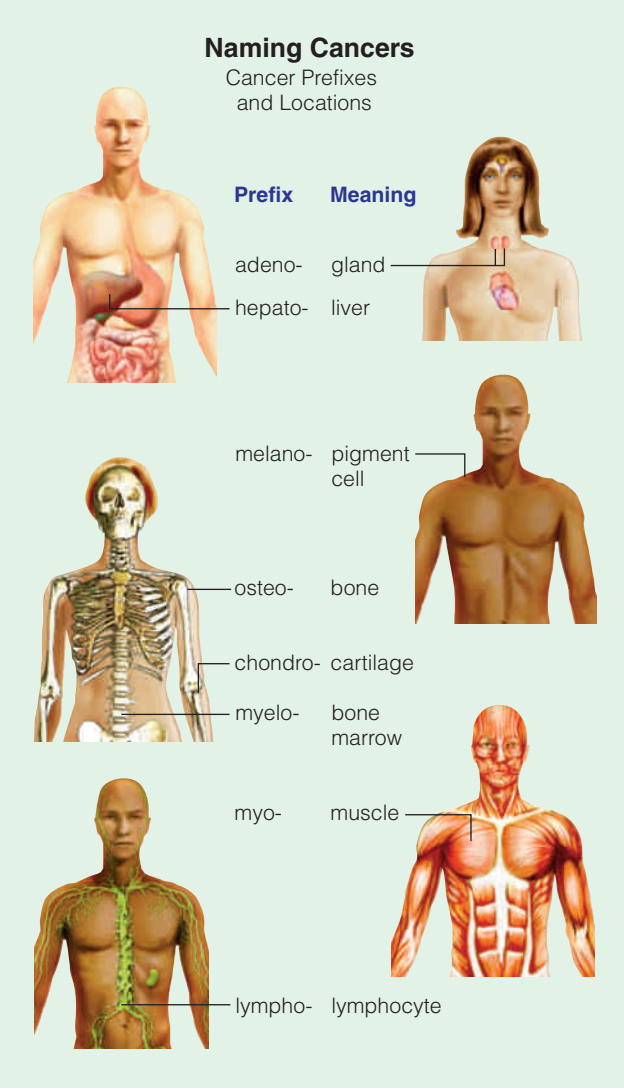
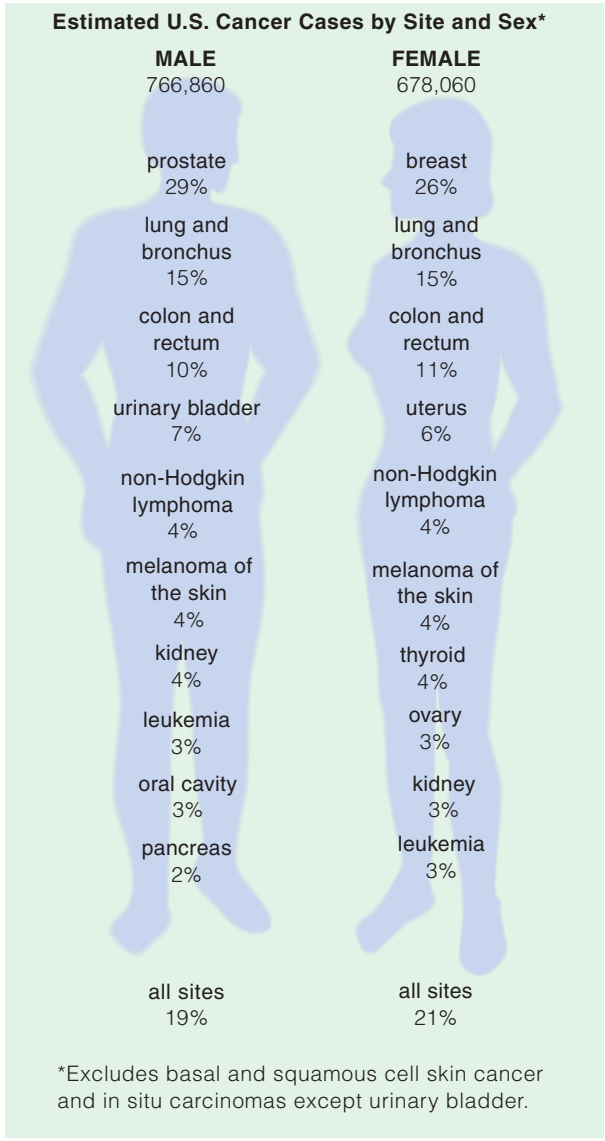


Figure 22.8 Cancer is named for the site in the body where it first develops. This list shows Latin prefixes used to indicate the location of various forms of carcinoma.

Take-Home Message

What determines the general type of a cancer?

- A cancer is categorized and named according to the tissue where it first develops.



Source: American Cancer Society, 2007.

Figure 22.9 In the United States, more than 1 million people are diagnosed with cancer each year. This chart shows the American Cancer Society's estimates of the incidence of common cancers in the United States in 2007.

22.5 Cancer Screening and Diagnosis

- **Early and accurate diagnosis of cancer is important to maximize the chances that a cancer can be cured.**

Routine screening is important for people with a family history of cancer or whose risk is elevated for some other reason, including simply getting older. Table 22.3 lists some recommended cancer screening tests.

Blood tests can detect chemical indications of cancer

To confirm or rule out cancer, various types of tests can refine the diagnosis. Blood tests can detect **tumor markers**, substances produced by specific types of cancer cells or by normal cells in response to the cancer. For example, as we noted earlier, the hormone HCG is a marker for certain cancers. Prostate-specific antigen, or PSA, is a useful marker for detecting prostate cancer, and a marker has been identified for ovarian cancer as well.

Medical imaging can reveal the site and size of tumors

Medical imaging includes methods such as MRI (magnetic resonance imaging), X-rays, ultrasound, and CT (computerized tomography). Unlike a standard X-ray, an MRI scan can reveal tumors that are obscured by bone, such as in the brain (Figure 22.10).

You may remember from Section 2.1 that **radioactive tracers** (substances with a radioisotope attached to them) are another important tool for diagnosing cancer. A doctor administers the tracer, then uses a tracking device such as a PET scanner to see where the tracer ends up in the body. For example, thyroid cancer be diagnosed using a tracer that includes a radioactive isotope of iodine (Figure 22.11).

Radioactively labeled monoclonal antibodies, which home in on tumor antigens, are useful for pinpointing the location and sizes of tumors of the colon, brain, bone, and some other tissues. A **DNA probe** (radioactively labeled DNA) can be used to locate mutated genes, such

TABLE 22.3 Recommended Cancer Screening Tests

Test or Procedure	Cancer	Sex	Age	Frequency
Breast self-examination	Breast	Female	20+	Monthly
Mammogram	Breast	Female	40–49	Every 1–2 years
			50+	Yearly
Testicle self-examination	Testicle	Male	18+	Monthly
Sigmoidoscopy	Colon	Male, Female	50+	Every 3–5 years
Fecal occult blood test	Colon	Male, Female	50+	Yearly
Digital rectal examination	Prostate, colorectal	Male, Female	40+	Colorectal: Yearly Prostate:Yearly up to age 75
Pap test	Uterus, cervix	Female	18+ and all sexually active women	Every other year until age 35; yearly thereafter
Pelvic examination	Uterus, ovaries, cervix	Female	18–39 40+	Every 1–3 years w/Pap, yearly
General checkup		Male, Female	20–39	Every 3 years
			40+	Yearly

Figure 22.10 MRI scanning is a noninvasive tool for diagnosing cancer. The patient is placed in a chamber that is surrounded by a magnet. The machine produces a magnetic field in which nuclei of common atoms in the body align and absorb energy. A computer analyzes the information and uses it to generate an image of soft tissues.

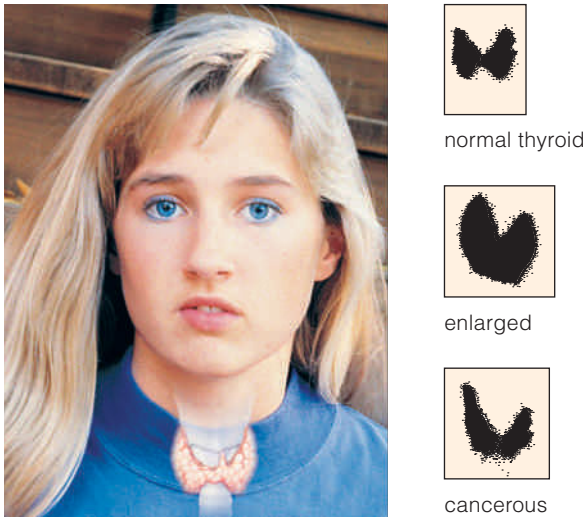


Figure 22.11 Radioactive tracers also can reveal cancer tumors. Shown above are scans of the thyroid gland from three patients who have ingested radioactive iodine, which is taken up by the thyroid.

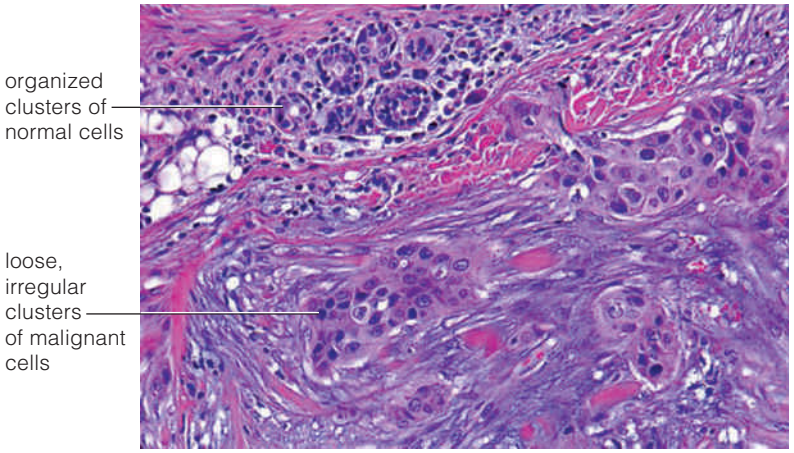


Figure 22.12 This light microscope image shows cancerous cells in breast tissue. The cancer is an adenocarcinoma that developed in one of the patient's milk ducts.

as the p53 tumor suppressor gene, or genes associated with some inherited cancers. This type of screening can allow people with increased genetic susceptibility to make medical and lifestyle choices that may reduce their cancer risk. The procedure is expensive, however, and few people have insurance that covers it.

Biopsy is the only sure way to diagnose cancer

When a test or exam suggests that a patient has cancer, the usual next step to confirm the diagnosis is **biopsy**. A small piece of suspect tissue is removed from the body through a hollow needle or exploratory surgery. A pathologist then microscopically examines cells of the tissue sample to see if cancer cells are present (Figure 22.12).

Table 22.4 lists the American Cancer Society's seven common cancer warning signs. Notice that the first letters of the signs spell CAUTION. Watching for these signs can help people spot cancer in its early stages, when treatment is most effective. Anyone who has one or more of these signs should be evaluated by a doctor as soon as possible.

TABLE 22.4 The Seven Warning Signs of Cancer*

Change in bowel or bladder habits and function
A sore that does not heal
Unusual bleeding or bloody discharge
Thickening or lump
Indigestion or difficulty swallowing
Obvious change in a wart or mole
Nagging cough or hoarseness

*Notice that the first letters of the signs spell the advice CAUTION.
Source: American Cancer Society

Take-Home Message

How is cancer diagnosed?

- Procedures for diagnosing cancer include blood tests for substances produced by cancer cells and various types of medical imaging.
- Biopsy is the definitive tool for diagnosing cancer.
- Everyone should be aware of the seven common warning signs of cancer.

22.6 Cancer Treatment and Prevention

- **When a person is diagnosed with cancer, a variety of weapons are available to combat it. And anyone can adopt an "anticancer lifestyle."**
- **Links to Monoclonal antibodies and immunotherapy 9.9, Cell cycle 18.3**

Patients understandably dread a diagnosis of cancer, but today many forms of cancer can be treated successfully. Even if a complete cure is not possible, modern treatment approaches may prolong a patient's life and improve the quality of life for years. The major weapons against cancer are chemotherapy drugs, radiation therapy, and surgery.

Surgery may even be a complete cure when a tumor is fully accessible and has not spread.

Chemotherapy and radiation kill cancer cells

Chemotherapy uses drugs to kill cancer cells (Figure 22.13). Most anticancer drugs are designed to kill dividing cells by disrupting some aspect of the normal cell cycle. Unfortunately, chemotherapy drugs are also toxic to rapidly dividing healthy cells such as hair cells, stem cells in bone marrow, immune system lymphocytes, and epithelial cells of the intestinal lining. This is why chemotherapy patients may suffer side effects such as hair loss, nausea, vomiting, and reduced immune responses. Atreatment option called *adjuvant therapy* (adjuvant means "helping") combines surgery and a less toxic dose of chemotherapy. A cancer patient might receive enough chemotherapy to shrink a tumor, for instance, then have surgery to remove what's left.

Drugs used in chemotherapy typically have been matched to the organ in which a cancer occurs—this drug for breast cancer, that one for lung cancer, and so on. A promising new strategy instead matches chemotherapy with the genetic characteristics of a patient's cancer. This approach recognizes that there are hundreds of genetically different subgroups of cancer, and that some subgroups have the same gene mutations—and chemical features—regardless of where the cancer develops. For example, the drug Gleevec works well against some types of leukemia and also against some sarcomas.

Like surgery, **radiation therapy** may be used when the cancer is small and has not spread (Figure 22.14). The radiation comes from radioisotopes such as radium 226 and cobalt 60. Like traditional chemotherapy, it is something of a "shotgun" approach to cancer treatment because it kills both cancer cells and healthy cells in the irradiated area.

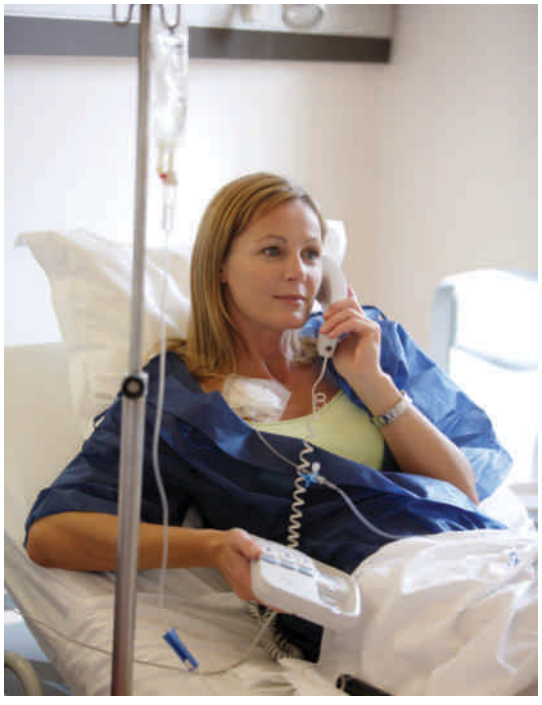


Figure 22.13 **Chemotherapy uses cell-killing drugs.** Patients usually receive chemotherapy over a period of weeks, then imaging tests are used to determine whether the patient's condition has improved.

Figure 22.14 **Radiation therapy kills cells with a targeted dose of lethal radiation.**

Because chemotherapy and radiation both damage or kill healthy body cells, cancer researchers have looked for more precise cancer treatments. Section 9.9 described how monoclonal antibodies can be used to deliver lethal doses of anticancer drugs to tumor cells while sparing healthy cells. The antibodies target cell surface markers (antigens) on various types of tumors. The idea is to link monoclonal antibodies that bind to tumor cell markers with lethal doses of cytotoxic (cell-killing) drugs. Recent experiments have shown promising results in some patients with one form of leukemia, a type of breast cancer, and certain gliomas (cancers that arise in glia in the central nervous system).

Interferons also can activate cytotoxic T cells and NK (natural killer) cells, which then may recognize and kill some types of cancer cells. So far, interferon therapy has been useful only against some rare forms of cancer.

Good lifestyle choices can limit cancer risk

None of us can control factors in our heredity or biology that might lead one day to cancer, but we can all make lifestyle decisions that promote health. The National Cancer Institute estimates that 40 percent of cancers are related to lifestyle factors, such as smoking, sun-tanning, and obesity that is due to improper diet and sedentary habits. The American Cancer Society recommends the following strategies for limiting cancer risk:

1. Avoid tobacco in any form, including secondary smoke from others (Figure 22.15).
2. Maintain a desirable weight. Being more than 40 percent overweight increases the risk of several cancers.
3. Eat a low-fat diet that includes plenty of vegetables and fruits. These foods contain antioxidants such as vitamin E, that may help prevent some kinds of cancer.
4. Drink alcohol in moderation. Heavy alcohol use, especially in combination with smoking, increases risk for cancers of the mouth, larynx, esophagus, and liver.
5. Learn whether your job or residence exposes you to such industrial agents as nickel, chromate, vinyl chloride, benzene, asbestos, and agricultural pesticides, which are associated with various cancers.
6. Protect your skin from excessive sunlight.

Figure 22.15 Lifestyle choices have a major impact on cancer risk. Eating a healthy diet and choosing not to smoke are just two ways everyone can improve their chances of avoiding cancer.

Take-Home Message

How is cancer treated?

- Surgery, chemotherapy, radiation, and other treatment strategies are used to fight cancer. However, the best defense is making lifestyle choices that promote health. Not smoking and eating a healthful diet are high on the list.

IMPACTS, ISSUES

Between You and Eternity

How Would You Vote?
Should mastectomy be limited to cancer treatment?
See CengageNOW for details, then vote online.

SOME women with an elevated genetic risk of developing breast cancer choose to have their breasts removed before cancer can arise. Although studies indicate that many of them would not have developed breast cancer, the women say that having the surgery removes doubt and gives them peace of mind.

Summary

Section 22.1 Overgrowing cells lead to a tissue mass called a tumor. In dysplasia, a common precursor to cancer, cells develop abnormalities in size, shape, and organization. Cancer results when the genetic controls over cell division are lost completely. Cancer cells (Figure 22.16) differ from normal cells in both structure and function. They usually have an over-large nucleus and altered surface proteins, and lack features of a normal, specialized body cell. Cancer cells also grow uncontrolled and can invade surrounding tissues, a process called metastasis.

Sections 22.2, 22.3 Cancer develops during carcinogenesis, a process that involves a series of genetic changes. Initially, mutation may alter a proto-oncogene into a cancer-causing oncogene. Infection by a virus can also insert an oncogene into a cell's DNA or disrupt normal controls over a proto-oncogene. One or more tumor suppressor genes must be missing or become mutated before a normal cell can be transformed into a cancerous one (Table 22.5).

A predisposition to a certain type of cancer can be inherited. Other causes of carcinogenesis are viral infection, chemical carcinogens, radiation, faulty immune system functioning, and possibly a breakdown in DNA repair.

- Use the animation and interaction on CengageNOW to learn more about cancer and metastasis.

Section 22.4 In general, a cancer is named according to the type of tissue in which it arises. Common ones include sarcomas (connective tissues such as muscle and bone), carcinomas (epithelium), adenocarcinomas (glands or their ducts), lymphomas (lymphoid tissues), and leukemias (blood-forming regions).

Section 22.5 Common methods for cancer diagnosis include blood testing for the presence of substances produced either by specific types of cancer cells or by normal cells in response to the cancer. Medical imaging (as by magnetic resonance imaging) also can aid diagnosis. Biopsy provides a definitive diagnosis.

Section 22.6 Cancer treatments include surgery, chemotherapy, and tumor irradiation. Under development are target-specific monoclonal antibodies and immune therapy using interferons and interleukins.

Lifestyle choices such as the decision not to use tobacco, to maintain a low-fat diet, and to avoid overexposure to direct sunlight and chemical carcinogens can help limit personal cancer risk.

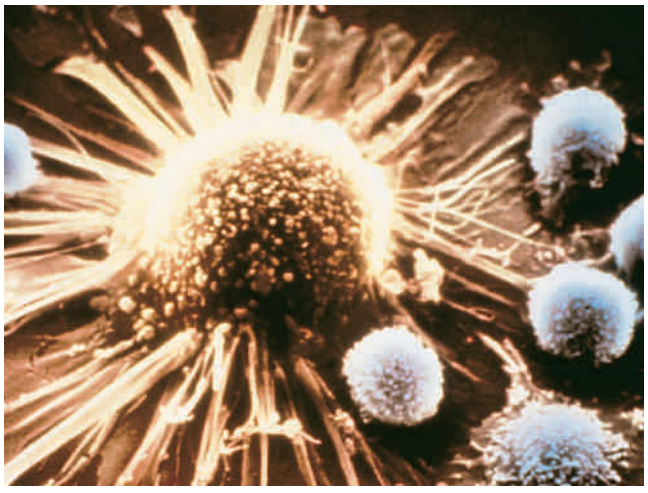


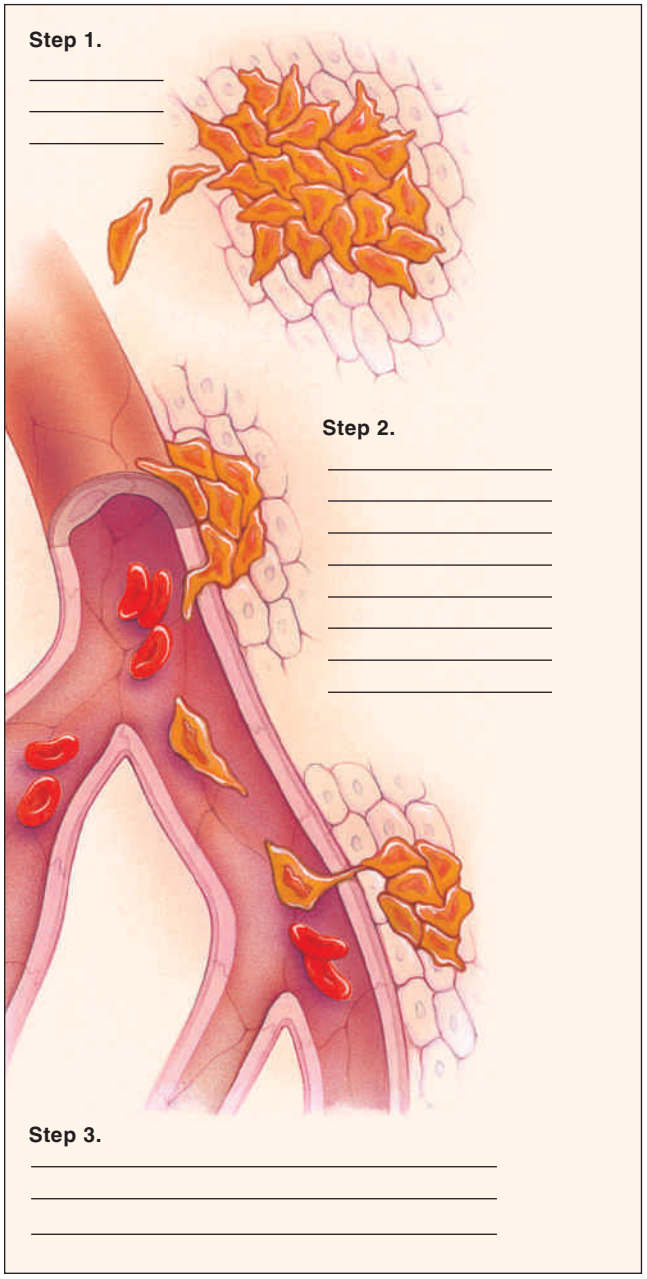
Figure 22.16 **This cancer cell is surrounded by white blood cells that may or may not be able to destroy it.** The cancer cell has extended dozens of "false feet" (pseudopodia) that help it move about in tissues.

TABLE 22.5 Cancer Causes and Contributing Factors

Cause/Factor	Impact
Oncogene	May alter control of cell division
Faulty tumor suppressor gene	Fails to halt runaway cell division
Viral infection	Switches proto-oncogene to oncogene or inserts an oncogene into the host cell DNA
Carcinogen	Damages DNA
Radiation	Damages DNA
Faulty immunity	Fails to tag cancer cells for destruction

Review Questions

1. How are cancer cells structurally different from normal cells of the same tissue? What is the relevance of altered surface proteins to uncontrolled growth?
2. What are the differences between a benign tumor and a cancerous one?
3. Write a short paragraph that summarizes the roles of proto-oncogenes, oncogenes, and tumor suppressor genes in carcinogenesis.
4. List the four main categories of cancer tumors.
5. What are the seven warning signs of cancer? (Remember the American Cancer Society's clue word, CAUTION.)
6. Using the diagram below as a guide, indicate the major steps in cancer metastasis.



Self-Quiz *Answers in Appendix V*

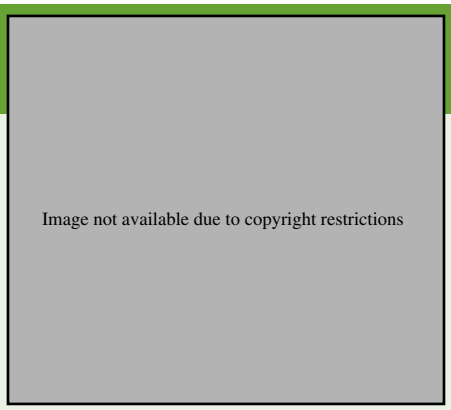
1. A tumor is _____.
   a. malignant by definition
   b. always enclosed by connective tissue
   c. a mass of tissue that may be benign or malignant
   d. always slow-growing
2. Cancer cells _____.
   a. lack normal controls over cell division
   b. secrete the growth factor angiogenin
   c. display altered surface proteins
   d. are not inhibited by contact with other cells
   e. all of the above
3. The onset of cancer seems to require the activity of an oncogene plus the absence or mutation of at least one _____.
4. Chemical carcinogens _____.
   a. include viral oncogenes
   b. can damage DNA and cause a mutation
   c. must be ingested in food
   d. are not found in foods
5. So far as we know, carcinogenesis is *not* triggered by _____.
   a. breakdowns in DNA repair
   b. a breakdown in immunity
   c. radiation
   d. protein deficiency
   e. inherited gene defects
6. Tumor suppressor genes _____.
   a. occur normally in cells
   b. promote metastasis
   c. are brought into cells by viruses
   d. only rarely affect the development of cancer
7. _____ is the definitive method for detecting cancer.
   a. Blood testing
   b. Physician examination
   c. Biopsy
   d. Medical imaging
8. The most common therapeutic approaches to treating cancer include all of the following except _____.
   a. chemotherapy
   b. irradiation of tumors
   c. surgery to remove cancerous tissue
   d. administering doses of vitamins
9. The goal of immune therapy is to _____.
   a. cause defective T cells in the thymus to disintegrate
   b. activate cytotoxic T cells
   c. dramatically increase the numbers of circulating macrophages
   d. promote the secretion of monoclonal antibodies
10. Currently, _____ cancer is the leading cause of death among adult females; _____ cancer is the leading cause of cancer death among adult males.
    a. lung; prostate
    b. breast; colon
    c. lung; lung
    d. breast; lung

Critical Thinking

1. Look back at the discussion of aging and DNA repair in Chapter 17, then propose an explanation of the observation that higher rates of cancer are associated with increasing age.
2. A textbook on cancer contains the following statement: "Fundamentally, cancer is a failure of the immune system." Why does this comment make sense?
3. Ultimately, cancer kills because it spreads and disturbs homeostasis. Consider, for example, a kidney cancer that metastasizes to the lungs and liver. What are some specific aspects of homeostasis that the spreading disease could affect?
4. Over the last few months, your best friend Mark has noticed a small, black-brown, raised growth developing on his arm. When you suggest that he have it examined by his doctor, he says he's going to wait and see if it gets any larger. You know that's not a very smart answer. Give three arguments that you can use to try to convince Mark to seek medical advice as soon as possible.
5. Some desperate cancer patients consume pills or other preparations containing shark cartilage, which the manufacturers tout as an anti-angiogenesis compound. The basis for these claims is the fact that blood vessels do not grow into cartilage. Responsible researchers point out that, regardless of the properties of cartilage, there is no way that *eating* it could provide any anticancer benefit. Why is this counterargument correct?

EXPLORE ON YOUR OWN

Most families have been touched by cancer in one way or another. The American Cancer Society website is a portal to a huge amount of reliable information on the risks for, causes of, and treatments for virtually any cancer. Choose a cancer to investigate and see how much you can learn about it in just half an hour. Does your research give you any new insights into your own risk for the cancer? What is your reaction to the stories of cancer survivors that are posted on the website?



Principles of Evolution

23

IMPACTS, ISSUES

Time on Your Mind

ASTEROIDS are rocky, metallic objects hurtling through space. Some are as large as 1,000 kilometers (about 750 miles) across. Dozens of them cross our planet's orbit.

In the past, asteroid impacts altered the course of evolution. A worldwide layer of a substance called iridium tells us that one struck Earth about 65 million years ago. The impact led to the extinction of the dinosaurs and many other life forms. Iridium is rare on Earth, but not in asteroids. Fossils of dinosaurs have never been found above that layer.

It has been only about 100,000 years since modern humans evolved. In fact, dozens of humanlike species arose in Africa during the 5 million years before our species—*Homo sapiens*—even showed up. So why are we the only ones left?

Early species of humans lived in small bands. What if most were casualties of the estimated twenty asteroids that struck when they were alive? What if our ancestors were just plain lucky? About 2.3 million years ago, a huge object from space hit the ocean, west of what is now Chile. If it had collided with the rotating Earth just a few hours earlier, our ancestors in southern Africa would have been wiped out, and we wouldn't be around today. Looking toward the future, astrophysicists predict that around 2028 a large asteroid will sweep close to Earth or the Moon—possibly a little too close for comfort.

Thinking about time and the changes it can bring is our task in this chapter. We will start with the basic principles of evolution and the kinds of evidence evolutionary biologists use in their work. Later we'll survey key trends in human evolution, and close the chapter with a look at what is currently known about the chemical origins of life on our planet.

KEY CONCEPTS

Basics of Evolution

The theory of evolution by natural selection draws on observations and ideas about how populations of organisms interact with their environment. Evolution occurs through inherited changes passed through the generations. **Sections 23.1–23.3**

Evidence for Evolution

Evidence for evolution comes from biogeography, fossils, and comparisons of body form, development, and biochemistry. **Sections 23.4–23.7**

Human Evolution

Trends in the evolution of humans include upright walking, refined vision and hand movements, and development of a complex brain and behaviors. **Sections 23.8, 23.9**

Life's Origins

Molecules of life and the first living cells are thought to have emerged on Earth around 3.8 billion years ago. **Section 23.10**

LINKS TO EARLIER CONCEPTS

- This chapter returns to a basic concept in biology, the evolution of life on Earth (1.2). The discussion in Chapter 1 of the use of the term "theory" in science (1.6) also applies to this chapter's discussion of one of the central ideas in biology, the theory of evolution by natural selection.
- Your reading here will draw on your understanding of genes (19.1, 20.1) and mutations in both genes and chromosomes (20.8, 20.9), and of how environmental factors can modify the expression of genes (19.6).
- The section on life's origins builds on your knowledge of enzymes and organic compounds (2.8), amino acids (2.11) and cell membranes (3.1).

How Would You Vote?

A large asteroid impact could obliterate civilization and much of Earth's biodiversity. Governments of the U.S. and some other nations currently spend millions, even billions, of dollars to search for and track asteroids. Do you think this is a wise use of public funds? See CengageNOW for details, then vote online.

23.1 A Little Evolutionary History

- **In Latin, the word *evolutio* means "unrolling." That image is an apt way to begin thinking of biological evolution.**

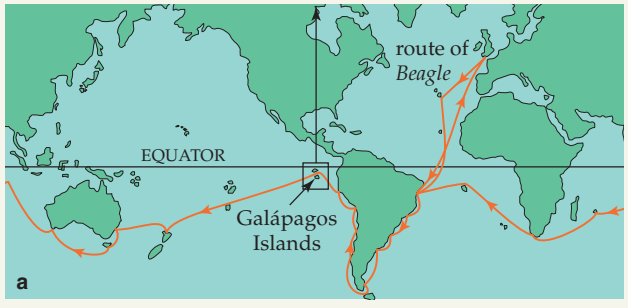
Biologists define **evolution** as genetic change in a line of descent through successive generations. All told, the evolution of life on Earth has resulted in many hundreds of thousands of species. Of those living today, some are closely related, others more distantly. As you'll read later in this chapter, we still can find biochemical evidence that we humans share a common ancestor with life forms as different from us as bacteria and corn plants. Shared ancestry is one of the core ideas in evolution.

In 1831, the source of Earth's amazing diversity of life forms was hotly disputed. Many people believed that all species had come into existence at the same time in the distant past, at the same center of creation, and had not changed since. By the mid-1800s, however, centuries of exploration and advances in the sciences of geology and comparative anatomy had raised questions. For example, why were some species found only in particular isolated regions? Why, on the other hand, were similar (but not identical) species found in widely separated parts of the world? Why did species as different as humans, whales, and bats have some strikingly similar body features? What was the significance of geologists' discoveries of similar fossil organisms in similar layers of Earth's sedimentary rocks—regardless of where in the world the layers were?

In 1831 Charles Darwin was a 22-year-old who wasn't sure what he wanted to do with his life. He had a degree in theology but wasn't interested in beng a clergyman. All he had ever wanted to do was hunt, fish, collect shells, or simply watch wildlife. A botanist who had befriended Darwin arranged for him to work as a naturalist aboard the HMS *Beagle* during a five-year voyage around the world (Figure 23.1). The *Beagle* sailed first to South America, and during the long Atlantic crossing Darwin studied geology and collected marine life. During stops along the coast and at various islands, he observed other species of organisms in environments ranging from sandy shores to high mountains. After returning to England in 1836, Darwin began talking with other naturalists about a topic that was on many scholars' minds—the growing body of evidence that life forms evolve, changing over time.

A clue as to how this might happen came from Thomas Malthus, a British clergyman and economist, who proposed that a population will tend to outgrow its resources, and so in time its members must compete for what is available. Darwin's observations also suggested that any population can produce more individuals than the environment can support, yet populations tend to be stable over time. For instance, a starfish can release 2,500,000 eggs a year, but the oceans are not filled with starfish. What determines who lives and who dies as predators, starvation, and environmental events take their toll? Chance could be a factor, but Darwin and others came up with a second major clue—that even members of the same species vary in their traits.

Darwin's melding of his observations of the natural world with the ideas of others led him to propose that evolution could occur by way of a process called **natural selection**. Widespread acceptance of this theory would not come until nearly 70 years later, when a new field, genetics, provided insights into how traits could vary. Now let's consider some current views of the mechanisms of evolution.



Take-Home Message

What is biological evolution, and what factors influenced the thinking of naturalists such as Charles Darwin?

- Evolution is genetic change in a line of descent through successive generations.
- Combining observations of the natural world with ideas about interactions of populations with their environment, Darwin forged his theory of evolution by natural selection.

Figure 23.1 Animated! Darwin's long voyage on the *Beagle* spurred his thinking about evolution. (**a**) The *Beagle*'s route from England to South America, where the ship called at (**b**) the Galápagos Islands. (**c**) Charles Darwin.

23.2 A Key Evolutionary Idea: Individuals Vary

- **Evolution occurs in populations of organisms. It begins when the genetic makeup of a population changes.**
- **Links to Concepts of heredity 19.1, Genes 20.1**

The history of life on Earth spans nearly 4 billion years. It is a story of how species originated, survived or went extinct, and stayed put or spread into new environments. The overall "plot" of the story is evolution, genetic change in lines of descent over time. **Microevolution** is the name for cumulative genetic changes that may give rise to new species. **Macroevolution** is the name for the large-scale patterns, trends, and rates of change among *groups* of species. Later on you'll get a fuller picture of these two patterns. Here, we begin with a fundamental principle of evolution: the traits of individuals in a population vary.

Individuals don't evolve—populations do

An individual fish, flower, bacterium, or person does not evolve. Evolution occurs only when there is change in the genetic makeup of *populations of organisms*. In biology, the definition of a population is very specific: A **population** is a group of individuals of the same species occupying a given area. As you know from your own experience with other people, there is lots of genetic variation within and among populations of the same species (Figure 23.2).

Overall, the members of a population have similar traits—that is, phenotypes. They have the same general form and appearance (*morphological* traits), their body structures function in the same way (*physiological* traits), and they respond the same way to certain basic stimuli (*behavioral* traits). However, the details of traits vary quite a bit. For instance, individual humans vary in the color of their body hair, as well as in its texture, amount, and distribution over the body. As we know from previous chapters, this example only hints at the immense genetic variation in human populations. Populations of most other species show the same kinds of variation.

Genetic differences produce variation

In theory, the members of a population have inherited the same number and kinds of genes. These genes make up the population's **gene pool**. Remember, though, that each kind of gene in the pool may have slightly different forms, called alleles. Variations in traits in a population—skin or hair color, say—result when individuals inherit different combinations of alleles. Whether your hair is black, brown, red, or blond depends on which alleles of certain genes you inherited from your mother and father.

If you go through a bag of chocolate candies that have different-colored sugar coatings, you'll see that some colors turn up more or less often than others do. The same is true for the gene alleles in a population. Some are much more common than others. The manufacturer can adjust the number of "reds" or "blues" in the overall mix of candy pieces, but where genes are concerned, changes come about by mutation, natural selection, and other processes. Those changes can lead to microevolution, which we consider next.

Take-Home Message

What is a biological population, and why do traits of individuals vary?

- A population is a group of individuals of the same species occupying a given area.
- Members of a population share many traits overall, but in most populations there also is a great deal of underlying genetic variation.
- Evolution is genetic change in lines of descent over time. It results from changes in the genetic makeup of populations of organisms.

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Figure 23.2 The traits of individuals in a population vary.

b) A small sample of the outward variation in our own species, *Homo sapiens*.

23.3 Microevolution: How New Species Arise

- Most people carry several mutations. From the perspective of evolution, mutations are important because they are the source of alleles—the alternative forms of genes.
- Links to Gene mutations and Changes in chromosomes 20.8, 20.9

Mutation produces new forms of genes

A **mutation** is harmful when it alters a trait such that an affected individual can't survive or reproduce as well as other individuals. For example, for us humans, small cuts are common. But before modern medical treatments were available, people with hemophilia, whose blood does not clot properly, could die young from such minor injuries. As a result, the various hemophilias were rare, because affected people rarely lived long enough to pass on the faulty genes. By contrast, a *beneficial trait* improves some aspect of an individual's functioning in the environment and so improves chances of surviving and reproducing. A *neutral trait*, such as attached earlobes in humans, doesn't help nor hurt survival.

Natural selection can reshape the genetic makeup of a population

Changes in genes are the raw material of microevolution, that process that leads to new species. Actually, several processes are included in this category, but the one that probably accounts for most changes in the mix of alleles in a gene pool is natural selection. As Section 23.1 noted, Darwin formulated his **theory of evolution by natural selection** by correlating his understanding of inheritance with certain features of populations. In 1859 he published his ideas in a classic book, *On the Origin of Species*. We can express the main points of Darwin's insight as follows:

1. **The individuals of a population vary in their body form, functioning, and behavior.**
2. **Many variations can be passed from generation to generation.** This simply means that different versions of genes—alleles—can pass from parents to offspring.
3. **In every set of circumstances, some versions of a trait are more advantageous than others.** That is, some traits impart a better chance of surviving and reproducing. The expression "survival of the fittest" is verbal shorthand for this advantage.
4. **Natural selection is the difference in survival and reproduction** that we observe in individuals who have different versions of a trait. The "fittest" traits—and the gene alleles that govern them—are more likely to be "selected" for survival.
5. **A population is evolving when some forms of a trait are becoming more or less common** relative to the other forms. The shifts are evidence that the corresponding versions of genes are becoming more or less common.
6. **Over time, shifts in the makeup of gene pools** have been responsible for the amazing diversity of life forms on Earth.

As natural selection occurs over time, organisms come to have characteristics that suit them to the conditions in a particular environment. We call this trend **adaptation**.

Recall from Section 1.6 that the accumulated evidence of evolution and natural selection has elevated both ideas to the status of fundamental principles of the living world. Later we will consider a few examples of this evidence.

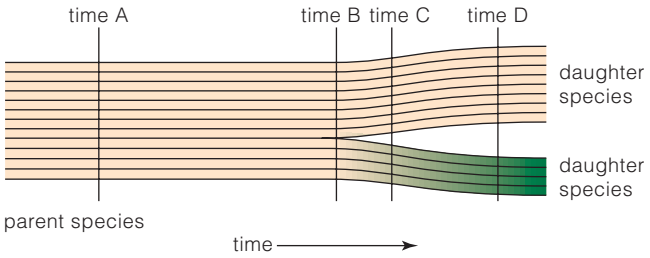
Chance can also change a gene pool

Natural selection is not the only process that can adjust the relative numbers of different alleles in a gene pool. Chance can also play a major role. This kind of gene pool tweaking is called **genetic drift**. Often the change is most rapid in small populations. In one type of genetic drift, called the *founder effect*, a few individuals leave a population and establish a new one. By chance, the relative numbers of various alleles in the new population probably will differ from those in the old group. For example, geneticists have strong evidence that ethnic Finns are descended from a small band of people who settled in what is now Finland about 4,000 years ago. Today, blond hair and blue eyes are distinctive Finnish features. In addition, at least 30 genetic disorders that are rare elsewhere are common in Finland.

Finnish boy

The makeup of a gene pool also can change as new individuals enter a population or other ones leave it. This physical movement of alleles, or **gene flow**, helps keep neighboring populations genetically similar. Over time it tends to counter the differences between populations that are brought about through mutation, genetic drift, and natural selection. In our modern age of international travel, the pace of gene flow among human populations has increased dramatically.

In Finland, there has historically been little gene flow. Climate and geography have isolated Finns from the rest of Europe for centuries. Even now, Finns have much less genetic variation than other Europeans.



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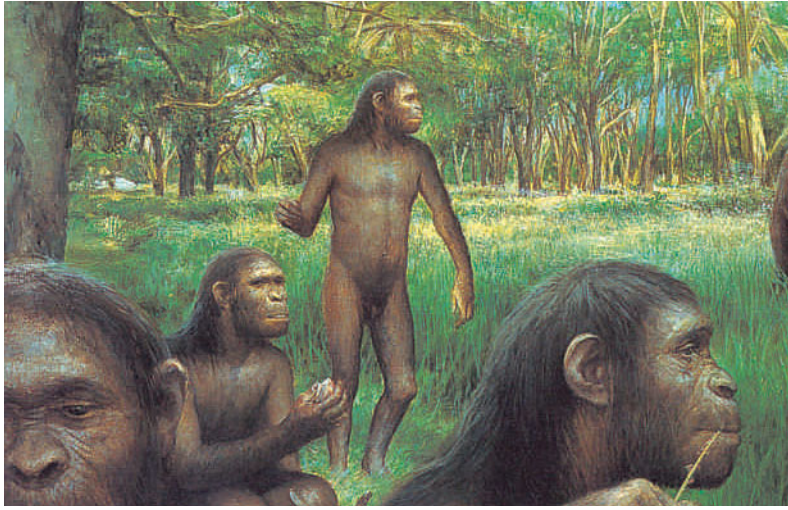


b

Figure 23.3 Divergence is the first step toward the formation of new species. (**a**) Horizontal lines in this diagram represent different populations. Because evolution is gradual, we cannot say at any one point in time that there are now two species rather than one. At time A there is only one species. At D there are two. At B and C the split has begun but isn't complete. (**b**) Artist's view of *Homo habilis* males in an East African woodland.

The ability to interbreed defines a species

For us humans and other sexually reproducing organisms, a **species** is a genetic unit consisting of one or more populations of organisms that usually closely resemble each other physically and physiologically. Members of a species can interbreed and produce fertile offspring under natural conditions. No matter how diverse their traits are, those individuals belong to the same species as long as they can interbreed successfully and so share a common gene pool. From this perspective, although a female lawyer in India may never meet up with an Icelandic fisherman, there is no biological reason why the two could not mate and produce children. But neither person could mate successfully with a chimpanzee, even though chimps and humans are closely related species and have more than 90 percent of their genes in common. In evolutionary terms, humans and chimpanzees are "reproductively isolated." Their genetic differences ensure that they can't mate and produce fertile offspring.

Reproductive isolation develops when gene flow between two populations stops. This often occurs when two populations become separated geographically. For example, we known that early members of the genus *Homo* diverged genetically, possibly when one or more populations emigrated out of Africa toward Asia and Europe. When populations are in different environments, mutation, natural selection, and genetic drift begin to operate independently in each one. These processes can change the gene pools of each in different ways. Eventually the differences can result in changes in body structure, function, or behavior that reduce the chances of successful interbreeding. The two populations may breed in different seasons, for example, or they may have different mating rituals. There may be bodily changes that physically interfere with mating. Other changes may prevent zygotes or hybrid offspring from developing properly.

The buildup of genetic differences between isolated populations is called *divergence* (Figure 23.3*a*). When the genetic differences are so great that members of the two populations can't interbreed, **speciation** has occurred: the populations have become separate species. Figure 23.3*b* is an artist's rendition of an extinct human species, *Homo habilis*. Clearly, there are many differences between *H. habilis* and our own species, *Homo sapiens*.

Speciation can be gradual or sudden

Although we know that factors such as mutation and natural selection trigger speciation, biologists disagree about the pace and timing of microevolution. In a model called *gradualism* new species emerge through many small changes in form over long spans of time. In other words, microevolution is constantly going on in tiny steps, and with time new species result. In the model called *punctuated equilibrium*, most evolutionary change occurs in bursts. That is, each species undergoes a spurt of changes in form when it first branches from the parental lineage, then changes very little for the rest of its time on Earth.

The driving force behind rapid changes in species may be dramatic changes in climate or some other aspect of the physical environment. This type of sudden change (in evolutionary terms) alters the physical conditions to which populations of organisms have become adapted. For example, the onset of an ice age changes the living conditions for species in affected land areas. A major shift in ocean currents (which help determine water temperature) might have the same effect on marine species. Punctuated equilibrium could help explain why the fossil record has scanty evidence of a continuum of microevolution—the "missing links" between closely related species. It's likely that both models have a place in explaining the history of life.

Take-Home Message

What is a species and how do new species come about?

- Natural selection and chance can alter the kinds and relative numbers of various gene alleles in a population. Accumulating genetic changes can result in the evolution of new species. A species is a unit of one or more populations of individuals that can successfully interbreed in nature.

23.4 Looking at Fossils and Biogeography

- **The fossil record and biogeography are important tools in reconstructing the intertwined journey of life and Earth.**

A **fossil** is recognizable, physical evidence of ancient life (Figure 23.4). The more Darwin and others learned about the similarities and differences among fossils and living organisms, the stronger the evidence became that such diversity is the result of evolution by natural selection as populations adapted to their surroundings.

Fossils are found in sedimentary rock

When an organism dies, its soft parts usually decompose first. As a result, the most common fossils are bones, teeth, shells, seeds, and other hard parts. **Fossilization** begins when an organism is buried in sediments or volcanic ash. With time, water seeps into the organic remains, infusing them with dissolved inorganic compounds. As more and more sediments accumulate above the burial site, the remains are subjected to increasing pressure. Over long spans of time, the chemical changes and growing pressure transform them to stony hardness.

Organisms are more likely to be preserved when they are buried quickly in the absence of oxygen. Entombment by volcanic ash or anaerobic mud (which lacks oxygen) satisfies this condition very well. Preservation also is favored when a burial site is not disturbed. Usually, though, fossils are broken, crushed, deformed, or swept away by erosion, rock slides, and other geologic events.

Fossil-containing layers of sedimentary rock formed long ago, when silt, volcanic ash, and other materials were gradually deposited, one above the other (Figure 23.5). This layering of sediments is called *stratification*. Although most sedimentary layers form horizontally, earthquakes or other geologic disturbances can tilt or break them.

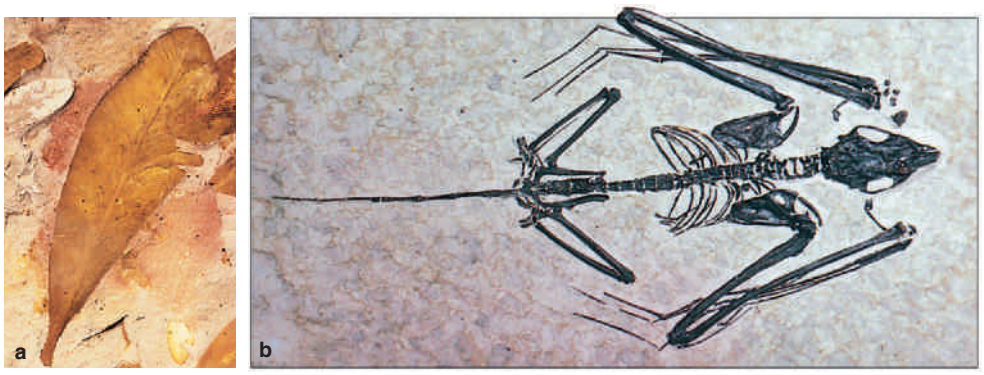


Figure 23.4 **High quality fossils such as these are rare.** (**a**) Fossilized leaf of an ancient fern. (**b**) The skeleton of a bat that lived 50 million years ago.

Figure 23.5 **The Grand Canyon of the American Southwest reveals sedimentary rock layers that formed over hundreds of millions of years.**

The fossil record is spotty

We currently have fossils of about 250,000 species, far more than in Darwin's day. However, judging from present diversity, there must have been millions of ancient, now-extinct species, and for several reasons we will not be able to recover fossils for most of them. Most of the important, large-scale movements in the Earth's crust have wiped out evidence from crucial periods in the history of life. In addition, most members of ancient communities simply have not been preserved. For example, plenty of hard-shelled mollusks and bony fishes are represented in the fossil record. Jellyfishes and soft-bodied worms are not, even though they may have been common. Population density and body size skew the record more. A population of ancient plants may have produced millions of pollen grains in each growing season, while the earliest human ancestors lived in small groups and produced few young. Therefore, the chance of finding a fossilized skeleton of an early human is small compared to the chance of finding spores of plant species that lived at the same time.

The fossil record is also biased toward certain environments and locations. Most species for which we have fossils lived on land or in shallow seas that, through geologic uplifting, became part of continents. We have only a few fossils from sediments beneath the ocean, which covers three-fourths of the Earth's surface. Also, most fossils have been discovered in the Northern Hemisphere. The reason is probably that most geologists have lived and worked there.

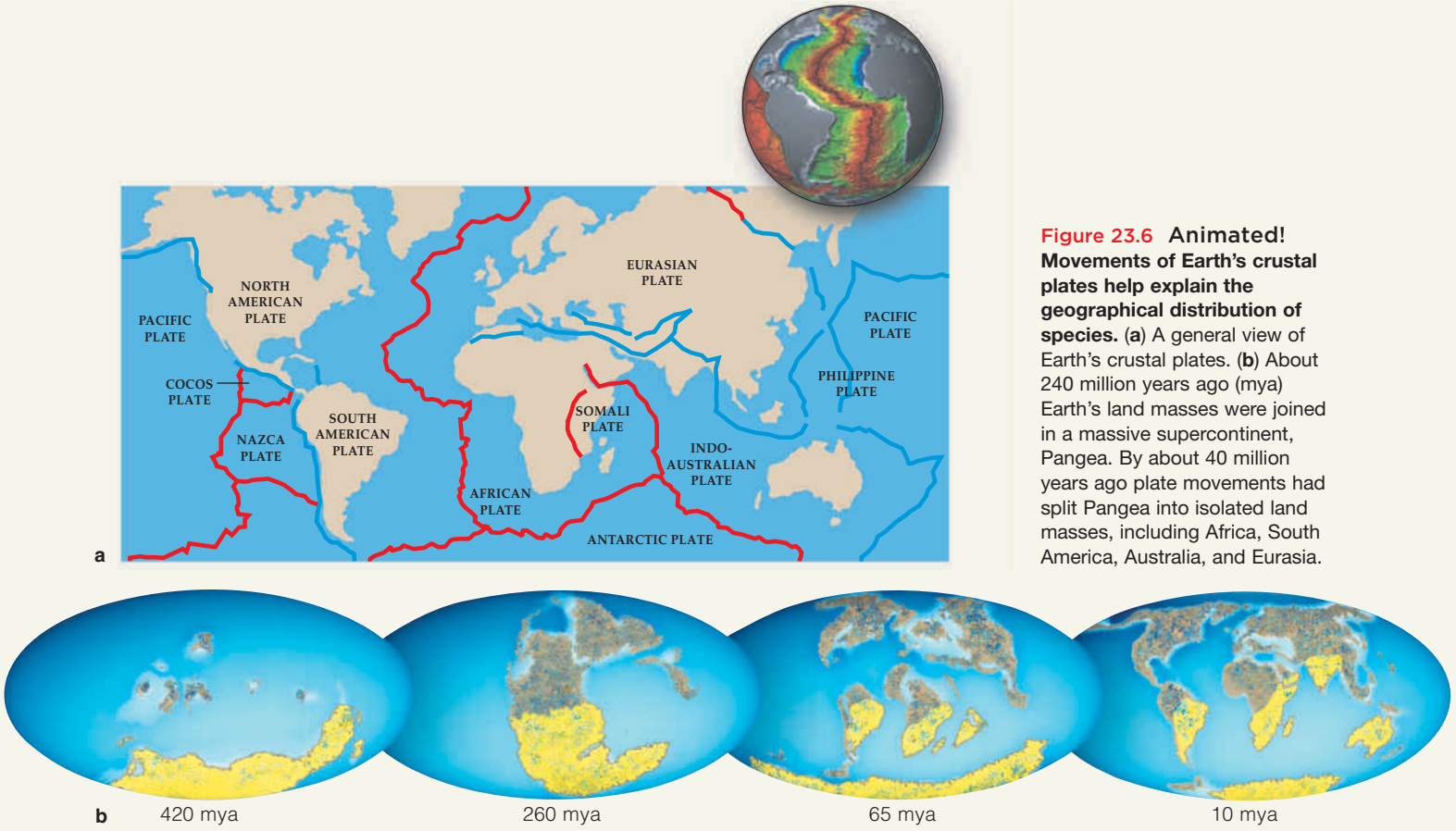


Figure 23.6 Animated!
Movements of Earth's crustal plates help explain the geographical distribution of species. (**a**) A general view of Earth's crustal plates. (**b**) About 240 million years ago (mya) Earth's land masses were joined in a massive supercontinent, Pangea. By about 40 million years ago plate movements had split Pangea into isolated land masses, including Africa, South America, Australia, and Eurasia.

How do we know how old a fossil is? Sedimentary rocks that contain fossils are dated by determining their position relative to nearby volcanic rocks. The age of the volcanic rocks is determined by **radiometric dating**. This method tracks the radioactive decay of an isotope of some element that had been trapped inside the rock when the rock formed. Like the ticking of a perfect clock, the decay rate is constant. Radiometric dating is about 90 percent accurate.

Biogeography provides other clues

Darwin also believed that the concept of evolution by natural selection could help shed light on the subject we know today as **biogeography**—the study of the world distribution of plants and animals. Biogeography asks the basic question of why certain species (and higher groupings) occur where they do. For example, why do Australia, Tasmania, and New Guinea have species of monotremes (egg-laying mammals such as the duckbilled platypus), while such animals are absent from other parts of the world where the living conditions are similar? And why do the tropics have the greatest diversity of life forms? The simplest explanation for such biogeographical patterns is that species occur where they do either because they evolved there from ancestral species or because they dispersed there from elsewhere.

Charles Darwin probably would have been fascinated to learn of modern *plate tectonics*, the movement of plates of Earth's crust (Figure 23.6). From studying evidence of such movements, we know that early in our planet's history all present-day continents, including Africa and South America, were parts of a massive "supercontinent" called Pangea (Figure 23.6*b*). By determining the locations of plates at different times in Earth's history, researchers can shed light on possible dispersal routes for some groups of organisms and when (in geological history) the movements took place.

Take-Home Message

How do the fossil record and biogeography provide evidence for evolution?

- Fossils are present in layers of sedimentary rocks. The deeper the layers, the older the fossils. The completeness of the fossil record varies, depending on the kinds of organisms represented, where they lived, and how stable their burial sites have been.
- Biogeographical patterns can provide clues to where a species arose. Along with evidence from plate tectonics, the patterns also may shed light on the routes by which some groups of organisms spread to new areas.

23.5 Comparing the Form and Development of Body Parts

- **Early evolutionary thinkers also noted patterns in the form of body parts. Modern biologists have shed light on evolutionary history by comparing stages of development in major groups of organisms.**

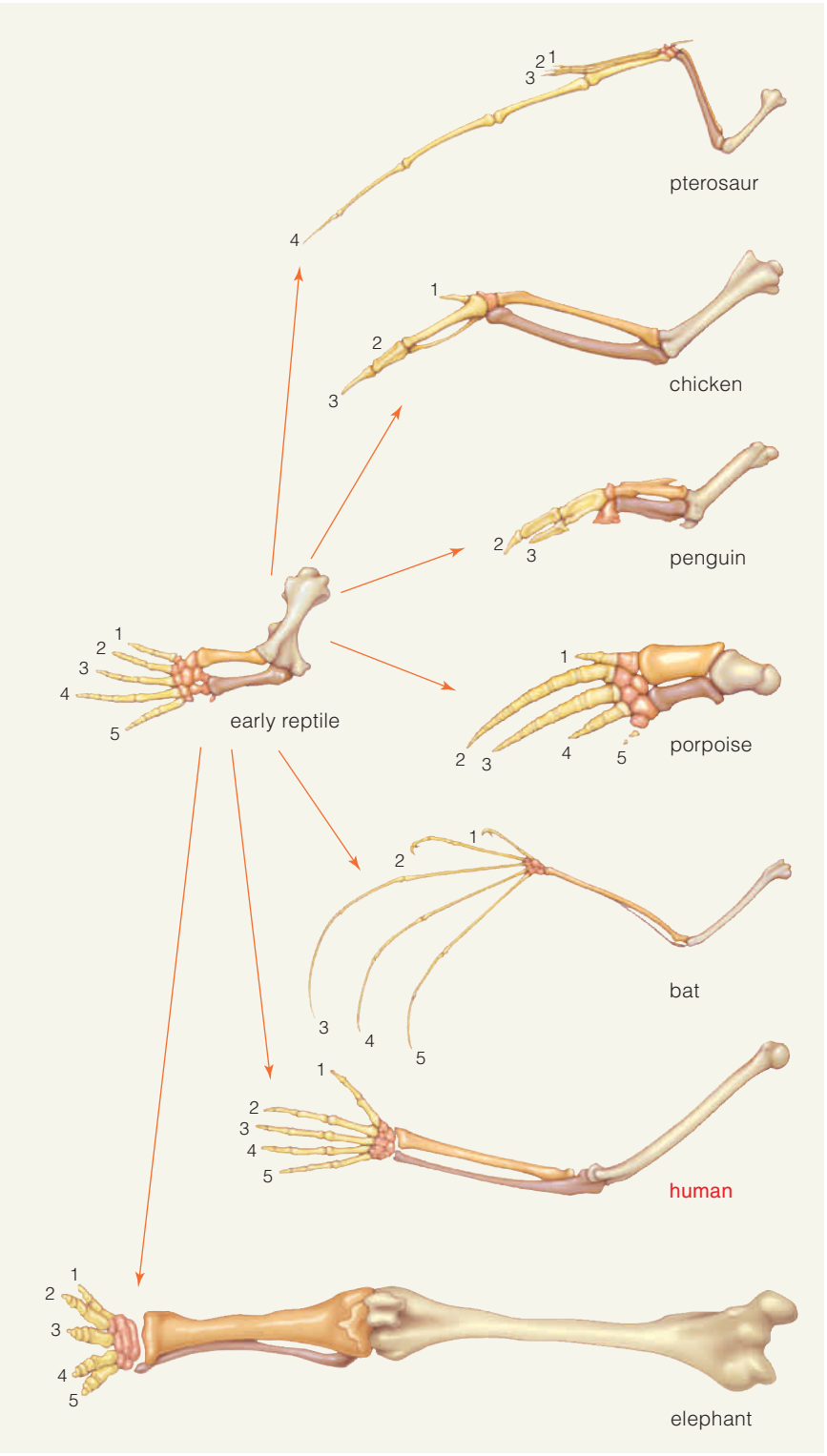


Figure 23.7 Animated! **The form of forelimbs of humans and other vertebrates diverged as different groups evolved.** This diagram starts with a generalized form of ancestral early reptiles. Diverse forms evolved even as similarities in the number and position of bones were preserved. The drawings are not to the same scale.

Comparing body forms may reveal evolutionary connections

Comparative morphology uses information contained in patterns of body form to reconstruct evolutionary history. When populations of a species branch out in different evolutionary directions, they diverge in their appearance, the functions of certain body parts, or both. Yet the related species also remain alike in many ways, because their evolution modifies a shared body plan. In such species we typically see **homologous structures**. These are the same body parts that have been modified in different ways in different lines of descent from a common ancestor (recall that *homo-* means "same").

For example, the same ancestral organism probably gave rise to most land-dwelling vertebrates, which have homologous structures. Apparently their common ancestor had four five-toed limbs. The limbs diverged in form and became wings in pterosaurs, birds, and bats (Figure 23.7). All these wings are homologous—they have the same parts. The five-toed limb also evolved into the flippers of porpoises and the anatomy of your own forearms and fingers.

Can body parts in organisms that *don't* have a recent common ancestor come to resemble one another in form and function? Yes. These **analogous structures** (from *analagos*, meaning "similar") arise when different lineages evolve in the same or similar environments. Different body parts, which were put to similar uses, were modified through natural selection and ended up resembling one another. This pattern of change is called *morphological convergence*. For example, a dolphin, a fast-swimming marine mammal, has a sleek, torpedo-shaped torso—and so does a tuna, a fast-swimming fish.

Development patterns also provide clues

Vertebrates include fishes, amphibians, reptiles, birds, and mammals. Yet despite how different these groups are, comparing the ways in which their embryos develop provides strong evidence of their evolutionary links.

Early in development, the embryos of all the different vertebrate lineages go through strikingly similar stages (Figure 23.8). During vertebrate evolution, mutations that disrupted an early stage of development would have had devastating effects on the organized interactions required for later stages. Evidently, embryos of different groups remained similar because mutations that altered early steps in development were selected against.

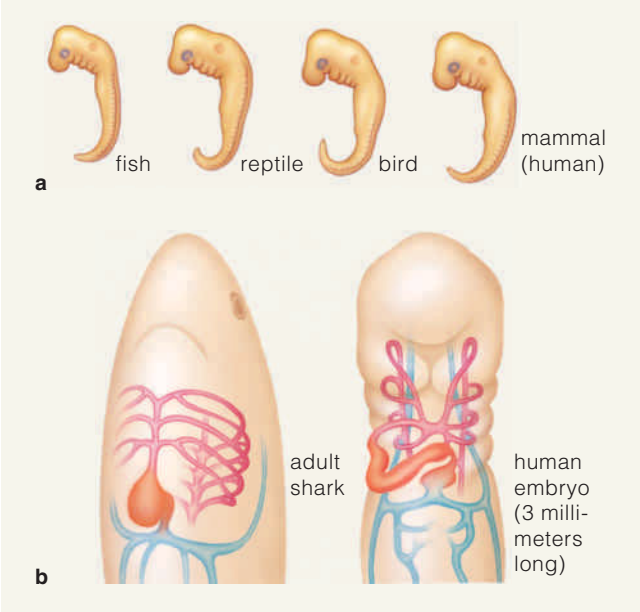


Figure 23.8 Animated! Comparing embryos also provides evidence of evolutionary relationships. Part (**a**) reveals that the early embryos of vertebrates are similar, even though the adults are very different. This is evidence of change in a common program of development. (**b**) Fishlike structures still form in the early embryos of reptiles, birds, and mammals. For example, a two-chambered heart (*orange*), certain veins (*blue*), and portions of arteries called aortic arches (*red*) develop in the embryos of sharks and other fishes. Adult fishes have them, too. The same structures form in an early human embryo.

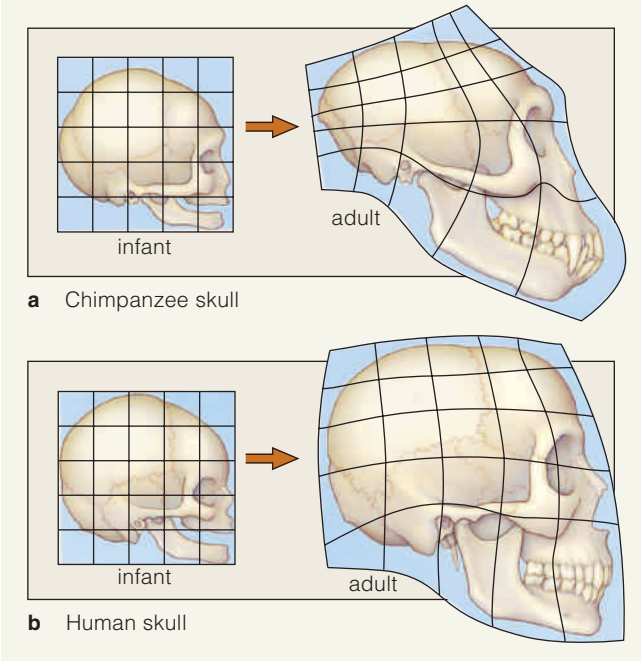


Figure 23.9 Animated! The skulls of a chimpanzee and a human start out with similar proportions but diverge as growth continues. Part (**a**) shows a chimp's skull, part (**b**) a human skull. Imagine that the skulls represented here are paintings on a blue rubber sheet divided into a grid. Stretching the sheet deforms the grid's squares. For the adult skulls, differences in size and shape in corresponding grid sections reflect differences in growth patterns.

So how did the *adults* of different vertebrate groups come to be so different? At least some differences resulted from mutations that altered the onset, rate, or time of completion of certain developmental steps. Such mutations would bring about changes in shape through increases or decreases in the size of body parts. They also could lead to adult body forms that still have some juvenile features. For instance, Figure 23.9 depicts how change in the growth rate at a key point in development may have produced differences in the proportions of chimpanzee and human skull bones, which are alike at birth. Later on, they change dramatically for chimps but only slightly for humans. Chimpanzees and humans arose from the same ancestral stock. Their genes are nearly identical. Even so, at some point on the separate evolutionary road leading to humans, some regulatory genes probably mutated in ways that proved adaptive. From then on, instead of promoting the rapid growth required for dramatic changes in skull bones, the mutated genes have blocked it.

As Figure 23.10 indicates, the bodies of humans, pythons, and other organisms can have what seem like useless *vestigial* structures. For example, consider your own ear-wiggling muscles—which four-footed mammals (such as dogs) use to orient their ears. In humans, such body parts are left over from a time when more functional versions were important for an ancestor.

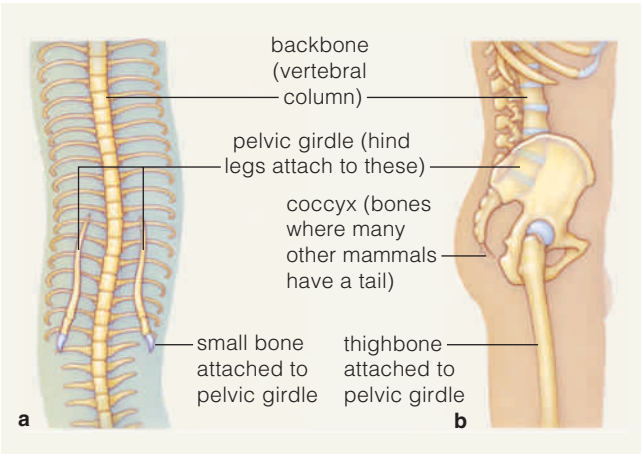


Figure 23.10 Animated! Vestigial body parts are "left over" from ancestral species. Some python bones (**a**) correspond to the pelvic girdle of other vertebrates, including humans. A snake has small vestigial hind limbs that are remnants from a limbed ancestor. (**b**) The human coccyx is a similar vestige from an ancestral species that had a bony tail, although muscles still attach to it.

Take-Home Message

What can we learn about evolution by comparing body form and development?

- In comparative morphology, patterns of body form reveal evolutionary information. Similar patterns of development also may provide clues to evolutionary relationships among organisms.

23.6 Comparing Genetics

- **Genetic similarities and differences also provide information about evolutionary connections.**
- **Links to Protein synthesis 21.3, the Genetic code 21.4**

The kinds and numbers of outward traits species do (or don't) share are clues to how closely they are related. The same holds true for genes and proteins. Remember, the DNA of each species contains instructions for making RNAs and then proteins. This means that comparisons of DNA, RNA, and proteins from different species are additional ways of evaluating evolutionary relationships.

For example, simply by comparing body form you might conclude that monkeys, humans, chimpanzees, and other **primates** are related. You can test this idea by looking for differences in the amino acid sequence of a protein, such as hemoglobin, that occurs in all primates. You also could decide to see whether the nucleotide sequences in their DNA match closely or not much at all. Logically, the species that are most similar in their biochemistry are the most closely related.

Over time, mutations crop up in most genes. When two species both have the same gene and its nucleotide sequence is the same or nearly so in both, they must be closely related. Otherwise there would be more genetic difference. If on the other hand the sequences are quite different, many neutral mutations must have occured in them. A very long time must have passed since the species shared a common ancestor.

For instance, many organisms produce cytochrome *c*, a protein of electron transport chains. Studies show that the gene coding for the protein has changed very little over vast spans of time. Human cytochrome *c* has a primary structure of 104 amino acids. Chimps have the identical amino acid sequence. It differs by 1 amino acid in rhesus monkeys, by 19 in turtles, and 56 in yeasts, a type of fungus. Given this biochemical information, would you assume humans are more closely related in evolutionary time to a chimpanzee, a rhesus monkey, or a turtle?

Take-Home Message

How can analyzing DNA provide information about evolution?

- Species that are more closely related will have more similar gene sequences than distantly related species do.

23.7 How Species Come and Go

- **The history of life on Earth is marked by extinction and by the evolution of new species.**

In extinction, species are lost forever

Extinction is the permanent loss of a species. Overall, species disappear at a fairly steady rate of "background extinction." A **mass extinction** is a sudden, widespread rise in extinctions above the background level (Figure 23.11). Major groups are wiped out simultaneously and the overall number of living species plummets. About 65 million years ago dinosaurs and many marine groups died out during a mass extinction, possibly due to environmental changes that occurred after one or more large meteorites struck Earth in a short time. The fossil record indicates that it may take as long as 100 million years for the overall number of species to recover after a mass extinction.

Era	Period	
		MASS EXTINCTION UNDER WAY
CENOZOIC	QUATERNARY	With high population growth rates and cultural practices (e.g., agriculture, deforestation), humans become major agents of extinction.
	1.8 mya	
	TERTIARY	
	65	*MASS EXTINCTION*
MESOZOIC	CRETACEOUS	Slow recovery after previous mass extinction, then adaptive radiation of some marine species and plants and animals on land. Asteroid impact, 85% of all species disappear from land and seas.
	145	
	JURASSIC	
	213	
	TRIASSIC	
	248	*MASS EXTINCTION*
PALEOZOIC	PERMIAN	Pangea forms; land area exceeds ocean surface area for first time. Asteroid impact? Major glaciation, colossal lava flows, 90%–95% of all species lost.
	286	
	CARBONIFEROUS	
	360	*MASS EXTINCTION*
	DEVONIAN	More than 70% of marine groups lost. Meteorite impact, sea level decline, global cooling?
	410	
	SILURIAN	
	440	*MASS EXTINCTION*
	ORDOVICIAN	Second most devastating extinction in seas; loss of nearly 100 families of marine invertebrates (animals without backbones).
	505	
	CAMBRIAN	
	544	*MASS EXTINCTION*
	(precambrian)	Massive glaciation; 79% of all species lost, including most microorganisms in the seas.

Figure 23.11 Many mass extinctions have occurred during Earth's history. Each extinction has been followed by a period of slow recovery, and the resulting mix of species is not the same as before.

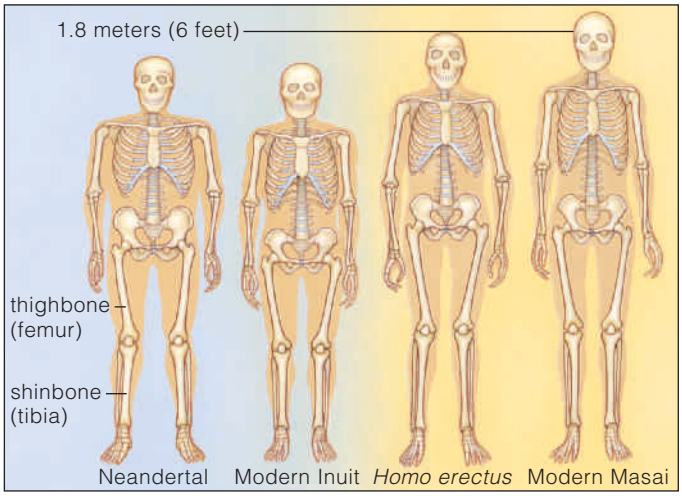


Figure 23.12 Climate is one agent of adaptive changes. Humans adapted to cold climates have a heat-conserving body—stockier, with shorter legs—compared to humans adapted to hot climates.

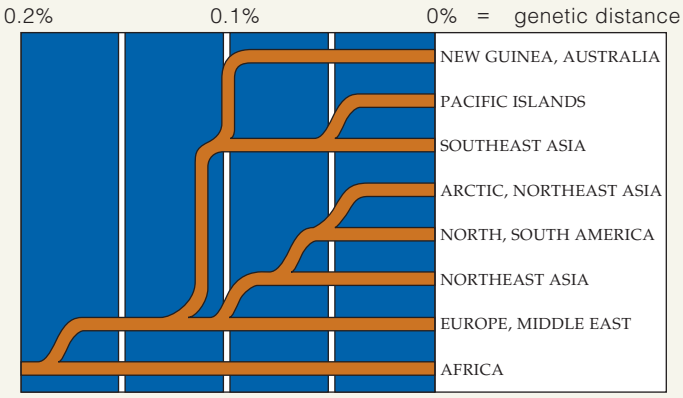
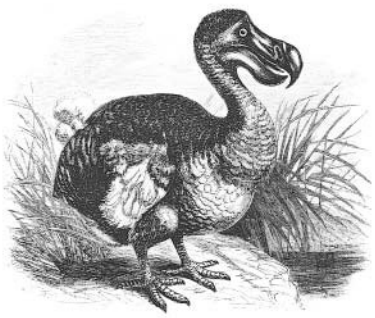


Figure 23.13 Animated! Here is one proposed family tree for populations of modern humans (*Homo sapiens*) that are native to different regions of the world. The diagram's branch points (suggested by biochemical studies) show presumed, small genetic divergences between populations.

You may be aware that in the past few hundred years human activities have caused the extinction of thousands of species. The dodo, a large flightless bird that evolved on the Indian Ocean island of Mauritius, is a famous example. The extinction rate is speeding up as we cut down forests, fill in wetlands, and otherwise destroy habitats of other animals and plants with which we share Earth. Global climate change is another factor that has contributed to patterns of extinctions. We will delve more deeply into these concerns in Chapter 25.



Engraving of a dodo

In adaptive radiation, new species arise

In **adaptive radiation**, new species of a lineage move into a wide range of habitats during bursts of microevolution. Many adaptive radiations have occurred during the first few million years after a mass extinction. Fossil evidence suggests this happened after dinosaurs went extinct. Many new species of mammals arose and radiated into habitats where dinosaurs had once lived.

Adaptive radiations also have occurred in the human lineage. The ancestors of modern humans, including the tool-using species *Homo habilis* ("handy man," pictured in Figure 23.3*b*), apparently remained in Africa until about 2 million years ago. Around that time, genetic divergence led to new species, including *Homo erectus*, a human species that the fossil record places on the evolutionary road to modern humans. *H. erectus* coexisted for a time with *H. habilis*. But while members of its sister species also were upright walkers, *H. erectus* really earned the name. Its populations walked out of Africa, going left into Europe or right into Asia. Judging from Middle Eastern fossils, our species, *Homo sapiens*, had evolved by 100,000 years ago.

What kinds of selection pressures triggered this adaptive radiation? Although we don't know for sure, this *was* a time of physical changes. One group of early humans, the Neandertals, had large brains and were massively built. Some Neandertal populations were the first humans to adapt to the coldest regions (Figure 23.12). Later genetic changes resulted in anatomically modern humans. Figure 23.13 shows a possible family tree for those groups. The tree's branches represent separate lines of descent from a common ancestor.

Take-Home Message

What are extinction and adaptive radiation?

- Species are always going extinct. In a mass extinction major groups of species go extinct in a short period of geological time.
- In adaptive radiation, new species rapidly (on a geological time scale) fill a range of habitats.

23.8 Evolution from a Human Perspective

- **Like other life forms, we humans have a well-defined place in the evolutionary scheme of things.**

All told, the evolution of life on Earth has given rise to many hundreds of thousands of species—some closely related, others more distantly. An organism's scientific name, always shown in italic type, has been a kind of shorthand for its place in the living world. In a binomial system devised centuries ago, the name has two parts—as in *Homo sapiens*, the binomial that is used for humans. The first part is the genus name. A **genus** (plural: genera) encompasses all the species that are similar to one another and distinct from others in certain traits. The second part of the name indicates the particular species within the genus.

Species are organized into a hierarchy of groupings. Table 23.1 lists them, using humans as the example. Each group above the genus level includes a larger array of organisms that share more general features.

Each lineage of life forms has its defining traits. We humans share certain characteristics with other primates (such as being land-dwellers). At the same time, we differ in major ways from other primate lineages, such as the New World monkeys (Figure 23.14*a*). We are genetically closer to the great apes (Figure 23.14*b*), and closest to the bonobos (Figure 23.14*c*).

Five trends mark human evolution

Primates evolved from ancestral mammals more than 60 million years ago. Fossils suggest that the first primates resembled small rodents. They may have foraged in the forest for insects, seeds, buds, and eggs. Between 54 and 38 million years ago, some primates were living in the trees—a habitat where natural selection would strongly favor some traits over others.

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Figure 23.14 The primates include several nonhuman species.

(**b**) A male gorilla. (

Precision grip and power grip The first mammals spread their toes apart to help support the body as they walked or ran on four legs. Primates still spread their toes or fingers. Many also make cupping motions, as when a monkey lifts food to its mouth. Other hand movements also developed in our ancient tree-dwelling relatives. Changes in hand bones allowed fingers to be wrapped around objects (that is, *prehensile* hand movements were possible), and the thumb and tip of each finger could touch (opposable movements).

In time, hands also began to be freed from load-bearing functions—they were not needed to support the body. Much later, refinements in hand movements led to the precision grip and the power grip:

These hand positions would enable early humans to make and use tools. They helped form the foundation for the development of early technologies and culture.

Improved daytime vision Early primates had an eye on each side of the head. Later ones had forward-directed eyes, an arrangement that is better for detecting shapes

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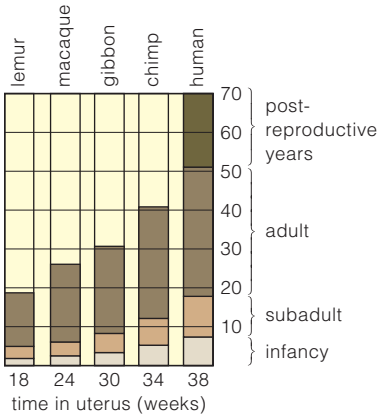
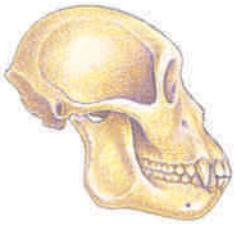


Figure 23.15
In primates we see a trend toward longer life spans and a longer period of dependency of the young.

and movements in three dimensions. Later modifications allowed the eyes to respond to variations in color and light intensity (dim to bright)—another advantage for life in the trees.



Jaw shape and teeth of an early primate

Changes in dentition Changes in the teeth and jaws of early primates accompanied a shift from eating insects, to fruits and leaves, and on to a mixed or *omnivorous* diet. Later on, rectangular jaws and long canine teeth came to be further defining features of monkeys and apes. Along the road leading to humans, a bow-shaped jaw and teeth that were smaller and all about the same length evolved.

Changes in the brain and behavior Living on tree branches also favored shifts in reproductive and social behavior. Imagine the advantages of single births over litters, for example, or of clinging longer to the mother. In many primate lineages, parents started to invest more effort in fewer offspring. They formed strong bonds with their young, maternal care became more intense, and the learning period grew longer (Figure 23.15).

Brain regions, such as the cerebral cortex, that are involved in information processing began to expand, and the brain case enlarged. New behavior promoted more brain development—which in turn stimulated more new behavior. In other words, brain modifications and behavioral complexity became closely linked. We see the links clearly in the parallel evolution of the human brain and culture. **Culture** is the sum total of behavior patterns of a social group, passed between generations by learning and symbolic behavior—especially language. The capacity for language arose among ancestral humans through changes in the skull bones and expansion of parts of the brain.

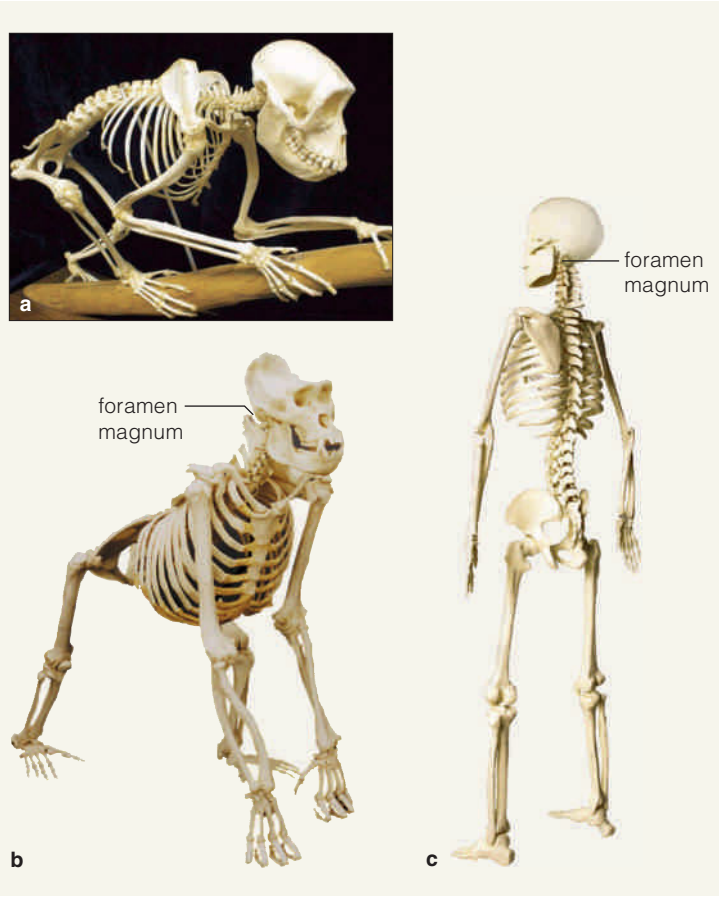


Figure 23.16 **Animated!** **Compare the skeletal organization of three primates.** Pictured are (**a**) monkeys, (**b**) apes (the gorilla is shown here), and (**c**) humans.

Upright walking Of all primates, only humans can stride freely on two legs for long periods of time. This two-legged gait, called **bipedalism**, emerged as elements of the ancestral primate skeleton were reorganized. As shown in Figure 23.16, humans have a shorter, S-shaped backbone as compared with apes and monkeys. In addition, in monkeys and apes the foramen magnum, the opening at the base of the skull where the spinal cord can connect with the brain, is at the back of the skull. In human, it is close to the center of the base of the skull. These and other features, such as the position and shape of the knee and ankle joints and pelvic girdle, make bipedalism possible. By current thinking, the evolution of bipedalism was the key change in the origin of human and humanlike species, both past and present.

Take-Home Message

What are five main trends in human evolution?

- Five trends emerged along the evolutionary road leading to humans. These trends are refined hand movements, improved vision, dentition generalized for an omnivorous diet, the interconnected development of a more complex brain and cultural behavior, and upright walking.

23.9 Emergence of Early Humans

- **By 36 million years ago tree-dwelling primates called anthropoids had evolved in tropical forests. One or more types were on or very close to the evolutionary road that would lead to monkeys, apes, and humans.**

Between 23 and 5 million years ago, apelike forms—the first *hominoids*—evolved and spread through Africa, Asia, and Europe. At that time, shifts in Earth's land masses and ocean circulation caused a long-term change in climate. Lush African forests began to give way to open woodlands and later to grasslands. Food became harder to find. In these new circumstances, most of the hominoids went extinct. A survivor was the common ancestor of two lineages that arose by 7 million years ago. One gave rise to the great apes, and the other to the first *hominids*.

Early hominids lived in central Africa

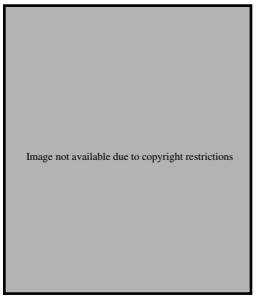
Sahelanthropus tchadensis was an ape or a hominid that lived in Central Africa about 6 or 7 million years ago, during the time when the ancestors of humans were becoming distinct from the apes (Figure 23.17*a*). The remains of another form, *Australopithecus afarensis*, are shown in Figure 23.17*b*. This individual, dubbed "Lucy," lived about 3.2 million years ago and had a slight build, unlike some other African hominids. Half a million years later, at what is now Laetoli, Tanzania, *A. afarensis* walked across fresh volcanic ash during a light rain, which turned the ash to quick-drying cement. We know little about how various hominids were related or whether they used tools, but the footprints at Laetoli (Figure 23.17*c*), as well as fossil hip and limb bones, confirm that they walked upright.

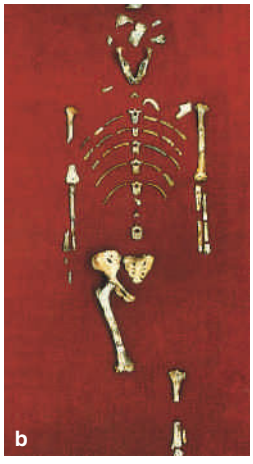
Is *Homo sapiens* "out of Africa"?

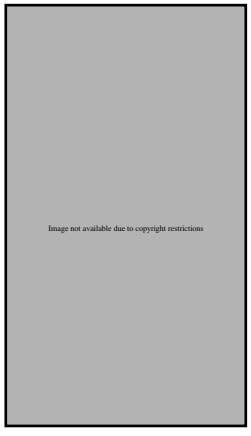
By a little over 2 million years ago, species of **humans**—members of the genus *Homo*—were living in woodlands of eastern Africa. One was *Homo habilis* (Figure 23.17*d*). Another was *Homo rudolfensis* (Figure 23.17*e*).

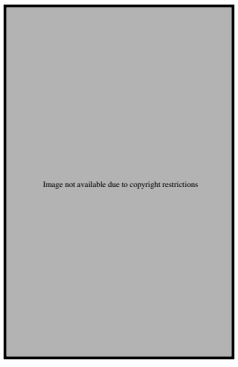
Compared to hominids, these early humans had a larger brain, smaller face, and thickly enameled teeth. They ate a mixed diet of plant and animal foods, and used tools. Fossil hunters have found many stone tools dating to the time of *H. habilis*.

Divergence produced *Homo erectus*, a species related to modern humans. Its name means "upright man." *Homo erectus* coexisted for a time with *H. habilis*. The fossil record indicates that between 2 million and 500,000 years ago, *H. erectus* began leaving Africa. Some still lived in Southeast Asia between 53,000 and 37,000 years ago. As recently as 30,000 years ago, the massively built and large-brained Neandertals lived in Europe and the Near East. Their extinction coincided with the origin of modern humans between 40,000 and 30,000 years ago. We don't know if the two groups interbred—Neandertal DNA has gene sequences that are not present in modern-day gene pools.









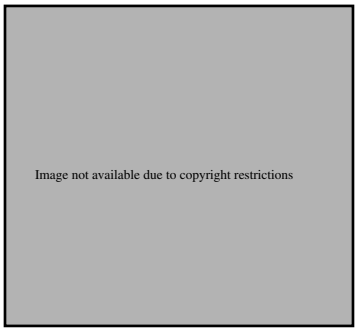


Figure 23.17 We have fossil evidence of African hominids and early humans.
b) Remains of "Lucy" (*Australopithecus afarensis*), who lived 3.2 million years ago. (

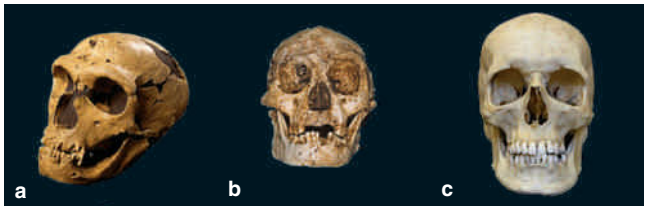


Figure 23.18 These fossil skulls are from early modern human forms. (**a**) A Neadertal skull (species *H. neanderthalensis*), (**b**) an *H. floriensis* skull, and (**c**) the skull of a modern human, *H. sapiens*.

But *where* did our species, *Homo sapiens*, originate? Researchers dispute this point, although all base their hypotheses on measurements of the small genetic differences among modern human populations. We know that by 1 million years ago, *H. erectus* was living in many regions. The *multiregional model* holds that *H. erectus* evolved along different paths in different regions, in response to local selection pressures. Subpopulations of *H. sapiens* may have evolved from these groups, with gene flow preventing speciation. In 2003, fossils of early humans that date to 18,000 years ago turned up on the Indonesian island of Flores. The species was named *H. floresiensis* (Figure 23.18). Its features suggest that it may be descended from *H. erectus*, which vanished 200,000 years ago.

In the *African emergence model*, humans arose in sub-Saharan Africa between 200,000 and 100,000 years ago, *then* moved out of Africa (Figure 23.19). Wherever they settled, they replaced *Homo erectus* populations that had preceded them. Phenotype differences that we associate with races evolved later.

Various lines of evidence support this model. A fossil from Ethiopia, in North Africa, indicates that *Homo sapiens* had evolved by 160,000 years ago. Also, genetic evidence from forty-three modern ethnic groups in Asia suggest that modern humans moved from Central Asia, along India's coast, then into Southeast Asia and southern China. Later on they dispersed north and west into China and Siberia, then down into the Americas.

Whatever the case, for the past 40,000 years, cultural evolution has outpaced biological evolution of the human species—and so we leave our story. In thinking about this subject, we can keep in mind that humans spread rapidly over the planet by devising cultural means to deal with a wide range of environments. They also developed cultural features such as art and religious beliefs People in some parts of the world still live as "stone age" hunters and gatherers even as other groups have moved to the age of high-tech. These differences are testimony to the remarkable behavioral flexibility and depth of human adaptations.

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Take-Home Message

What were important groups of hominids and early humans?

- About 7 million years ago apelike hominds, including *A. afarensis*, evolved in Africa. The genus *Homo* arose about 2 million years ago and included several populations of *H. erectus*. *Homo sapiens*, modern humans, is the only remaining species in this genus.

H. sapiens
fossil from Ethiopia,
160,000 years old

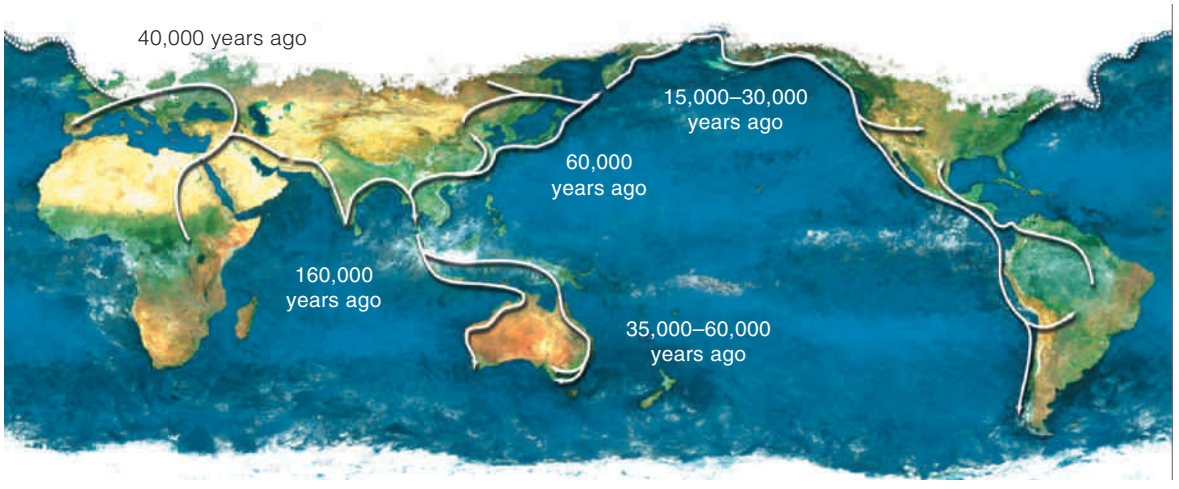


Figure 23.19 The map shows estimated times when populations of early *Homo sapiens* were colonizing different regions of the world, based on radiometric dating of fossils. The presumed dispersal routes (*white* lines) seem to support the African emergence model.

23.10 Earth's History and the Origin of Life

- **Experiments provide indirect evidence of how life may have emerged on Earth.**
- **Link to the Characteristics of life 1.1**

Four billion years ago, Earth was a thin-crusted, fiery inferno (Figure 23.20). Yet within 200 million years, life had originated on its surface! Geological upheavals and erosion have obliterated all physical traces of the origin of life. Still, researchers from various "walks of science" have been able to put together a plausible explanation of how life began.

Conditions on early Earth were intense

What were the physical and chemical conditions on Earth at the time of life's origin? To answer this question, we need to know a little bit about what the young Earth was like. When patches of its crust were forming, heat and gases blanketed Earth. This first atmosphere probably consisted of gaseous hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), and carbon dioxide (CO_2). Were gaseous oxygen (O_2) and water also present? Probably not. Rocks don't release much oxygen during volcanic eruptions. Even if oxygen *were* released, those small amounts would have reacted at once with other elements, and any water would have evaporated because of the intense heat.

When the crust finally cooled and solidified, water condensed into clouds and the rains began. For millions of years, runoff from rains stripped mineral salts and other compounds from Earth's parched rocks. Salt-laden waters collected in depressions in the crust and formed the early seas.

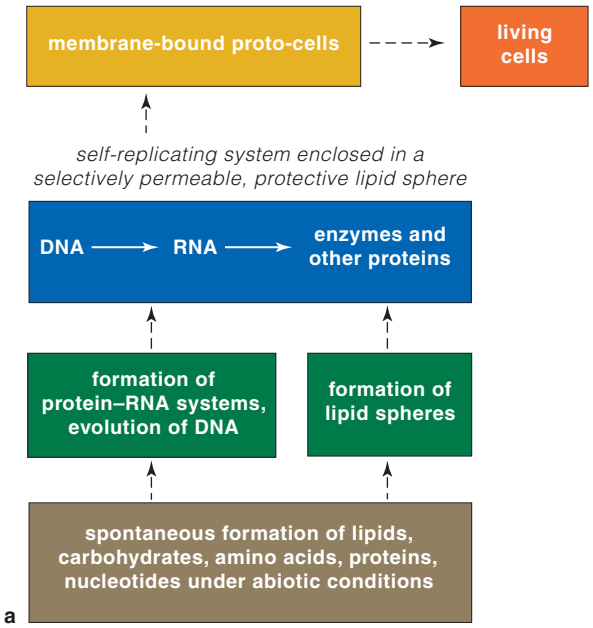
The foregoing events were crucial to the beginning of life. Without an oxygen-free atmosphere, the organic compounds that started the story of life never would have formed on their own. Why? Oxygen would have attacked them and disrupted their functioning (as free radicals of oxygen do in cells). Without liquid water, cell membranes would not have formed, because cell membranes take on their bilayer organization only in water.

As you know, cells are the basic units of life. Each has a capacity for independent existence. Cells could never simply have appeared one day on the early Earth. Their emergence required the existence of biological molecules built from organic compounds. It also required metabolic pathways, which could be organized and controlled inside the confines of a cell membrane. Let's look at some current ideas about these essential events.

Biological molecules paved the way for cells to evolve

Some scientists believe that the structure shown in Figure 23.21 is a fossilized string of cells that is 3.5 billion years old. The first living cells probably emerged around 3.8 billion years ago and may have resembled certain

Figure 23.20 The primordial Earth, about 4 billion years ago, may have looked something like this. Within another 500 million years, various types of living cells would be present on the surface.



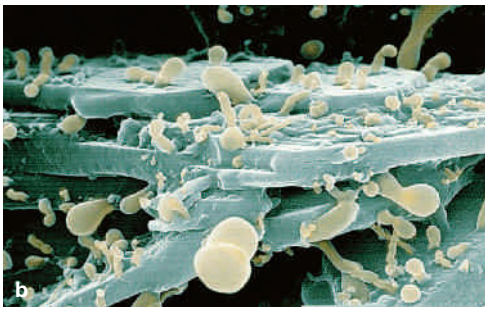


Figure 23.22 There are several hypotheses about how life began on Earth. (**a**) One possible sequence of events that may have led to the first self-replicating systems, then to the first living cells. (**b**) Nanobes—possible models for the first "pre-cells" on Earth.

modern bacteria that do not require or use oxygen. Before something as complex as a cell was possible, however, biological molecules must have come about through **chemical evolution**. Researchers have been able to put together several reasonable scenarios by which life on Earth could have emerged.

Rocks collected from Mars, meteorites, and Earth's moon—which all formed at the same time as Earth, from the same cosmic cloud—contain precursors of biological molecules. Possibly, sunlight, lightning, or heat escaping from Earth's crust supplied enough energy to drive chemical reactions that yielded more complex organic molecules. In various experiments that recreated conditions on the early Earth, molecules such as amino acids, glucose, ribose, deoxyribose, and other sugars were produced from formaldehyde. Adenine was produced from hydrogen cyanide. Adenine plus ribose occur in ATP, NAD, and other nucleotides vital to cells.

How did complex compounds such as proteins form? In one scenario, these kinds of molecules could have assembled on clay in the muck of tidal flats. Clay is formed of thin, stacked layers of aluminosilicates with metal ions at its surface. Clay and metal ions attract amino acids. From experiments we know that when clay is warmed by sunlight, then alternately dried out and moistened, it actually promotes reactions that produce complex organic compounds.

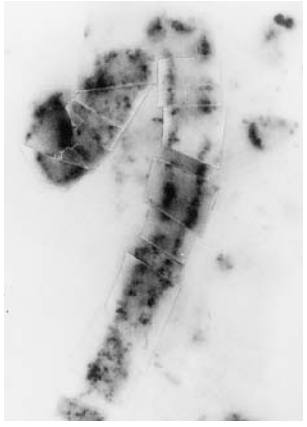


Figure 23.21 Is this a 3.5 billion-year-old fossil? Some researchers believe that this is a string of walled cells. It was unearthed in the Warrawoona rocks of Western Australia.

In another hypothesis, a variety of complex organic compounds formed near deep-sea hydrothermal vents. Today, species of primitive bacteria thrive in and around the vents. In laboratory tests, when amino acids were heated and immersed in water, they ordered themselves into small proteinlike molecules.

You may recall from Chapter 1 that metabolism and reproduction are two basic characteristics of life. During the first 600 million years of Earth history, enzymes, ATP, and other molecules that are important in metabolism could have assembled spontaneously in places where they were near one another. If so, their proximity would have promoted chemical interactions—and possibly the beginning of metabolic pathways.

In the area of reproduction, it's possible that the first "molecule of life" was not DNA but RNA. Simple self-replicating systems of RNA, enzymes, and coenzymes have been created in some laboratories. If so, how DNA entered the picture is still a mystery.

Figure 23.22*a* summarizes some key events that may have led to the first cells. Before cells could exist, there must have been membrane-bound sacs that sheltered molecules such as DNA (or RNA), key amino acids, and the like. Here again, this kind of structure has formed in the laboratory. Working with hot rocks from nearly 4 kilometers (2.5 miles) below Earth's surface, researchers in Australia also have found threadlike and bloblike structures that contain DNA and other organic compounds enclosed in a membrane (Figure 23.22*b*). These "nanobes" appear to grow and take up substances from outside. They are simpler than living cells, but some scientists think they could be like the forerunners of the first living cells. With time we may discover if that is correct.

Take-Home Message

How did life arise on Earth?

- Experiments and other research suggest that the organic molecules we associate with life arose through chemical evolution under the conditions that existed on the early Earth. However, we know little for certain about how life originated on our planet.

IMPACTS, ISSUES

Time on Your Mind

A LARGE asteroid impact could wipe out civilization and much of the life on Earth. Governments of the United States and some other nations currently spend large sums to search for and track asteroids while other needs, such as education and public health programs, may be less than adequately funded.

How Would You Vote?

Do you think taxpayers should have to pay for costly research programs to monitor asteroids in space? See CengageNOW for details, then vote online.

Summary

Section 23.1 Evolution modifies existing species. Therefore, broadly speaking, all species, past and present, share a common ancestry. The naturalist Charles Darwin proposed that evolution could occur by way of a process he named natural selection.

Section 23.2 In biology, a population is a group of individuals of the same species occupying a given area. The totality of genes in a population make up its gene pool. Each kind of gene may have different alleles, and these genetic variations produce variations in traits.

The relative numbers of different alleles—that is, the different versions of genes—can change as a result of four processes of microevolution: mutation, genetic drift, gene flow, and natural selection (Table 23.2). The large-scale patterns, trends, and rates of change among groups of species over time are called macroevolution.

Section 23.3 The theory of evolution by natural selection holds that there may be a difference in the survival and reproduction among members of a population that vary in one or more traits. That is, under prevailing conditions, one form of a trait may be favored because individuals that have it tend to survive and therefore to reproduce more often, so it becomes more common than other forms of the trait.

Organisms tend to come to have characteristics that suit them to the conditions in a particular environment. This trend is called adaptation.

TABLE 23.2 Major Processes of Microevolution

Mutation	A heritable change in DNA
Genetic drift	Random fluctuation in allele frequencies over time, due to chance occurrences alone
Gene flow	Movement of alleles among populations through migration of individuals
Natural selection	Change or stabilization of allele frequencies due to differences in survival and reproduction among variant members of a population

A species is a genetic unit consisting of populations of organisms that closely resemble each other and that can interbreed and produce fertile offspring under natural conditions. New species come into being when the differences between isolated populations become so great that their members are not able to interbreed successfully in nature.

- Use the animation and interaction on CengageNOW to learn more about genetic drift, directional selection, and how species become reproductively isolated.

Section 23.4 Evidence of evolutionary relationships comes in part from fossils and studies of biogeography. Fossils are dated using radiometric dating.

- Use the animation and interaction on CengageNOW to learn more about how fossils form and the geologic time scale.

Sections 23.5, 23.6 Comparative morphology often reveals similarities in embryonic development that indicate an evolutionary relationship. Similarities may reveal homologous structures, shared as a result of descent from a common ancestor. Alternatively, analogous structures arise when different lineages evolve in the same or similar environments. In comparative biochemistry, gene mutations that have accumulated in different species provide evolutionary clues.

Section 23.7 In a mass extinction, major lineages perish abruptly. Adaptive radiation is a burst of evolutionary activity; a lineage rapidly produces many new species. Both kinds of events have changed the course of biological evolution many times.

Section 23.8 We see five major evolutionary trends in the primate lineage leading to *H. sapiens*. These are (1) a transition to bipedalism, with related changes in the skeleton; (2) increased motor skills related to structural modification of the hands; (3) more reliance on daytime vision, including color vision and depth perception; (4) transition away from specialized eating habits, with corresponding modification of dentition; and (5) the enlargement and reorganization of the brain.

Section 23.9 Humans (*Homo sapiens*) are classified in the hominid family of the primate order, and are members of the only existing species of the genus *Homo*. In human evolution, the development of a larger, more complex

brain correlated with increasingly sophisticated technology and with the development of complex behaviors and culture. For the last 40,000 years, human cultural evolution has outpaced our species' biological evolution.

Section 23.10 Life originated on Earth about 3.8 billion years ago. Various experiments provide indirect evidence that life originated under conditions that presumably existed on the early Earth.

Comparisons of the composition of cosmic clouds and of rocks from other planets and Earth's moon suggest that precursors of the complex molecules associated with life were available.

When researchers simulated primordial conditions, chemical precursors assembled into sugars, amino acids, and other organic compounds.

Metabolic pathways could have evolved as a result of chemical competition for the limited supplies of organic molecules that had accumulated in the seas.

Self-replicating systems of RNA, enzymes, and coenzymes have been synthesized in the laboratory. How DNA entered the picture is not yet understood.

- Use the animation and interaction on CengageNOW to see experiments on how organic compounds can form spontaneously, and investigate the scientific history of life on Earth.

Review Questions

1. Distinguish between microevolution and macroevolution.
2. As shown in Figure 23.23 below, there is considerable variation in the facial features of humans. Explain this fact in terms of the concept of the gene pool.
3. Explain how natural selection differs from adaptation.
4. Explain the difference between:
   a. divergence and gene flow
   b. homologous and analogous structures
5. Explain the difference between a primate and a hominid.
6. Describe the chemical and physical environment in which the first living cells may have evolved.

Self-Quiz *Answers in Appendix V*

1. A _____ is a genetic unit consisting of one or more populations of organisms that usually closely resemble one another physically and physiologically.
2. The relative numbers of different genes (alleles) in a gene pool change as a result of four processes of microevolution: _____, _____, _____, and _____.
3. A difference in survival and reproduction among members of a population that vary in one or more traits is called _____.
4. The fossil record of evolution correlates with evidence from _____.
   a. the geologic record
   b. radiometric dating
   c. comparing development patterns and morphology
   d. comparative biochemistry
   e. all of the above
5. Comparative biochemistry _____.
   a. is based mainly on the fossil record
   b. often reveals similarities in embryonic development stages that indicate evolutionary relationships
   c. is based on mutations that have accumulated in the DNA of different species
   d. compares the proteins and the DNA from different species to reveal relationships
   e. both c and d are correct
6. Comparative morphology _____.
   a. is based mainly on the fossil record
   b. shows evidence of divergences and convergences in body parts among certain major groups
   c. compares the proteins and the DNA from different species to reveal relationships
   d. both b and c are correct
7. In _____, new species of a lineage move into a wide range of habitats by way of bursts of microevolutionary events.
   a. an adaptive radiation
   b. natural selection
   c. genetic drift
   d. punctuated equilibrium
8. The pivotal modification in hominid evolution was _____.
   a. the transition to bipedalism
   b. hand modification that increased manipulative skills
   c. a shift from omnivorous to specialized eating habits
   d. less reliance on smell, more on vision
   e. expansion and reorganization of the brain

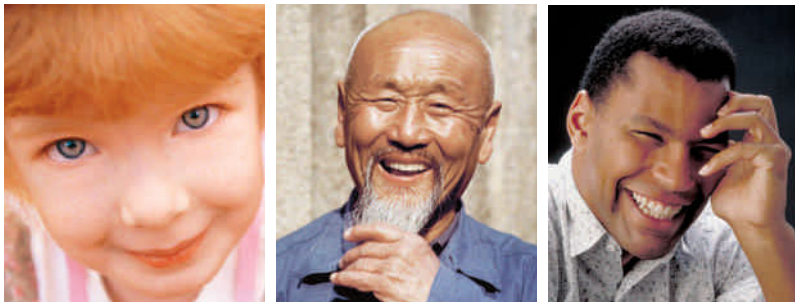


Figure 23.23 Humans show a great deal of variation in their outward appearance.

Critical Thinking

1. The cheetahs in Figure 23.24 are among the approximately 20,000 of these sleek, swift cats left in the world. One reason cheetahs have become endangered is that about 10,000 years ago cheetahs experienced a severe loss in their numbers, and since then the survivors have been inbreeding. As a result, today's cheetah gene pool has very little variation and includes alleles that reduce the sperm counts of males and impair the animals' resistance to certain diseases. Based on what you've read in this chapter about genetic variation, does it seem likely that a "gene therapy" program might be able to correct the genetic problems and help cheetahs make a comeback? Explain your answer.
2. Humans can inherit various alleles for the liver enzyme ADH (alcohol dehydrogenase), which breaks down alcohol. People of Italian and Jewish descent commonly have a form of ADH that detoxifies alcohol very rapidly. People of northern European descent have forms of ADH that are moderately effective in alcohol breakdown, while people of Asian descent typically have ADH that is less efficient at processing alcohol. Explain why researchers have been able to use this information to help trace the origin of human use of alcoholic beverages.
3. In 1992 the frozen body of a Stone Age man was discovered in the Austrian Alps. Although the "Iceman" died about 5,300 years ago, his body is amazingly well preserved and researchers have analyzed DNA extracted from bits of his tissue. Can these studies tell us something about early human evolution? Explain your reasoning.
4. Scientists Craig Venter and Claire Fraser are working to create a "minimal organism." They are starting with a bacterium, *Mycoplasma genitalium*, which has only 517 genes. By disabling its genes one at a time, they discovered that between 265 and 350 of them code for essential proteins. Venter and Fraser are synthesizing the essential genes and inserting them, one by one, into an engineered cell consisting of only a plasma membrane and cytoplasm. They want to see how few genes it takes to build a new life form. What properties would such a cell have to exhibit for you to conclude that it was alive?

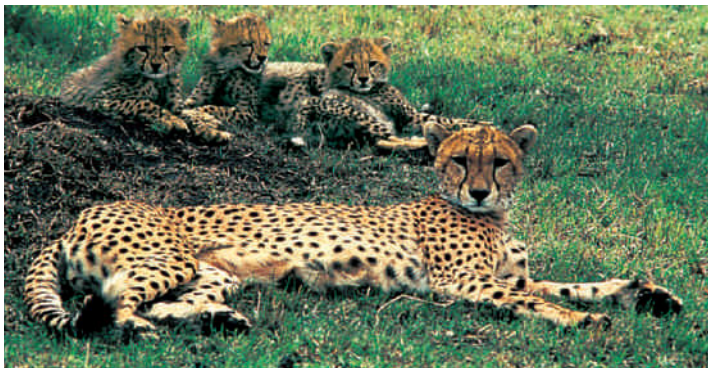


Figure 23.24 **Genetically, the world's remaining cheetahs vary only a little—the result of inbreeding.**

EXPLORE ON YOUR OWN

About 50,000 years ago humans began domesticating wild dogs. By about 14,000 years ago, people started to favor new breeds of dogs using artificial selection. Dogs having desired forms of traits were selected from each litter and later encouraged to breed. Those with undesired forms of traits were passed over.

This process has produced scores of domestic dog breeds, including sheep-herding border collies, sled-pulling huskies, and dogs as strikingly different as Great Danes and chihuahuas (Figure 23.25).

With a little bit of sleuthing on the Web or in a library, you should be able to discover numerous other examples of how humans have used artificial selection to develop desired animal breeds or plant varieties.

Figure 23.25 **The Great Dane (legs, left) and the chihuahua are both "designer" dog breeds.**

How has artificial selection affected aspects of your own life, such as pets, foods you eat, and ornamental garden plants?

Principles of Ecology

24

IMPACTS, ISSUES

Change in the Air

EACH year from July to October, firefighters in dry western states gear up for wildfire season, when there may be little or no rain and the risk of forest fires surges. In California the summer of 2008 brought the worst fire season in 50 years, with more than 1 million acres and dozens of homes burned in a series of massive wildfires—most triggered by dry lightning storms, some stoked by arsonists. Several courageous firefighters died in the line of duty.

A series of dry winters set the stage for the infernos. For several years running, winter and spring rains had been few and far between, and the snowpack in California's Sierra Nevada mountains was only about 30 percent of normal—or what used to be normal. While occasional droughts have always been part of California's weather picture, the current "dry" is more ominous. Throughout the West, fire officials are bracing for many more years like 2008 because Earth is warming, a trend that most climate experts expect will change climates for the long term. These experts predict that in the mountains of western North America, average temperatures will rise, so there will be less snow, drier forests, and more intense wildfires.

Elsewhere climate change is expected to have other effects—more severe hurricanes in the Atlantic and cyclones in the Pacific, melting glaciers and Arctic ice, rising sea levels that cause coastal flooding around the globe. Climate shifts also may allow the wider spread of diseases that formerly were common only in the tropics.

All these changes will ripple through our planet's ecosystems and affect a wide variety human activities, from where people choose to live to the availability of reliable energy and water supplies and the kinds of crops farmers can grow.

In this chapter we begin thinking how humans and other organisms interact with their environment, the area of study called *ecology*. This topic will lead to our survey of human impacts on Earth's ecosystems and resources in Chapter 25.

LINKS TO EARLIER CONCEPTS

- This chapter aims to place your study of human biology in the broader context of the whole living world (1.3).
- You will gain a global perspective on the energy and raw materials that sustain living organisms (2.1, 3.13). You will also learn how a global water cycle makes water available for life processes in organisms (2.5).

KEY CONCEPTS

Principles of Ecology

Ecology is the study of interactions of organisms with one another and the environment. Energy flows through ecosystems, passing from organism to organism by way of food webs. Sections 24.1–24.3

Chemical Cycles

Nutrients cycle in ecosystems. In biogeochemical cycles, water and nutrients such as carbon and nitrogen move from the physical environment to organisms, then back to the environment. Sections 24.4–24.8

How Would You Vote?

"Greenhouse gases" such as carbon dioxide contribute to global warming. Exhaust from motor vehicles is a major source of these gases, but the better mileage a vehicle gets, the lower its emissions. Should minimum fuel economy standards for cars and trucks be increased? See CengageNOW for details, then vote online.

24.1 Some Basic Principles of Ecology

- **The biosphere consists of those regions of Earth's crust, waters, and atmosphere where organisms live.**
- **Link to Life's organization 1.3**

The Earth's surface is remarkably diverse. In climate, soils, vegetation, and animal life, its deserts differ from hardwood forests, which differ from tropical rain forests, prairies, and arctic tundra. Oceans, lakes, and rivers differ physically and in their arrays of organisms. Each of these realms is called a **biome** (Figure 24.1).

Ecology is the study of the interactions of organisms with one another and with the physical environment. The general type of place in which a species normally lives is its **habitat**. For example, muskrats live in a stream habitat, damselfish in a coral reef habitat. The habitat of any organism has certain characteristic physical and chemical features. Every species also interacts with others that occupy the same habitat. Humans live in "disturbed" habitats, which we have deliberately altered for purposes such as agriculture and urban development. Directly or indirectly, the populations of all species in a habitat interact with one another as a **community**.

A species' **niche** ("nitch") consists of the various physical, chemical, and biological conditions the species needs to live and reproduce in an ecosystem. Examples of those conditions include the amount of water, oxygen, and other nutrients a species needs, the temperature ranges it can tolerate, the places it finds food, and the type of food it consumes. *Specialist* species have narrow niches. They may be able to use only one or a few types of food or live only in one type of habitat. For example, the red-cockaded woodpecker builds its nest mainly in longleaf pines that are at least 75 years old. Humans and houseflies are examples of *generalist* species with broad niches. Both can live in a range of habitats and eat many types of food.

An **ecosystem** consists of one or more communities of organisms interacting with one another and with the physical environment through a flow of energy and a cycling of materials. Figure 24.2 shows some typical organisms of an arctic tundra ecosystem.

Communities of organisms make up the *biotic*, or living, parts of an ecosystem. New communities may develop in habitats that were once empty of life, such as land exposed by a retreating glacier, or in a previously disturbed inhabited area such as an abandoned pasture. Through a process called **succession**, the first species to thrive in the habitat are then replaced by others, which are replaced by others in a predictable sequence. Eventually the composition of species stabilizes as long as other conditions remain the same. This more or less stable array of species is called a **climax community**.

Figure 24.1 Major types of ecosystems on Earth are called biomes. They include land biomes such as the hot desert near Tucson, Arizona (**a**), and aquatic realms such as the mountain lake in (**b**), which lies in the Canadian Rockies.

In *primary* succession, changes begin when pioneer species colonize a newly available habitat, such as a recently deglaciated region (Figure 24.3). In *secondary* succession, a community develops toward the climax state after parts of a habitat have been disturbed. For example, this pattern occurs in abandoned fields, where wild grasses and other plants spring up when cultivation stops. Changing climate, natural disasters (such as forest fires), and other factors often interfere with succession so we rarely see truly stable climax communities.

Take-Home Message

How do we define an ecological habitat and community, and what is an ecosystem?

- The general type of place where a species lives is its habitat. The populations of all species in a habitat make up a community.
- An ecosystem consists of one or more communities interacting with one another and with the physical environment through a flow of energy and a cycling of materials.

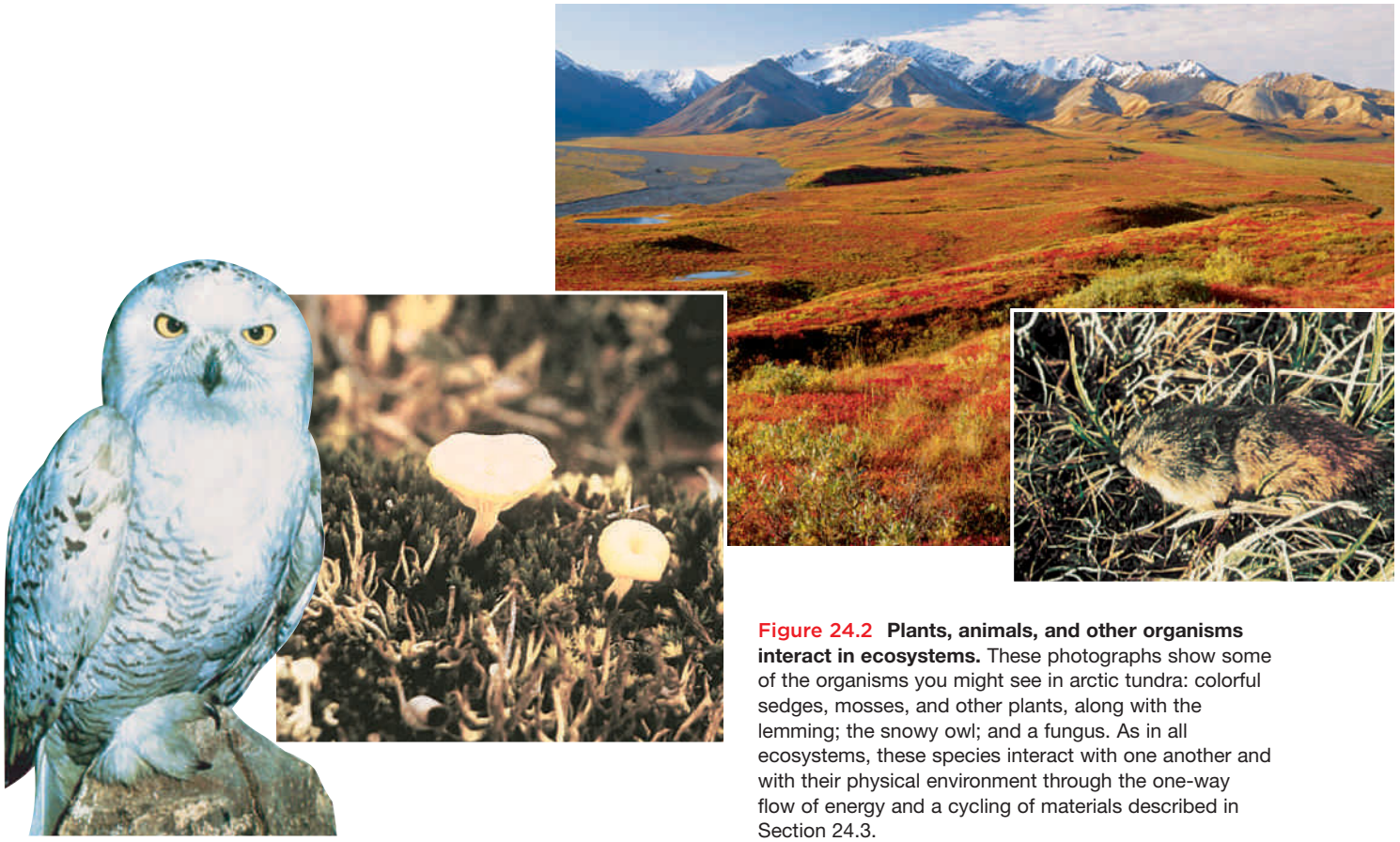


Figure 24.2 Plants, animals, and other organisms interact in ecosystems. These photographs show some of the organisms you might see in arctic tundra: colorful sedges, mosses, and other plants, along with the lemming; the snowy owl; and a fungus. As in all ecosystems, these species interact with one another and with their physical environment through the one-way flow of energy and a cycling of materials described in Section 24.3.

Figure 24.3 Alaska's Glacier Bay provides examples of primary succession. (**a**) A glacier is receding, leaving newly exposed soil. (**b**) The first plants are lichens, mosses, and small flowering plants that can grow and spread over glacial till. (**c**) Within 20 years, young alders begin to flourish. (**d**) After 80 years, a climax community of spruces crowds out the mature alders. (**e**) In areas deglaciated for more than a century, dense forests of Sitka spruce dominate.

24.2 Feeding Levels and Food Webs

- **Although there are many different types of ecosystems, they are all alike in many aspects of their structure and function.**

Nearly every ecosystem runs on energy from the sun. Plants and other photosynthetic organisms are **producers** (or *autotrophs*, which means "self-feeders"). They capture sunlight energy and use it to build organic compounds from inorganic raw materials (Figure 24.4).

All other organisms in an ecosystem are **consumers** (or *heterotrophs*, "other-feeders"). One way or another, consumers take in energy that has been stored in the tissues of producers. For the most part, consumers fall into four categories:

Herbivores such as grazers and insects eat plants; they are *primary* consumers.

Carnivores such as lions eat animals. Carnivores are *secondary* or *tertiary* (third-level) consumers.

Omnivores such as humans, dogs, and grizzly bears feed on a variety of foods, either plant or animal.

Decomposers such as fungi, bacteria, and worms get energy from the remains or products of organisms.

Producers obtain an ecosystem's nutrients *and* its initial pool of energy. As they grow, they take up water and carbon dioxide (which provide oxygen, carbon, and hydrogen), as well as minerals such as nitrogen. These materials, recall, are the building blocks for biological molecules. When decomposers get their turn at this organic matter, they can break it down to inorganic bits. If those bits are not washed away or otherwise removed from the system, producers can reuse them as nutrients.

It is important to remember that ecosystems must have an ongoing input of energy, as from the sun. Often they depend on outside sources of nutrients as well (as when erosion carries minerals into a lake). Ecosystems also *lose* energy and nutrients. Most of the energy that producers capture eventually is lost to the environment in the form of metabolic heat. Though generally recycled, some nutrients also are lost, as when minerals are leached out of soil by water seeping down through it.

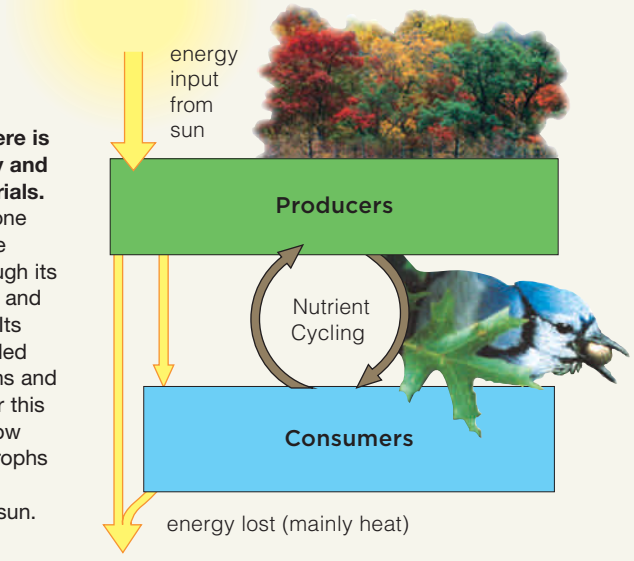


Figure 24.4
Animated! In ecosystems, there is a flow of energy and cycling of materials. Energy flows in one direction: into the ecosystem, through its living organisms, and then out from it. Its nutrients are cycled among autotrophs and heterotrophs. For this model, energy flow starts with autotrophs that can capture energy from the sun.

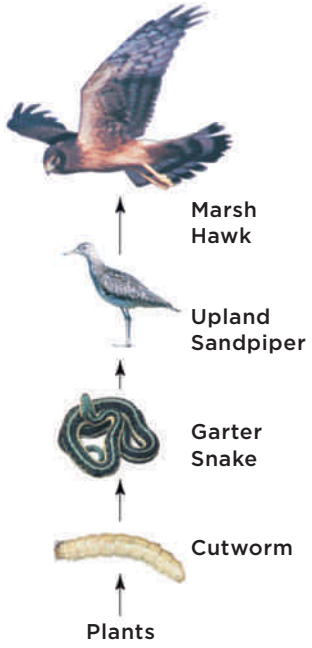
Energy moves through a series of ecosystem feeding levels

Each species in an ecosystem has its own position in a hierarchy of feeding levels (also called *trophic levels; troph* means "nourishment"). A key factor in how any ecosystem functions is the transfer of energy from one of its feeding levels to another.

Primary producers, which gain energy directly from sunlight, make up the first feeding level. Corn plants in a field or waterlilies in a pond are examples. Snails and other herbivores that feed on the producers are at the next feeding level. Birds and other primary carnivores that prey on the herbivores form a third level. A hawk that eats a snake is a secondary carnivore. Decomposers, humans, and many other organisms can obtain energy from more than one source. For this reason they can't be assigned to a single feeding level.

Food chains and webs show who eats whom

A linear sequence of who eats whom in an ecosystem is sometimes called a **food chain**. However, you won't often find such a simple, isolated chain as this one. Most species belong to more than one food chain, especially when they are at a low feeding level. It's more accurate to view food chains as cross-connecting with one another in **food webs**. Figure 24.5 shows a typical food web in an arctic ecosystem.



A simple food chain

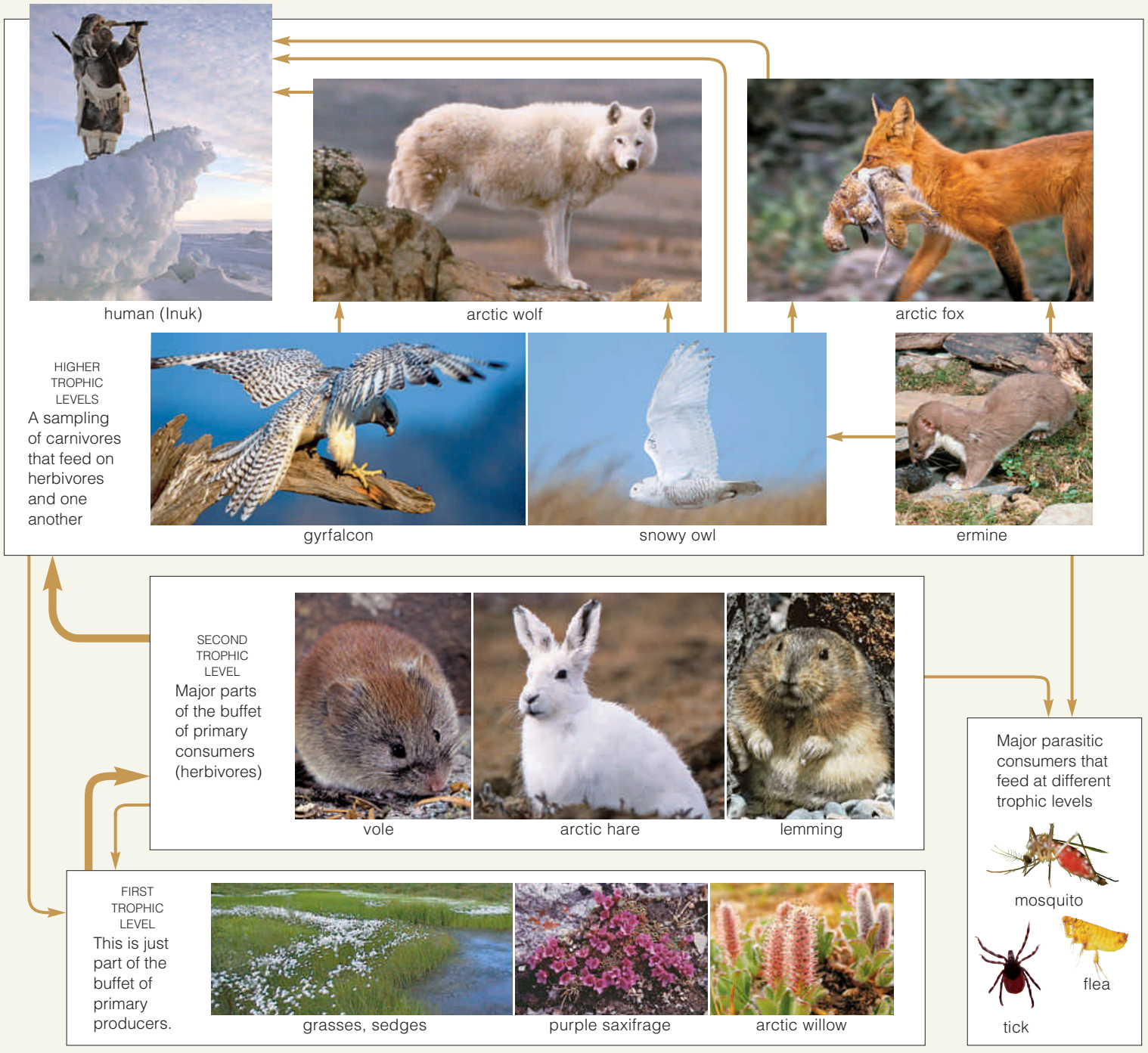


Figure 24.5 Animated! **An arctic food web on land has several feeding levels.**

Take-Home Message

What is a food web?

- A food web is a network of crossing, interlinked food chains. It is made up of primary producers and a variety of consumers and decomposers.
- By way of food webs, different species in an ecosystem are interconnected.

24.3 Energy Flow through Ecosystems

- **Energy flows into food webs from an outside source, usually the sun. Energy leaves mainly when organisms lose heat that is generated by their metabolism.**

Producers capture and store energy

In land ecosystems, the usual primary producers are plants. The rate at which they take in and store energy in their tissues during a given period of time is called the ecosystem's **primary productivity**. How much energy actually gets stored in the tissues of plants depends on how many individual plants live there, and on the balance between energy the plants trap (by photosynthesis) and energy they use for their life processes.

Other factors also affect the final amount of stored energy in an ecosystem at any given time. For example, how much energy ecosystems trap and store depends partly on how large the producers are, the availability of mineral nutrients, how much sunlight and rainfall are available during a growing season, and the temperature range. The harsher the conditions, the less new plant growth per season—so the productivity will be lower. As Figure 24.6 shows, there are big differences in the primary productivity in different ecosystems.

Consumers subtract energy from ecosystems

An **ecological pyramid** is a way to represent the energy relationships of an ecosystem. In these pyramids, primary producers form a base for tiers of consumers above them.

Biomass is the combined weight of all of an ecosystem's organisms at each tier. In Figure 24.7*a* you can see the *biomass pyramid* (measured in grams per square meter) for one small aquatic ecosystem. This kind of biomass pyramid is very common in nature. There are lots of primary producers—plants—and few top carnivores such as bears, lions, or killer whales.

Some biomass pyramids have the smallest tier on the bottom. A pond or the sea is like this. In those ecosystems primary producers have less biomass (they collectively weigh less) than consumers feeding on them. The producers consist of phytoplankton (tiny floating photosynthetic organisms), which grow and reproduce fast enough to provide a steady supply of food for a much greater biomass of zooplankton (small floating animals). Zooplankton in turn become food for larger animals.

An *energy pyramid* also shows how usable energy declines as it flows through an ecosystem. An energy pyramid has a large energy base at the bottom (Figure 24.7*b*) and is always "right-side up." It gives a more accurate picture of the ever-diminishing amounts of energy flowing through the ecosystem's feeding levels.

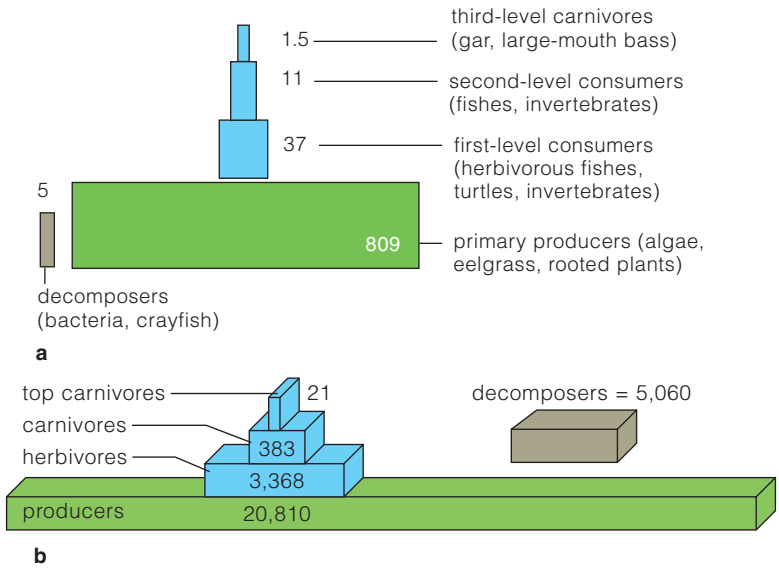


Figure 24.7 Ecological pyramids show the tiered structure of ecosystems. (**a**) A biomass pyramid. (**b**) An energy pyramid.

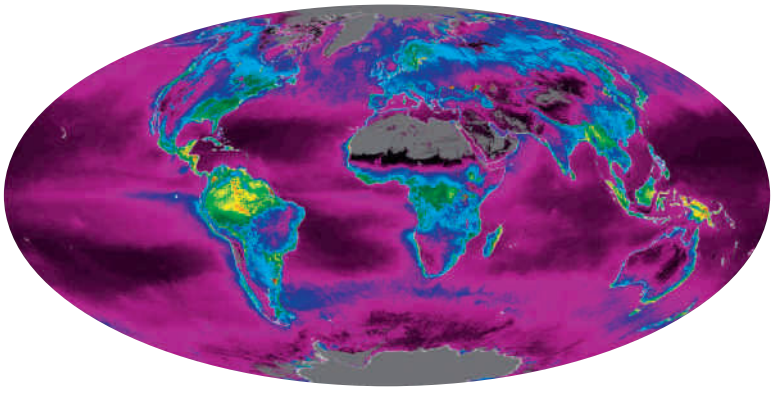


Figure 24.6 This image summarizes satellite data on Earth's primary productivity during 2002. Productivity is coded as *red* (highest) down through *orange*, *yellow*, *green*, *blue*, and *purple* (lowest).

Take-Home Message

How does energy flow through ecosystems?

- Energy enters ecosystems from outside—usually from the sun. Energy leaves ecosystems mainly by the loss of metabolic heat from organisms.
- Primary productivity is the total energy stored by an ecosystem's photosynthesizers in a given amount of time, after the plants' own energy needs are met.
- Ecological pyramids depict the tiered feeding (trophic) structure of ecosystems. A biomass pyramid shows the combined weight of organisms in each tier. An energy pyramid shows the loss of usable energy from the base tier to higher levels.

24.4 Introduction to Biogeochemical Cycles

- **Ecosystems depend on primary productivity. This is why the availability of water, carbon dioxide, and the mineral ions that serve as nutrients for producers have such an important impact on ecosystems.**
- **Links to Molecules 2.3, Ions 2.4**

In a **biogeochemical cycle**, ions or molecules of a nutrient are moved from the environment to organisms, then back to the environment—part of which serves as a reservoir for them. They generally move slowly through the reservoir, compared to their rapid movement between organisms and the environment. Figure 24.8 provides an overview of the relationship between most ecosystems and the biogeochemical part of the cycles.

Each year, the amount of a nutrient that cycles through a major ecosystem is more than enters or leaves. Together with nutrient recycling, fresh inputs help maintain an ecosystem's nutrient reserves. For instance, rainfall, snowfall, and the slow weathering of rocks help replenish the reserves. At the other end of the balance sheet, ecosystems also can lose some of their nutrient reserves. For example, various minerals may be washed away by runoff from irrigated cropland.

There are three types of biogeochemical cycles, based on the part of the environment that has the largest supply of the ion or molecule being considered. As you will see later, in the *global water cycle*, oxygen and hydrogen move in the form of water molecules. In **atmospheric cycles**, much of the nutrient—carbon and nitrogen, for example—is in the form of a gas. **Sedimentary cycles** move phosphorus and other chemicals that do not occur as gases. Such solid nutrients move from land to the seafloor and return to dry land only through geological uplifting, which may take millions of years. The Earth's crust is the main storehouse for these substances.

Take-Home Message

What is a biogeochemical cycle?

- In a biogeochemical cycle, nutrients move from the environment to organisms, then back to their reservoir in the environment.
- Nutrients usually move slowly through the environment but rapidly *between* organisms and the environment.

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24.5 The Water Cycle

- **You already know that water is vital for all organisms. It also carries nutrients into and out of ecosystems.**
- **Link to Water and life 2.5**

Driven by solar energy, Earth's waters move slowly, on a vast scale, from the ocean into the atmosphere, to land, and back to the ocean—the main reservoir. Water evaporating into the lower atmosphere initially stays aloft in the form of vapor, clouds, and ice crystals. It returns to Earth as precipitation, mostly rain and snow. Ocean currents and prevailing wind patterns influence this global *hydrologic cycle*, or **water cycle** (Figure 24.9).

Have you ever heard a news report about concerns over changes in a watershed? A *watershed* is any area in which the precipitation is funneled into a single body of water, such as a stream, river, or bay. Watersheds can be vast. The Mississippi River watershed extends across roughly one-third of the United States.

Most water entering a watershed seeps into soil or becomes surface runoff that moves into streams. Plants take up water and dissolved minerals from soil, then lose water through their leaves. Research shows that the plant life in a watershed can be vital to preventing the loss of soil nutrients in runoff.

Measurements of the inputs and losses of water at watersheds have practical applications. For example, cities and towns that depend on surface water supplies in watersheds (such as reservoirs) can adjust their water use based on seasonal variations.

Take-Home Message

What is the water cycle?

- In the water cycle, water slowly moves from the oceans through the atmosphere, onto land, then back to the oceans.
- A watershed is an area where the precipitation is funneled into a single body of water, such as a stream, river, or bay.

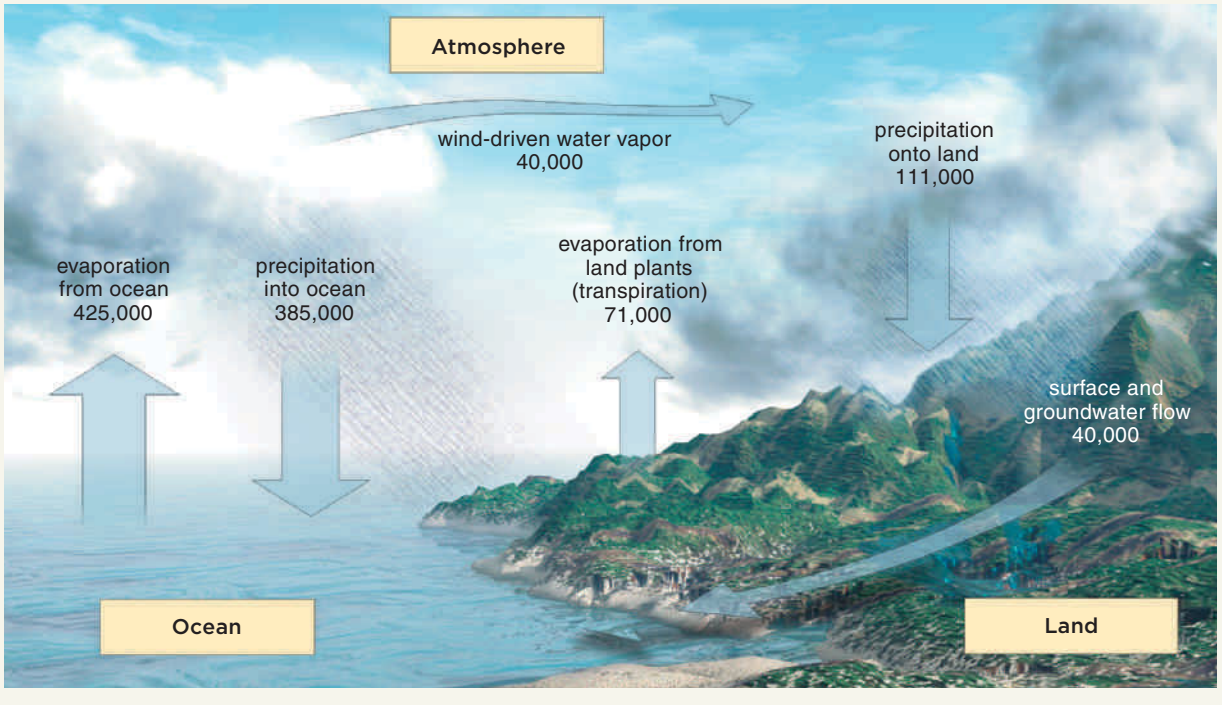


Figure 24.9 Animated! **In the water cycle, water moves from oceans to the atmosphere, the land, and back to the ocean.** *Yellow* boxes indicate the main reservoirs. *Arrow* labels identify the processes involved in the movement of water between reservoirs, measured in cubic kilometers per year.

24.6 Cycling Chemicals from Earth's Crust

- **We continue our look at biogeochemical cycling with one of the sedimentary cycles—one that involves chemicals locked in Earth's crust.**
- **Links to Organic compounds 2.8, ATP 2.13**

Living organisms can't survive without small amounts of phosphorus. This mineral is a key component of ATP, NADPH, phospholipids, nucleic acids, and many other organic compounds.

In the **phosphorus cycle**, the mineral phosphorus moves from land to sediments in the seas and then back to land (Figure 24.10). Earth's crust is the main storehouse for phosphorus and for other minerals such as calcium and potassium.

Phosphorus usually is present in rock formations on land, in the form of phosphates. Through the natural processes of weathering and erosion, phosphates enter rivers and streams, which eventually carry them to the ocean. There, mainly on the continental shelves (which are closest to dry land), phosphorus accumulates with other minerals. Millions of years pass. Where crustal plates collide, part of the seafloor may be uplifted and drained. Over geologic time, weathering releases phosphates from the newly exposed rocks—and the geochemical phase of the phosphorus cycle begins again.

The ecosystem phase of the phosphorus cycle is much more rapid. Plants can take up dissolved phosphorus so quickly and efficiently that they may deplete the supply in soil. Herbivores obtain phosphorus by eating plants, carnivores get it by consuming herbivores, and all animals excrete phosphorus as a waste product in urine and feces. It is also released to the soil as organic matter decomposes. Plants then take up phosphorus, rapidly recycling it in the ecosystem.

Phosphorus is linked to some ecological problems, including the *eutrophication* of lakes. This is the name for nutrient enrichment of a body of water. Although eutrophication is a natural process, human activities can speed it up and upset the natural balance. An example is Lake Washington in Seattle, where runoff containing large amounts of phosphorus from fertilizer or detergents (in sewage) triggered the growth of thick, slimy mats of algae. The solution was to severely limit discharges into the lake. With time, the algal blooms stopped.

Take-Home Message

Why is the phosphorus cycle an example of a sedimentary cycle?

- Earth's crust is the main storehouse for phosphorus and other minerals that move through ecosystems as part of sedimentary cycles. The geochemical phase of these cycles advances very slowly.

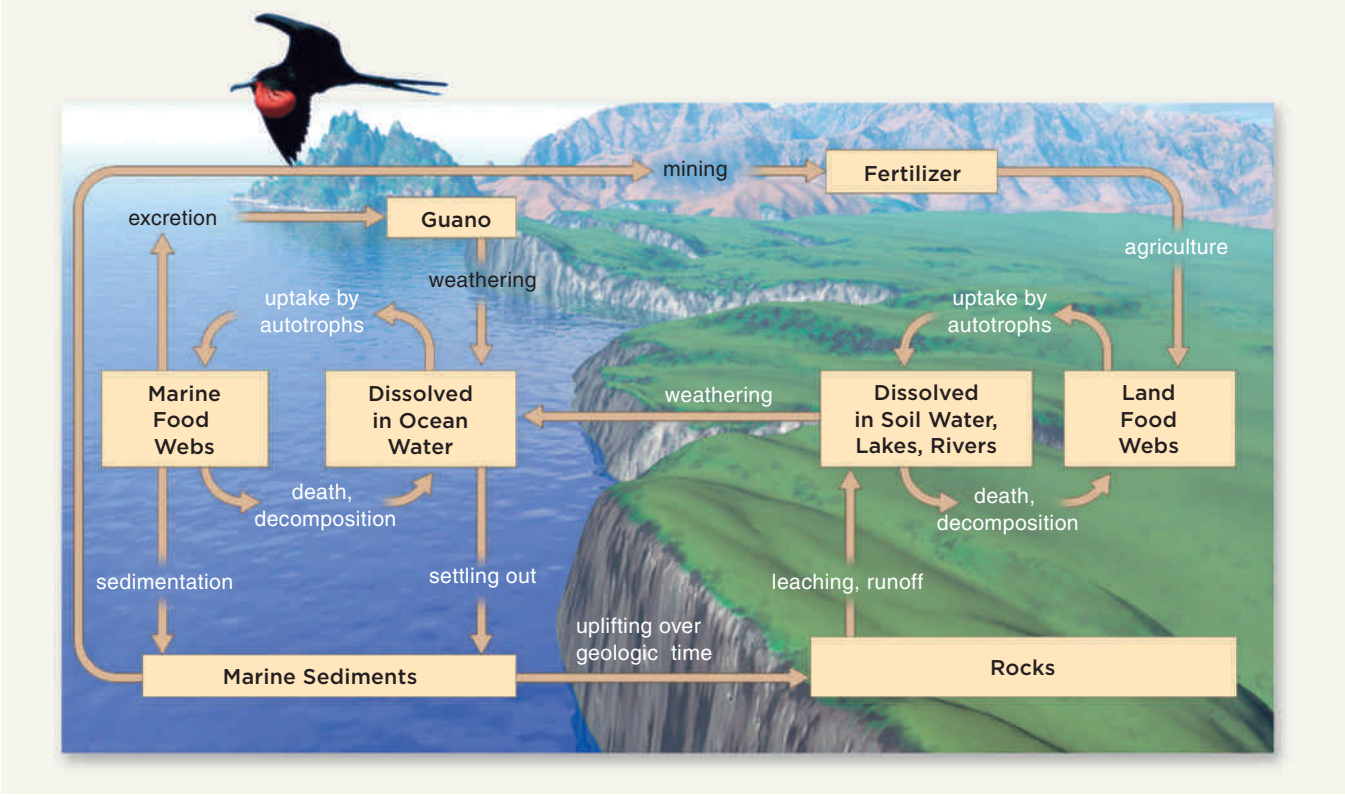


Figure 24.10 Animated! **The phosphorus cycle is an example of a sedimentary cycle.**

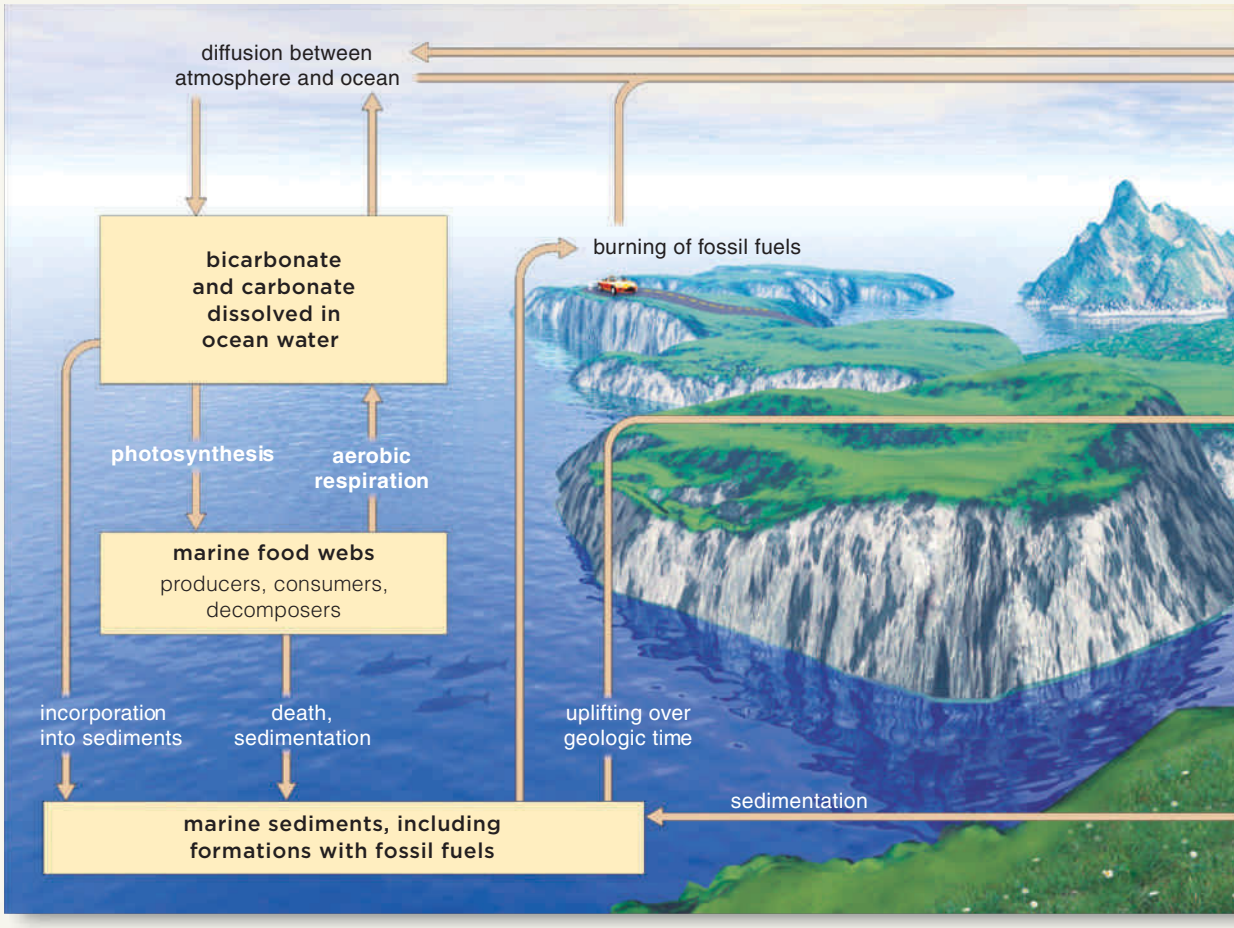
24.7 The Carbon Cycle

- **Carbon moves through the atmosphere and food webs on its way to and from the oceans, sediments, and rocks.**

Figure 24.11 sketches the global **carbon cycle**. Sediments and rocks hold most of the carbon, followed by the ocean, soil, atmosphere, and land biomass. Carbon enters the atmosphere as cells engage in aerobic respiration, as fossil fuels burn, and when volcanoes erupt and release it from rocks in Earth's crust. Most atmospheric carbon occurs as carbon dioxide (CO_2). Most carbon dissolved in the ocean is in the forms of bicarbonate and carbonate.

You've likely seen bubbles of CO_2 rising to the surface of a glass of carbonated soda. Why doesn't the CO_2 in warm ocean surface waters escape to the atmosphere? Driven by winds and regional differences in water density, water makes a gigantic loop from the surface of the Pacific and Atlantic Oceans to the Atlantic and Antarctic seafloors. There its CO_2 moves into deep "storage" before bottom water loops up again (Figure 24.12). This looping movement is a factor in carbon's distribution in the biosphere and the global carbon "budget."

Photosynthesizers capture billions of metric tons of carbon atoms in organic compounds every year. However, the average length of time that a carbon atom is held in any given ecosystem varies quite a bit. For example, organic wastes and remains decompose rapidly in tropical rain forests, so not much carbon accumulates at the surface of soils. In marshes, bogs, and other places where there is little or no oxygen, decomposers cannot break down organic compounds completely, so carbon gradually builds up in peat and other forms of compressed organic matter. Also, in ancient aquatic ecosystems, carbon was incorporated in shells and other hard parts. The shelled organisms died and sank, then were buried in sediments. The same things are happening today. Carbon remains buried for many millions of years in deep sediments until part of the seafloor is uplifted above the ocean surface through geologic forces. Other buried carbon is slowly converted to long-standing reserves of gas, petroleum,



A

Figure 24.11 Animated!
Carbon cycles through the oceans, atmosphere, and the bodies of organisms. Part (**a**) shows the cycle through typical marine ecosystems. Part (**b**) shows how carbon cycles through land ecosystems. *Yellow* boxes indicate the main carbon reservoirs. The vast majority of carbon atoms are in sediments and rocks, followed by ever lesser amounts in ocean water, soil, the atmosphere, and biomass. Here are typical annual fluxes in the global distribution of carbon, in gigatons:

From atmosphere to plants by carbon fixation	120
From atmosphere to ocean	107
To atmosphere from ocean	105
To atmosphere from plants	60
To atmosphere from soil	60
To atmosphere from fossil-fuel burning	5
To atmosphere from net destruction of plants	2
To ocean from runoff	0.4
Burial in ocean sediments	0.1

and coal, which we humans have been tapping for use as fossil fuels.

Human activities, including the burning of fossil fuels, are putting more carbon into the atmosphere than can be cycled to the ocean reservoir. This factor is contributing to global warming and climate change, topics we will consider in some detail in Chapter 25.

Take-Home Message

What is the global carbon cycle?

- In the carbon cycle, carbon is released by the metabolic processes of organisms, by decomposing organic material, by fossil fuel burning, and by geologic events.
- Much of Earth's carbon moves into the atmosphere (as carbon dioxide gas) and becomes dissolved in the oceans.
- Carbon may be buried in deep sea or land-based sediments for millions of years before cycling back into organisms.

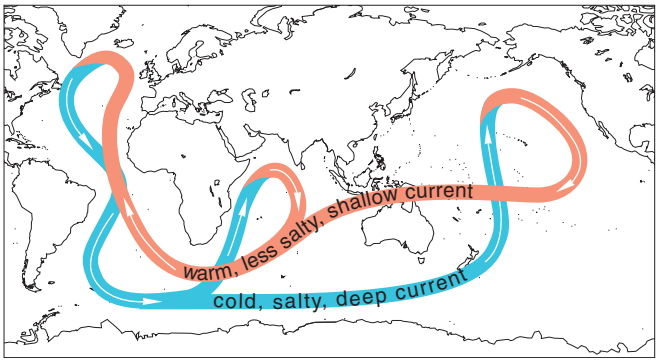
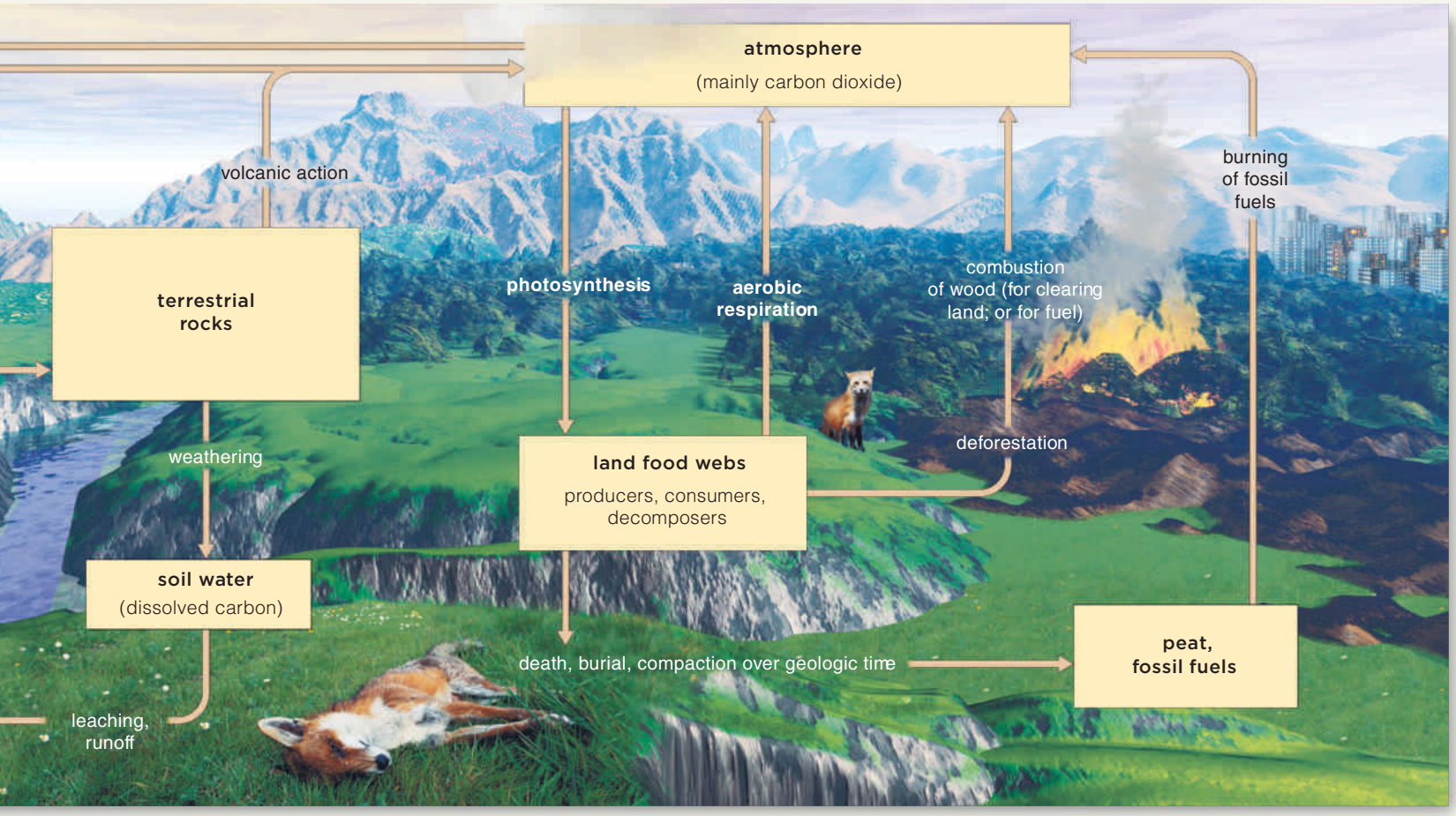


Figure 24.12 A "loop" of moving ocean water delivers carbon dioxide to carbon's deep ocean reservoir. The CO_2 sinks in the cold, salty North Atlantic and rises in the warmer Pacific.



B

24.8 The Nitrogen Cycle

- **Nitrogen, a component of our proteins and nucleic acids, moves in both an atmospheric and a sedimentary cycle called the nitrogen cycle.**

Gaseous nitrogen (N_2) makes up about 80 percent of the atmosphere, the largest nitrogen reservoir. Among organisms, only a few kinds of bacteria can break the triple covalent bonds that hold its two atoms together.

Figure 24.13 shows the **nitrogen cycle**. As you can see, bacteria play key roles. They convert nitrogen to forms plants can use, and they also release nitrogen to complete the cycle. Land ecosystems lose more nitrogen through leaching of soils, although leaching provides nitrogen inputs to aquatic ecosystems such as streams, lakes, and the oceans.

Nitrogen fixation is the process in which certain bacteria convert N_2 to ammonia (NH_3), which then dissolves to form ammonium (NH_4^+). Plants assimilate and use this nitrogen to make amino acids, proteins, and nucleic acids. Plant tissues are the only nitrogen source for humans and other animals.

Bacteria and some fungi also break down nitrogen-containing wastes and remains of organisms. The decomposers use part of the released proteins and amino acids for their own life processes. But most of the nitrogen is still in the decay products, in the form of ammonia or ammonium, which plants take up. In a process called **nitrification**, bacteria convert these compounds to nitrite (NO_2^-). Other bacteria use the nitrite in metabolism and produce nitrate (NO_3^-), which plants also use.

Certain plants are better than others at securing nitrogen. The best are legumes such as peas and beans, which have mutually beneficial associations with nitrogen-fixing bacteria. In addition, most land plants have similar associations with fungi, forming specialized roots that enhance the plant's ability to take up nitrogen.

Some nitrogen is lost to the air by **denitrification**, when bacteria convert nitrate or nitrite to N_2 and a bit of nitrous oxide (N_2O). Much of the N_2 escapes into the atmosphere, completing the nitrogen cycle.

Take-Home Message

What is the nitrogen cycle?

- Nitrogen cycles from the atmosphere, through nitrogen-fixing organisms in soil and water, into plants and then to consumers, and ultimately back into the atmosphere.

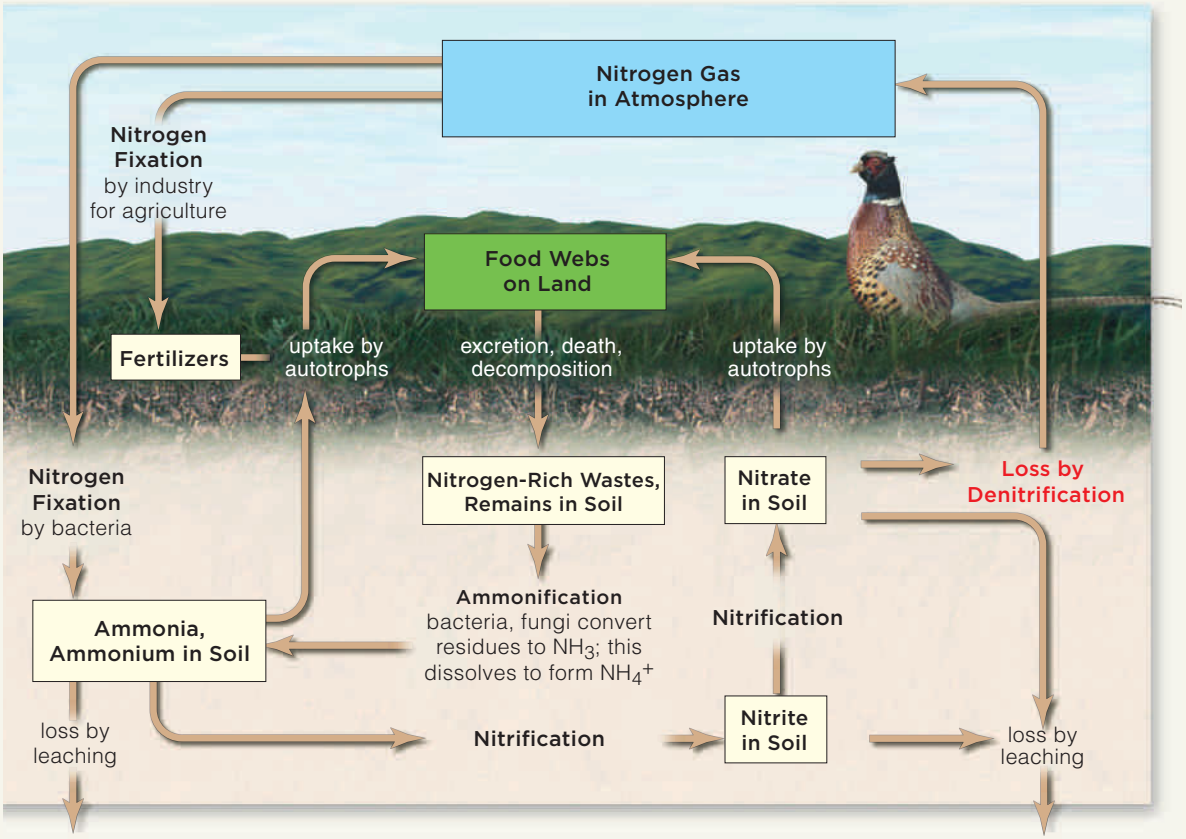


Figure 24.13
Animated!
In the nitrogen cycle bacteria play key roles. The atmosphere is the largest nitrogen reservoir.

IMPACTS, ISSUES

Change in the Air

FOSSIL fuel burning is one factor that is boosting the amount of carbon dioxide in the atmosphere. The increase is a major factor in global warming. Exhaust from motor vehicles is a major source of CO_2, but the better mileage a vehicle gets, the lower its emissions.

How Would You Vote?

Should minimum fuel economy standards for cars and trucks be increased? See CengageNOW for details, then vote online.

Summary

Section 24.1 Ecology is the study of interactions of organisms with one another and with their physical environment. The regions of Earth's crust, waters, and atmosphere where organisms live make up the biosphere. Every kind of organism has a habitat where it normally lives. The species in a given habitat associate with each other as a community.

An ecosystem encompasses producers, consumers, and decomposers and their physical environment. All interact with their environment and with one another through a flow of energy and a cycling of materials. A species' niche consists of the combined physical, chemical, and biological conditions it needs to live and reproduce in an ecosystem.

In ecological succession, the first species that take hold in a habitat are later replaced by others which themselves are replaced until conditions support a more or less stable array of species in the habitat.

Section 24.2 Ecosystems gain and lose energy and nutrients. Sunlight is the main energy source. Primary producers (photosynthesizing plants or algae) convert solar energy to forms that consumers can use. Primary producers also assimilate many of the nutrients that are transferred to other members of the system.

Consumers include herbivores, which feed on plants; carnivores, which feed on animals; and omnivores, which have combination diets. Consumers also include decomposers, such as fungi and bacteria that feed on particles of dead or decomposing material.

An ecosystem's energy supply is transferred through feeding (trophic) levels. Primary producers make up the first feeding level, herbivores make up the next, carnivores the next, and so on.

Organisms that get energy from more than one source cannot be assigned to a single feeding level.

A food chain is a straight-line sequence of who eats whom in an ecosystem. Food chains usually cross-connect in intricate food webs.

- Use the animation and interaction on CengageNOW to learn about energy flow, the cycling of materials, and food webs.

Section 24.3 Primary productivity is the rate at which producers capture and store a given amount of energy in a given time period in an ecosystem. The amount of energy flowing through consumer levels drops at each energy transfer through the loss of metabolic heat and as food energy is shunted into organic wastes. Energy relationships in an ecosystem can be represented as an ecological pyramid in which producers form a base for successive levels of consumers.

Section 24.4–24.8 In a biogeochemical cycle, a substance moves from the physical environment, into organisms, then back to the environment.

Water enters and leaves ecosystems through the water cycle. The phosphorus cycle is a sedimentary cycle in which phosphorus in Earth's crust moves to marine sediments, then back to the land. In the carbon cycle and the nitrogen cycle, where the elements exist mainly as atmospheric gases, the elements move through food webs and then ultimately return to the atmosphere.

- Use the animation and interaction on CengageNOW to learn more about the carbon cycle and other biogeochemical cycles.

Review Questions

1. Explain what an ecosystem is, and name the central roles that producers play in all ecosystems.
2. Explain the difference between an organism's habitat and its niche.
3. Define and give examples of the different feeding levels in ecosystems. Which feeding level is most likely to include most humans?
4. Explain the difference between a food chain and a food web in an ecosystem.
5. Describe the reservoirs and organisms involved in the carbon cycle and the nitrogen cycle.

Self-Quiz *Answers in Appendix V*

1. _____ can be thought of as an ecosystem.
   a. A freshwater spring
   b. A rain forest
   c. A city
   d. All of the above
2. Ecosystems have _____.
   a. energy gains and losses
   b. nutrient cycling but not losses
   c. one feeding level
   d. a and b

3. _____ is the study of how organisms interact with one another as well as with their physical and chemical environment.

4. Feeding levels can be described as _____.
   a. structured feeding relationships
   b. who eats whom in an ecosystem
   c. a hierarchy of energy transfers
   d. all of the above

5. A feeding relationship that proceeds from algae to a fish, then to a fisherman, and then to a shark is _____.
   a. a food chain
   b. a food web
   c. a and b

6. Primary productivity is affected by _____.
   a. photosynthesis and energy use by plants
   b. how many plants are neither eaten nor decomposed
   c. rainfall
   d. temperatures
   e. all of the above

7. Match the following terms with the suitable description.

____ ecological pyramid	a. water or nutrients moving from the environment, to organisms, then back
____ biogeochemical cycle	b. producers, consumers, decomposers
____ ecosystem parts	c. producers capturing and storing energy in their tissues
____ primary productivity	d. energy relationships in an ecosystem

Critical Thinking

1. Imagine and describe a situation whereby you would be a participant (not the top predator) in a food chain.
2. The use of off-road recreational vehicles may double in the next twenty years. Enthusiasts would like increased access to government-owned deserts like the one pictured in Figure 24.1*a*. Some argue that deserts are the perfect places for off-roaders because "there's nothing there." Explain whether you agree, and why.
3. If you were growing a vegetable garden, what variables might affect its net primary production?

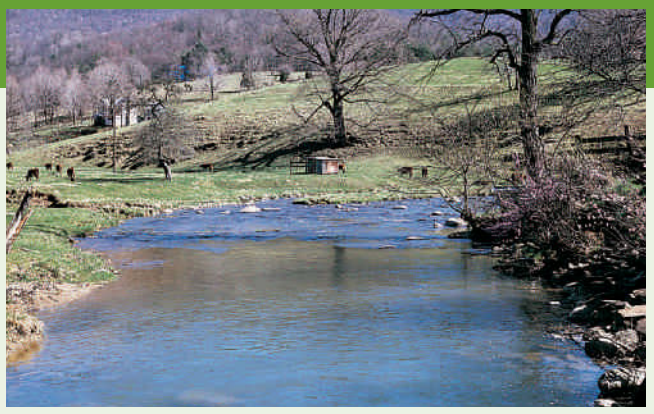
EXPLORE ON YOUR OWN

Benjamin Franklin once remarked, "It's not until the well runs dry that we know the worth of water." Everybody needs water, and as Chapter 25 describes more fully, that essential fluid is in increasingly short supply. Have you ever wondered about your own "water impact"? You can get an idea using the following average statistics:

In a typical U.S. home, flushing toilets, washing hands, and bathing account for about 78% of the water used.

Nearly all toilets installed in the United States since 1994 use 1.6 gallons for each flush. Older toilets use about 4 gallons.

A shower uses about 5 gallons per minute (less if you have a low-flow shower head). Brushing teeth with the water running uses about 2 gallons. Shaving with the water running full blast can use up to 20 gallons.



Washing dishes with an automatic dishwasher uses about 15 gallons; handwashing dishes with the water running doubles that water use.

Using these numbers as a guide, keep track of your water use for a typical day. Are there ways you could conserve and still meet your basic needs?

Human Impacts on the Biosphere

25

IMPACTS, ISSUES

So Long, Blue Bayou

EACH Labor Day, the coastal Louisiana town of Morgan City celebrates the Louisiana Shrimp and Petroleum Festival. The state is the nation's top shrimp harvester and the third largest producer of petroleum, which is refined into gasoline and other fossil fuels.

As the introduction to Chapter 24 noted, fossil fuel burning is one cause of warming of Earth's lower atmosphere and global climate change. One effect we are already seeing is the disappearance of coastal marshes due to rising sea level in places such as the Louisiana coast. The shrimp fishing camp pictured at left was built in a marsh that now no longer exists. Today it sits marooned in the rising waters of Barataria Bay, and shrimp boats must go elsewhere in search of a catch. Experts warn of looming economic disaster, because if the trends we are seeing today continue, in 50 years all of Louisiana's current coastal lowlands will be under water.

Scientists studying climate change also are making another prediction—more massive hurricanes such as the category 5 Hurricane Katrina, which slammed into the Gulf Coast in 2005. High winds and flooding ruined countless buildings in New Orleans and parts of Miississippi and Texas, and more than 1,700 people died.

As global temperatures rise, there are other impacts far from the coast. For example, inland heat waves are becoming more intense and more people are dying of heat stroke. Wildfires are becoming more frequent and more devastating. Mosquitoes that spread diseases such as the West Nile virus are able to survive in places that were too cold for them a few years ago.

This chapter will give you the tools to think critically about human impacts on Earth's environments. Decisions we make today about global climate change and other environmental issues are likely to shape Earth's ecosystems and the quality of human life far into the future.

LINKS TO EARLIER CONCEPTS

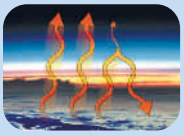
- This chapter aims to place your study of human biology in the broader context of biosphere—the whole living world (1.3).
- Discussions of climate change and thinning of the ozone layer will expand on your knowledge of the carbon cycle (24.7).
- Learning about human impacts on natural resources and biodiversity will draw on your understanding of ecosystems and biogeochemical cycles (24.1, 24.4).

KEY CONCEPTS

Human Population Growth

Humans have sidestepped some natural limits on population growth. Soaring human population size has lead to many impacts on the natural world. Sections 25.1–25.3

Global Climate Change



Warming of Earth's lower atmosphere due to increases in greenhouse gases has begun to change climate patterns. Sections 25.4, 25.5

Impacts on Resources and Biodiversity

Human activities and increasing demand for natural resources are creating pollution and straining ecosystems. Sections 25.6–25.10

How Would You Vote?

Resort areas along the U.S. mid-Atlantic and Gulf coasts regularly are threatened by hurricanes, and now by rising sea level. Property owners have traditionally looked to government to supply low-cost flood insurance and restore storm-damaged beaches. Critics object to taxpayer-funded restoration and say homes should no longer be built in such areas. Would you support a ban on new construction in risky areas? See CengageNOW for details, then vote online.

25.1 Human Population Growth

- **Advances in agriculture, industrialization, sanitation, and health care have fueled ever-faster growth of the human population. This growth is a major factor in changes that are occuring in Earth's ecosystems.**

The human population has grown rapidly

In 2008, there were 6.8 billion people on Earth (Figure 25.1). It took a long time, 2.5 million years, for the human population to reach the 1 billion milestone. It took less than 200 years more to reach 6 billion!

In any population, the growth rate is determined by the balance between births and deaths, plus gains and losses from immigration and emigration. Populations in different parts of the world grow at different rates, but overall, birth rates have been coming down worldwide. Death rates are falling, too, mainly because improved nutrition and health care are lowering infant mortality rates (the number of infants per 1,000 who die within their first year). However, the HIV/AIDS pandemic has sent death rates soaring in some African countries.

The six countries expected to show the most growth are India, China, Pakistan, Nigeria, Bangladesh, and Indonesia, in that order. China and India combined dwarf all other countries in population size. They make up 38 percent of the world population. The United States is next in line. But with about 305 million people, it represents less than 5 percent of the world population.

The **total fertility rate (TFR)** is the average number of children born to women of a population during their reproductive years. In 1950, the worldwide TFR averaged 6.5. Currently it is 2.8, which is still far above replacement level of 2.1—the number of children a couple must have to replace themselves.

These numbers are averages. In many developed nations TFRs are at or below replacement levels. Rates are highest in developing countries in western Asia and Africa. Figure 25.2 has some examples of the differences in the population distribution.

Even if every couple decides to bear no more than two children, the world population will keep growing for 60 years. It is projected to reach nearly 9 billion by 2050. Can we grow enough food and find enough drinkable water, energy sources, and all the wood, steel, and other materials to meet everyone's basic needs? That seems like a tall order, especially because billions of people do not have those necessities even now.

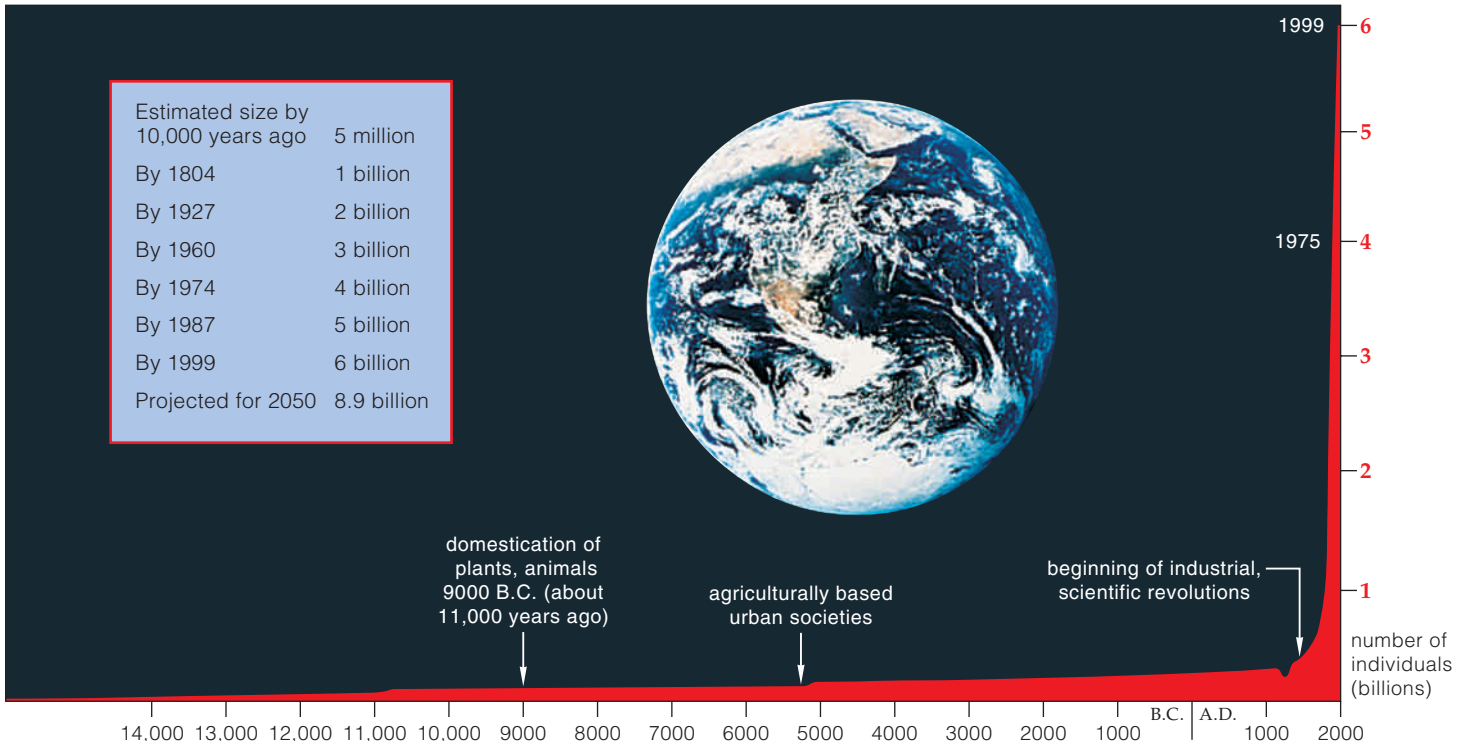


Figure 25.1 Agricultural revolutions, industrialization, and improvements in health care have sustained the accelerated growth of the human population over the last two centuries. In the growth curve (*red*) the vertical axis represents world population, in billions. (The dip between the years 1347 and 1351 is the time when 60 million people died from bubonic plague in Asia and Europe.) The *blue* box lists how long it took for the human population to increase from 5 million to 6 billion.

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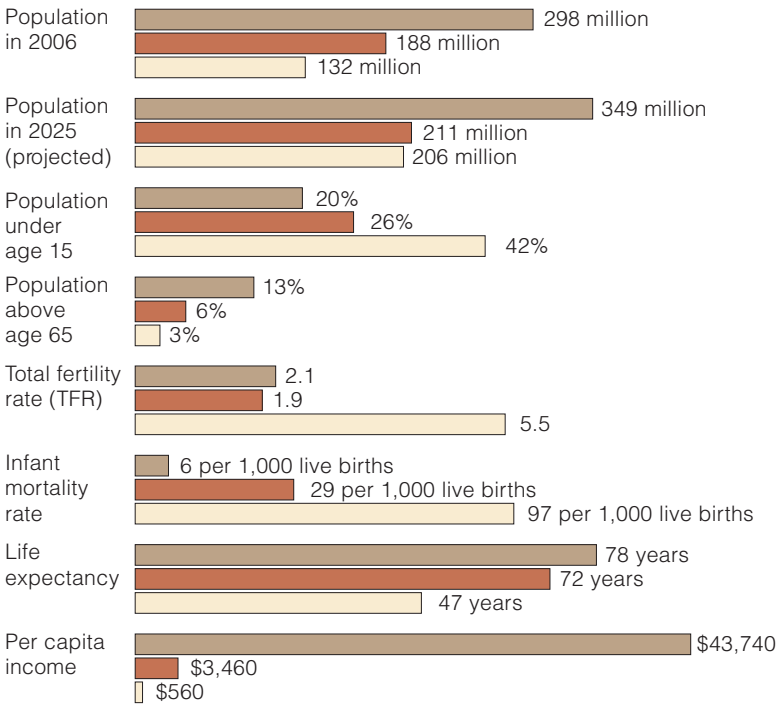


Population statistics help predict growth

A population's **demographics**—its vital statistics, such as its size, age structure, and density—strongly influence its growth and its impact on ecosystems. Ecologists define population size as the number of individuals in the population's gene pool. **Population density** is the total number of individuals in a given area of habitat, such as the number of people who live within a hectare of land. Another demographic is the general pattern in which the population's members are distributed in their habitat. We humans are social animals. We tend to cluster in villages, towns, and cities, where we interact with one another and have access to jobs and other resources.

A population's **age structure** tracks the relative numbers of individuals of each age. These are often divided into prereproductive, reproductive, and postreproductive age categories. In theory, people in the first category will be able to produce offspring when they are sexually mature. Along with the people in the second category, they help make up the population's **reproductive base**. The population of the United States has a narrow base and is an example of slow growth. This pattern contrasts with the age structure in rapidly growing populations, which have a broad reproductive base (Figure 25.3).

Take-Home Message

Why is the human population growing so rapidly, especially in developing countries?

- Advances in agriculture, industrialization, sanitation, and health care have allowed human population growth to surge in the last several centuries.
- Differences in population growth among countries correlate with economic development. The human population will soon reach a level that will severely strain Earth's resources.

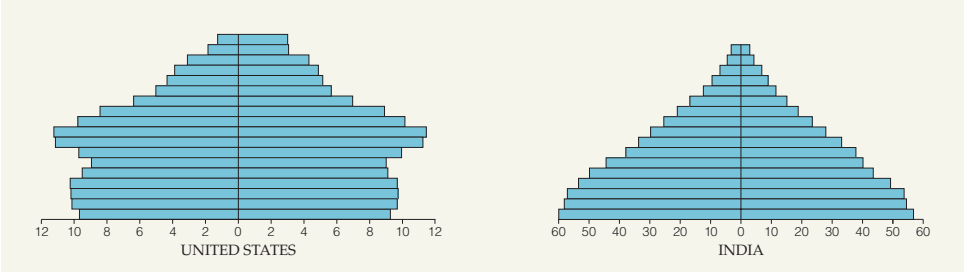


Figure 25.3 Animated! **An age structure diagram provides a snapshot of the number of people in a population who are of reproductive age.** These diagrams show age structure of the populations of the United States and India in 1997.

25.2 Nature's Controls on Population Growth

- **The human population cannot continue to grow faster and faster. Even when conditions are ideal, there is a maximum rate at which any population can grow.**

Human populations can grow at a maximum rate of 2 to 5 percent per year. The rate is determined by how soon individuals begin to reproduce, how often they reproduce, and how many offspring are born each time.

Even when a population is not at its full reproductive potential, it can experience **exponential growth** (in doubling increments from 2 to 4, then 8, 16, 32, 64, and so on). For instance, it is biologically possible for human females to bear twenty children or more, but few do so. Yet since the mid-1700s, our population has been growing exponentially. It can't do so forever, however, because "Mother Nature" doesn't work that way.

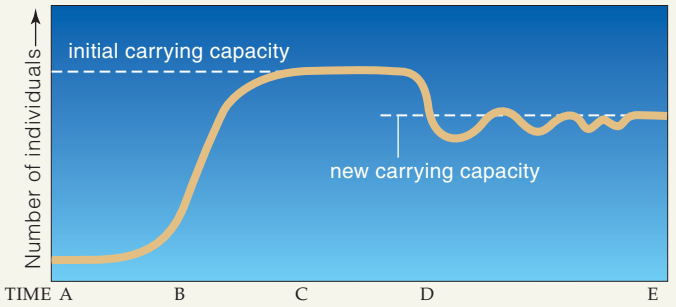


Figure 25.4 Animated! The S-shaped curve of logistic growth. The curve flattens out as the carrying capacity is reached. Changed environmental conditions can reduce the environment's carrying capacity. This happened to the human population in Ireland in the late 19th century, when a fungus wiped out the potatoes that were the mainstay of the diet.

There is a limit on how many people Earth can support

Environmental factors prevent most populations of organisms from reaching their full biotic potential. For instance, when a basic resource such as food or water is in short supply, it becomes a **limiting factor** on growth. Other kinds of limiting factors include predation (as by pathogens) and competition for living space.

The concept of limiting factors is important because it defines the **carrying capacity**—the number of individuals of a species that can be sustained indefinitely by the resources in a given area. Some experts believe that Earth has the resources to support from 7 to 12 billion humans, with a reasonable standard of living for many. Others believe that the current human population of 6.8 billion is already exceeding Earth's carrying capacity. These viewpoints share the basic premise that overpopulation is the root of many, if not most, of the environmental problems the world now faces.

A low-density population starts to grow slowly, then goes through a rapid growth phase, and then growth levels off once the carrying capacity is reached. This pattern is called **logistic growth**. A plot of logistic growth gives us an S-shaped curve (Figure 25.4). This curve is a simple approximation of what goes on in the natural world.

Some natural population controls are related to population density

When a growing population's density increases, the high density and overcrowding result in competition for resources. They also put individuals at increased risk of being killed by infectious diseases and parasites, which are more easily spread in crowded living conditions. These are **density-dependent controls** on population growth. Once such factors take their toll on a population and its density decreases, the pressures ease and the population may grow once more.

A classic example is the bubonic plague that killed 60 million Asians and Europeans—about one-third of the population—during the Middle Ages. *Yersinia pestis*, the bacterium responsible, normally lives in wild rodents, and fleas transmit it to new hosts. It spread like wildfire through the cities of medieval Europe because dwellings were crowded together, sanitation was poor, and rats were everywhere. In 1994, bubonic plague and a related disease, pneumonic plague, raced through rat-infested cities in India where garbage and animal carcasses had piled up for months in the streets. Only crash efforts by public health officials averted a public health crisis.

Density-independent controls can also operate. These are events such as floods, earthquakes, or other natural disasters that cause deaths regardless of whether the members of a population are crowded or not.

Take-Home Message

Why can't Earth support an unlimited number of humans?

- Because resources are not unlimited, over the long term a given area can support only a finite number of individuals of any species, including humans. Other factors that limit population growth include disease organisms and effects of pollution.

25.3 Ecological "Footprints" and Environmental Problems

- **Population growth and the unsustainable use of natural resources are two major root causes of the environmental problems we face today and in the future.**

Today we hear constantly about environmental challenges facing humanity. Many of these problems are due directly or indirectly to the growing human population and its demand for natural resources.

Everyone has an ecological footprint

As societies strive to become more affluent, they replace natural landscapes such as forests with cropland, factories, and housing developments. Their citizens also want the conveniences of affluent life—cars, labor-saving appliances, computers, cell phones, and other electronic gadgets to name a few. Having more money also allows people to travel over long distances and to buy more food—often, more meat and fish—sometimes from sources thousands of miles away. The net result of these and other changes is a growing **ecological footprint**—a short-hand term for the total resources a population consumes and the resulting wastes that are returned to the environment. Each of us has a personal ecological footprint as well.

Ecological footprints vary widely. For example, in a year the average consumer in the United States uses 100 times the resources consumed by someone in the poorest regions of Africa and Asia (Figure 25.5). The ecological footprints of people in rapidly developing nations such as China and India are growing at the same rapid pace.

Resources are renewable or nonrenewable

Overall, our planet's resources fall into two categories. **Renewable resources**, such as fresh water and forests, can be tapped indefinitely if they are replenished. On the other hand, fossil fuels and minerals such as copper are for all intents and purposes **nonrenewable resources**. Earth's crust contains finite, limited amounts of them. More may form over many millions of years, but not on a human time scale. Therefore nonrenewable resources can be depleted, leaving us to our technological ingenuity to find usable, cost-effective replacements.

Pollution can result from human activities

Often, using a resource produces wastes that the user must dispose of. All too often in technologically advanced societies, wastes or chemical by-products of industry and agriculture create pollution. A **pollutant** is a substance that in some way harms the health, activities, or survival of a population.

Natural events such as a volcanic eruption can release pollutants, but today most pollution comes from human activities. There are two basic sources for pollution. A **point source** is a single place or outlet, such as a leaky toxic waste dump. A **nonpoint source** is not tied to a particular location and so is harder to pin down. Pesticide runoff from farms and homes into a river or bay is an example.

In the remainder of this chapter we will be looking at some basic types of natural resources, such as water, land, and forests. In each case we will consider the effects of human activities, starting with the impact of industry and fossil fuel use on the air we breathe.

Take-Home Message

What is an ecological footprint, and what is a pollutant?

- An ecological footprint is the sum total of resources used by a population or person, together with the resulting wastes.
- Renewable resources can be replenished and so in theory may be available indefinitely. There are only finite amounts of nonrenewable resources, which can't be readily replenished.
- A pollutant is a substance that harms health, activities, or the survival of a population.

Figure 25.5 Who has the largest ecological footprint? In Africa the rural poor rely heavily on homegrown crops rather than on foods from a grocery store. They also typically lack access to conveniences people in wealthier regions take for granted—not to mention basic necessities such as public sanitation and a reliable supply of clean drinking water.

25.4 Assaults on Our Air

- **A variety of human activities are polluting the air, with major consequences for ecosystems and human health.**

Air pollutants include carbon dioxide, oxides of nitrogen and sulfur, and chlorofluorocarbons (CFCs). Others are photochemical oxidants formed as the sun's rays interact with certain chemicals. The United States releases more than 700,000 metric tons of air pollutants every day.

In some weather conditions, a layer of cool, dense air gets trapped under a warmer air layer (Figure 25.6). As a result of this *thermal inversion*, the atmospheric condition called **smog** develops. Some of the worst air pollution disasters have been due to thermal inversions.

Where winters are cold and wet, **industrial smog** forms as a gray haze over industrialized cities that burn coal and other fossil fuels for manufacturing, heating, and generating electric power. The burning releases airborne dust, smoke, ashes, soot, asbestos, oil, bits of lead and other heavy metals, and sulfur oxides. Most industrial smog forms in cities of developing countries, including China and India, as well as in eastern Europe.

In warm climates, **photochemical smog** forms as a brown, smelly haze over large cities. The key culprit is nitric oxide. After it is released from vehicles, nitric oxide reacts with oxygen in the air to form nitrogen dioxide. When exposed to sunlight, nitrogen dioxide can react with hydrocarbons (such as partly burned gasoline) to form photochemical oxidants. Some of those in smog resemble tear gas; even traces can sting the eyes, irritate lungs, and damage crops.

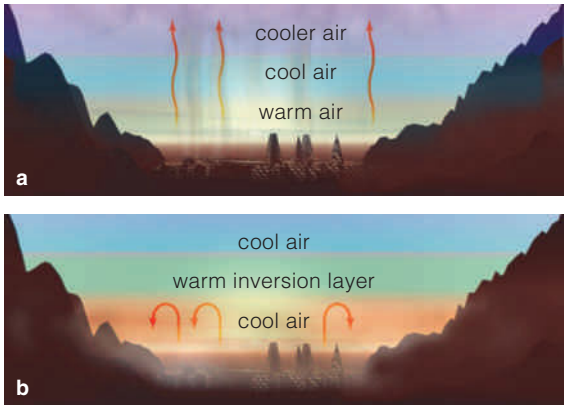


Figure 25.6 Thermal inversions set the stage for smog. Part (**a**) shows how air normally would circulate in smog-forming regions. Part (**b**) shows how air pollutants become trapped under a thermal inversion layer.

Oxides of sulfur and nitrogen are among the worst air pollutants. These substances come mainly from power plants and factories fueled by coal, oil, and gas, as well as from motor vehicles. Dissolved in atmospheric water, they form weak sulfuric and nitric acids that winds may disperse over great distances. If they fall to Earth in rain and snow, they form **acid rain**. Acid rain can be much more acidic than normal rainwater, sometimes as acidic as lemon juice (pH 2.3). The acids eat away at marble, metals, even nylon (Figure 25.7*a*). They also seriously damage the chemistry of ecosystems (Figure 25.7*b*).

Canadian researchers have reported that inhaled soot particles from a steel mill caused DNA mutations that showed up in the sperm of male mice and were passed on to offspring. More study is needed to learn whether such pollution-spurred mutations can cause disease in mice—or in humans who also breathe the polluted air.

Figure 25.7 Acid rain causes widespread damage. (**a**) A coal-burning power plant (left) and a stone sculpture eroded by acid rain (right). (**b**) Part of a forest in Great Smoky Mountains National Park, where nitrogen oxides and other forms of air pollution have killed trees.

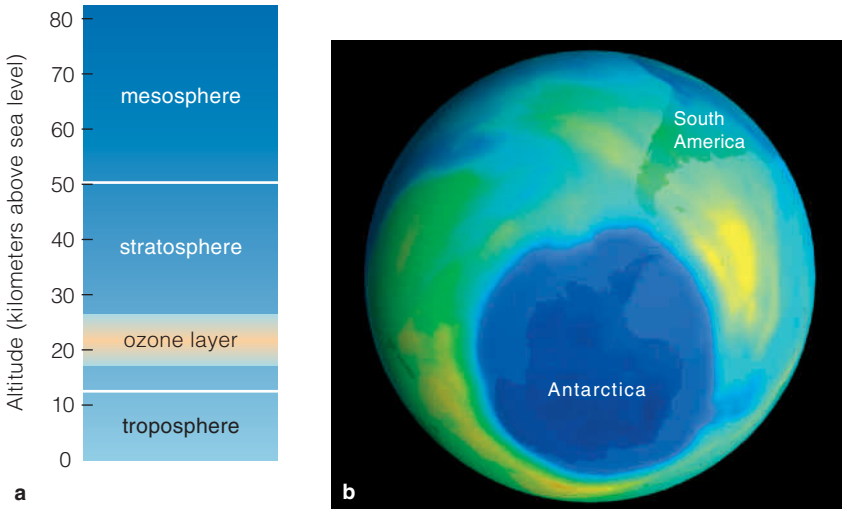


TABLE 25.1 Some Predicted Effects of Ozone Depletion

More skin cancers, eye cataracts, and worse sunburns
Increased acid rain and photochemical smog
Reduced ocean phytoplankton, harming ocean food webs and human seafood supplies
Increased global warming due to CFCs in the troposphere

Figure 25.8 Ozone concentrated in the stratosphere helps shield life on Earth from UV radiation. (**a**) The location of the ozone layer. (**b**) Seasonal ozone thinning above Antarctica in 2001. Darkest blue indicates the area with the lowest ozone level, at that time the largest recorded.

Air pollution has damaged the ozone layer

Ozone is a molecule of three oxygen atoms (O_3). It occurs in two regions of Earth's atmosphere. In the troposphere, the region closest to Earth's surface, ozone is part of smog and can damage the respiratory system (as well as other organisms). On the other hand, ozone in the next atmospheric layer—the stratosphere (17–48 kilometers, or 11–30 miles above Earth)—intercepts harmful ultraviolet radiation that can cause skin cancer and eye cataracts. **Ozone thinning** has damaged this protective screen. September through mid-October, an ozone "hole" appears over the Antarctic, extending over an area about the size of the continental United States. Since 1987 the ozone layer over the Antarctic has been thinning by about half every year; a new hole, over the Arctic, appeared in 2001. That year the Antarctic hole was the biggest ever, covering an area greater than North America (Figure 25.8).

Chlorofluorocarbons (CFCs) are the main ozone depleters. These gases (compounds of chlorine, fluorine, and carbon) are used as coolants in refrigerators and air conditioners and in solvents and plastic foams. They slowly escape into the air and do not break down easily. Through a series of chemical steps, each of their chlorine molecules can destroy over 10,000 molecules of ozone. A widely used fungicide called methyl bromide is even worse. It will account for 15 percent of ozone thinning in future years unless production stops.

CFC production in developed countries has been phased out. Some developing countries have announced plans to phase it out within the next few years. Methyl bromide production may also end soon. Even if these efforts succeed, it will be decades before ozone thinning is reversed. Current scientific models project that ozone depletion over the poles will be severe until at least 2019. In the meantime we can expect some ongoing negative impacts (Table 25.1). One of these repercussions, the loss of ocean phytoplankton (microscopic floating plantlike organisms), will worsen global warming, the topic we turn to next.

Take-Home Message

What harm does air pollution do?

- Air pollution can have local, regional, and global impacts. These include smog, acid rain, and thinning of Earth's protective ozone layer as CFCs and other compounds destroy ozone molecules.

25.5 Global Warming and Climate Change

- **Human activities have increased the concentrations of greenhouse gases in the lower atmosphere so that the average temperature is warming. This warming is driving major changes in Earth's climate.**

A variety of gases in Earth's atmosphere play a key role in shaping the average temperature near its surface. Temperature, in turn, has huge effects on global and regional climates.

Atmospheric molecules of carbon dioxide, water, ozone, methane, nitrous oxide, and chlorofluorocarbons are the major players in interactions that affect global temperature. Collectively, the gases act like the panes of glass in a greenhouse—hence their name, "greenhouse gases." Wavelengths of visible light pass through these gases to Earth's surface, which absorbs them and then emits them as heat. Greenhouse gases slow the escape of this heat back into space. Instead, much of it radiates back toward Earth's surface (Figure 25.9).

With time, heat builds up in the lower atmosphere and the air temperature near the surface rises. This warming action is known as the **greenhouse effect**. Without it, Earth's surface would be too cold to support life.

In the 1950s, researchers in a laboratory on Hawaii's highest volcano began a long-term program of measuring the concentrations of greenhouse gases in the atmosphere. They found that carbon dioxide concentrations follow the annual cycle of plant growth (that is, primary production) in the Northern Hemisphere. This includes the growth of phytoplankton at the ocean surface. CO_2 levels drop in summer, when photosynthesis rates are highest (and plants use lots of CO_2). They rise in winter, when photosynthesis by plants slows.

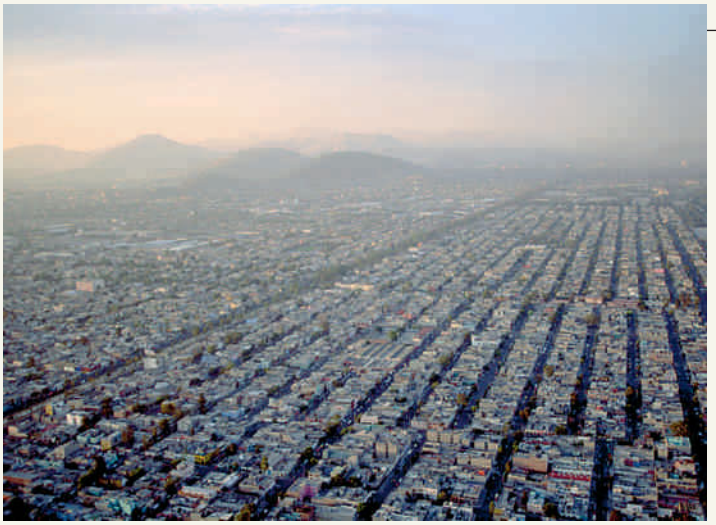
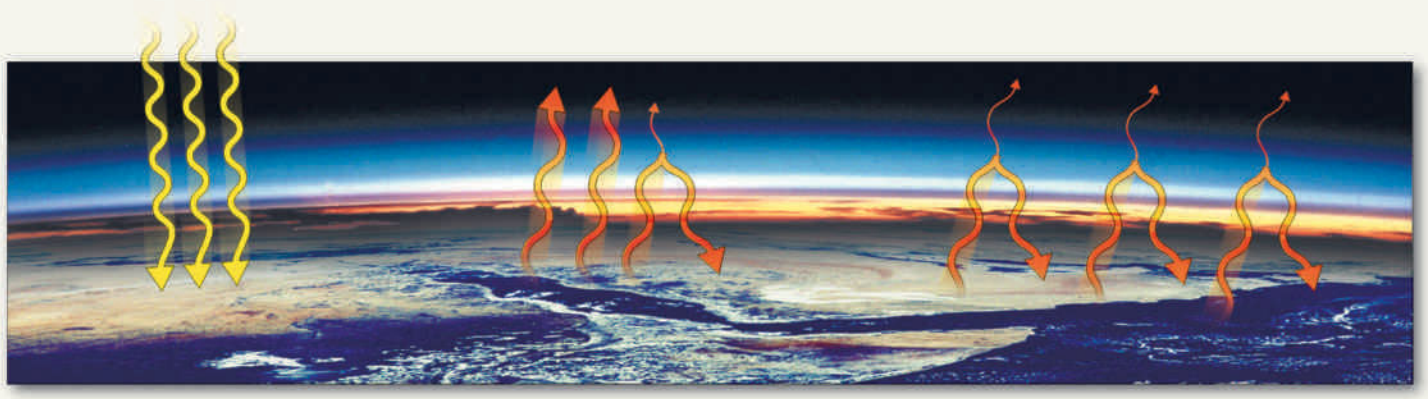


Figure 25.10 Animated! Human activities produce large amounts of greenhouse gases. *Facing page*, Recorded changes in global temperature between 1875 and 2008. At this writing, the hottest year on record in the Northern Hemisphere was 2005. Above, Mexico City on a smoggy morning. With more than 10 million residents, it's the world's largest city.

The troughs and peaks in Figure 25.10 (facing page) are annual lows and highs of global carbon dioxide concentrations. For the first time, scientists have been able to see the big picture regarding effects of the carbon balances for an entire hemisphere. Notice the midline of the troughs and peaks in the cycle. It shows that the concentration of carbon dioxide is steadily increasing, as are the concentrations of other greenhouse gases.



A Rays of sunlight penetrate the lower atmosphere and warm Earth's surface.

B The surface radiates heat (infrared wavelengths) to the lower atmosphere. Some heat escapes into space. But greenhouse gases and water vapor absorb some infrared energy and radiate a portion of it back toward Earth.

C Increased concentrations of greenhouse gases trap more heat near Earth's surface. Sea surface temperature rises, more water evaporates into the atmosphere, and Earth's surface temperature rises.

Figure 25.9 Animated! The greenhouse effect warms Earth's surface.

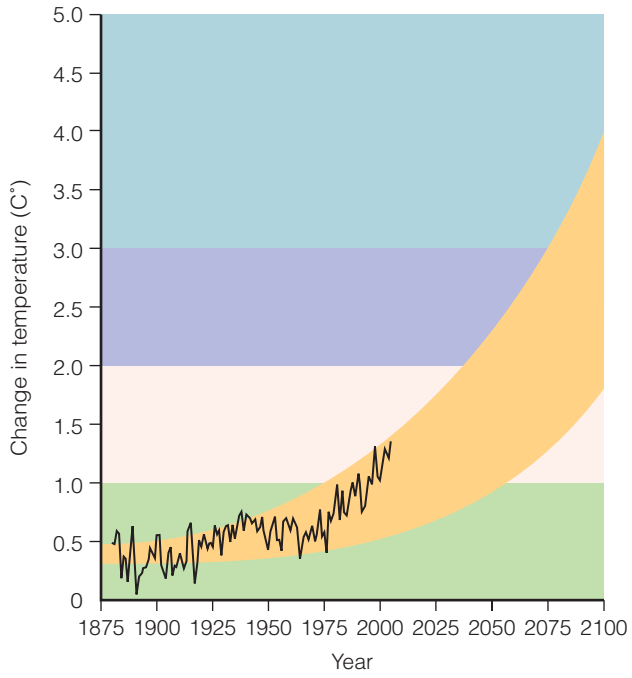


Figure 25.11 Glaciers are in retreat in high mountains all over the world. In Glacier Bay, Alaska rocks and gravel now are exposed where ice covered the land ten years earlier (left).

Greenhouse gas levels are far higher than they were in most of the past. Carbon dioxide may be at its highest level since 420,000 years ago, perhaps even longer.

Today the great majority of climate scientists agree that the increase in greenhouse gases is a factor in **global warming**, a long-term rise in temperature near Earth's surface. Since direct measurements started in 1861, the lower atmosphere's temperature has risen by more than 1°F, mostly since 1946. Nine of the ten hottest years occurred between 1990 and the present. In 2007, the combined findings of nineteen different climate research programs and the Intergovernmental Panel on Climate Change (IPCC) were clear: It is almost certain that Earth's surface will warm by 3.6–8.1°F by the year 2100. Irreversible **global climate change** is under way, and it is happening much faster than expected.

What will climate change mean for us?

Continued temperature increases will have drastic effects on the climate of every region on Earth. Here we can only mention a few examples of the projected impacts.

To begin with, climate change may benefit agriculture in regions where winters become milder. In the Arctic, where sea ice once made the ocean impassible for much of the year, warming will ensure open channels and opportunities for fisheries. Several nations already are planning to expand commercial fishing operations there.

Elsewhere the impacts may be much less desirable. As evaporation increases, so will overall precipitation. Intense rains and flooding are expected to become more frequent in some regions while other regions likely will experience more frequent and intense droughts. Current research suggests that severe, extended droughts may wipe out agriculture in parts of Africa where many people are desperately poor and farm small plots for food.

Glaciers all over the world are retreating (Figure 25.11) and polar ice is rapidly melting. As the chapter introduction described, one result of these changes is rising sea level in many coastal areas. The IPCC projects an average rise of 0.6 to 1.9 feet by 2100. If this estimate is accurate, in your lifetime the sea may submerge up to a third of the world's coastal wetlands and coral reefs, begin to flood many large coastal cities and agricultural lands, and erode away large chunks of coastlines such as the Atlantic coast of the United States.

Disappearing glaciers also will wipe out a major source of freshwater for domestic and agricultural use in India, parts of South America and Africa, as well as western North America.

Although this discussion may seem depressing, it is important to remember that many smart people are working on strategies for slowing global warming and climate change. *Explore on Your Own* at the end of this chapter suggests ways you can learn more about climate change and active efforts to limit its effects.

Take-Home Message

What is global warming and how is it affecting Earth's climate?

- Global warming is the long-term rise in Earth's surface temperature due to the rapid accumulation of greenhouse gases in the atmosphere.
- Warming has produced the beginning of what may be a major shift in Earth's climate.

25.6 Problems with Water and Wastes

- **Three of every four humans do not have enough clean water to meet basic needs. Most of Earth's water is salty (in oceans). Of every million liters of water on our planet, only 6 liters are readily usable for human activities.**

Water issues affect 75 percent of humans

As the human population grows exponentially, so do the demands and impacts on Earth's limited supply of fresh water.

About a third of the world's food grows on land that is irrigated with water piped in from groundwater, lakes, or rivers. Irrigation water often contains large amounts of mineral salts. Where soil drainage is poor, evaporation may cause salt buildup, or *salinization*. Globally, salinization is estimated to have reduced yields on 25 percent of all irrigated cropland. Large-scale irrigation (Figure 25.12) is depleting groundwater stored in the Ogallala aquifer, which extends from South Dakota to Texas and has been providing about 30 percent of the groundwater used for irrigation in the United States. In some areas the farmers are working to reduce their water use by switching to more efficient irrigation systems.

Communities located in deserts have been notorious water wasters. In a 1999 estimate, Las Vegas, Nevada—desert home of golf courses, swimming pools, and lush lawns—was said to use more water per resident than any other city in the world. Since then, dwindling supplies have forced the city to launch a program of water conservation. In coastal areas, overuse of groundwater can cause saltwater intrusion into human water supplies. Much of the United States is experiencing water problems (Figure 25.13).

In many regions, agricultural runoff pollutes public water sources with sediments, pesticides, and fertilizers. Power plants and factories pollute water with chemicals (including carcinogens), radioactive materials, and excess heat. Such pollutants may accumulate in lakes, rivers, and bays before reaching their ultimate destination, the oceans (Figure 25.14). Contaminants from human activities have begun to turn up even in supposedly "pure" water in underground aquifers.

Many people view the oceans as convenient refuse dumps. Cities throughout the world dump untreated sewage, garbage, and other noxious debris into coastal waters. Cities along rivers and harbors maintain shipping channels by dredging the polluted muck and barging it out to sea. We don't yet know the full impact such practices may have on fisheries that provide human food.

Figure 25.12 Large-scale irrigation is common in many U.S. agricultural areas. A center-pivot sprinkler system is about 70 to 80 percent efficient.

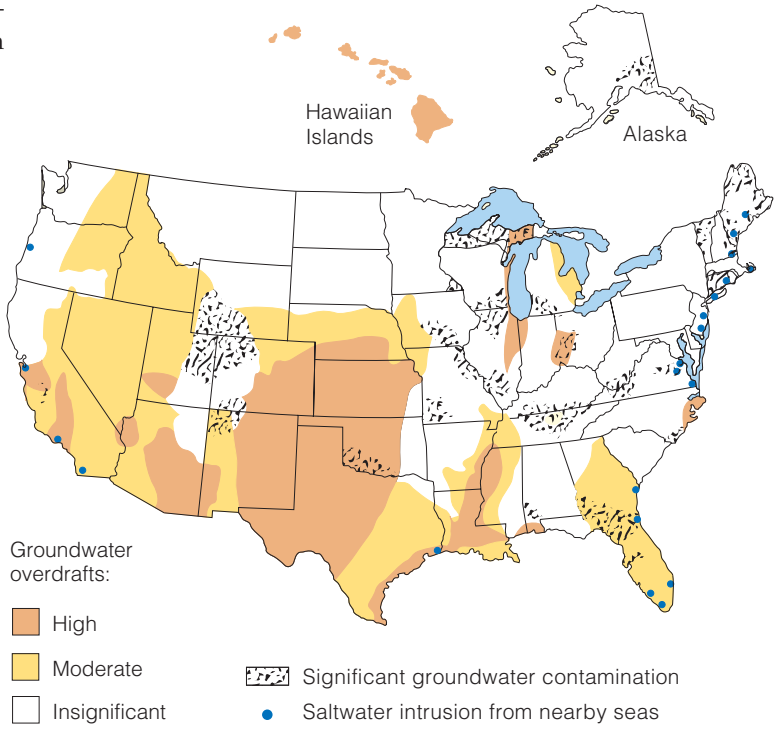


Figure 25.13 Many areas of the United States have groundwater troubles.

Figure 25.14 Industrial wastes polluted Lake Erie. A steel mill in Lackawanna, New York, discharged industrial wastes into Lake Erie until 1983, when the mill was closed. Major efforts to clean up Lake Erie have been under way.

Managing solid wastes is another challenge

In 2006, the United States generated 251 million tons of garbage—an average of 4.6 pounds (2.1 kilograms) per person each day.

In natural ecosystems, solid wastes are recycled, but we humans bury them in landfills or incinerate them. Incinerators can add heavy metals and other pollutants to the air and leave a highly toxic ash that must be disposed of safely. Land that is both available and acceptable for landfills is scarce and becoming scarcer. All landfills eventually leak, posing a threat to groundwater supplies. That is one reason why communities increasingly take the "not in my back yard" (NIMBY) approach to landfills. For some highly populated areas, the "solution" has been to ship much of their garbage to rural areas (often in other states or countries) or dump it in the ocean.

Some components of trash may stay around for decades, especially if they contain plastic. Plastic bags may still be intact after forty or fifty years and parts of a disposable diaper will last more than 100 years.

On the plus side, about one-third of the total U.S. trash is recycled (Figure 25.15). That still leaves many millions of tons of plastic containers and glass bottles for society to deal with. To reduce the impact of plastic trash, consumers can buy fewer disposable items such as razors and avoid buying plastic when other, less environmentally harmful products exist. If plastic is used, it can be recycled. These days most communities make recycling easy with curbside pickups or recycling centers. Many grocery stores and other businesses provide free bins where plastic bags also can be recycled.

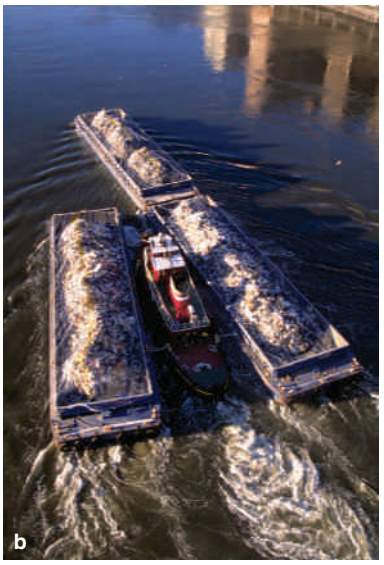


Figure 25.15 Recycling is an important part of efforts to manage solid wastes. (**a**) Recyclable material includes many plastics, glass containers, metal cans, and often other items. Many communities have special facilities for recycling items such as batteries, computers, and paint cans, which contain hazardous substances such as mercury and lead. (**b**) A garbage barge laden with trash.

Take-Home Message

How have human activities affected water supplies and the management of solid wastes?

- Worldwide, human water supplies are threatened by overuse and by pollution with agricultural and industrial wastes.
- Worldwide, people also generate trillions of tons of solid wastes. Landfills are rapidly filling up and land for new ones is becoming scarcer.
- Recycling helps reduce solid waste and conserve resources.

25.7 Problems with Land Use and Deforestation

- **The demand for food, housing, and forest products has led to widespread deforestation, agricultural practices that harm the environment, and the loss of habitat for other species.**
- **Link to Genetic engineering of plants 21.7**

Like other ecological problems, those related to land use are linked to the rapid growth of the human population. People must have places to live and grow food, as well as materials to build homes and use as fuel.

Feeding and housing billions of humans requires land and other scarce resources

Only 25 percent of Earth is dry land, and only a fraction of that is available for human use. Today, almost a quarter of Earth's land is being used for agriculture. Scientists have made valiant efforts to improve crop production on existing land. As part of the "green revolution," research has been geared to improving the varieties of crop plants for higher yields and exporting modern agricultural practices and equipment to developing countries.

Unfortunately, the green revolution is based on huge inputs of fertilizers and pesticides and ample irrigation to sustain high-yield crops (Figure 25.16). It is based also on fossil fuel energy to drive farm machines. Crop yields *are* four times as high as from traditional methods. But modern practices use up to 100 times more energy and minerals such as nitrogen and phosphorus. Also there are signs that limiting factors are coming into play to slow down further increases in crop yields.

Overgrazing of livestock on marginal lands is a prime cause of **desertification**—the conversion of grasslands or cropland to a desertlike state that does not readily support useful plants (Figure 25.17). Worldwide, this has happened to about 10 million square kilometers over the past 50 years, and the trend is continuing.

Development of land for housing, towns, and cities also has an ecological price. One of the most important is the loss of habitat used by other species. In areas where water is scarce, such as much of the western United States, housing developments also increase the pressure on limited water supplies and political wrangling over access to them. As climate change alters conditions in these areas, these problems will be increasingly difficult to solve. We will return to the topic of habitat losses in Section 25.9.

Figure 25.16 Agriculture requires large amounts of land and water. Rice must grow in shallow water of continuously flooded fields. It is a major staple food crop for tens of millions of people in Asia.

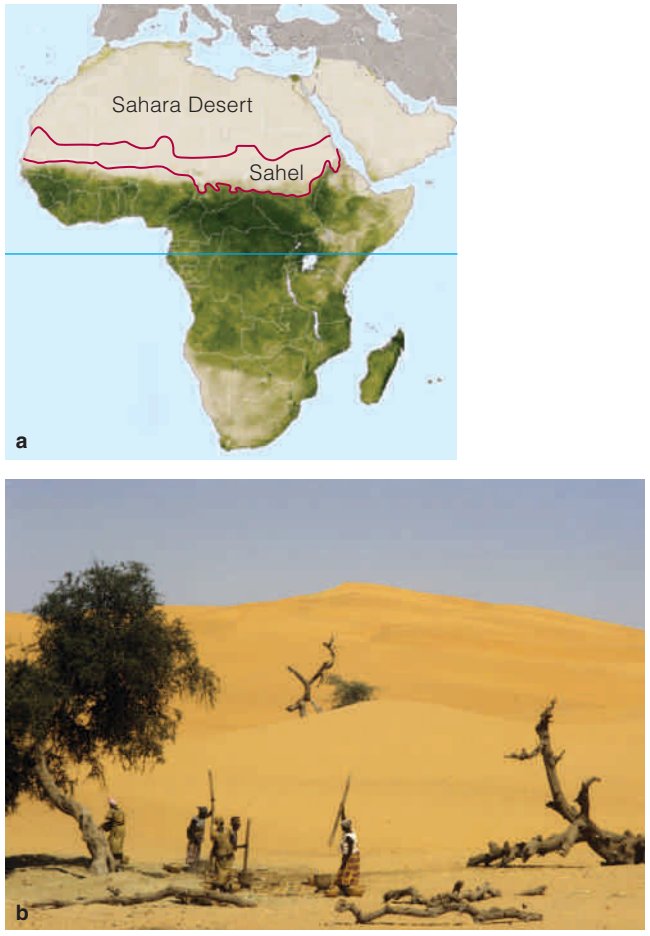


Figure 25.17 Desertification has become a major problem in parts of Africa. (**a**) A satellite photo taken in 2005. Red lines mark the huge area where desertification has occurred. (**b**) People who live in this area can barely eke out a living on the land.

Deforestation has global repercussions

The world's great forests influence the biosphere in many ways. Like giant sponges, forested watersheds absorb, hold, and gradually release water. Forests also help control soil erosion, flooding, and sediment buildup in rivers, lakes, and reservoirs.

Deforestation is the name for removal of all trees from large tracts of land for logging, agricultural, or grazing operations. The loss of vegetation exposes the soil, and this promotes leaching of nutrients and erosion, especially on steep slopes. Cleared plots soon become infertile and are abandoned. The photograph in Figure 25.18*a* shows forest destruction in the Amazon basin of South America.

Deforestation is linked with several ecological problems. One of the most troubling effects relates to the global carbon cycle. Tropical forests absorb much of the sunlight reaching equatorial regions of Earth's surface. When the forests are cleared, the land becomes "shinier," and reflects more incoming energy back into space. The many millions of photosynthesizing trees in these vast forests help sustain the global cycling of carbon and oxygen. When trees are harvested or burned, carbon stored in their biomass is released to the atmosphere in the form of carbon dioxide—and this may be boosting the greenhouse effect.

About half the world's tropical forests have been cut down for cropland, fuel wood, grazing land, and timber. Deforestation is greatest in Brazil, Indonesia, Colombia, and Mexico (Figure 25.18*b*). If clearing continues at present rates, within a few years only Brazil and Zaire will have large tropical forests. By 2035, most of *their* forests will be gone.

Conservation biologists are attempting to reverse the trend. For example, in Brazil, a coalition of 500 groups is working to preserve the country's remaining tropical forests. In Kenya, women have planted millions of trees. Their success has inspired similar programs in more than a dozen countries in Africa. In eastern North America, forested land has increased in recent years due to regrowth in logged areas and the creation of commercial tree plantations. Elsewhere, such as the western United States, British Columbia (western Canada), and Siberia, logging is rapidly clearing vast tracts of old growth temperate forests (Figure 25.18*c*).

Take-Home Message

How are human activities affecting Earth's land?

- Most modern agriculture depends on heavy applications of fertilizers and pesticides and uses machinery that runs on fossil fuels.
- Large-scale deforestation promotes soil erosion, loss of soil nutrients, and probably is contributing to greenhouse warming of the atmosphere.

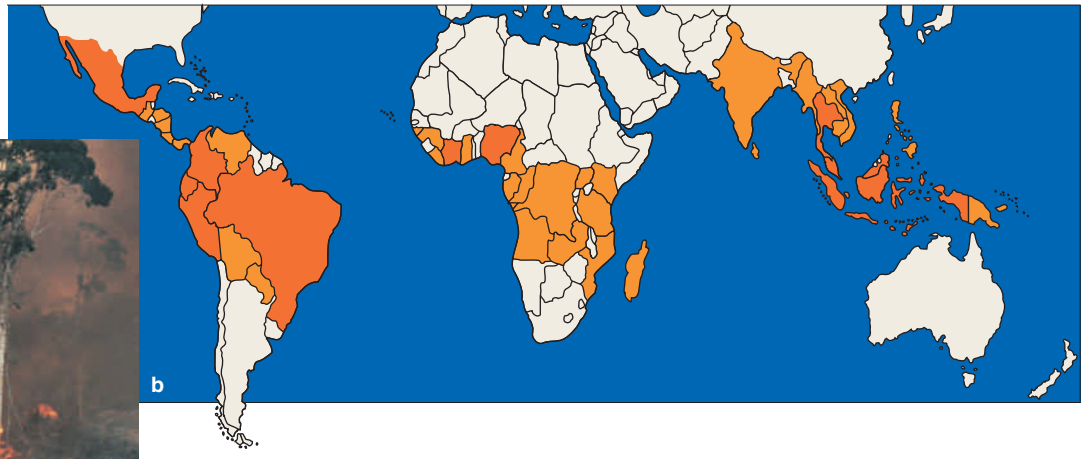


Figure 25.18 Huge tracts of tropical and temperate lands are being deforested. (**a**) Forest destruction in South America. (**b**) *Red* shading on this map indicates countries where about 2,000 to 14,800 square kilometers of tropical forests are removed annually. Orange indicates sites of "moderate" tropical deforestation (100 to 1,900 square kilometers). (**c**) A huge clear-cut in a temperate conifer forest in British Columbia.

25.8 Moving Toward Renewable Energy Sources

- **Paralleling the growth of the human population is a steep rise in energy consumption.**

In theory, our planet has ample energy supplies to meet human needs for transportation and other uses. For example, world reserves of coal can meet our energy needs for at least several centuries. There are pros and cons associated with all energy sources. But as society wrestles with the rising costs and environmental risks associated with nonrenewable forms of energy such as coal and petroleum, pressure is building for a large-scale shift to renewable energy sources such as solar and wind energy.

Figure 25.19 shows the percentages of different energy sources used globally. Overall, developed countries use far more energy per person. This is a major reason why consumers in developed countries have a much larger ecological footprint.

There are growing issues with fossil fuels

Oil, coal, and natural gas are **fossil fuels**, the fossilized remains of ancient forests. Although there is plenty of coal in the ground, known oil and gas reserves may be used up in this century. As the reserves run out in accessible areas—with political and market forces increasing the strain—pressure has mounted to drill in wilderness areas in Alaska, offshore, and other fragile environments. Due in part to the associated environmental costs, many people oppose the idea.

Increased coal burning is not popular either. It has been a major source of air pollution, because most reserves contain low-quality, high-sulfur coal. In addition, extraction and transportation of these fuels have harmful impacts. Oil harms many species when it leaks from pipelines or from ships. Strip mining for coal degrades the immediate area and often lowers the water quality of nearby streams. And as we have seen, burning fossil fuels also contributes to acid rain and adds to the greenhouse effect.

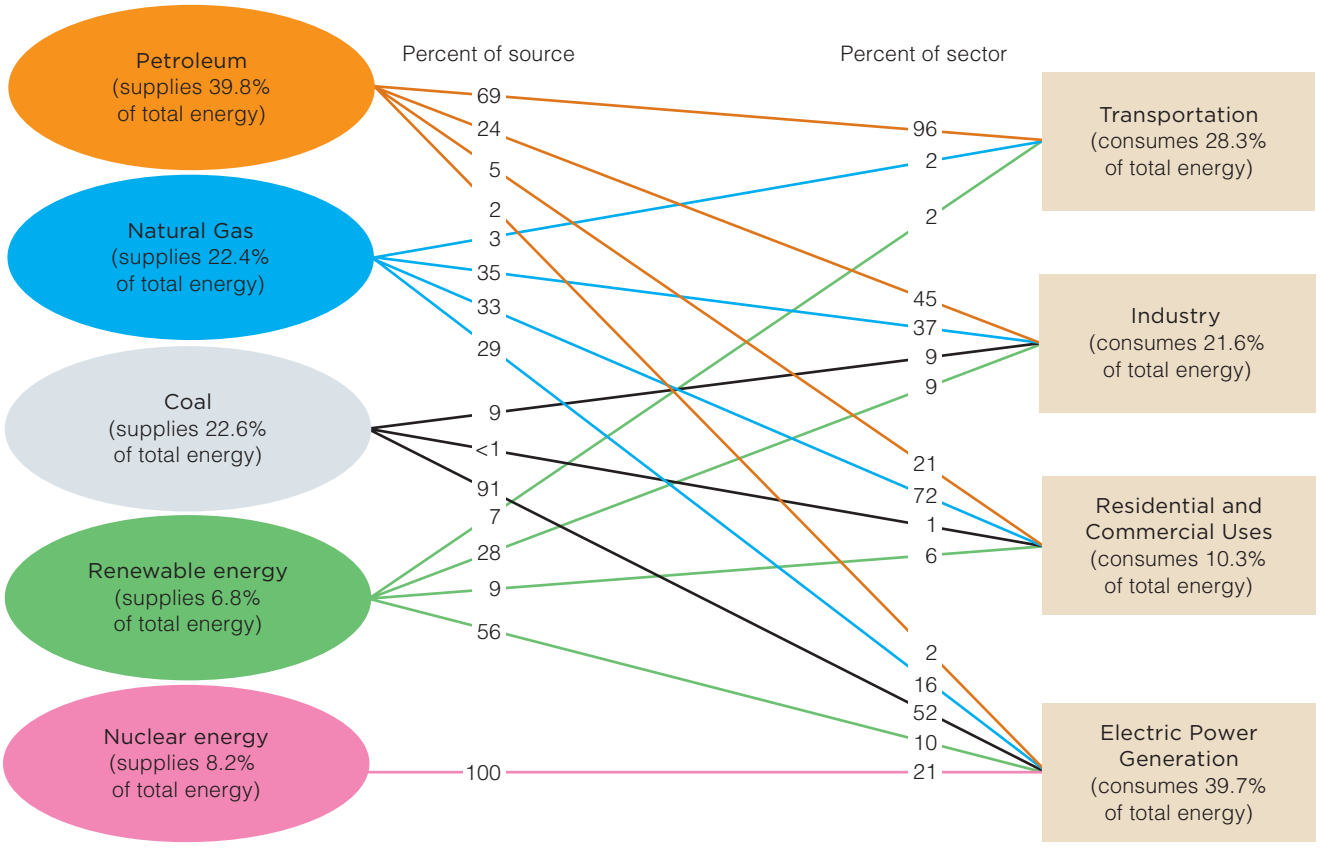


Figure 25.19 Currently, most of our energy comes from nonrenewable sources. This diagram links the sources of energy used in the United States in 2006 and different sectors of users. For example, petroleum supplies 96 percent of the transportation sector's energy needs, and this amounts to 69 percent of all the petroleum consumed in the United States.

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Figure 25.20 **Electricity-producing photovoltaic cells are placed in panels that collect sunlight, a renewable source of energy.**

Can "green" energy sources meet the need?

Fossil fuels are the main source of power for all forms of transportation. The search for environmentally acceptable alternatives has gone in several directions.

Today solar power produced by photovoltaic cells in panels such as those shown in Figure 25.20 is becoming a viable alternative in places where there is plenty of sunlight much of the year. Technological advances are bringing down the cost, but a homeowner who wants to install enough solar panels to supply all of a home's electricity often must spend tens of thousands of dollars.

Most automakers now sell hybrid vehicles that run on a combination of gasoline and electric power generated by batteries. There also has been much research aimed at developing all-electric vehicles and hydrogen fuel cells to power cars. So far, though, both are extremely expensive and impractical. Few electric-car "charging stations" exist, and the process for making hydrogen fuel cells generates high levels of greenhouse gases.

Another renewable option involves liquid **biofuels**—products such as *ethanol* and *biodiesel* made from plants and organic wastes. Unfortunately, growing most biofuel species (such as corn) and manufacturing and delivering the liquid fuel to consumers actually costs *more* in energy than it produces.

Hydropower from dams is a renewable energy source, but it too has drawbacks. For example, dams in rivers of the Pacific Northwest and California generate a great deal of electricity, but they also prevent endangered salmon from returning to streams above the dam to breed. As the salmon populations have suffered, so have endangered whales that feed on salmon in the ocean.

There are other alternatives, although none has yet proven itself for widespread use. In windy places, the mechanical energy of wind generates electricity as wind turns giant turbines (Figure 25.21). Analysts have estimated that a "wind power corridor" stretching from Texas north through South and North Dakota would generate enough electricity to meet the needs of 80 percent of the continental United States. Some people object to the turbines as eyesores and point out that the turbine blades kill birds.

What about nuclear power?

Today, nuclear power generates electricity at a relatively low cost. Increasing its use would decrease dependence on oil from the politically unstable Middle East. Also, nuclear power does not contribute to global warming, acid rain, or smog. So why hasn't there been a "nuclear power revolution"? Safety concerns are a major reason. For instance, there is always the potential for a meltdown if the reactor core becomes overheated. This happened at Chernobyl in Ukraine in 1986, when the reactor core melted through its concrete containment slab, contaminating groundwater and releasing potentially deadly radiation. Millions of people throughout Europe were exposed to dangerous levels of radioactive fallout and increased risk of certain cancers.

Radioactive wastes also are highly dangerous. Some must be isolated for 10,000 years or longer, and there is little agreement on the best way to store them. Debate swirled around the decision to store nuclear wastes generated in the United States in a remote area of Nevada.

In the final analysis, all commercially produced energy has some kind of negative environmental impact. Experts agree on one thing: The best way to minimize that impact is to use less energy.

Take-Home Message

What are the challenges for tapping renewable energy sources?

- Demand is increasing for safe, cost-effective, renewable energy alternatives. All of the technologies now available or being developed have drawbacks. Energy conservation is the best way to limit negative environmental impacts.

25.9 Endangered Species and the Loss of Biodiversity

- **Today human activities are a major cause of the rapid loss of other species.**

A major mass extinction is under way, and we humans are largely responsible for it. By one estimate our actions are leading to the premature extinction of six species an hour! At present the major culprits are destruction of wildlife habitats and the overexploitation of wild species for food or profit.

Habitat loss pushes species to the brink

The underlying causes of today's rapid pace of species extinctions are human population growth and economic policies that promote unsustainable exploitation. As our population grows, we clear, occupy, and damage more land to supply food, fuel, timber, and other resources (Figure 25.22*a*). In some regions, the combination of rapid population growth and poverty pushes the poor to cut forests, grow crops on marginal land, overgraze grasslands, and poach endangered animals (Figure 25.22*b*).

Globally, tropical deforestation is the greatest killer of species. The loss of plant species is extremely important because most animals depend directly or indirectly on plants for food, and often for shelter as well. We humans also have traditionally depended on plants as sources of medicines. For example, we get two anticancer drugs from a tropical plant called the rosy periwinkle. Unfortunately, most of its native forest habitat on the island of Madagascar has been cleared away to make room for human enterprises. Climate change also has begun affecting species such as the polar bear, which recently was listed as endangered by the U.S. Environmental Protection Agency (Figure 25.23). No giant asteroids have hit Earth for 65 million years. Yet a major extinction event is under way. Throughout the world, human activities are swiftly driving many species to extinction. An **endangered species** is an endemic species extremely vulnerable to extinction. *Endemic* means it originated in only one geographic region and lives nowhere else.

In the United States we are destroying the habitats of wild species at a dizzying pace. For instance, we have logged more than 90 percent of old-growth forests and drained half the wetlands, which filter human water supplies and provide homes for waterfowl and juvenile fishes. Hundreds of native species in these areas have gone extinct and dozens more are endangered.

Marine resources are being overharvested

People have been looking to the seas as a major source of food for the expanding human population, but there, too, little attention has been given to sustainable use of marine resources. One recent study estimated that the annual catch of nearly 30 percent of marine fish and shellfish is now less than 10 percent of the recorded maximum. The threatened species include Atlantic cod, black sea bass, and several species of shark (Figure 25.24).

Figure 25.22 Habitat loss and overexploitation of wildlife is a major threat to the survival of many species. (**a**) Cities displace wild species and require huge amounts of resources to sustain the people who live in them. (**b**) Confiscated products made from endangered species. It's estimated that 90 percent of the illegal wildlife trade, which threatens hundreds of species of animals and plants, goes undetected.

Figure 25.23 Melting Arctic ice has put polar bears at risk. These polar bears are checking out a U.S. Navy submarine in the Arctic Ocean. The bears hunt from ice shelves and floes, but the ice appears to be melting rapidly due to climate change.

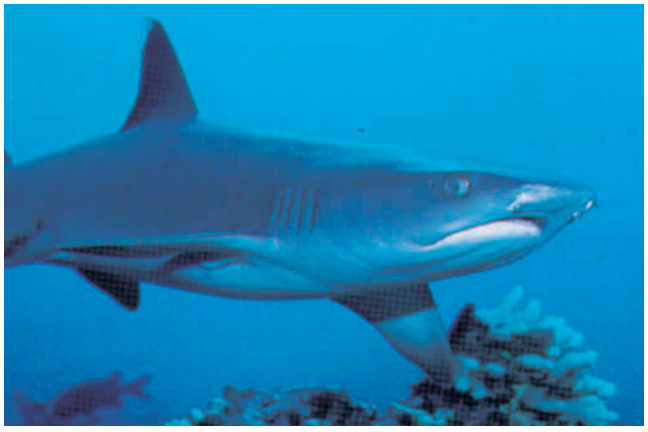


Figure 25.24 Worldwide, sharks are among the animals increasingly at risk of overexploitation by human enterprises.

The principle of sustainability is the answer

We humans are the dominant species on our planet, but many people have begun to wonder how long that will be the case. As you have read in this chapter, by our sheer numbers and many of our activities we have disturbed many, if not virtually all, ecosystems on the planet. That course cannot continue for much longer. Fortunately, governments and individuals are beginning to embrace the **principle of sustainability**. This principle is simple: By controlling our population growth, using resources wisely, embracing renewable energy sources, and protecting the wild places where other species live, we will be taking steps that help ensure our own survival as well.

Take-Home Message

What are major threats to biodiversity?

- Human population growth and resource overuse have led to widespread destruction of the habitats where many other species live. As a result, species are rapidly going extinct.
- A shift to the principle of sustainability is vital if our species is to thrive and survive.

25.10 Biological Magnification

Wildlife can be harmed and even driven to extinction by the process called **biological magnification**. This term refers to an increase in concentration of a nondegradable (or slowly degradable) substance in organisms as it is passed upward through food chains.

An example is the peregrine falcon, which nearly went extinct as a result of biological magnification of DDT. This synthetic pesticide was first used in the tropics during World War II to kill mosquitos that carried malaria. Later in Europe it helped control body lice that were transmitting a bacterium that causes typhus. After the war, it seemed like a good idea to use DDT against agricultural, garden, or forest pests.

DDT can build up in the tissues of animals that come into contact with it in the air, water, or food. After the war, it began to move through the global environment, infiltrate food webs, and affect organisms in ways that no one had predicted. In cities where DDT was sprayed to control Dutch elm disease, songbirds started dying. In streams flowing through forests where DDT was sprayed to control spruce budworms, salmon started dying. In croplands sprayed to control one kind of pest, new kinds of pests moved in. DDT was killing off natural predators that had been keeping pest populations in check.

Much later, side effects of biological magnification started showing up far from the areas where DDT was applied. Most devastated were species at the top of food chains, including bald eagles, brown pelicans, ospreys, and peregrine falcons (*above*). These predators fell prey to a product of DDT breakdown that interferes with physiological processes. The birds produced eggs with thin, brittle shells—and many of the chick embryos didn't survive to hatching time. Some species, including the peregrine falcon, were facing extinction.

DDT now has been banned in the United States for decades, except for limited applications where public health is endangered. Populations of peregrine falcons and other birds have begun to recover. Even today, however, some birds lay thin-shelled eggs. They pick up DDT at their winter ranges in Latin America, where DDT is still widely used. As recently as 1990, the California State Department of Health closed a fishery off Los Angeles because DDT from industrial waste discharges that ended 25 years before were still contaminating that ecosystem.

IMPACTS, ISSUES

So Long, Blue Bayou

IN COMMUNITIES historically threatened by storms such as hurricanes and now by rising sea level as well, property owners benefit from federal programs that restore valuable beachfront and provide low-cost flood insurance. Critics say that homes should no longer be built in the most vulnerable areas, and that taxpayers should not have to bear the home repair costs of people who choose to live there.

How Would You Vote?

Would you support a ban on federal flood insurance and taxpayer-funded beach restoration in areas that are most vulnerable to sea level rise and hurricanes? See CengageNOW for details, then vote online.

Summary

Section 25.1 Recent, rapid growth of the human population has been due mainly to advances in agriculture, industrialization, sanitation, and health care. Differences in growth among countries correlate partly with levels of economic development and partly with demographics such as population density and age structure. Populations of countries with a large reproductive base generally grow the fastest.

- Use the animation and interaction on CengageNOW to learn how to estimate population size, and observe patterns of logistic and exponential growth.

Section 25.2 Carrying capacity is the number of individuals of a species that can be sustained long-term by the available resources in an area.

Populations initially show logistic growth—rapid growth that levels off when carrying capacity is reached. Carrying capacity, competition, and other factors limit population growth. Density-dependent controls on growth include competition for resources, disease, and predation.

Section 25.3 An ecological footprint is the sum total of resources used by a population or person, together with the resulting wastes. If renewable resources are replenished they may be available indefinitely. Nonrenewable resources (such as fossil fuels) can't be readily replenished.

A pollutant is a substance that harms the health, activities, or survival of a population.

Sections 25.4–25.9 Exponential growth of the human population has brought increased pollution and demands for energy, water, food, and waste disposal sites.

Air pollutants are present in industrial and photochemical smog and acid rain. Widespread deforestation is associated with leaching of soil nutrients, erosion, and possible disruption of the global carbon cycle.

Fossil fuels are nonrenewable and are major sources of air pollution. To meet the increasing demand for energy, conservation and the development of alternative, renewable energy sources will be crucial.

Human population growth and related activities also are contributing to the rapid loss of other species.

Review Questions

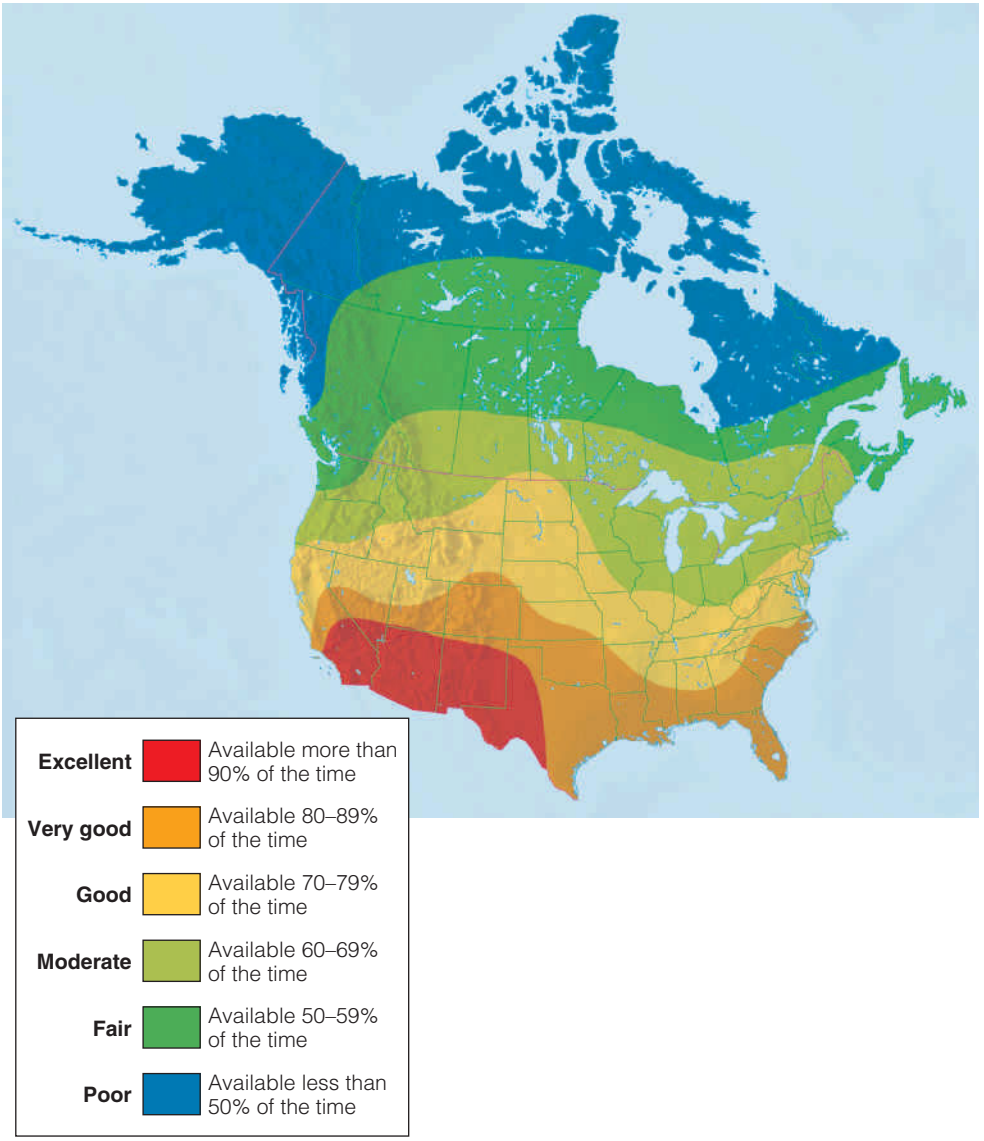
1. Describe at least two ways that human activities are altering air quality.
2. Explain the difference between global warming and global climate change.
3. Describe the greenhouse effect. Make a list of twenty agricultural and other products that you depend on. Are any implicated in global warming?
4. What is deforestation, and how does large-scale deforestion damage an ecosystem?

Self-Quiz *Answers in Appendix V*

1. The number of individuals that can be sustained indefinitely by the resources in a given region is the _____.
   a. biotic potential
   b. carrying capacity
   c. environmental resistance
   d. density-dependent control
2. _____ shields organisms against the sun's UV wavelengths.
   a. A thermal inversion
   b. Acid rain
   c. The ozone layer
   d. The greenhouse effect
3. Acid rain is one outcome of _____.
   a. coal burning
   b. gas and oil burning
   c. some industrial processes
   d. all of the above
4. Greenhouse gases _____.
   a. slow the escape of heat from Earth into space
   b. are produced by natural and human activities
   c. are at higher levels than they were 100 years ago
   d. all of the above
5. All the following are renewable energy sources except _____.
   a. hydropower
   b. wind
   c. natural gas
   d. solar energy
6. Earth's biodiversity is threatened mainly by _____.
   a. the spread of disease organisms due to climate change
   b. habitat destruction by human activities
   c. disasters such as wildfires and hurricanes
   d. water pollution
   e. all of the above

Critical Thinking

1. The map (right) shows the availability of direct solar energy in the United States and Canada. Some areas are good candidates for solar heating systems and use of solar cells to produce electricity (see legend). What is the potential for making more use of solar energy where you live?
2. Some researchers and policymakers are proposing that we should protect entire ecosystems, such as forests, rather than just endangered species. Opponents say that this approach might endanger property values. Would you favor setting aside large tracts of land for restoration? Or would you consider such efforts too intrusive on individual rights of property ownership?
3. Some people have proposed that all nuclear power plants in the United States be phased out over the next 20 years. Explain why you agree or disagree with this idea.



EXPLORE ON YOUR OWN

Section 25.3 discussed the ecological footprint concept—the total resources a population consumes and the resulting wastes that are returned to the environment. You may also have heard about the personal "carbon footprint" we each have with respect to climate change. The idea is that each of us does things that produce lots of carbon dioxide emissions, such as driving a car or taking a plane to a vacation spot.

Many websites provide information on assessing one's carbon footprint and offer suggestions for reducing it. Do some online research to learn more about this concept and then list at least five things you think you could realistically do to reduce yours.

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APPENDIX I

CONCEPTS IN CELL METABOLISM

The Nature and Uses of Energy

Any time an object is not moving, it has a store of **potential energy**—a capacity to do work, simply owing to its position in space and the arrangement of its parts. If a stationary runner springs into action, some of the runner's potential energy is transformed into **kinetic energy**, the energy of motion.

Energy on the move does work when it imparts motion to other things—for example, when you throw a ball. In skeletal muscle cells in your arm, the energy currency ATP (adenosine triphosphate, Section 3.13) gave up some of its potential energy to molecules of contractile units and set them in motion. The combined motions in many muscle cells resulted in the movement of whole muscles. The transfer of energy from ATP also resulted in the release of another form of kinetic energy called **heat**, or *thermal energy*.

The potential energy of molecules is called **chemical energy** and is measured as kilocalories. A **kilocalorie** is the amount of energy it takes to heat 1,000 grams of water from 14.5°C to 15.5°C at standard pressure.

As noted in Chapter 3, cells use energy for chemical work, to stockpile, build, rearrange, and break apart substances. They channel it into *mechanical work*—to move cell structures and the whole body or parts of it. They also channel it into *electrochemical work*—to move charged substances into or out of the cytoplasm or an organelle compartment.

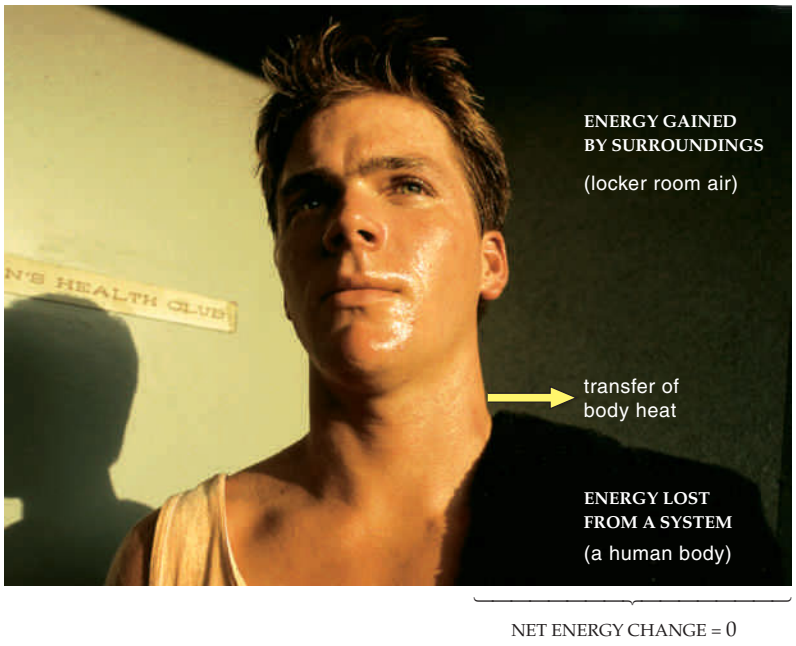


Figure A-1

Laws of Thermodynamics

We cannot create energy from scratch; we must first get it from someplace else. Why? According to the **first law of thermodynamics**, the total amount of energy in the universe remains constant. More energy cannot be created; existing energy cannot vanish or be destroyed. It can only be converted from one form to some other form. For instance, when you eat, your cells extract energy from food and convert it to other forms, such as kinetic energy for moving about.

With each metabolic conversion, some of the energy escapes to your surroundings, as heat. Even when you "do nothing," your body gives off about as much heat as a 100-watt lightbulb because of conversions in your cells. The energy being released is transferred to atoms and molecules that make up the air, and in this way it heats up the surroundings, as shown in Figure A-1. In general, the body cannot recapture energy lost as heat, but the energy still exists in the environment outside the body. Overall, there is a one-way flow of energy in the universe.

The human body obtains its energy mainly from the covalent bonds in organic compounds, such as glucose and glycogen. When the compounds enter metabolic reactions, specific bonds break or are rearranged. For example, your cells release usable energy from glucose by breaking all of its covalent bonds. After many steps, six molecules of carbon dioxide and six of water remain. Compared with glucose, these leftovers have more stable arrangements of atoms, but chemical energy in their bonds is much less. Why? Some energy was lost at each breakdown step leading to their formation. This is why

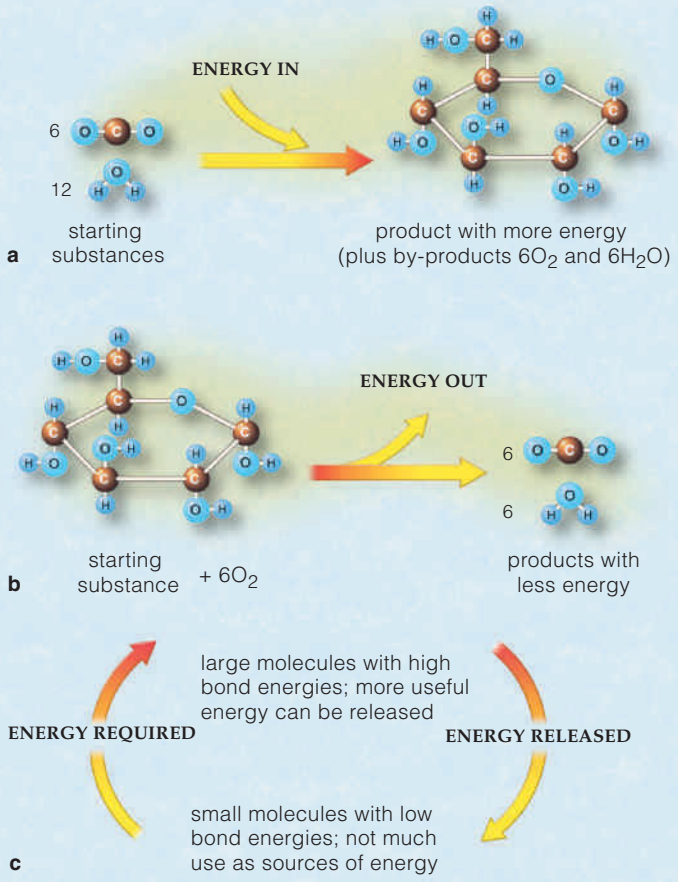


Figure A-2

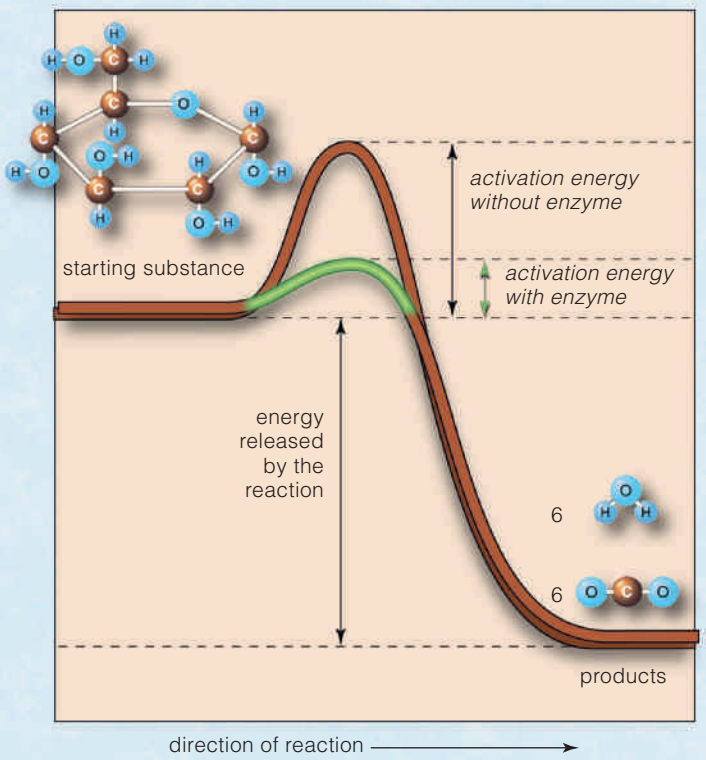


Figure A-3

glucose is a much better source of usable energy than, for example, water is.

As the molecular events just described take place, some heat is lost to the surroundings and cannot be recaptured. Said another way, no energy conversion can ever be 100 percent efficient. Therefore, the total amount of energy in the universe is spontaneously flowing from forms rich in energy (such as glucose) to forms having less and less of it. This is the main point of the **second law of thermodynamics**.

Examples of Energy Changes

When cells convert one form of energy to another, there is a change in the amount of potential energy that is available to them. Cells of photosynthetic organisms, notably green plants, convert energy in sunlight into chemical energy, which is stored in the bonds of organic compounds. The outcome is a net increase in energy in the product molecule (such as glucose), as diagrammed in Figure A-2*a*. A reaction in which there is a net increase in energy in the product compound is an **endergonic reaction** (meaning energy in). By contrast, reactions in cells that break down glucose (or another energy-rich compound) release energy. They are called **exergonic reactions** (meaning energy out).

The Role of Enzymes in Metabolic Reactions

The catalytic molecules called **enzymes** are crucial actors in metabolism. To better understand why, it helps to begin with the idea that in cells, molecules or ions of substances are always moving at random. As a result of this random motion, they are constantly colliding. Metabolic reactions may take place when participating molecules collide—but only *if* the energy associated with the collisions is great enough. This minimum amount of energy required for a chemical reaction is called **activation energy**. Activation energy is a barrier that must be surmounted one way or another before a reaction can proceed.

Nearly all metabolic reactions are reversible. That is, they can run "forward," from starting substances to products, or in "reverse," from a product back to starting substances. Which way such a reaction runs depends partly on the ratio of reactant to product. When there is a high concentration of reactant molecules, the reaction is likely to run strongly in the forward direction. On the other hand, when the product concentration is high enough, more molecules or ions of the product are available to revert spontaneously to reactants. Any reversible reaction tends to run spontaneously toward **chemical equilibrium**—the point at which it will be running at about the same pace in both directions.

As just described, before reactants enter a metabolic reaction they must be activated by an energy input; only then will the steps leading to products proceed. And while random collisions *might* provide the energy for reactions, our survival depends on thousands of reactions taking place with amazing speed and precision. This is the key function of enzymes, for *enzymes lower the activation energy barrier* (Figure A-3). As Section 3.13 described, substrates and enzymes interact at the enzyme's active site. According to the **induced fit model**, a surface region of each substrate has chemical groups that are almost but not quite complementary to chemical groups in an active site. However, as substrates settle into the site, the contact strains some of their bonds, making them easier to break. There also are interactions among charged or polar groups that prime substrates for conversion to an activated state. With these changes, substrates fit precisely in the enzyme's active site. They now are in an activated state, in which they will react spontaneously.

Glycolysis: The First Stage of the Energy-Releasing Pathway

Energy that is converted into the chemical bond energy of adenosine triphosphate—ATP—fuels cell activities. Cells make ATP by breaking down carbohydrates (mainly glucose), fats, and proteins. During the breakdown reactions, electrons are stripped from intermediates, then energy associated with the liberated electrons drives the formation of ATP.

Recall that cells rely mainly on **aerobic respiration**, an oxygen-dependent pathway of ATP formation. The main energy-releasing pathways of aerobic respiration all start with the same reactions in the cytoplasm. During this initial stage of reactions, called **glycolysis**, enzymes break apart and rearrange a glucose molecule into two molecules of pyruvate, which has a backbone of three carbon atoms. Following up on the discussion in Section 3.14, here you can track in a bit more detail on what happens to a glucose molecule in the first stage of aerobic respiration.

Glucose is one of the simple sugars. Each molecule of glucose contains six carbon, twelve hydrogen, and six oxygen atoms, all joined by covalent bonds (Figure A-4). The carbons make up the backbone. With glycolysis, glucose or some other carbohydrate in the cytoplasm is partially broken down, the result being two molecules of the three-carbon compound pyruvate:

glucose → glucose-6-phosphate → 2 pyruvate

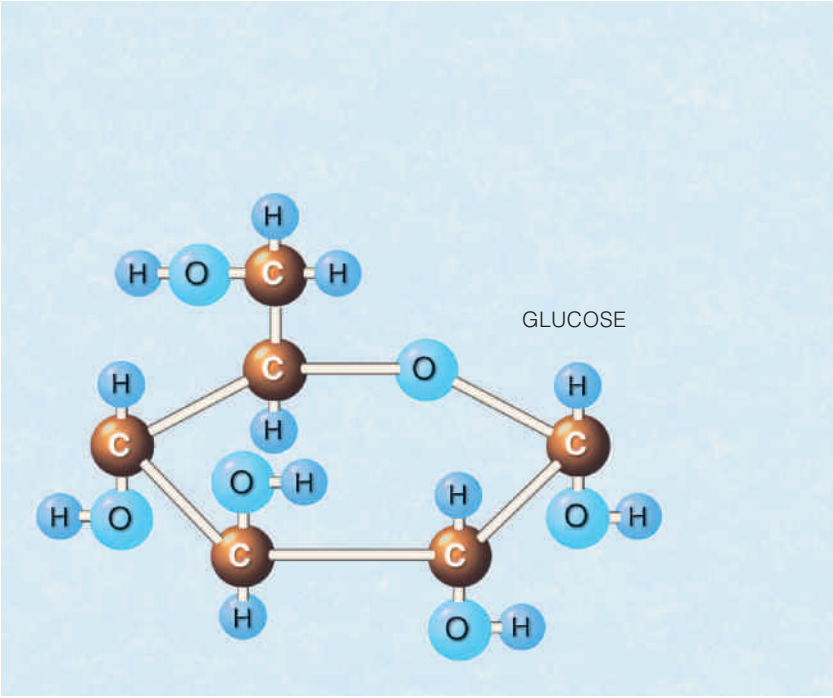


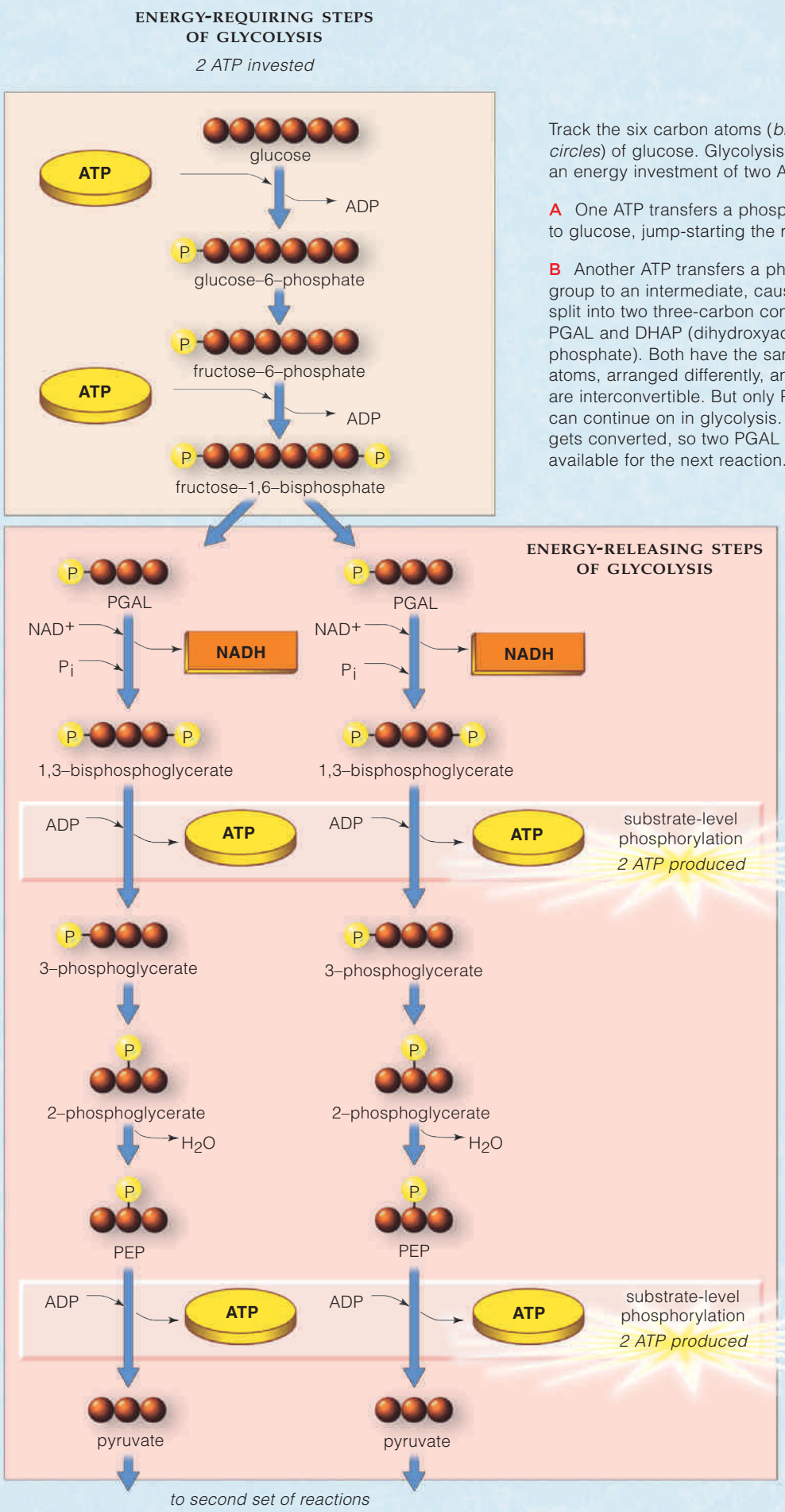
Figure A-4

The first steps of glycolysis require energy. As diagrammed in Figure A-5 on page A-4, they advance only when two ATP molecules each transfer a phosphate group to glucose and so donate energy to it. Such transfers, recall, are phosphorylations. In this case, they raise the energy content of glucose to a level that is high enough to allow the *energy-releasing* steps of glycolysis to begin.

The first energy-releasing step breaks the activated glucose into two molecules. Each of these molecules is called PGAL (phosphoglyceraldehyde). Next, each PGAL is converted to an unstable intermediate that allows ATP to form by giving up a phosphate group to ADP. The next intermediate in the sequence does the same thing. Thus, a total of four ATP form by **substrate-level phosphorylation**. This metabolic event is the direct transfer of a phosphate group from a substrate of a reaction to some other molecule—in this case, ADP. Remember, though, two ATP were invested to jump-start the reactions. So the *net* energy yield is only two ATP.

Meanwhile, the coenzyme NAD^+ picks up electrons and hydrogen atoms liberated from each PGAL, thus becoming NADH. When the NADH gives up its cargo at a different reaction site, it reverts to NAD^+. Said another way, like other coenzymes NAD^+ is reusable.

In sum, glycolysis converts energy stored in glucose to a transportable form of energy, in ATP. NAD^+ picks up electrons and hydrogen that are removed from each glucose molecule. The electrons and hydrogen have roles in the next stage of reactions. So do the end products of glycolysis—the two molecules of pyruvate.



Track the six carbon atoms (*brown circles*) of glucose. Glycolysis requires an energy investment of two ATP:

A One ATP transfers a phosphate group to glucose, jump-starting the reactions.

B Another ATP transfers a phosphate group to an intermediate, causing it to split into two three-carbon compounds: PGAL and DHAP (dihydroxyacetone phosphate). Both have the same atoms, arranged differently, and they are interconvertible. But only PGAL can continue on in glycolysis. DHAP gets converted, so two PGAL are available for the next reaction.

C Two NADH form when each PGAL gives up two electrons and a hydrogen atom to NAD^+.

D Two intermediates each transfer a phosphate group to ADP. *Thus, two ATP have formed by direct phosphate group transfers.* The original energy investment of two ATP is now paid off.

E Two more intermediates form. Each gives up one hydrogen atom and an —OH group. These combine as water. Two molecules called PEP form by these reactions.

F Each PEP transfers a phosphate group to ADP. *Once again, two ATP have formed by substrate-level phosphorylation.*

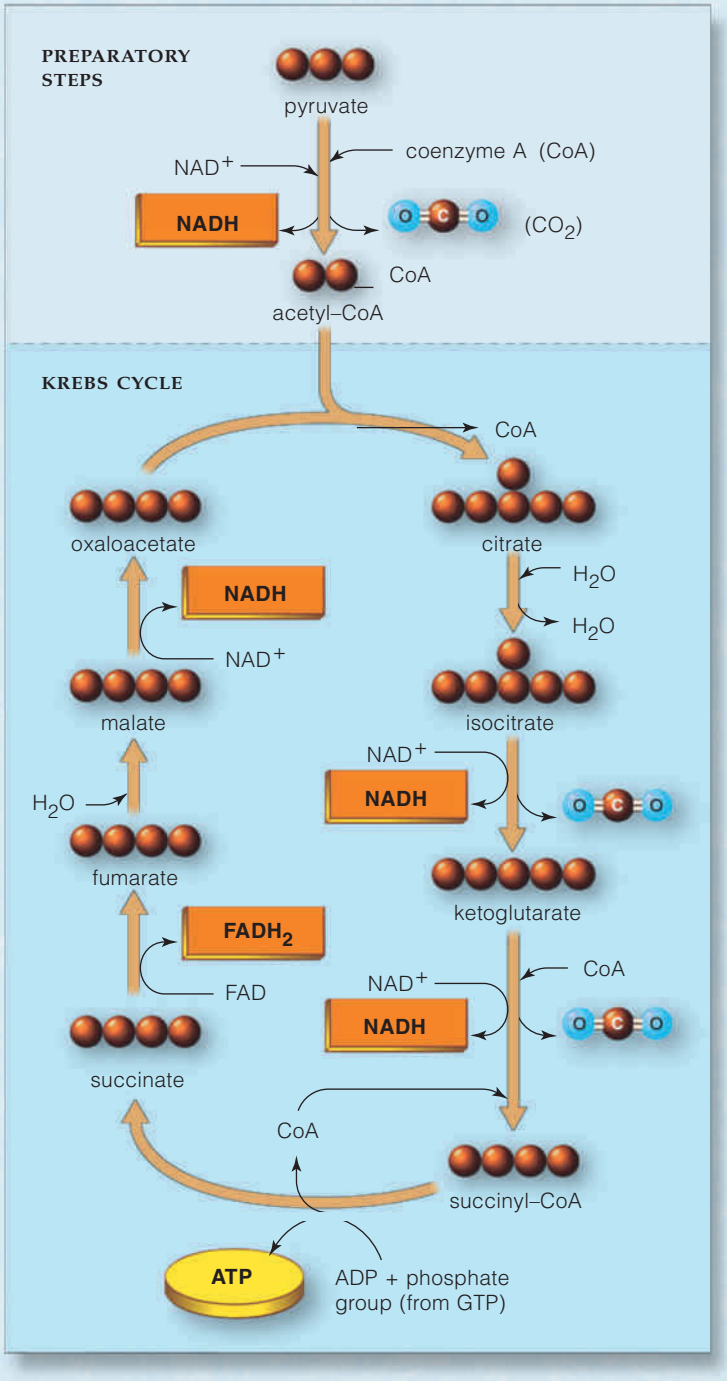
In sum, glycolysis has a net energy yield of two ATP for each glucose molecule. Two NADH also form during the reactions, and two molecules of pyruvate are the end products.

Figure A-5 Glycolysis, first stage of the main energy-releasing pathways. The reaction steps proceed inside the cytoplasm of every living prokaryotic and eukaryotic cell. In this example, glucose is the starting material. By the time the reactions end, two pyruvate, two NADH, and four ATP have been produced. Cells invest two ATP to start glycolysis, however, so the net energy yield of glycolysis is two ATP.

Depending on the type of cell and on environmental conditions, the pyruvate may enter the second set of reactions of the aerobic pathway, which includes the Krebs cycle. Or it may be used in other reactions, such as a fermentation pathway.

Second Stage of the Aerobic Pathway

When pyruvate molecules formed by glycolysis leave the cytoplasm and enter a mitochondrion, the scene is set for both the second and the third stages of the aerobic pathway. Figure A-6 diagrams these steps in detail.



A Pyruvate from glucose enters a mitochondrion. It undergoes initial conversions before entering cyclic reactions (the Krebs cycle).

B Pyruvate is stripped of a carboxyl group (COO^-), which departs as CO_2. It also gives up hydrogen and electrons to NAD^+, forming NADH. Then a coenzyme joins with the remaining two-carbon fragment, forming acetyl–CoA.

C The acetyl–CoA transfers its two-carbon group to oxaloacetate, a four-carbon compound that is the entry point into the Krebs cycle. The result is citrate, with a six-carbon backbone. Addition and then removal of H_2O changes citrate to isocitrate.

D Isocitrate enters conversion reactions, and a COO^- group departs (as CO_2). Hydrogen and electrons are transferred to NAD^+, forming NADH.

E Another COO^- group leaves (as CO_2) and another NADH forms. The resulting intermediate attaches to a coenzyme A molecule, forming succinyl–CoA. *At this point, three carbon atoms have been released, balancing out the three that entered the mitochondrion (in pyruvate).*

F Now the attached coenzyme is replaced by a phosphate group (donated by the substrate GTP). That phosphate group becomes attached to ADP. Thus, for each turn of the cycle, one ATP forms by substrate-level phosphorylation.

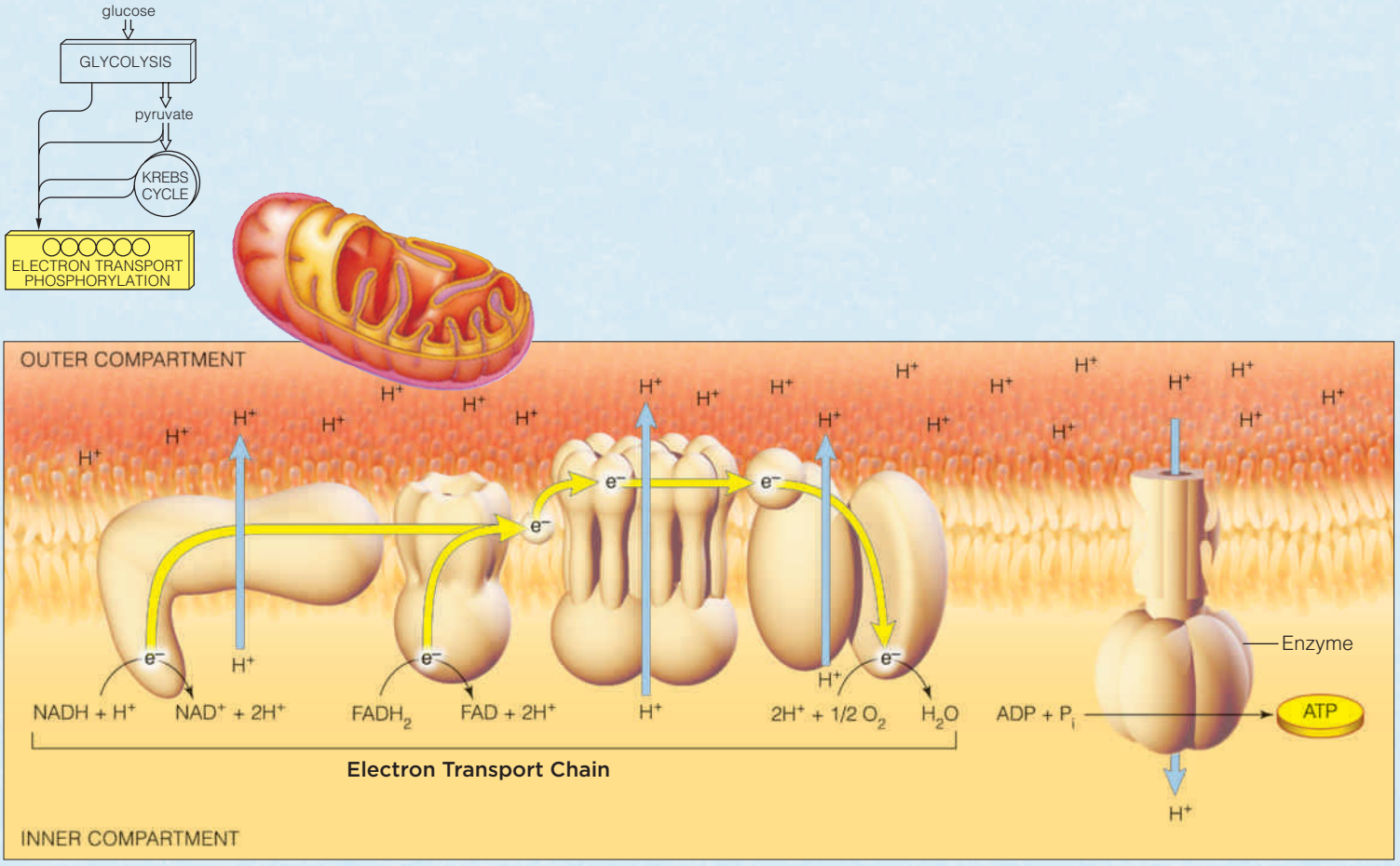
G Electrons and hydrogen are transferred to FAD, forming $FADH_2$.

H In the final conversion reactions, the oxaloacetate is regenerated, and hydrogen and electrons are transferred to NAD^+, forming NADH.

Figure A-6 Second stage of aerobic respiration: the Krebs cycle and reaction steps that precede it. For each three-carbon pyruvate molecule entering the cycle, three CO_2, one ATP, four NADH, and one $FADH_2$ molecules form. The steps shown proceed *twice*, because each glucose molecule was broken down earlier to *two* pyruvate molecules.

Third Stage of Aerobic Cellular Respiration

Most ATP is produced in the third stage of the aerobic pathway. Electron transport systems and neighboring proteins called ATP synthases serve as the production machinery. They are embedded in the inner membrane that divides the mitochondrion into two compartments (Figure A-7). They interact with electrons and H^+ ions, which coenzymes deliver from reaction sites of the first two stages of the aerobic pathway.



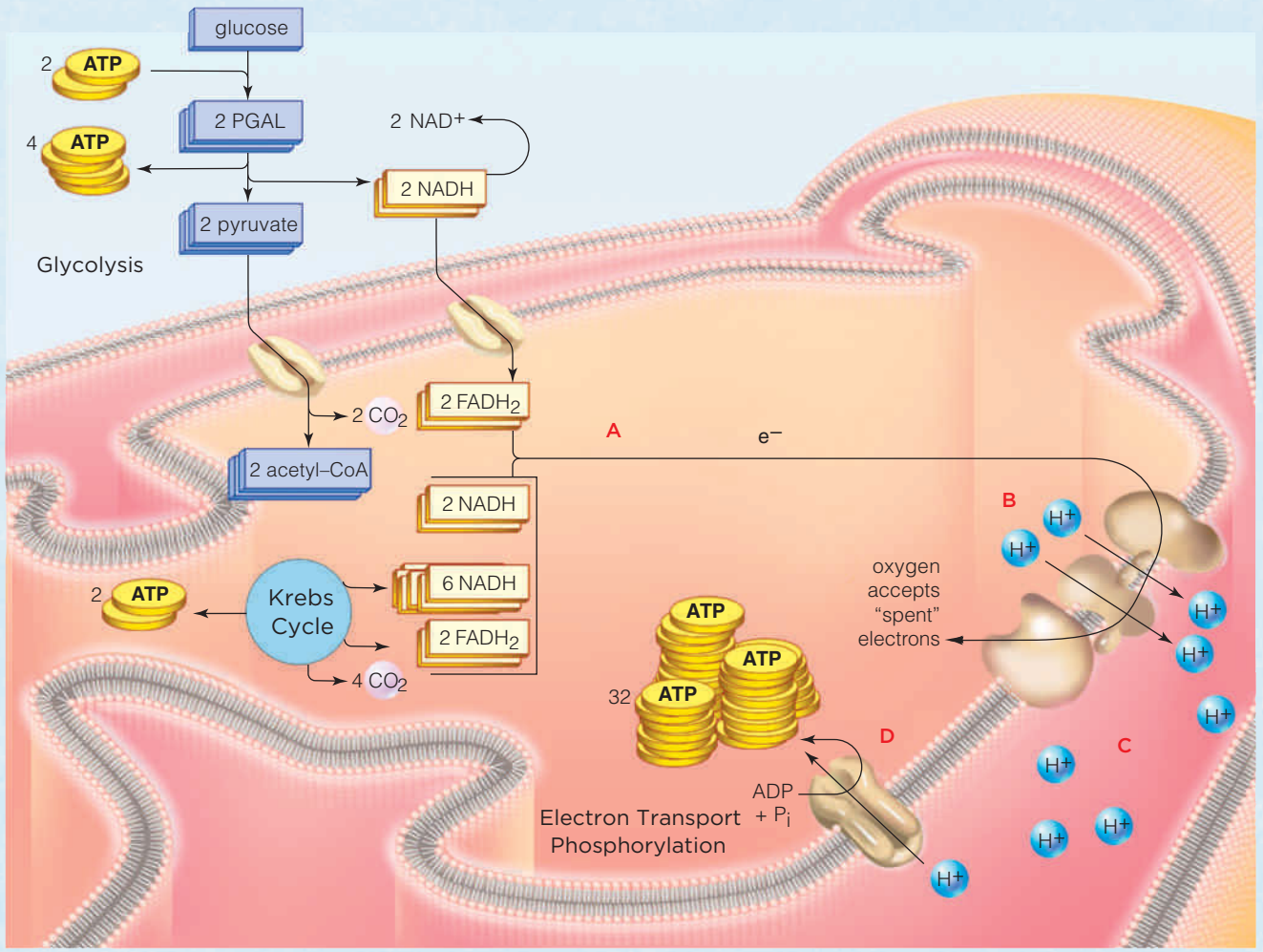
A At the inner mitochondrial membrane, NADH and $FADH_2$ give up electrons to transport chains. When electrons are moved through the chains, unbound hydrogen (H^+) is shuttled across the membrane to the outer compartment.

B Oxygen is the final acceptor of electrons at the end of the transfer chain.

C H^+ concentration and electric gradients now exist across the membrane. H^+ follows the gradients through the interior of enzymes, to the inner compartment. The flow drives the formation of ATP from ADP and phosphate (P_i).

Figure A-7 Electron transfer phosphorylation, the third and final stage of aerobic respiration.

Summary of Glycolysis and Aerobic Cellular Respiration



A Electrons and hydrogen from NADH and $FADH_2$ that formed during the first and second stages enter electron transport chains.

B As electrons are being transferred through these chains, H^+ ions are shuttled across the inner membrane, into the outer compartment.

C More H^+ accumulates in the outer compartment than in the inner one. Chemical and electric gradients have been established across the inner membrane.

D Hydrogen ions follow the gradients through the interior of enzymes, driving ATP formation from ADP and phosphate (P_i).

Figure A-8 Summary of the harvest from the energy-releasing pathway of aerobic respiration. Commonly, thirty-six ATP form for each glucose molecule that enters the pathway. But the net yield varies according to shifting concentrations of reactants, intermediates, and end products of the reactions. It also varies among different types of cells.

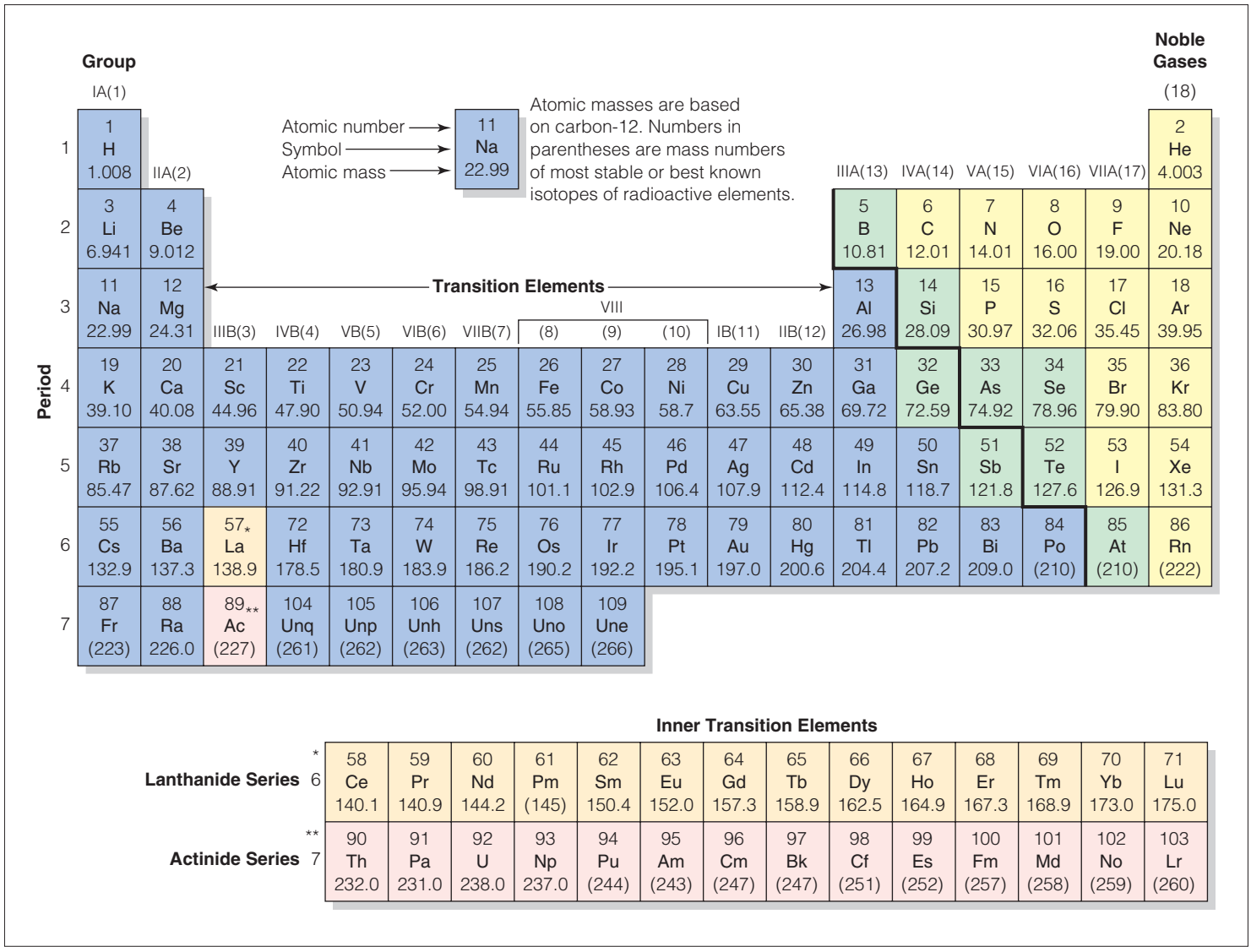
Cells differ in how they use the NADH from glycolysis, which cannot enter mitochondria. At the outer mitochondrial membrane, these NADH give up electrons and hydrogen to transport proteins, which shuttle the electrons and hydrogen across the membrane. NAD^+ or FAD already inside the mitochondrion accept them, thus forming NADH or $FADH_2$.

Any NADH inside the mitochondrion delivers electrons to the highest possible entry point into a transport system. When it does, enough H^+ is pumped across the inner membrane to make three ATP. By contrast, any $FADH_2$ delivers them to a lower entry point. Fewer hydrogen ions can be pumped, so only *two* ATP can form.

In liver, heart, and kidney cells, for example, electrons and hydrogen from glycolysis enter the highest entry point of transport systems, so the energy harvest is thirty-eight ATP. More commonly, as in skeletal muscle and brain cells, they are transferred to FAD—so the harvest is thirty-six ATP.

APPENDIX II

PERIODIC TABLE OF THE ELEMENTS



Period	IA(1)	IIA(2)	IIIB(3)	IVB(4)	VB(5)	VIB(6)	VIIB(7)	VIII (8)	VIII (9)	VIII (10)	IB(11)	IIB(12)	IIIA(13)	IVA(14)	VA(15)	VIA(16)	VIIA(17)	(18)
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.7	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57* La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.0	89** Ac (227)	104 Unq (261)	105 Unp (262)	106 Unh (263)	107 Uns (262)	108 Uno (265)	109 Une (266)									

Lanthanide Series * 6	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
Actinide Series ** 7	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np 237.0	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

APPENDIX III

UNITS OF MEASURE

Metric-English Conversions

Length

English		*Metric*
inch	=	2.54 centimeters
foot	=	0.30 meter
yard	=	0.91 meter
mile (5,280 feet)	=	1.61 kilometer

To convert	*multiply by*	*to obtain*
inches	2.54	centimeters
foot	30.00	centimeters
centimeters	0.39	inches
millimeters	0.039	inches

Weight

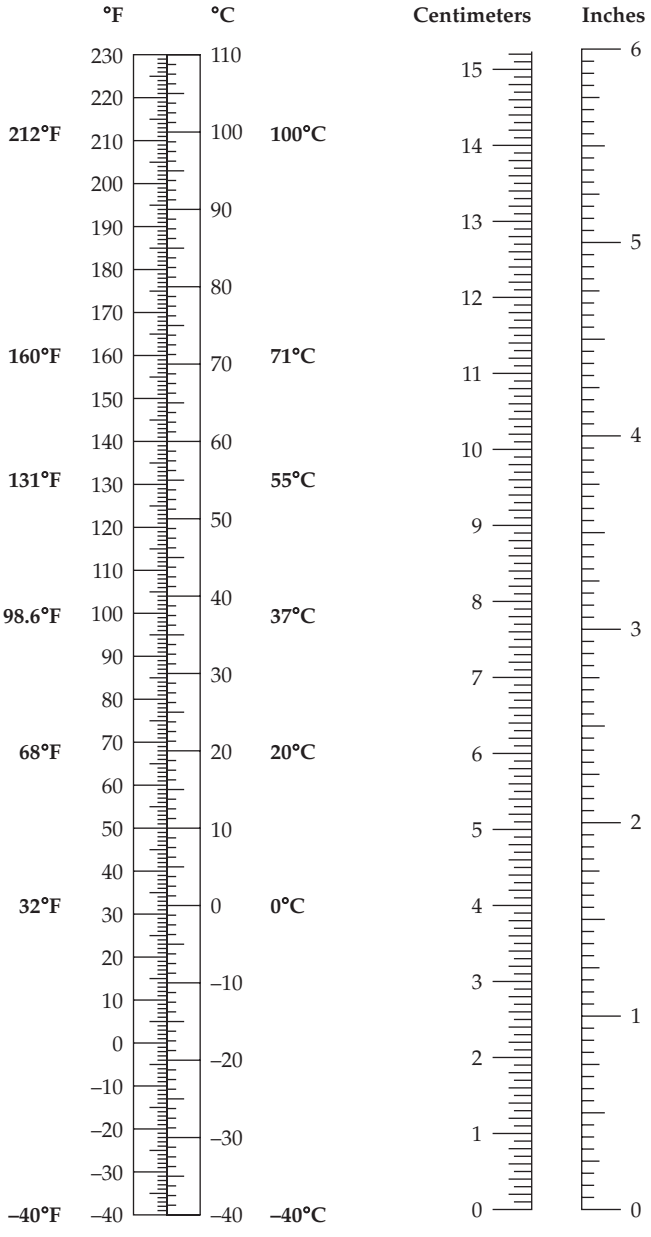
English		*Metric*
grain	=	64.80 milligrams
ounce	=	28.35 grams
pound	=	453.60 grams
ton (short) (2,000 pounds)	=	0.91 metric ton

To convert	*multiply by*	*to obtain*
ounces	28.3	grams
pounds	453.6	grams
pounds	0.45	kilograms
grams	0.035	ounces
kilograms	2.2	pounds

Volume

English		*Metric*
cubic inch	=	16.39 cubic centimeters
cubic foot	=	0.03 cubic meter
cubic yard	=	0.765 cubic meters
ounce	=	0.03 liter
pint	=	0.47 liter
quart	=	0.95 liter
gallon	=	3.79 liters

To convert	*multiply by*	*to obtain*
fluid ounces	30.00	milliliters
quart	0.95	liters
milliliters	0.03	fluid ounces
liters	1.06	quarts



To convert temperature scales:

Fahrenheit to Celsius: $°C = 5/9(°F - 32)$

Celsius to Fahrenheit: $°F = 9/5(°C + 32)$

APPENDIX IV

ANSWERS TO GENETICS PROBLEMS

CHAPTER 19

1. a: *AB*
   b: *AB* and *aB*
   c: *Ab* and *ab*
   d: *AB, aB, Ab,* and *ab*

2. a: *AaBB* will occur in all the offspring.
   b: 25% *AABB*; 25% *AaBB*; 25% *AABb*; 25% *AaBb*
   c: 25% *AaBb*; 25% *Aabb*; 25% *aaBb*; 25% *aabb*
   d: 1/16 *AABB* (6.25%)
   1/8 *AaBB* (12.5%)
   1/16 *aaBB* (6.25%)
   1/8 *AABb* (12.5%)
   1/4 *AaBb* (25%)
   1/8 *aaBb* (12.5%)
   1/16 *AAbb* (6.25%)
   1/8 *Aabb* (12.5%)
   1/16 *aabb* (6.25%)

3. a: Mother must be heterozygous for both genes; father is homozygous recessive for both genes. The first child is also homozygous recessive for both genes.
   b: The probability that the second child will not be able to roll the tongue and will have detached earlobes is 1/4 (25%).

4. a: ABC
   b: ABc, aBc
   c: ABC, ABc, aBC, aBc
   d: ABC, ABc, AbC, Abc, aBC, aBc, abC, abc

5. Because Molly does not exhibit the recessive hip disorder, she must be either homozygous dominant (HH) for this trait, or heterozygous (Hh). If the father is homozygous dominant (HH), then he and Molly cannot produce offspring that are homozygous recessive (hh), and so none of their offspring will have the undesirable phenotype. However, if Molly is a heterozygote for the trait, notice that the probability is 1/2 (50%) that a puppy will be heterozygous (Hh) and so carry the trait.

6. a: The mother must be heterozygous (I^Ai). The man having type B blood could have fathered the child if he were also heterozygous (I^Bi).
   b: If the man is heterozygous, then he *could be* the father. However, because any other type B heterozygous male could also be the father, one cannot say that this particular man absolutely must be. Actually, any male who could contribute an O allele (*i*) could have fathered the child. This would include males with type O blood (*ii*) or type A blood who are heterozygous.

7. The probability is 1/2 (50%) that a child of this couple will be a heterozygote and have sickle cell trait. The probability is 1/4 (25%) that a child will be homozygous for the sickling allele and so will have sickle cell anemia.

8. For these ten traits, all the man's sperm will carry identical genes. He cannot produce genotypically different sperm. The woman can produce eggs with four genotypes. This example underscores the fact that the more heterozygous gene pairs that are present, the more genetically different gametes are possible.

9. The mating between two carriers of a lethal trait is *Ll* × *Ll*.

Progeny genotypes: 1/4 *LL* + 1/2 *Ll* + 1/4 *ll*.
Phenotypes: 1/4 homozygous survivors (*LL*)

1/2 heterozygous survivors (*Ll*)

1/4 lethal (*ll*) nonsurvivors

10. Bill's genotype: *Aa Ss Ee*
    Marie's genotype: *AA SS EE*

No matter how many children Bill and Marie have, the probability is 100% that each child will have the

parents' phenotype. Because Marie can produce only dominant alleles, there is no way that a child could inherit a *pair* of recessive alleles for any of these three traits—and that is what would be required in order for the child to show the recessive phenotype. Thus the probability is zero that a child will have short lashes, high arches, and no achoo syndrome.

11. The white-furred parent's genotype is *bb*; the black-furred parent must be *Bb*; because if it were *BB* all offspring would be heterozygotes (*Bb*) and would have black fur. A monohybrid cross between a heterozygote and a homozygote typically yields a 1:1 phenotype ratio. Four black and three white guinea pigs is close to a 1:1 ratio.

CHAPTER 20

1. Key: Among other complicated issues, here you must consider whether (in your view) a person's gender is determined by "genetic sex" or by reproductive structures. Also, review the discussion of sex determination at the beginning of Chapter 14. In addition, note that the secondary sex characteristics of normal males, which are due to the sensitivity of cells to testosterone, include greater muscle mass—which is why males typically are physically stronger than females.

2. The probability is the same for each child: 1/2, or 50%.

3. a: From his mother.

   b: A male can produce two types of gametes with respect to an X-linked gene. One type will possess only a Y chromosome and so lack this gene; the other type will have an X chromosome and will have the X-linked gene.

   c: A female homozygous for an X-linked gene will produce just one type of gamete containing an X chromosome with the gene.

   d: A female heterozygous for an X-linked gene will produce two types of gametes. One will contain an X chromosome with the dominant allele, and the other type will contain an X chromosome with the recessive allele.

4. Most of chromosome 21 has been translocated to chromosome 14. While this individual has 46 chromosomes, there are in fact three copies of chromosome 21. The third copy of chromosome 21 is attached to chromosome 14.

5. No. Many traits are sex-influenced and controlled by genes on autosomes.

6. 50%. His mother is heterozygous for the allele, so there is a 50% chance that any male offspring will inherit the allele. Since males do not inherit an X chromosome from their fathers, the genotype of the father is irrelevant to this question.

7. The allele for cystic fibrosis is recessive. Most of the carriers are heterozygous for the allele and do not have the cystic fibrosis phenotype.

8. The parent with typical pigmentation is heterozygous for the albinism allele. The probability that any one child will have the albinism phenotype is 50%. However, with a small sample of only four offspring, there is a high probability of a deviation from a 1:1 ratio due to the random mixes of alleles that occur during meiosis and fertilization (discussed in Chapter 18).

APPENDIX V

ANSWERS TO SELF-QUIZZES

CHAPTER 1: 1. DNA, 2. cell, 3. Homeostasis, 4. vertebrates, mammals, 5. nine, 6. c, 7. d, 8. c, 9. b

CHAPTER 2: 1. carbon, 2. a, 3. c, 4. c, 5. d, 6. b, 7. b, 8. c, 9. c, e, b, d, a, 10. a (plus R group interactions)

CHAPTER 3: 1. d, 2. cytoskeleton, 3. c, 4. a, 5. d, 6. b, g, f, d, c, a, e, 7. d, 8. d, 9. c, e, d, a, b, 10. b, 11. b, a, c, 12. The electron transport systems and carrier proteins required for ATP formation are embedded in the membrane between the inner and outer compartment of the mitochondrion.

CHAPTER 4: 1. d, 2. c, 3. b, 4. b, 5. a, 6. c, 7. c, 8. Receptors, integrator, effectors, 9. d, e, c, b, a

CHAPTER 5: 1. Skeletal and muscular, 2. d, 3. d, 4. c, 5. b, 6. a, 7. skull, rib cage, and vertebral column; pectoral girdles, pelvic girdle, and bones of extremities, 8. g, d, f, e, c, b, h, a

CHAPTER 6: 1. Skeletal and muscular, 2. skeletal, cardiac, smooth, 3. d, 4. b, 5. d, 6. f, d, e, a, b, g, c

CHAPTER 7: 1. a, 2. systole, diastole, 3. b, 4. c, 5. b, 6. a, 7. a, 8. d, 9. d, b, a, c, 10. c, a, b

CHAPTER 8: 1. d, 2. d, 3. c, 4. b, 5. d, a, c, e, b

CHAPTER 9: 1. d, 2. f, 3. d, 4. d, 5. b, 6. d, 7. a, 8. Tears are surface barriers that may wash away pathogens, 9. c, b, a, e, d, f

CHAPTER 10: 1. d, 2. b, 3. d, 4. b, 5. c, 6. e, 7. c, 8. d, 9. d, 10. d, 11. f, a, e, d, b, c

CHAPTER 11: 1. digesting, absorbing, eliminating, 2. caloric, energy, 3. carbohydrates, 4. essential amino acids, essential fatty acids, 5. b, 6. c, 7. d, 8. c, 9. e, d, a, b, c

CHAPTER 12: 1. d, 2. f, 3. a, 4. b, 5. c, 6. d, 7. a, 8. d, 9. b, d, e, c, a

CHAPTER 13: 1. stimuli, 2. action potentials, 3. neurotransmitter, 4. c, 5. b, 6. c, 7. e, d, b, c, a

CHAPTER 14: 1. stimulus, 2. sensation, 3. Perception, 4. d, 5. b, 6. d, 7. c, 8. e, 9. b, 10. c, 11. b, 12. e, c, d, a, b

CHAPTER 15: 1. f, 2. d, 3. b, 4. d, 5. e, 6. b, 7. b, 8. b, 9. b, e, g, d, f, a, c, 10. d, a, b, c, e

CHAPTER 16: 1. hypothalamus, 2. b, 3. d, 4. c, 5. b, 6. d

CHAPTER 17: 1. a, 2. a, 3. c, 4. morphogenesis, 5. c, 6. c, 7. d, a, f, e, c, b, 8. e, 9. e

CHAPTER 18: 1. mitosis; meiosis, 2. chromosomes; DNA, 3. c, 4. diploid, 5. c, 6. a, 7. b, 8. b, 9. b, 10. d, 11. d, b, c, a

CHAPTER 19: 1. a, 2. c, 3. a, 4. c, 5. b, 6. d, 7. b, 8. d, 9. c, a, d, b

CHAPTER 20: 1. c, 2. e, 3. e, 4. c, 5. d, 6. c, 7. d, 8. d, 9. d, 10. c, e, d, b, a

CHAPTER 21: 1. three, 2. b, 3. c, 4. c, 5. a, 6. a, 7. c, 8. a, 9. e, c, d, a, b, 10. c, 11. c

CHAPTER 22: 1. c, 2. e, 3. tumor suppressor gene, 4. b, 5. d, 6. a, 7. c, 8. d, 9. b, 10. c

CHAPTER 23: 1. species, 2. mutation, genetic drift, gene flow, and natural selection, 3. natural selection, 4. e, 5. e, 6. b, 7. a, 8. a

CHAPTER 24: 1. d, 2. d, 3. Ecology, 4. d, 5. a, 6. e, 7. d, a, b, c

CHAPTER 25: 1.b, 2. c, 3. d, 4. d, 5. c, 6. b.

APPENDIX VI

A PLAIN ENGLISH MAP OF THE HUMAN CHROMOSOMES AND SOME ASSOCIATED TRAITS

Haploid set of human chromosomes. The banding patterns characteristic of each type of chromosome appear after staining with a reagent called Giemsa. The locations of some of the 20,065 known genes (as of November 2005) are indicated. Also shown are locations that, when mutated, cause some of the genetic diseases discussed in the text.

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GLOSSARY

abdominal cavity Body cavity that holds the stomach, liver, pancreas, most of the intestine, and several other organs.

ABO blood typing Method of characterizing an individual's blood according to whether one or both of two protein markers, A and B, are present at the surface of red blood cells. The O signifies that neither marker is present.

abortion Spontaneous or induced expulsion of the embryo or fetus from the uterus.

absorption The movement of nutrients, fluid, and ions across the gastrointestinal tract lining and into the internal environment.

accommodation In the eye, adjustments of the lens position that move the focal point forward or back so that incoming light rays are properly focused on the retina.

acetylcholine (ACh) A neurotransmitter that can excite or inhibit various target cells in the brain, spinal cord, glands, and muscles.

acetyl-CoA (uh-SEED-ul) Coenzyme A with a two-carbon fragment from pyruvate attached. In the second stage of aerobic respiration, it transfers the fragment to oxaloacetate for the Krebs cycle.

achondroplasia Genetic disorder that results in abnormally short arms and legs in affected adults.

acid A substance that releases hydrogen ions in water.

acid–base balance State in which extracellular fluid is neither too acidic nor too basic, an outcome of controls over its concentrations of dissolved ions.

acidity Of a solution, an excess of hydrogen ions relative to hydroxyl ions.

acid rain Wet acid deposition; falling of rain (or snow) rich in sulfur and nitrogen oxides.

acromegaly Oversecretion of growth hormone during adulthood; bones and facial features become abnormally enlarged.

acrosome An enzyme-containing cap that covers most of the head of a sperm and helps the sperm penetrate an egg at fertilization.

actin (AK-tin) A globular contractile protein. In muscle cells, actin interacts with another protein, myosin, to bring about contraction.

action potential An abrupt, brief reversal in the steady voltage difference (resting membrane potential) across the plasma membrane of a neuron.

active site A crevice on the surface of an enzyme molecule where a specific reaction is catalyzed.

active transport The pumping of one or more specific solutes through a transport protein that spans the lipid bilayer of a cell membrane. Most often, the solute is transported against its concentration gradient. The protein is activated by an energy boost, as from ATP.

adaptation [L. *adaptare,* to fit] In evolutionary biology, the process of becoming suited (or more suited) to a given set of environmental conditions. Of sensory neurons, a decrease in the frequency of action potentials (or their cessation) even when a stimulus is maintained at constant strength.

adaptive immunity Immune responses that the body develops in response to antigens of specific pathogens, toxins, or abnormal body cells.

adaptive radiation A burst of speciation events, with lineages branching away from one another as they partition the existing environment or invade new ones.

adaptive trait A trait that helps an organism survive and reproduce under a given set of environmental conditions.

adenine (AH-de-neen) A purine; a nitrogen-containing base in certain nucleotides; a building block of DNA.

adenocarcinoma Cancer of a gland or its ducts.

ADH Antidiuretic hormone. Produced by the hypothalamus and released by the posterior pituitary, it stimulates reabsorption in the kidneys and so reduces urine volume.

adhering junctions Cell junctions that cement cells together.

adipose tissue A type of connective tissue having an abundance of fat-storing cells and blood vessels for transporting fats.

adrenal cortex (ah-DREE-nul) Outer portion of the adrenal gland; its hormones have roles in metabolism, inflammation, maintaining extracellular fluid volume, and other functions.

adrenal medulla Inner region of the adrenal gland; its hormones help control blood circulation and carbohydrate metabolism.

aerobic cellular respiration (air-OH-bik) [Gk. *aer,* air, and *bios,* life] The main energy-releasing metabolic pathway of ATP formation, in which oxygen is the final acceptor of electrons removed from glucose or some other organic compound. The pathway proceeds from glycolysis through the Krebs cycle and electron transport phosphorylation. A typical net yield is 36 ATP for each glucose molecule.

afferent arteriole In the urinary system, an arteriole that delivers blood to each nephron.

age structure Of a population, the number of individuals in each of several or many age categories.

agglutination (ah-glue-tin-AY-shun) The clumping together of foreign cells that have invaded the body (as pathogens or in tissue grafts or transplants). Clumping is caused by cross-linking between antibody molecules that have already bound an antigen at the surface of the foreign cells.

aging A range of processes, including the breakdown of cell structure and function, by which the body gradually deteriorates.

agranulocyte Class of white blood cells that lack granular material in the cytoplasm; includes the precursors of macrophages (monocytes) and lymphocytes.

AIDS Acquired immunodeficiency syndrome. A set of chronic disorders following infection by the human immunodeficiency virus (HIV), which destroys key cells of the immune system.

alcohol Organic compound that includes one or more hydroxyl groups (—OH); it dissolves readily in water. Sugars are examples.

aldosterone (al-DOSS-tuh-roan) Hormone secreted by the adrenal cortex that helps regulate sodium reabsorption by the kidneys.

allantois (ah-LAN-twahz) [Gk. *allas,* sausage] One of four extraembryonic membranes that form during embryonic development. In humans, it functions in early blood formation and development of the urinary bladder.

allele (uh-LEEL) For a given location on a chromosome, one of two or more slightly different chemical forms of a gene that code for different versions of the same trait.

allele frequency The relative abundances of each kind of allele carried by the individuals of a population.

allergen Any normally harmless substance that provokes inflammation, excessive mucus secretion, and other immune responses.

allergy An immune response made against a normally harmless substance.

all-or-none principle Principle that states that individual cells in a muscle's motor units always contract fully in response to proper stimulation. If the stimulus is below a certain threshold, the cells do not respond at all.

alveolus (al-VEE-uh-lus), plural alveoli [L. *alveus,* small cavity] Any of the many cup-shaped, thin-walled outpouchings of respiratory bronchioles. A site where oxygen diffuses from air in the lungs to the blood, and carbon dioxide diffuses from blood to the lungs.

Alzheimer's disease Degenerative, eventually fatal brain disorder in which abnormal plaques and fibrous tangles gradually destroy brain tissue.

amine hormone A hormone derived from the amino acid tyrosine.

amino acid (uh-MEE-no) A small organic molecule having a hydrogen atom, an amino group, an acid group, and an R group covalently bonded to a central carbon atom. The subunit of polypeptide chains, which represent the primary structure of proteins.

ammonification (uh-MOAN-ih-fih-KAY-shun) A process by which certain microorganisms break down nitrogen-containing wastes and remains of other organisms.

amnesia A loss of fact memory.

amnion (AM-nee-on) One of four extraembryonic membranes. It becomes a fluid-filled sac in which the embryo (and fetus) can grow, move freely, and be protected from sudden temperature shifts and impacts.

amoebic dysentery Type of severe diarrhea caused by a protozoan.

anabolism A metabolic activity that assembles small molecules into more complex molecules that store energy.

anaerobic pathway (AN-uh-ROW-bik) [Gk. *an,* without, and *aer,* air] Metabolic pathway in which a substance other than oxygen serves as the final acceptor of electrons that have been stripped from substrates.

anal canal The canal from the rectum to the anus through which feces pass.

analogous structures Body parts, once different in separate lineages, that were put to comparable uses in similar environments and that came to resemble one another in form and function. They are evidence of morphological convergence.

anaphase (AN-uh-faze) The stage at which microtubules of a spindle apparatus separate sister chromatids of each chromosome and move them to opposite spindle poles. During anaphase I of meiosis, the two members of each pair of homologous chromosomes separate. During anaphase II, sister chromatids of each chromosome separate.

anaphylactic shock A whole-body allergic response in which a person's blood pressure plummets, among other symptoms.

anemias Disorders that indicate that red blood cells, which contain hemoglobin, are not delivering enough oxygen to meet the body's needs.

aneuploidy (AN-yoo-ploy-dee) A change in the chromosome number following inheritance of one extra or one fewer chromosome than usual.

aneurysm A pouchlike weak spot in an artery.

antibiotic [Gk. *anti,* against] A normal metabolic product of certain microorganisms that kills or inhibits the growth of other microorganisms.

antibody Any of a variety of Y-shaped receptor molecules with binding sites for specific antigens. Only B cells produce antibodies, then position them at their surface or secrete them.

antibody-mediated immunity The B cell defensive response to pathogens in the body wherein antibodies are produced.

anticodon In a tRNA molecule, a sequence of three nucleotide bases that can pair with an mRNA codon.

antigen (AN-tih-jen) [Gk. *anti*, against, and *genos*, race, kind] Substance that is recognized as foreign to the body and that triggers an immune response. Most antigens are protein molecules at the surface of infectious agents or tumor cells.

antigen–MHC complex Unit consisting of fragments of an antigen molecule bound to MHC proteins. MHC complexes displayed at the surface of an antigen-presenting cell such as a macrophage promote an immune response by lymphocytes.

antigen-presenting cell A macrophage or other cell that displays antigen–MHC complexes at its surface and so promotes an immune response by lymphocytes.

antioxidant A chemical that can give up an electron to a free radical before the free radical damages DNA or some other cell constituent.

anus Terminal opening of the gastrointestinal tract.

aorta (ay-OR-tah) [Gk. *airein*, to lift, heave] Main artery of systemic circulation; carries oxygenated blood away from the heart to all body regions except the lungs.

aortic body Any of several receptors in artery walls near the heart that respond to changes in levels of carbon dioxide and oxygen in arterial blood.

apoptosis (APP-oh-TOE-sis) Genetically programmed cell death. Molecular signals lead to self-destruction in body cells that have finished their prescribed functions or have become altered, as by infection or transformation into a cancerous cell.

appendicular skeleton (ap-en-DIK-yoo-lahr) Bones of the limbs, hips, and shoulders.

appendix A slender projection from the cup-shaped pouch (cecum) at the start of the colon. It may function in defense.

arrhythmia Irregular or abnormal heart rhythm, often caused by stress, drug effects, or coronary artery disease.

arteriole (ar-TEER-ee-ole) Any of the blood vessels between arteries and capillaries. They are control points where the volume of blood delivered to different body regions can be adjusted.

artery Any of the large-diameter blood vessels that conduct deoxygenated blood to the lungs and oxygenated blood to all body tissues. The thick, muscular artery wall allows arteries to smooth out pulsations in blood pressure caused by heart contractions.

asexual reproduction Mode of reproduction by which offspring arise from a single parent and inherit the genes of that parent only.

asthma Lung disorder in which the bronchioles narrow due to spasms in smooth muscle in their walls.

astigmatism Vision problem in which one or both corneas have an uneven curvature and cannot bend incoming light rays to the same focal point.

atherosclerosis Condition in which an artery's wall thickens and loses its elasticity, and the vessel becomes clogged with lipid deposits. In the artery wall, abnormal smooth muscle cells accumulate, and there is an increase in connective tissue. Plaques consisting of lipids, calcium salts, and fibrous material extend into the artery lumen, preventing normal blood flow.

atherosclerotic plaque Cholesterol and other lipids that build up in the arterial wall, leaving less room for flowing blood.

atmosphere The region of gases, airborne particles, and water vapor enveloping Earth.

atmospheric cycle A biogeochemical cycle in which the atmosphere is the largest reservoir of an element. The carbon and nitrogen cycles are examples.

atom The smallest unit of matter that is unique to a particular element.

atomic number The number of protons in the nucleus of each atom of an element; it differs for each element.

ATP Adenosine triphosphate (ah-DEN-uh-seen try-FOSS-fate) A nucleotide composed of adenine, ribose, and three phosphate groups. As the main energy carrier in cells, it directly or indirectly delivers energy to or picks up energy from nearly all metabolic pathways.

ATP/ADP cycle In cells, a mechanism of ATP renewal. When ATP donates a phosphate group to other molecules (and so energizes them), it reverts to ADP, then forms again by phosphorylation of ADP.

atrioventricular (AV) node In the septum dividing the heart atria, a site that contains bundles of conducting fibers. Stimuli arriving at the AV node from the cardiac pacemaker (sinoatrial node) pass along the bundles and continue on via Purkinje fibers to contractile muscle cells in the ventricles.

atrioventricular valve One-way flow valve between the atrium and ventricle in each half of the heart.

atrium (AY-tree-um) Upper chamber in each half of the heart; the right atrium receives deoxygenated blood (from tissues) entering the pulmonary circuit of blood flow, and the left atrium receives oxygenated blood from pulmonary veins.

autoimmunity Misdirected immune response in which lymphocytes mount an attack against normal body cells.

automated DNA sequencing Machine method of determining the sequence of nucleotides in DNA using standard and modified versions of the four DNA nucleotides.

autonomic nerves (ah-toe-NOM-ik) Those nerves leading from the central nervous system to the smooth muscle, cardiac muscle, and glands of internal organs and structures—that is, to the visceral portion of the body.

autosomal dominant inheritance Condition arising from the presence of a dominant allele on an autosome (not a sex chromosome). The allele is always expressed to some extent, even in heterozygotes.

autosomal recessive inheritance Condition arising from a recessive allele on an autosome (not a sex chromosome). Only recessive homozygotes show the resulting phenotype.

autosome Any chromosome that is not a sex (gender-determining) chromosome.

autotroph (AH-toe-trofe) [Gk. *autos,* self, and *trophos,* feeder] An organism able to build its own large organic molecules by using carbon dioxide and energy from the physical environment. Compare *heterotroph*.

axial skeleton (AX-ee-uhl) The skull, backbone, ribs, and breastbone (sternum).

axon Of a neuron, a long, cylindrical extension from the cell body, with finely branched endings. Action potentials move rapidly, without alteration, along an axon; their arrival at axon endings may trigger the release of neurotransmitter molecules that influence an adjacent cell.

B lymphocyte The only white blood cell that produces antibodies, then positions them at the cell surface or secretes them as weapons in immune responses.

bacterial conjugation The transfer of plasmid DNA from one bacterial cell to another.

baroreceptor reflex The short-term control over arterial pressure. It keeps blood pressure within normal limits in the face of sudden changes in blood pressure.

Barr body In the cells of females, a condensed X chromosome that was inactivated during early embryonic development.

basal body A centriole that, after having given rise to the microtubules of a flagellum or cilium, remains attached to its base in the cytoplasm.

basal metabolic rate Amount of energy required to sustain body functions when a person is resting, awake, and has not eaten for 12–18 hours.

base A substance that accepts H^+ in water.

base pair A pair of hydrogen-bonded nucleotide bases in two strands of nucleic acids. In a DNA double helix, adenine pairs with thymine, and guanine with cytosine. When an mRNA strand forms on a DNA strand during transcription, uracil (U) pairs with the DNA's adenine.

base-pair substitution A mutation occurring in a replicating DNA molecule (a chromosome) when one base is wrongly substituted for another in a base pair.

basement membrane Noncellular layer of mostly proteins and polysaccharides that is sandwiched between an epithelium and underlying connective tissue.

basophil Fast-acting white blood cell that secretes histamine and other substances during inflammation.

B cell *See* B lymphocyte.

bicarbonate–carbon dioxide buffer system A system used to restore the body's normal pH level by neutralizing excess H^+ and allowing for the exhalation of carbon dioxide formed during the reaction. It does not eliminate the excess H^+ and therefore has only a temporary effect.

bile A yellowish fluid made in the liver, stored in the gallbladder, and released into the upper small intestine where it aids in the digestion and absorption of fats.

biofuel An alternative, renewable fuel made from plants and organic wastes.

biogeochemical cycle The movement of an element such as carbon or nitrogen from the environment to organisms, then back to the environment.

biogeography [Gk. *bios,* life, and *geographein,* to describe the surface of Earth] The study of major land regions, each having distinguishing types of plants and animals.

biological clock Internal time-measuring mechanism that has a role in adjusting an organism's daily activities, seasonal activities, or both in response to environmental cues.

biological magnification The increasing concentration of a nondegradable or slowly degradable substance in body tissues as it is passed along food chains.

biology The scientific study of life.

biomass The combined weight of all the organisms at a particular feeding (trophic) level in an ecosystem.

biome A broad, vegetational subdivision of a biogeographic realm shaped by climate, topography, and composition of regional soils.

biopsy Diagnostic procedure in which a small piece of tissue is removed from the body through a hollow needle or exploratory surgery, and then examined for signs of a particular disease (often cancer).

biosphere [Gk. *bios,* life, and *sphaira,* globe] All regions of Earth's waters, crust, and atmosphere in which organisms live.

biosynthetic pathway A metabolic pathway in which small molecules are assembled into large organic molecules.

bipedalism A habitual standing and walking on two feet, as by humans.

blastocyst (BLASS-tuh-sist) [Gk. *blastos,* sprout, and *kystis,* pouch] In embryonic development, a blastula stage consisting of a hollow ball of surface cells and an inner cell mass.

blastomere One of the small, nucleated cells that form during cleavage of a zygote.

blastula (BLASS-chew-lah) An embryonic stage consisting of a ball of cells produced by cleavage.

blood A fluid connective tissue composed of water, solutes, and formed elements (blood cells and platelets); it carries substances to and from cells and helps maintain an internal environment that is favorable for cell activities.

blood pressure Fluid pressure, generated by heart contractions, that keeps blood circulating.

blood–brain barrier Term applied to modified structure of brain capillaries that helps control which bloodborne substances reach neurons in the brain.

bolus Softened, lubricated ball of food, created by chewing and mixing of food with saliva.

bone Connective tissue that functions in movement and locomotion, protection of other organs, mineral storage, and (in some bones) blood cell production.

bone marrow A connective tissue where blood cells are formed.

bone remodeling Process of ongoing calcium deposits and withdrawals from bone that adjusts bone strength and maintains levels of calcium and phosphorus in blood.

bone tissue Mineral-hardened connective tissue; the main tissue in bone.

botulism Disease caused by exposure to a biological toxin produced by the bacterium *Clostridium botulinum.*

Bowman's capsule Cup-shaped portion of a nephron that receives water and solutes being filtered from blood.

brain Organ that receives, integrates, stores, and retrieves information, and coordinates appropriate responses by stimulating and inhibiting the activities of different body parts.

brain case The eight bones that together surround and protect the brain.

brain stem The midbrain, pons, and medulla oblongata, the core of which contains the reticular formation that helps govern activity of the nervous system as a whole.

bronchiole A component of the finely branched bronchial tree inside each lung.

bronchitis Inflammation of the bronchial walls that destroys wall tissue and can eventually block parts of the respiratory tract.

bronchus plural bronchi (BRONG-cuss, BRONG-kee) [Gk. *bronchos,* windpipe] Tubelike branchings of the trachea that lead into the lungs.

buffer system A weak acid and the base that forms when it dissolves in water. The two work as a pair to counter slight shifts in pH.

bulbourethral glands Two glands of the male reproductive system that secrete mucus-rich fluid into the urethra when the male is sexually aroused.

bulk A volume of fiber and other undigested material that absorption processes in the colon cannot decrease.

Burkitt lymphoma Type of lymphoma that involves sites other than the lymph nodes.

cancer A malignant tumor, the cells of which show profound abnormalities in the plasma membrane and cytoplasm, abnormal growth and division, and weakened capacity for adhesion within the parent tissue (leading to metastasis). Unless eradicated, cancer is lethal.

candidiasis Vaginal yeast infection; symptoms include vaginal discharge, itching, and irritation.

capillary [L. *capillus,* hair] A thin-walled blood vessel that functions in the exchange of gases and other substances between blood and interstitial fluid.

capillary bed Dense capillary networks containing true capillaries where exchanges occur between blood and tissues, and also thoroughfare channels that link arterioles and venules.

carbaminohemoglobin A hemoglobin molecule that has carbon dioxide bound to it; $HbCO_2$.

carbohydrate [L. *carbo,* charcoal, and *hydro,* water] A simple sugar or large molecule composed of sugar units. All cells use carbohydrates as structural materials, energy stores, and transportable forms of energy. The three classes of carbohydrates include monosaccharides, oligosaccharides, and polysaccharides.

carbon cycle A biogeochemical cycle in which carbon moves from its reservoir in the atmosphere, through oceans and organisms, then back to the atmosphere.

carbonic anhydrase Enzyme in red blood cells that catalyzes the conversion of unbound carbon dioxide to carbonic acid and its dissociation products, thereby helping maintain the gradient that keeps carbon dioxide diffusing from interstitial fluid into the blood.

carcinogen (kar-SIN-uh-jen) An environmental agent or substance, such as ultraviolet radiation, that can trigger cancer.

carcinogenesis The transformation of a normal cell into a cancerous one.

carcinoma Cancer of the epithelium, including skin cells and epithelial linings of internal organs.

cardiac conduction system (KAR-dee-ak) Set of noncontractile cells in heart muscle that spontaneously produce and conduct the electrical events that stimulate heart muscle contractions.

cardiac cycle The sequence of muscle contraction and relaxation constituting one heartbeat.

cardiac muscle Type of muscle found only in the heart wall; cardiac muscle cells contract as a single unit.

cardiac output The amount of blood each ventricle of the heart pumps in one minute.

cardiac pacemaker Sinoatrial (SA) node; the source of the normal rate of heartbeat. The self-excitatory cardiac muscle cells that spontaneously generate rhythmic waves of excitation over the heart chambers.

cardiovascular system Organ system that is composed of the heart and blood vessels and that functions in the rapid transport of blood to and from tissues.

carnivore [L. *caro, carnis,* flesh, and *vovare,* to devour] An animal that eats other animals.

carotid artery Artery in the neck that contains baroreceptors, which monitor arterial pressure.

carotid body Any of several sensory receptors that monitor carbon dioxide and oxygen levels in blood; located at the point where carotid arteries branch to the brain.

carrier An organism in which a pathogen is living without causing disease symptoms.

carrier protein A protein that binds specific substances and changes shape in ways that shunt the substances across a plasma membrane. Some carrier proteins function passively; others require an energy input.

carrying capacity The maximum number of individuals in a population (or species) that can be sustained indefinitely by a given environment.

cartilage A type of connective tissue with solid yet pliable intercellular material that resists compression.

cartilaginous joint Type of joint in which cartilage fills the space between adjoining bones; only slight movement is possible.

catabolism Metabolic activity that breaks down large molecules into simpler ones, releasing the components for use by cells.

cataracts Clouding of the eye's lens associated with aging.

cell [L. *cella,* small room] The smallest living unit; an organized unit that can survive and reproduce on its own, given DNA instructions and suitable environmental conditions, including appropriate sources of energy and raw materials.

cell body The part of a neuron that contains its nucleus and organelles.

cell cortex An array of cross-linked, bundled, gel-like microfilaments that reinforces the cell's plasma membrane.

cell count The number of cells of a given type in a microliter of blood.

cell cycle Events during which a cell increases in mass, roughly doubles its number of cytoplasmic components, duplicates its DNA, then undergoes nuclear and cytoplasmic division. It extends from the time a new cell is produced until it completes its own division.

cell determination Process that determines what an embryonic cell will become—a neuron or epithelial cell for example.

cell differentiation The gene-guided process by which cells in different locations in the embryo become specialized.

cell-mediated immunity The T cell defensive response to pathogens in the body, wherein cytotoxic T cells attack the invaders directly.

cell theory A fundamental theory in biology, which states that (1) all organisms are composed of one or more cells, (2) the cell is the smallest unit that still retains a capacity for independent life, and (3) all cells arise from pre-existing cells.

cell-to-cell junction A point of contact that physically links two cells or that provides functional links between their cytoplasm.

cellular respiration The process by which cells break apart carbohydrates, lipids, or proteins to form ATP.

central nervous system The brain and spinal cord.

centriole (SEN-tree-ohl) A cylinder of triplet microtubules that gives rise to the microtubules of cilia and flagella.

centromere (SEN-troh-meer) [Gk. *kentron,* center, and *meros,* a part] A small, constricted region of a chromosome having attachment sites for microtubules that help move the chromosome during nuclear division.

cerebellum (ser-ah-BELL-um) [L. diminutive of *cerebrum,* brain] Hindbrain region with reflex centers for maintaining posture and refining limb movements.

cerebral cortex Thin surface layer of the cerebral hemispheres. Some regions of the cortex receive sensory input, others integrate information and coordinate appropriate motor responses.

cerebral hemispheres The left and right sides of the cerebrum, which are separated by a deep fissure.

cerebrospinal fluid Clear extracellular fluid that surrounds and cushions the brain and spinal cord.

cerebrum (suh-REE-bruhm) Part of the forebrain; the most complex integrating center.

cervix The lower part of the uterus.

channel protein Type of transport protein that serves as a pore through which ions or other water-soluble substances move across the plasma membrane. Some channels remain open, while others are gated and open and close in controlled ways.

chemical bond A union between the electron structures of two or more atoms.

chemical evolution Process by which biological molecules evolved.

chemical synapse (SIN-aps) [Gk. *synapsis,* union] A small gap, the synaptic cleft, that separates two neurons (or a neuron and a muscle cell or gland cell) and that is bridged by neurotransmitter molecules released from the presynaptic neuron.

chemoreceptor (KEE-moe-ree-sep-tur) Sensory receptor that detects chemical energy (ions or molecules) dissolved in the surrounding fluid.

chemotherapy The use of therapeutic drugs to kill cancer cells.

CHH Cartilage-hair hypoplasia; a disease, caused by mutation of a single gene, that affects multiple organ systems, including the skeletal, integumentary, and immune systems.

chlamydia Sexually transmitted disease caused by infection by the bacteria *Chlamydia trachomatis.* The bacterium infects cells of the genital organs and urinary tract.

chlorofluorocarbon (CFC) (klore-oh-FLOOR-oh-car-bun) One of a variety of odorless, invisible compounds of chlorine, fluorine, and carbon, widely used in commercial products, that are contributing to the destruction of the ozone layer above Earth's surface.

chorion (CORE-ee-on) One of four extraembryonic membranes; it encloses the embryo and the three other membranes. Absorptive structures (villi) that develop at its surface are crucial for the transfer of substances between the embryo and mother.

chromatid Of a duplicated eukaryotic chromosome, one of two DNA molecules and its associated proteins. One chromatid remains attached to its "sister" chromatid at the centromere until they are separated from each other during a nuclear division; then each is a separate chromosome.

chromatin A cell's DNA and all of the proteins associated with it.

chromosome (CROW-moe-soam) [Gk. *chroma,* color, and *soma,* body] A double-stranded DNA molecule that carries genetic information.

chromosome number The number of each type of chromosome in all cells except dividing germ cells or gametes.

chyme (KIME) The thick mixture of swallowed food boluses and acidic gastric fluid in the stomach that enters the small intestine during digestion.

cilium (SILL-ee-um), plural cilia [L. *cilium,* eyelid] Of eukaryotic cells, a short, hairlike projection that contains a regular array of microtubules. Cilia serve as motile structures, help create currents of fluids, or are part of sensory structures.

circadian rhythm (ser-KAYD-ee-un) [L. *circa,* about, and *dies,* day] A cycle of physiological events that is completed every 24 hours or so, even when environmental conditions remain constant.

clavicle Long, slender collarbone that connects the pectoral girdle with the sternum (breastbone).

cleavage Stage of development when mitotic cell divisions convert a zygote to the ball of cells called the blastula.

cleavage furrow Of a cell undergoing cytoplasmic division, a shallow, ringlike depression that forms at the cell surface as contractile microfilaments pull the plasma membrane inward. It defines where the cytoplasm will be cut in two.

cleavage reaction Enzyme action that splits a molecule into two or more parts; hydrolysis is an example.

climate Prevailing weather conditions for an ecosystem, including temperature, humidity, wind speed, cloud cover, and rainfall.

climax community Following primary and secondary succession, the array of species that remains more or less steady under prevailing conditions.

clonal selection hypothesis Hypothesis that lymphocytes activated by a specific antigen will rapidly multiply and differentiate into huge subpopulations of cells, all having the parent cell's specificity against that antigen.

cloning vector Plasmid that has been modified in the laboratory to accept foreign DNA.

cochlea Coiled, fluid-filled chamber of the inner ear. Sound waves striking the eardrum become converted to pressure waves in the cochlear fluid, and the pressure waves ultimately cause a membrane to vibrate and bend sensory hair cells. Signals from bent hair cells travel to the brain, where they may be interpreted as sound.

codominance Condition in which a pair of nonidentical alleles are both expressed, even though they specify two different phenotypes.

codon One of a series of base triplets in an mRNA molecule, most of which code for a sequence of amino acids of a specific polypeptide chain. (Of 64 codons, 61 specify different amino acids and three of these also serve as start signals for translation; one other serves only as a stop signal for translation.)

coenzyme A type of nucleotide that transfers hydrogen atoms and electrons from one reaction site to another. NAD^+ is an example.

cofactor A metal ion or coenzyme; it helps catalyze a reaction or serves briefly as an agent that transfers electrons, atoms, or functional groups from one substrate to another.

coitus Sexual intercourse.

colon (CO-lun) The large intestine.

community The populations of all species occupying a habitat; also applied to groups of organisms with similar lifestyles in a habitat.

compact bone Type of dense bone tissue that makes up the shafts of long bones and outer regions of all bones. Narrow channels in compact bone contain blood vessels and nerves.

comparative morphology [Gk. *morph,* form] Anatomical comparisons of major evolutionary lineages.

complement system A set of about 30 proteins circulating in blood plasma with roles in nonspecific defenses and in immune responses. Some trigger lysis of pathogens, others promote inflammation, and others stimulate phagocytes to engulf pathogens.

compound A substance in which the relative proportions of two or more elements never vary. Organic compounds have a backbone of carbon atoms arranged as a chain or ring structure. The simpler, inorganic compounds do not have comparable backbones.

concentration gradient A difference in the number of molecules (or ions) of a substance between two adjacent regions, as in a volume of fluid.

conclusion In scientific reasoning, a statement that evaluates a hypothesis based on test results.

concussion Temporary upset of the electrical activity of brain neurons resulting from a blow to the head.

condensation reaction Chemical step in which two molecules become covalently bonded into a larger molecule, and water often forms as a by-product.

cone cell In the retina, a type of photoreceptor that responds to intense light and contributes to sharp daytime vision and color perception.

conjunctivitis Inflammation of the conjunctiva, a membrane that lines the inside of the eyelids and the white of the eye.

connective tissue A tissue type that consists of cells in a matrix that contains a ground substance and protein fibers. This category includes fibrous connective tissues, cartilage, bone tissue, blood, and adipose (fat) tissue.

consumer [L. *consumere,* to take completely] Of ecosystems, a heterotrophic organism that obtains energy and raw materials by feeding on the tissues of other organisms. Herbivores, carnivores, omnivores, and parasites are examples.

continuous variation A more or less continuous range of small differences in a given trait among all the individuals of a population.

control group In a scientific experiment, a group used to evaluate possible side effects of a test involving an experimental group. Ideally, the control group should differ from the experimental group only with respect to the variable being studied.

controlled experiment An experiment that tests only one prediction of a hypothesis at a time.

core temperature The body's internal temperature, as opposed to temperatures of the tissues near its surface. Normal human core temperature is about 37°C (98.6°F).

cornea Transparent tissue in the outer layer of the eye, which causes incoming light rays to bend.

coronary artery Either of two arteries leading to capillaries that service cardiac muscle.

corpus callosum (CORE-pus ka-LOW-sum) A band of 200 million axons that functionally link the two cerebral hemispheres.

corpus luteum (CORE-pus LOO-tee-um) A glandular structure that develops from cells of a ruptured ovarian follicle. It secretes progesterone and some estrogen, both of which maintain the lining of the uterus (endometrium).

cortex [L. *cortex,* bark] In general, a rindlike outer layer; the kidney cortex is an example.

covalent bond (koe-VAY-lunt) [L. *con,* together, and *valere,* to be strong] A sharing of one or more electrons between atoms or groups of atoms. When electrons are shared equally, the bond is nonpolar. When electrons are shared unequally, the bond is polar—slightly positive at one end and slightly negative at the other.

cranial cavity Body cavity that houses the brain.

creatine phosphate Organic compound that transfers phosphate to ADP in a rapid, short-term pathway that generates ATP.

Creuzfeldt-Jakob disease A fatal brain disease caused by an infectious prion that causes "mad cow" disease in cattle.

cri-du-chat Genetic disorder that leads to mental retardation and an abnormally shaped larynx.

critical thinking Objective evaluation of information.

cross-bridge The interaction between actin and myosin filaments that is the basis of muscle cell contraction.

crossing over During prophase I of meiosis, an interaction between a pair of homologous chromosomes. Their nonsister chromatids break at the same place along their length and exchange corresponding segments at the break points. Crossing over breaks up old combinations of alleles and puts new ones together in chromosomes.

culture The sum total of behavior patterns of a social group, passed between generations by learning and by symbolic behavior, especially language.

cutaneous membrane A dry, sturdy epithelial membrane; the skin.

cyclic AMP Cyclic adenosine monophosphate. A nucleotide that has roles in intercellular communication, as when it serves as a second messenger (a cytoplasmic mediator of a cell's response to signaling molecules).

cystic fibrosis Genetic malabsorption disorder in which dry, thickened mucus clogs the airways, making breathing difficult and leading to bacterial infections.

cystitis Inflammation of the bladder usually resulting from an infection of the urinary tract.

cytokine Any of the chemicals released by white blood cells that help muster or strengthen defense responses.

cytokinesis (sigh-toe-kih-NEE-sis) [Gk. *kinesis,* motion] Cytoplasmic division; the splitting of a parent cell into two daughter cells.

cytomembrane system [Gk. *kytos,* hollow vessel] Organelles that function as a system to modify, package, and distribute newly formed proteins and lipids. Endoplasmic reticulum, Golgi bodies, lysosomes, and a variety of vesicles are its components.

cytoplasm (SIGH-toe-plaz-um) [Gk. *plassein,* to mold] All cellular parts, particles, and semifluid substances enclosed by the plasma membrane except for the nucleus.

cytosine (SIGH-toe-seen) A pyrimidine; one of the nitrogen-containing bases in nucleotides.

cytoskeleton A cell's internal "skeleton." Its microtubules and other components structurally support the cell and organize and move its internal components.

cytosol The jellylike fluid portion of the cytoplasm.

cytotoxic T cell Type of T lymphocyte that directly kills infected body cells and tumor cells by lysis.

decomposer [L. *de-,* down, away, and *companere,* to put together] A heterotroph that obtains energy by chemically breaking down the remains, products, or wastes of other organisms. Decomposers help cycle nutrients to producers in ecosystems. Certain fungi and bacteria are examples.

deductive logic Pattern of thinking by which a person makes inferences about specific consequences or specific predictions that must follow from a hypothesis.

deforestation The removal of all trees from a large tract of land, such as the Amazon Basin or the Pacific Northwest.

deletion At the cellular level, loss of a segment from a chromosome. In a DNA molecule, loss of one to several base pairs.

demographics A population's vital statistics.

denaturation (deh-nay-chur-AY-shun) Of a protein, the loss of three-dimensional shape following disruption of hydrogen bonds and other weak bonds.

dendrite (DEN-drite) [Gk. *dendron,* tree] A short, slender extension from the cell body of a neuron.

dendritic cell A type of white blood cell that alerts the adaptive immune system when an antigen is present in tissue fluid of the skin or body linings.

denitrification (dee-nite-rih-fih-KAY-shun) The conversion of nitrate or nitrite by certain bacteria to gaseous nitrogen (N_2) and a small amount of nitrous oxide (N_2O).

dense connective tissue A type of fibrous connective tissue with more collagen fibers than loose connective tissue; it is strong but not very flexible.

density-dependent controls Factors, such as predation, parasitism, disease, and competition for resources, that limit population growth by reducing the birth rate, increasing the rates of death and dispersal, or all of these.

density-independent controls Factors such as storms or floods that increase a population's death rate more or less independently of its density.

dermis The layer of skin underlying the epidermis, consisting mostly of dense connective tissue.

desertification (dez-urt-ih-fih-KAY-shun) The conversion of grasslands, rain-fed cropland, or irrigated cropland to desertlike conditions, with a drop in agricultural productivity of 10 percent or more.

development Of complex multicellular species, a series of stages that begins with the formation of gametes, followed by fertilization and subsequent embryonic and adult phases.

diabetes insipidus A disease state marked by excessive urination which can lead to dehydration; sometimes a result of damage to the posterior lobe of the pituitary.

diabetes mellitus A metabolic disease in which lack of insulin causes glucose to build up in the blood, leading to a variety of symptoms including dehydration and widespread damage to blood vessels.

diaphragm (DIE-uh-fram) [Gk. *diaphragma,* to partition] Muscular partition between the thoracic and abdominal cavities, the contraction and relaxation of which contributes to breathing. Also, a contraceptive device used temporarily to prevent sperm from entering the uterus during sexual intercourse.

diastole Relaxation phase of the cardiac cycle.

diffusion Net movement of like molecules (or ions) down their concentration gradient.

digestion The breakdown of food particles into nutrient molecules small enough to be absorbed.

digestive system Organ system with specialized regions where food is ingested, digested, and absorbed and undigested residues are stored, then eliminated.

dihybrid cross In genetics, an experimental cross in which offspring inherit two gene pairs, each consisting of two nonidentical alleles.

diploid number (DIP-loyd) The chromosome number of somatic cells and of germ cells prior to meiosis. Such cells have two chromosomes of each type (that is, pairs of homologous chromosomes). Compare *haploid number*.

disaccharide (die-SAK-uh-ride) [Gk. *di,* two, and *sakcharon,* sugar] A type of simple carbohydrate, of the class called oligosaccharides; two monosaccharides covalently bonded.

disease Condition that develops when the body's defenses cannot prevent a pathogen's activities from interfering with normal body functions.

disease vector Something (such as an insect) that carries a pathogen from an infected person or contaminated material to new hosts.

disjunction The separation of each homologue from its partner during anaphase I of meiosis.

distal tubule The tubular section of a nephron most distant from the glomerulus; a major site of water and sodium reabsorption.

divergence Accumulation of differences in allele frequencies between populations that have become reproductively isolated from one another.

DNA Deoxyribonucleic acid (dee-OX-ee-rye-bow-new-CLAY-ik). For all cells (and many viruses), the molecule of inheritance. A category of nucleic acids, each usually consisting of two nucleotide strands twisted together helically and held together by hydrogen bonds. The nucleotide sequence encodes the instructions for assembling proteins, and, ultimately, a new individual.

DNA chip A microarray of thousands of DNA sequences that are stamped onto a glass plate; can help identify mutations and diagnose diseases by pinpointing which genes are silent and which are being expressed in a body tissue.

DNA clone An identical copy of foreign DNA that was inserted into plasmids (typically, bacteria).

DNA fingerprint Of each individual, a unique array of RFLPs, resulting from the DNA sequences inherited from each parent.

DNA polymerase (poe-LIM-uh-rase) Enzyme that assembles a new strand on a parent DNA strand during replication; also takes part in DNA repair.

DNA probe Very short stretch of DNA designed to base-pair with part of a gene being studied and labeled with an isotope to distinguish it from DNA in the sample being investigated.

DNA repair Following an alteration in the base sequence of a DNA strand, a process that restores the original sequence, as carried out by DNA polymerases, DNA ligases, and other enzymes.

DNA replication The process by which the hereditary material in a cell is duplicated for distribution to daughter nuclei.

DNA sequencing A process that provides information about genes, including their size, their location on chromosomes, and the order of their nucleotides.

dominant allele In a diploid cell, an allele that masks the expression of its partner on the homologous chromosome.

Down syndrome Genetic disorder in which affected people inherit three copies of chromosome 21. Mental retardation is a major symptom.

drug addiction Chemical dependence on a drug, which assumes an "essential" biochemical role in the body following habituation and tolerance.

Duchenne muscular dystrophy Genetic disorder linked to the X chromosome that leads to wasting of muscle tissue.

duodenum (doo-oh-DEE-num) The first section of the small intestine.

duplication A change in a chromosome's structure resulting in the repeated appearance of a gene sequence.

dysplasia An abnormal change in the sizes, shapes, and organization of cells in a tissue.

ecological footprint The sum total of resources used by a population or an individual, together with the resulting waste products.

ecological pyramid A way to represent the energy relationships of an ecosystem.

ecology [Gk. *oikos,* home, and *logos,* reason] Study of the interactions of organisms with one another and with their physical and chemical environment.

ecosystem [Gk. *oikos,* home] An array of organisms and their physical environment, all of which interact through a flow of energy and a cycling of materials.

ectoderm [Gk. *ecto,* outside, and *derma,* skin] The outermost primary tissue layer (germ layer) of an embryo, which gives rise to the outer layer of the integument and to tissues of the nervous system.

effector A muscle (or gland) that responds to signals from an integrator (such as the brain) by producing movement (or chemical change) that helps adjust the body to changing conditions.

effector cell Of the differentiated subpopulations of lymphocytes that form during an immune response, the type of cell that engages and destroys the antigen-bearing agent that triggered the response.

efferent arteriole In the urinary system, the arteriole that carries filtered blood from the nephron.

egg A mature female gamete; also called an ovum.

elastic connective tissue A form of dense connective tissue found in organs that must stretch; made up mostly of the protein elastin, it is quite flexible.

electrocardiogram (ECG) A recording of the electrical activity of the heart's cardiac cycle.

electrolyte Any chemical substance, such as a salt, that ionizes and dissociates in water and is capable of conducting an electrical current.

electron Negatively charged unit of matter, with both particulate and wavelike properties, that occupies one of the orbitals around the atomic nucleus. Atoms can gain, lose, or share electrons with other atoms.

electron transfer When a molecule donates one or more electrons to another molecule.

electron transport system An organized array of enzymes and cofactors, bound in a cell membrane, that accept and donate electrons in sequence. When such systems operate, hydrogen ions (H^+) flow across the membrane, and the flow drives ATP formation and other reactions.

element Any substance that cannot be decomposed into substances with different properties.

elimination The excretion of undigested and unabsorbed food residues from the rectum.

embryo (EM-bree-oh) [Gk. *en,* in, and probably *bryein,* to swell] Of animals, a new individual that forms by cleavage, gastrulation, and other early developmental events.

embryonic disk In early development, the oval, flattened cell mass that gives rise to the embryo shortly after implantation.

emerging disease Disease caused by a new strain of an existing pathogen or one that is now exploiting an increased availability of human hosts.

emphysema Lung disorder, often caused by smoking, in which the lungs become so distended and inelastic that gas exchange is difficult.

emulsification In digestion, the breaking of large fat globules into a suspension of fat droplets coated with bile salts.

encapsulated receptor Receptor surrounded by a capsule of epithelial or connective tissue; common near the body surface.

encephalitis Inflammation of the brain, usually caused by a virus.

end product Substance present at the end of a metabolic pathway.

endangered species Endemic (native) species highly vulnerable to extinction.

endemic disease A disease that occurs more or less continuously in a region.

endergonic reaction Chemical reaction resulting in a net gain in energy.

endocrine gland A ductless gland that secretes hormones, which usually enter interstitial fluid and then the bloodstream.

endocrine system System of cells, tissues, and organs that is functionally linked to the nervous system and that exerts control by way of hormones and other chemical secretions.

endocytosis (en-doe-sigh-TOE-sis) Movement of a substance into cells in which the substance becomes enclosed by a patch of plasma membrane that sinks into the cytoplasm, then forms a vesicle around it. Phagocytic cells also engulf pathogens this way.

endoderm [Gk. *endon,* within, and *derma,* skin] The inner primary tissue layer, or germ layer, of an embryo, which gives rise to the inner lining of the gut and organs derived from it.

endomembrane system System in cells that includes the endoplasmic reticulum, Golgi bodies, and various kinds of vesicles, and in which new proteins are modified into final form and lipids are assembled.

endometrium (en-doh-MEET-ree-um) [Gk. *metrios,* of the womb] Inner lining of the uterus consisting of connective tissue, glands, and blood vessels.

endoplasmic reticulum (ER) (en-doe-PLAZ-mik reh-TIK-yoo-lum) An organelle that begins at the nucleus and curves through the cytoplasm. In rough ER (which has many ribosomes on its cytoplasmic side), new polypeptide chains acquire specialized side chains. In many cells, smooth ER (with no attached ribosomes) is the main site of lipid synthesis.

endotherm Organism such as a human that maintains body temperature from within, generally by metabolic activity and controls over heat conservation and dissipation.

energy The capacity to do work.

energy carrier A molecule that delivers energy from one metabolic reaction site to another. ATP is the premier energy carrier; it readily donates energy to nearly all metabolic reactions.

energy pyramid A pyramid-shaped representation of an ecosystem's trophic structure (feeding levels), illustrating the energy losses at each transfer to a different feeding level.

enzyme (EN-zime) One of a class of proteins that greatly speed up (catalyze) reactions between specific substances. The substances that each type of enzyme acts upon are called its substrates.

eosinophil Fast-acting, phagocytic white blood cell that targets worms, fungi, and other large pathogens.

epidemic A disease outbreak in an area or population that occurs above predicted or normal levels.

epidermis The outermost tissue layer of skin.

epiglottis A flaplike structure at the start of the larynx, positioned to direct the movement of air into the trachea or food into the esophagus.

epinephrine (ep-ih-NEF-rin) Adrenal hormone that raises blood levels of glucose and fatty acids; also increases the heart's rate and force of contraction.

epiphyseal plate Cartilage that covers either end of a growing long bone, permitting the bone to lengthen. The epiphyseal plate is replaced by bone when growth stops in late adolescence.

epiphysis Each end of a long bone.

epithelium (ep-ih-THEE-lee-um) A tissue consisting of one or more layers of cells that covers the body's external surfaces and lines its internal cavities and tubes. Epithelium has one free surface; the opposite surface rests on a basement membrane between it and an underlying connective tissue. Epidermis is an example.

erythrocyte (eh-RITH-row-site) [Gk. *erythros,* red, and *kytos,* vessel] Red blood cell.

esophagus (ee-SOF-uh-gus) Tubular portion of the digestive system that receives swallowed food and leads to the stomach.

essential amino acid Any of eight amino acids from protein that the body cannot synthesize and must be obtained from food.

essential fatty acid Any of the fatty acids that the body cannot synthesize and must be obtained from food.

estrogen (ESS-tro-jen) A sex hormone that helps oocytes mature, triggers changes in the uterine lining during the menstrual cycle and pregnancy, and maintains secondary sexual traits; also influences body growth and development.

eukaryotic cell (yoo-carry-AH-tic) [Gk. *eu,* good, and *karyon,* kernel] A cell that has a "true nucleus" and other membrane-bound organelles. Compare *prokaryotic cell*.

evolution, biological [L. *evolutio,* act of unrolling] Genetic change within a line of descent over time. A population is evolving when some forms of a trait are becoming more or less common relative to the other kinds of traits. The shifts are evidence of changes in the relative abundances of alleles for that trait, as brought about by mutation, natural selection, genetic drift, and gene flow.

excitatory postsynaptic potential (EPSP) One of two competing signals at an input zone of a neuron; a graded potential that brings the neuron's plasma membrane closer to the threshold required for an action potential to fire.

excretion Any of several processes by which the urinary system removes excess water, excess or harmful solutes, or waste materials.

exercise Activity that increases the level of contractile activity in muscles.

exergonic reaction Chemical reaction that shows a net loss in energy.

exocrine gland (EK-suh-krin) [Gk. *es,* out of, and *krinein,* to separate] Glandular structure that secretes products, usually through ducts or tubes, to a free epithelial surface.

exocytosis (ek-so-sigh-TOE-sis) Movement of a substance out of a cell by means of a transport vesicle that fuses with the plasma membrane and releases its contents to the outside.

exon Of eukaryotic cells, any of the nucleotide sequences of a pre-mRNA molecule that are spliced together to form the mature mRNA transcript and are ultimately translated into protein.

expansion mutation A gene mutation in which a nucleotide sequence is repeated over and over.

experiment A test in which some phenomenon in the natural world is manipulated in controlled ways to gain insight into its function, structure, operation, or behavior.

expiration Expelling air from the lungs; exhaling.

exponential growth (ex-po-NEN-shul) Pattern of population growth in which greater and greater numbers of individuals are produced during the successive doubling times; the pattern that emerges when the per capita birth rate remains even slightly above the per capita death rate, putting aside the effects of immigration and emigration.

extinction Irrevocable loss of a species.

extracellular fluid All the fluid not inside cells; includes plasma (the liquid portion of blood) and tissue fluid (which occupies the spaces between cells and tissues).

extracellular matrix A material, largely secreted, that helps hold many animal tissues together in certain shapes; it consists of fibrous proteins and other components in a ground substance.

extraembryonic membranes Membranes that form along with a developing embryo, including the yolk sac, amnion, allantois, and chorion.

eyes Sensory organs that allow vision; they contain tissue with a dense array of photoreceptors.

F_1 (first filial generation) The offspring of an initial genetic cross.

F_2 (second filial generation) The offspring of parents who are the first filial generation from a genetic cross.

facilitated diffusion A form of passive transport where transport proteins provide a channel through which solutes cross a cell membrane.

FAD Flavin adenine dinucleotide, a nucleotide coenzyme. When delivering electrons and unbound protons (H^+) from one reaction to another, it is abbreviated $FADH_2$.

familial hypercholesterolemia Genetic disorder that leads to dangerously high blood cholesterol.

fat A lipid with a glycerol head and one, two, or three fatty acid tails. The tails of saturated fats have only single bonds between carbon atoms and hydrogen atoms attached to all other bonding sites. Tails of unsaturated fats additionally have one or more double bonds between certain carbon atoms.

fatty acid A long, flexible hydrocarbon chain with a —COOH group at one end.

faulty enamel trait Genetic disorder linked to the X chromosome in which tooth enamel fails to develop properly.

femur Thighbone; longest bone of the body.

fermentation [L. *fermentum,* yeast] A type of anaerobic pathway of ATP formation; it starts with glycolysis, ends when electrons are transferred back to one of the breakdown products or intermediates, and regenerates the NAD^+ required for the reaction. Its net yield is two ATP per glucose molecule broken down.

fertilization [L. *fertilis,* to carry, to bear] Fusion of a sperm nucleus with the nucleus of an egg, which thereupon becomes a zygote.

fetus Term applied to an embryo after it reaches the age of eight weeks.

fever Body temperature that has climbed above the normal set point, usually in response to infection. Mild fever promotes an increase in body defense activities.

fibrous connective tissue A specialized form of connective tissue that is strong and stretchy; the three types are loose, dense, and elastic.

fibrous joint Type of joint in which fibrous connective tissue unites the adjoining bones and no cavity is present.

fight–flight response The combination of sympathetic and parasympathetic nerve responses that prompt the body to react quickly to intense arousal.

filtration In urine formation, the process by which blood pressure forces water and solutes out of glomerular capillaries and into the cupped portion of a nephron wall (glomerulus).

flagellum (fluh-JELL-um), plural flagella [L., *whip*] Tail-like motile structure of many eukaryotic cells; it has a distinctive 9 + 2 array of microtubules. In humans only sperm have a flagellum.

fluid mosaic model Model of membrane structure in which proteins are embedded in a lipid bilayer or attached to one of its surfaces. The lipid molecules give the membrane its basic structure, impermeability to water-soluble molecules, and (through packing variations and movements) fluidity. Proteins carry out most membrane functions, such as transport, enzyme action, and reception of signals or substances.

follicle (FOLL-ih-kul) In an ovary, a primary oocyte (immature egg) together with the surrounding layer of cells.

food chain A straight-line sequence of who eats whom in an ecosystem.

food pyramid Chart of a purportedly well-balanced diet; continually being refined.

food web A network of cross-connecting, interlinked food chains encompassing primary producers and an array of consumers, detritivores, and decomposers.

forebrain Brain region that includes the cerebrum and cerebral cortex, the olfactory lobes, and the hypothalamus.

fossil Physical remains or other evidence of an organism that lived in the distant past. Most fossils are skeletons, shells, leaves, seeds, and tracks that were buried in rock layers before they decomposed.

fossil fuels The fossilized remains of ancient forests. Examples include oil, coal, and natural gas. Fossil fuels are nonrenewable resources.

fossilization How fossils form. An organism or traces of it become buried in sediments or volcanic ash. Water and dissolved inorganic compounds infiltrate the remains. Accumulating sediments exert pressure above the burial site. Over time, the pressure and chemical changes transform the remains to stony hardness.

fovea Funnel-shaped depression in the center of the retina where photoreceptors are densely arrayed and visual acuity is the greatest.

free nerve endings Thinly myelinated or unmyelinated branched endings of sensory neurons in skin and internal tissues. They serve as mechanoreceptors, thermoreceptors, or pain receptors.

free radical Any highly reactive molecule or molecule fragment having an unpaired electron.

FSH Follicle-stimulating hormone. The name comes from its function in females, in whom FSH helps stimulate follicle development in ovaries. In males, it acts in the testes as part of a sequence of events that trigger sperm production.

functional group An atom or group of atoms that is covalently bonded to the carbon backbone of an organic compound and that influences its behavior.

gallbladder Organ of the digestive system that stores bile secreted from the liver.

gamete (GAM-eet) A haploid cell that functions in sexual reproduction. Sperm and eggs are examples.

ganglion (GANG-lee-un), plural ganglia [Gk. *ganglion,* a swelling] A clustering of cell bodies of neurons in regions other than the brain or spinal cord.

gap junctions Channels that connect the cytoplasm of adjacent cells and help cells communicate by promoting the rapid transfer of ions and small molecules between them.

gastric juice Highly acidic mix of water and secretions from the stomach's glandular epithelium (HCl, mucus, pepsinogens, etc.) that kills ingested microbes and begins food breakdown.

gastrointestinal (GI) tract The digestive tube, extending from the mouth to the anus and including the stomach, small and large intestines, and other specialized regions with roles in food transport and digestion.

gastrulation (gas-tru-LAY-shun) The stage of embryonic development in which cells become arranged into primary tissue layers (germ layers); in humans, the layers are an inner endoderm, an intermediate mesoderm, and a surface ectoderm.

gene A unit of information about a heritable trait that is passed on from parents to offspring. Each gene has a specific location on a chromosome. Chemically, a gene is a sequence of nucleotides in a DNA molecule.

gene flow A microevolutionary process; a physical movement of alleles out of a population as individuals leave (emigrate) or enter (immigrate); allele frequencies change as a result.

gene library A mixed collection of bacteria that contain many different cloned DNA fragments.

gene mutation Small-scale change in the nucleotide sequence of a gene.

gene pair In diploid cells, the two alleles at a given locus on a pair of homologous chromosomes.

gene pool Sum total of all genotypes in a population. More accurately, allele pool.

gene therapy Generally, the transfer of one or more normal genes into body cells in order to correct a genetic defect.

genetic abnormality An uncommon version of an inherited trait.

genetic code [After L. *genesis,* to be born] The correspondence between nucleotide triplets in DNA (then in mRNA) and specific sequences of amino acids in the resulting polypeptide chains; the basic language of protein synthesis.

genetic disorder An inherited condition that results in mild to severe medical problems.

genetic drift A microevolutionary process; a change in allele frequencies over the generations due to chance events alone.

genetic engineering Altering the information content of DNA through use of recombinant DNA technology.

genetic recombination Presence of a new combination of alleles in a DNA molecule compared to the parental genotype; the result of processes such as crossing over at meiosis, chromosome rearrangements, gene mutation, and recombinant DNA technology.

genital herpes Infection of tissues in the genital area by a herpes simplex virus; an extremely contagious sexually transmitted disease.

genital warts Painless growths caused by infection of epithelium by the human papillomavirus.

genome All the DNA in a haploid number of chromosomes of a species.

genomics The study of whole genomes.

genotype (JEEN-oh-type) Genetic constitution of an individual. Can mean a single gene pair or the sum total of the individual's genes. Compare *phenotype.*

genus plural genera (JEEN-us, JEN-er-ah) [L. *genus,* race, origin] A grouping of species more closely related to one another in body form, ecology, and history than to others at the same level of classification.

germ cell The cell of sexual reproduction; germ cells give rise to gametes. Compare *somatic cell.*

germ layer One of three primary tissue layers that forms during gastrulation and that gives rise to certain tissues of the adult body. Compare ectoderm; endoderm; mesoderm.

gigantism Excessive growth caused by the overproduction of growth hormone during childhood.

gland A secretory cell or multicellular structure derived from epithelium and often connected to it.

glaucoma Disorder in which too much aqueous humor builds up inside the eyeball and collapses the blood vessels serving the retina.

glial cells *See* neuroglia.

glioma Cancer of the glial cells of the brain.

global climate change Major shifts in weather patterns worldwide.

global warming A long-term increase in the temperature of Earth's lower atmosphere.

glomerular capillaries The set of blood capillaries inside the Bowman's capsule of a nephron.

glomerulonephritis A general term for a large number of kidney disorders.

glomerulus (glow-MARE-you-luss), plural glomeruli [L. *glomus,* ball] The first portion of the nephron, where water and solutes are filtered from blood.

glucagon (GLUE-kuh-gone) Hormone that stimulates conversion of glycogen and amino acids to glucose; secreted by alpha cells of the pancreas when the flow of glucose decreases.

glucocorticoid Hormone secreted by the adrenal cortex that influences metabolic reactions that help maintain the blood glucose level.

gluconeogenesis The process by which liver cells synthesize glucose.

glycemic index A list that ranks a food according to its effect on blood sugar (glucose).

glyceride (GLISS-er-eyed) One of the molecules, commonly called fats and oils, that has one, two, or three fatty acid tails attached to a glycerol backbone. They are the body's most abundant lipids and its richest source of energy.

glycerol (GLISS-er-all) [Gk. *glykys,* sweet, and L. *oleum,* oil] A three-carbon molecule with three hydroxyl groups attached; together with fatty acids, a component of fats and oils.

glycogen (GLY-kuh-jen) A storage polysaccharide that can be readily broken down into glucose subunits.

glycolysis (gly-CALL-ih-sis) [Gk. *glykys,* sweet, and *lysis,* loosening or breaking apart] Initial reactions by which glucose (or some other organic compound) is partially broken down to pyruvate with a net yield of two ATP. Glycolysis occurs in the cell cytoplasm and oxygen has no role in it.

glycoprotein A protein having oligosaccharides covalently bonded to it. Most human cell surface proteins and many proteins circulating in blood are glycoproteins.

Golgi body (GOHL-gee) Organelle in which newly synthesized polypeptide chains as well as lipids are modified and packaged in vesicles for export or for transport to specific locations within the cytoplasm.

gonad (GO-nad) Primary reproductive organ in which gametes are produced. Ovaries and testes are gonads.

gonorrhea The sexually transmitted disease caused by the bacterium *Neisseria gonorrhoeae.* This bacterium can infect epithelial cells of the genital tract, rectum, eye membranes, and the throat.

graded potential Of neurons, a local signal that slightly changes the voltage difference across a small patch of the plasma membrane. Such signals vary in magnitude, depending on the stimulus. With prolonged or intense stimulation, they may spread to a trigger zone of the membrane and initiate an action potential.

granulocyte Class of white blood cells that have a lobed nucleus and various types of granules in the cytoplasm; includes neutrophils, eosinophils, and basophils.

granulosa cell An estrogen-secreting cell of the epithelial lining of a follicle.

Graves disease A toxic goiter caused by an excess of thyroid hormones in the blood.

gray matter The dendrites, neuron cell bodies, and neuroglial cells of the spinal cord and cerebral cortex.

greenhouse effect Warming of the lower atmosphere due to the presence of the following greenhouse gases: carbon dioxide, methane, nitrous oxide, ozone, water vapor, and chlorofluorocarbons.

ground substance The intercellular material made up of cell secretions and other noncellular components.

growth factor A type of signaling molecule that can influence growth by regulating the rate at which target cells divide.

guanine A nitrogen-containing base; one of those present in nucleotide building blocks of DNA and RNA.

habitat [L. *habitare,* to live in] The type of place where an organism normally lives, characterized by physical features, chemical features, and the presence of certain other species.

hair A flexible structure of mostly keratinized cells, rooted in skin with a shaft above its surface.

hair cell Type of mechanoreceptor that may give rise to action potentials when bent or tilted.

half-life The time it takes for half of a quantity of radioisotope to decay into a different, more stable isotope.

haploid number (HAP-loyd) The chromosome number of a gamete that, as an outcome of meiosis, is only half that of the parent germ cell (it has only one of each pair of homologous chromosomes). Compare *diploid number.*

HCG Human chorionic gonadotropin. A hormone that helps maintain the lining of the uterus during the menstrual cycle and during the first trimester of pregnancy.

HDL A high-density lipoprotein in blood; it transports cholesterol to the liver for further processing.

headache Pain in the head often caused by tension in muscles or blood vessels in the face, neck, and scalp.

heart Muscular pump that keeps blood circulating through the body.

heart attack Damage to or death of heart muscle.

heart failure Disorder in which the heart is weakened and does not pump blood with normal efficiency.

helper T cell Type of T lymphocyte that produces and secretes chemicals that promote formation of large effector and memory cell populations.

hemoglobin (HEEM-oh-glow-bin) [Gk. *haima,* blood, and L. *globus,* ball] Iron-containing, oxygen-transporting protein that gives red blood cells their color.

hemophilia Genetic disorder in which blood does not clot normally; the affected person risks dying from any injury that causes bleeding.

hemostasis (hee-mow-STAY-sis) [Gk. *haima,* blood, and *stasis,* standing] Stopping of blood loss from a damaged blood vessel through coagulation, blood vessel spasm, platelet plug formation, and other mechanisms.

hepatic portal vein Vessel that receives nutrient-laden blood from villi of the small intestine and transports it to the liver, where excess glucose is removed. The blood then returns to the general circulation via a hepatic vein.

hepatitis B An extremely contagious, sexually transmitted disease caused by infection by the hepatitis B virus. Chronic hepatitis can lead to liver cirrhosis or cancer.

hepatitis C Blood-borne virus that causes severe liver cirrhosis and sometimes cancer.

herbivore [L. *herba,* grass, and *vovare,* to devour] Plant-eating animal.

heterotroph (HET-er-oh-trofe) [Gk. *heteros,* other, and *trophos,* feeder] Organism that cannot synthesize its own organic compounds and must obtain nourishment by feeding on autotrophs, each other, or organic wastes. Animals, fungi, many protists, and most bacteria are heterotrophs. Compare *autotroph.*

heterozygous condition (het-er-oh-ZYE-guss) [Gk. *zygoun,* join together] For a given trait, having nonidentical alleles at a particular locus on a pair of homologous chromosomes.

hindbrain One of the three divisions of the brain; the medulla oblongata, cerebellum, and pons; includes reflex centers for respiration, blood circulation, and other basic functions; also coordinates motor responses and many complex reflexes.

histamine Local signaling molecule that promotes inflammation; makes arterioles dilate and capillaries more permeable (leaky).

histone Any of a class of proteins that are intimately associated with DNA and that are largely responsible for its structural (and possibly functional) organization in eukaryotic chromosomes.

histoplasmosis Lung disease caused by a fungus.

HIV Human immunodeficiency virus, which destroys key cells of the immune system and causes AIDS.

Hodgkin's disease Malignant lymphoma whose symptoms include intense itching and night sweats.

homeostasis (hoe-me-oh-STAY-sis) [Gk. *homo,* same, and *stasis,* standing] A physiological state in which the physical and chemical conditions of the internal environment are being maintained within tolerable ranges.

homeostatic feedback loop An interaction in which an organ (or structure) stimulates or inhibits the output of another organ, then shuts down or increases this activity when it detects that the output has exceeded or fallen below a set point.

hominid [L. *homo,* man] All species on the evolutionary branch leading to modern humans. *Homo sapiens* is the only living representative.

hominoids Apes, humans, and their recent ancestors.

Homo erectus A hominid lineage that emerged between 1.5 million and 300,000 years ago and that may include the direct ancestors of modern humans.

Homo habilis A type of early hominid that may have been the maker of stone tools that date from about 2.5 million years ago.

Homo sapiens The species of modern humans that emerged between 300,000 and 200,000 years ago.

homologous chromosome (huh-MOLL-uh-gus) [Gk. *homologia,* correspondence] (also called a *homologue*) One of a pair of chromosomes that resemble each other in size, shape, and the genes they carry, and that line up with each other at meiosis I. The X and Y chromosomes differ in these respects but still function as homologues.

homologous structure The same body part, modified in different ways, in different lines of descent from a common ancestor.

homozygous condition (hoe-moe-ZYE-guss) Having two identical alleles at a given locus (on a pair of homologous chromosomes).

homozygous dominant condition Having two dominant alleles at a given gene locus (on a pair of homologous chromosomes).

homozygous recessive condition Having two recessive alleles at a given gene locus (on a pair of homologous chromosomes).

hormone [Gk. *hormon,* to stir up, set in motion] Any of the signaling molecules secreted from endocrine glands, endocrine cells, and some neurons that the bloodstream distributes to nonadjacent target cells (any cell having receptors for that hormone).

host An organism that can be infected by a pathogen.

Human Genome Project A research project in which the estimated 3 billion nucleotides present in the DNA of human chromosomes were sequenced.

human immunodeficiency virus (HIV) The pathogen that causes AIDS (acquired immune deficiency syndrome) by destroying lymphocytes.

human papillomavirus (HPV) Virus that causes genital warts; strains of HPV are found in nearly all cervical cancers.

humerus The long bone of the upper arm.

Huntington disease Genetic disorder in which the basal nuclei of the brain degenerate.

hybrid offspring Of a genetic cross, offspring with a pair of nonidentical alleles for a trait.

hydrocarbon A molecule having only hydrogen atoms attached to a carbon backbone.

hydrogen bond A weak attraction between an electronegative atom and a hydrogen atom that is already taking part in a polar covalent bond.

hydrogen ion A free (unbound) proton; a hydrogen atom that has lost its electron and so bears a positive charge (H^+).

hydrologic cycle A biogeochemical cycle, driven by solar energy, in which water moves slowly through the atmosphere, on or through surface layers of land masses, to the ocean and back again.

hydrolysis (high-DRAWL-ih-sis) [L. *hydro,* water, and Gk. *lysis,* loosening or breaking apart] Enzyme-driven reaction in which covalent bonds break, splitting a molecule into two or more parts, and H^+ and OH^- (derived from a water molecule) become attached to the exposed bonding sites.

hydrophilic substance [Gk. *philos,* loving] A polar substance that is attracted to the polar water molecule and so dissolves easily in water. Sugars are examples.

hydrophobic substance [Gk. *phobos,* dreading] A nonpolar substance that is repelled by the polar water molecule and so does not readily dissolve in water. Oil is an example.

hydroxide ion Ionized compound of one oxygen and one hydrogen atom (OH^-).

hyperopia Also known as farsightedness; nearby objects appear blurry because their images are focused behind the retina, not on it.

hyperplasia An abnormal enlargement of tissue that leads to a tumor.

hypertonic solution A fluid having a greater concentration of solutes relative to another fluid.

hypodermis A subcutaneous layer having stored fat that helps insulate the body; although not part of skin, it anchors skin while allowing it some freedom of movement.

hypothalamus [Gk. *hypo,* under, and *thalamos,* inner chamber] A brain center that monitors visceral activities (such as salt–water balance and temperature control) and that influences related forms of behavior (as in hunger, thirst, and sex).

hypothesis A possible explanation of a specific phenomenon.

hypotonic solution A fluid that has a lower concentration of solutes relative to another fluid.

immune response A series of events by which B and T cells recognize a specific antigen, undergo repeated cell divisions that form huge lymphocyte populations, and differentiate into subpopulations of effector and memory cells. Effector cells engage and destroy antigen-bearing agents. Memory cells enter a resting phase and are activated during subsequent encounters with the same antigen.

immune system Interacting white blood cells that defend the body through self/nonself recognition, specificity, and memory. T and B cell antigen receptors ignore the body's own cells yet collectively recognize a billion specific threats. Some B and T cells formed in a primary response are set aside as memory cells for future battles with the same antigen.

immunity The body's overall ability to resist and combat any substance foreign to itself.

immunization Various processes, including vaccination, that promote increased immunity against specific diseases.

immunodeficiency Disorder in which a person's immune system is weakened or absent.

immunoglobulin Any of the five classes of antibodies that participate in defense and immune responses. Examples are IgM antibodies (first to be secreted during immune responses) and IgG antibodies (which activate complement proteins and neutralize many toxins).

immunotherapy Procedures that enhance a person's immunological defenses against tumors or certain pathogens.

implantation Series of events in which a blastocyst (pre-embryo) invades the endometrium (lining of the uterus) and becomes embedded there.

independent assortment Genetic principle that each gene pair tends to assort into gametes independently of other gene pairs located on nonhomologous chromosomes.

induced-fit model Model of enzyme action whereby a bound substrate induces changes in the shape of the enzyme's active site, resulting in a more precise molecular fit between the enzyme and its substrate.

inductive logic Pattern of thinking by which a person derives a general statement from specific observations.

infection Invasion and multiplication of a pathogen in a host. *Disease* follows if defenses are not mobilized fast enough; the pathogen's activities interfere with normal body functions.

infectious mononucleosis A disease caused by the Epstein-Barr virus, which affects white blood cells, causing them to overproduce agranulocytes.

inflammation Process in which, in response to tissue damage or irritation, phagocytes and plasma proteins, including complement proteins, leave the bloodstream, then defend and help repair the tissue. Occurs during both nonspecific and specific (immune) defense responses.

influenza Disease in which an infection begins in the nose or throat and spreads to the lungs.

inheritance The transmission, from parents to offspring, of body structures and functions that have a genetic basis.

inhibiting hormone A signaling molecule produced and released by the hypothalamus that controls secretions by the anterior lobe of the pituitary gland.

inhibitory postsynaptic potential (IPSP) Of neurons, one of two competing types of graded potentials at an input zone; tends to drive the resting membrane potential away from the threshold required to trigger a nerve impulse.

innate immunity The body's inborn, preset immune responses, which act quickly when tissue is damaged or microbes have invaded.

inner cell mass In early development, a clump of cells in the blastocyst that will give rise to the embryonic disk.

insertion The end of a muscle that is attached to the bone that moves most when the muscle contracts.

inspiration The drawing of air into the lungs; inhaling.

insulin Pancreatic hormone that lowers the level of glucose in blood by causing cells to take up glucose; also promotes the synthesis of fat and protein and inhibits the conversion of protein to glucose.

integration, neural [L. *integrare,* to coordinate] Moment-by-moment summation of all excitatory and inhibitory synapses acting on a neuron; occurs at each level of synapsing in a nervous system.

integrator Of homeostatic systems, a control point where different bits of information are pulled together in the selection of a response. The brain is an example.

integument [L. *integere,* to cover] The organ system that provides a protective body covering; in humans, the skin, oil and sweat glands, hair, and nails.

interferon Protein produced by T cells that interferes with viral replication. Some interferons also stimulate the tumor-killing activity of macrophages.

interleukin One of a variety of chemical communication signals—secreted by macrophages and helper T cells—that drive immune responses.

intermediate Substance that forms between the start and end of a metabolic pathway.

intermediate filament A ropelike element of the cytoskeleton that mechanically strengthens cells.

internal environment The fluid bathing body cells and tissues; it consists of blood plus interstitial fluid.

internal respiration Movement of oxygen into tissues from the blood, and of carbon dioxide from tissues into the blood.

interneuron Any of the neurons in the brain and spinal cord that integrate information arriving from sensory neurons and that influence other neurons in turn.

interphase Of cell cycles, the time interval between nuclear divisions in which a cell increases its mass, roughly doubles the number of its cytoplasmic components, and finally duplicates its chromosomes (replicates its DNA).

interstitial fluid (in-ter-STISH-ul) [L. *interstitus,* to stand in the middle of something] The extracellular fluid in spaces between cells and tissues.

intervertebral disk One of a number of disk-shaped structures containing cartilage that serve as shock absorbers and flex points between vertebrae.

intracellular fluid The fluid inside cells.

intron A noncoding portion of a newly formed mRNA molecule.

inversion A change in a chromosome's structure after a segment separated from it was then inserted at the same place, but in reverse. The reversal alters the position and order of the chromosome's genes.

in vitro fertilization Conception outside the body ("in glass" petri dishes or test tubes).

ion (EYE-on) An atom or a compound that has gained or lost one or more electrons and hence has acquired an overall negative or positive charge.

ionic bond An association between ions of opposite charge.

iris Of the eye, a circular pigmented region behind the cornea with a "hole" in its center (the pupil) through which incoming light enters.

isotonic solution A fluid having the same solute concentration as a fluid against which it is being compared.

isotope (EYE-so-tope) For a given element, an atom with the same number of protons as the other atoms but with a different number of neutrons.

joint An area of contact or near-contact between bones.

juxtaglomerular apparatus In kidney nephrons, a place where the arterioles of the glomerulus come into contact with the distal tubule. Cells in this region secrete renin, which triggers hormonal events that stimulate increased reabsorption of sodium.

karyotype (CARRY-oh-type) A preparation of an individual's of metaphase chromosomes arranged by length, shape, and the location of the centromere.

keratin A tough, water-insoluble protein manufactured by most epidermal cells.

keratinization (care-at-in-iz-AY-shun) Process by which keratin-producing epidermal cells of skin die and collect at the skin surface as keratin-containing "bags" that form a barrier against dehydration, bacteria, and many toxic substances.

keratinocytes Cells of the epidermis that make keratin.

kidney One of a pair of organs that filter organic wastes, toxins, and other substances from the blood and help regulate the volume and solute concentrations of extracellular fluid.

kidney stones Deposits of uric acid, calcium salts, and other substances that have settled out of urine and collected in the renal pelvis.

kilocalorie 1,000 calories of heat energy, or the amount of energy needed to raise the temperature of 1 kilogram of water by 1°C; the unit of measure for the caloric value of foods.

Klinefelter syndrome Disorder that produces the genotype XXY; affected males have low fertility and often some mental retardation.

Krebs cycle Together with a few conversion steps that precede it, the stage of aerobic respiration in which pyruvate is completely broken down to carbon dioxide and water. Coenzymes accept the protons (H^+) and electrons removed from intermediates during the reactions and deliver them to the next stage.

lactate fermentation Anaerobic pathway of ATP formation in which pyruvate from glycolysis is converted to the three-carbon compound lactate, and NAD^+ (a coenzyme used in the reactions) is regenerated. Its net yield is two ATP.

lactation The production of milk by hormone-primed mammary glands.

lacteal Small lymph vessel in villi of the small intestine that receives absorbed triglycerides. Triglycerides move from the lymphatic system to the general circulation.

large-cell carcinoma Type of lung cancer; along with adenocarcinomas, it accounts for 48 percent of all lung cancers.

large intestine The colon; a region of the GI tract that receives unabsorbed food residues from the small intestine and concentrates and stores feces until they are expelled from the body.

larynx (LARE-inks) A tubular airway that leads to the lungs. It contains vocal cords, where sound waves used in speech are produced.

latency Of viruses, a period of time during which viral genes remain inactive inside the host cell.

LDL Low-density lipoprotein that transports cholesterol; excess amounts contribute to atherosclerosis.

lens Of the eye, a saucer-shaped region behind the iris containing multiple layers of transparent proteins. Ligaments can move the lens, which focuses incoming light onto photoreceptors in the retina.

leukemias Cancers of the white blood cells that cause the runaway multiplication of abnormal cells and the destruction of bone marrow.

leukocytes White blood cells.

Leydig cell In testes, cells in connective tissue around the seminiferous tubules that secrete testosterone and other signaling molecules.

LH Luteinizing hormone, secreted by the anterior lobe of the pituitary gland. In males it acts on Leydig cells of the testes and prompts them to secrete testosterone. In females, LH stimulates follicle development in the ovaries.

life cycle Recurring series of genetically programmed events from the time individuals are produced until they themselves reproduce.

ligament A strap of dense, elastic, regular connective tissue that connects two bones at a joint.

limbic system Brain regions that, along with the cerebral cortex, collectively govern emotions.

limiting factor Any essential resource that is in short supply and so limits population growth.

lineage (LIN-ee-age) A line of descent.

linkage The tendency of genes located on the same chromosome to end up in the same gamete. For any two of those genes, the probability that crossing over will disrupt the linkage is proportional to the distance separating them.

lipid A greasy or oily compound of mostly carbon and hydrogen that shows little tendency to dissolve in water, but that dissolves in nonpolar solvents (such as ether). Cells use lipids as energy stores and structural materials, especially in membranes.

lipid bilayer The structural basis of cell membranes, consisting of two layers of mostly phospholipid molecules. Hydrophilic heads force all fatty acid tails of the lipids to become sandwiched between the hydrophilic heads.

lipoprotein Molecule that forms when proteins circulating in blood combine with cholesterol, triglycerides, and phospholipids absorbed from the small intestine.

liver Organ with roles in storing and interconverting carbohydrates, lipids, and proteins absorbed from the gut; disposing of nitrogen-containing wastes; and other tasks.

local signaling molecule A molecule that alters chemical conditions in the immediate vicinity where it is secreted, then is swiftly broken down.

locus (LOW-cuss) The location of a particular gene on a chromosome.

logistic growth (low-JIS-tik) Pattern of population growth in which a low-density population slowly increases in size, goes through a rapid growth phase, then levels off once the carrying capacity is reached.

loop of Henle The hairpin-shaped, tubular region of a nephron that functions in reabsorption of water and solutes.

loose connective tissue Flexible fibrous connective tissue with few fibers and cells.

lung One of a pair of sac-shaped organs that provide a moist surface for gas exchange.

lung cancer Malignant tumor in the lungs, most often caused by carcinogens in cigarette smoke.

lymph (limf) [L. *lympha,* water] Tissue fluid that has moved into the vessels of the lymphatic system.

lymph capillary A small-diameter vessel of the lymph vascular system that has no obvious entrance; tissue fluid moves inward by passing between overlapping endothelial cells at the vessel's tip.

lymph node A lymphoid organ that serves as a battleground of the immune system; each lymph node is packed with macrophages and lymphocytes that cleanse lymph of pathogens before it reaches the blood.

lymph vascular system [*vasculum,* a small vessel] The vessels of the lymphatic system, which take up and transport excess tissue fluid and reclaimable solutes as well as fats absorbed from the digestive tract.

lymphatic system An organ system with vessels that take up fluid and solutes from interstitial fluid and deliver them to the bloodstream; its lymphoid organs have roles in immunity.

lymphocyte A T cell or B cell.

lymphoid organ The lymph nodes, spleen, thymus, tonsils, adenoids, and other organs with roles in immunity.

lymphoma Cancer of lymphoid tissues in organs such as lymph nodes.

lysis [Gk. *lysis,* a loosening] Essentially, damage to a plasma membrane that leads to cell death.

lysosome (LYE-so-sohm) A cell organelle that contains enzymes that can break down polysaccharides, proteins, nucleic acids, and some lipids.

lysozyme Present in mucous membranes that line body surfaces, an infection-fighting enzyme that attacks and destroys various types of bacteria.

macroevolution The large-scale patterns, trends, and rates of change among groups of species.

macrophage A phagocytic white blood cell. It engulfs anything detected as foreign. Some also become antigen-presenting cells that serve as the trigger for immune responses by T and B lymphocytes. Compare *antigen-presenting cell*.

macular degeneration Disorder in which part of the retina breaks down and causes a blind spot.

malabsorption disorder Disease caused by anything that interferes with the uptake of nutrients across the lining of the small intestine.

malaria Disease due to infection by a protozoan (transmitted by mosquitos); symptoms include shaking, chills, and a high fever.

malignant melanoma The most dangerous form of skin cancer that typically develops after intense exposure to the sun.

malnutrition A state in which body functions or development suffer due to inadequate or unbalanced food intake.

mammal A type of vertebrate; the only animal having offspring that are nourished by milk produced by mammary glands of females.

mandible The lower jaw; the largest single facial bone.

Marfan syndrome Genetic disorder that disrupts the structure and function of the protein fibrillin, a component of connective tissue. In particular smooth muscle in the aorta may be affected, causing the aorta to burst.

mass extinction An abrupt rise in extinction rates above the background level; a catastrophic, global event in which large groups of organisms are wiped out simultaneously.

mass number The total number of protons and neutrons in an atom's nucleus. The relative masses of atoms are also called atomic weights.

mast cell A type of white blood cell that releases enzymes and histamine during tissue inflammation.

matrix In connective tissue, fiberlike structural proteins together with a "ground substance" of polysaccharides that give each kind of tissue its particular properties.

mechanical processing In digestion, the breaking up and mixing of food by the teeth, tongue, and peristalsis.

mechanoreceptor Sensory cell or cell part that detects mechanical energy associated with changes in pressure, position, or acceleration.

medical imaging Any of several diagnostic methods including magnetic resonance imaging (MRI), X-ray, ultrasound, and cat scanning (CT).

medulla oblongata Part of the brain stem with reflex centers for respiration, blood circulation, and other vital functions.

meiosis (my-OH-sis) [Gk. *meioun,* to diminish] Two-stage nuclear division process in which the chromosome number of a germ cell is reduced by half, to the haploid number. (Each daughter nucleus ends up with one of each type of chromosome.) Meiosis forms gametes.

melanocytes Cells in the deepest layer of epidermis that produce the brown-black pigment melanin found in keratinocytes.

membrane attack complexes Structures that form pores in the plasma membrane of a pathogen, causing lysis (disintegration).

memory The storage and retrieval of information about previous experiences; underlies the capacity for learning.

memory cell Any of the various B or T cells of the immune system that are formed in response to invasion by a foreign agent and that are available to mount a rapid attack if the same type of invader reappears.

meninges Membranes of connective tissue that are layered between the skull bones and the brain and cover and protect the neurons and blood vessels that service the brain.

meningitis Inflammation of the meninges covering the brain and/or spinal cord.

menopause (MEN-uh-pozz) [L. *mensis,* month, and *pausa,* stop] End of the reproductive period of a human female's life cycle.

menstrual cycle The cyclic release of oocytes and priming of the endometrium (lining of the uterus) to receive a fertilized egg; the complete cycle averages about 28 days in female humans.

menstruation Periodic sloughing of the blood-enriched lining of the uterus when pregnancy does not occur.

mesoderm (MEH-so-derm) [Gk. *mesos,* middle, and *derm,* skin] In an embryo, a primary tissue layer (germ layer) between ectoderm and endoderm. Gives rise to muscle; organs of circulation, reproduction, and excretion; most of the internal skeleton; and connective tissue layers of the gastrointestinal tract and integument.

messenger RNA (mRNA) A linear sequence of ribonucleotides transcribed from DNA and translated into a polypeptide chain; the only type of RNA that carries protein-building instructions.

metabolic acidosis Lower than optimal blood pH caused by diabetes mellitus.

metabolic pathway An orderly sequence of enzyme-driven reactions by which cells maintain, increase, or decrease the concentrations of particular substances.

metabolic syndrome Slightly elevated blood sugar that increases the risk of developing type 2 diabetes.

metabolism (meh-TAB-oh-lizm) [Gk. *meta,* change] All controlled, enzyme-driven chemical reactions by which cells acquire and use energy. Through these reactions, cells synthesize, store, break apart, and eliminate substances in ways that contribute to growth, survival, and reproduction.

metaphase Of mitosis or meiosis II, the stage when each duplicated chromosome has become positioned at the midpoint of the microtubular spindle, with its two sister chromatids attached to microtubules from opposite spindle poles. Of meiosis I, the stage when all pairs of homologous chromosomes are positioned at the spindle's midpoint, with the two members of each pair attached to opposite spindle poles.

metastasis The process in which cancer cells break away from a primary tumor and migrate (via blood or lymphatic tissues) to other locations, where they establish new cancer sites.

MHC marker Any of a variety of proteins that are self markers. Some occur on all body cells of an individual; others occur only on macrophages and lymphocytes.

micelle (my-CELL) Tiny droplet of bile salts, fatty acids, and monoglycerides; plays a role in fat absorption from the small intestine.

microevolution Changes in allele frequencies brought about by mutation, genetic drift, gene flow, and natural selection.

microfilament [Gk. *mikros,* small, and L. *filum,* thread] One of a variety of cytoskeletal components. Actin and myosin filaments are examples.

micrograph Photograph of an image brought into view with the aid of a microscope.

microorganism Organism, usually single-celled, too small to be observed without a microscope.

microtubule A cytoskeletal element with roles in cell shape, motion, and growth and in the structure of cilia and flagella.

microvillus (my-crow-VILL-us) [L. *villus,* shaggy hair] A slender extension of the cell surface that functions in absorption or secretion.

midbrain A brain region that evolved as a coordination center for reflex responses to visual and auditory input; together with the pons and medulla oblongata, part of the brain stem, which includes the reticular formation.

mineral An inorganic substance required for the normal functioning of body cells.

mineralocorticoid Hormone secreted by the adrenal cortex that mainly regulates the concentrations of mineral salts in extracellular fluid.

miscarriage The spontaneous expulsion of an embryo or fetus.

mitochondrion (my-toe-KON-dree-on), plural mitochondria. Organelle that specializes in ATP formation; it is the site of the second and third stages of aerobic respiration.

mitosis (my-TOE-sis) [Gk. *mitos,* thread] Type of nuclear division that maintains the parental chromosome number for daughter cells. It is the basis of bodily growth and the repair of tissue damage.

mixture Atoms of two or more elements intermingled in proportions that can and usually do vary.

molecule A unit of matter in which chemical bonding holds together two or more atoms of the same or different elements.

monoclonal antibody [Gk. *monos,* alone] Antibody produced in the laboratory by a population of genetically identical cells that are clones of a single "parent" antibody-producing cell.

monohybrid cross In genetics, an experimental cross in which offspring inherit a pair of nonidentical alleles for a single trait being studied, so that they are heterozygous.

monomer A small molecule that is commonly a subunit of polymers, such as the sugar monomers of starch.

monosaccharide (mon-oh-SAK-ah-ride) [Gk. *sakharon,* sugar] The simplest carbohydrate, with only one sugar unit. Glucose is an example.

monosomy Condition in which one of the chromosomes in a gamete has no homologue.

morphogenesis (more-foe-JEN-ih-sis) [Gk. *morphe,* form, and *genesis,* origin] Processes by which differentiated cells in an embryo become organized into tissues and organs.

morphological convergence Process in which lineages that are only distantly related evolve in response to similar environmental pressures, becoming similar in appearance, functions, or both. Analogous structures are evidence of this evolutionary pattern.

morula A compact ball of sixteen embryonic cells formed after the third round of cleavage.

motility In digestion, the movement of ingested material through the GI tract.

motor neuron A neuron that delivers signals from the brain and spinal cord that can stimulate or inhibit the body's effectors (muscles, glands, or both).

motor protein A type of protein that can move cell parts in a sustained, directional way.

motor unit A motor neuron and the muscle fibers under its control.

mucuous membranes (mucosae) Pink, moist membranes that line the tubes and cavities of various body systems; most absorb or secrete substances.

multifactorial trait A trait that is shaped by more than one gene as well as by environmental factors.

multiple allele system A gene that has three or more different molecular forms (alleles).

multiple sclerosis Autoimmune disease that can be triggered by a virus and destroys myelin sheaths of neurons in the central nervous system.

muscle fatigue A decline in the ability of a muscle to contract; occurs when a muscle has been kept in a state of strong contraction as a result of continuous, high-frequency stimulation.

muscle tension A mechanical force, exerted by a contracting muscle, that resists opposing forces such as gravity and the weight of objects being lifted.

muscle tissue Tissue having cells able to contract in response to stimulation, then passively lengthen and so return to their resting state.

muscle tone In muscles, a steady low-level contracted state that helps stabilize joints and maintain general muscle health.

muscle twitch Muscle response in which the muscle contracts briefly, then relaxes, when a brief stimulus activates a motor unit.

muscular system Skeletal muscles, which attach to bones and pull on them to move the body and its parts.

mutation, gene [L. *mutatus,* a change] A heritable change in DNA due to the deletion, addition, or substitution of one or several bases in the nucleotide sequence.

myelin sheath Of many sensory and motor neurons, an axonal sheath that affects how fast action potentials travel; formed from the plasma membranes of Schwann cells that wrap repeatedly around the axon and are separated from each other by a small node.

myocardium The cardiac muscle tissue.

myofibril (MY-oh-fy-brill) One of many threadlike structures inside a muscle cell; each is functionally divided into sarcomeres, the basic units of contraction.

myopia Also known as nearsightedness; distant objects appear blurry because their images are focused in front of the retina, not on it.

myosin (MY-uh-sin) A contractile protein. In muscle cells, it interacts with the protein actin to bring about contraction.

NAD^+ Nicotinamide adenine dinucleotide; a nucleotide coenzyme. When carrying electrons and unbound protons (H^+) between reaction sites, it is abbreviated NADH.

NADP Nicotinamide adenine dinucleotide phosphate; a phosphorylated nucleotide coenzyme. When carrying electrons and unbound protons (H^+) between reaction sites, it is abbreviated $NADPH_2$.

nasal cavity The region of the respiratory system in the nosewhere inhaled air is warmed, moistened, and filtered of airborne particles and dust.

natural killer cell Cell of the immune system, a type of lymphocyte, that kills tumor cells (by lysis) or cells infected by a virus.

natural selection A difference in survival and reproduction among members of a population that vary in one or more traits.

negative feedback mechanism A homeostatic feedback mechanism in which an activity changes some condition in the internal environment and so triggers a response that reverses the change.

nephritis Inflammation of the kidneys.

nephron (NEFF-ron) [Gk. *nephros,* kidney] Of the kidney, a slender tubule in which water and solutes filtered from blood are selectively reabsorbed and in which urine forms.

nerve Cordlike communication line of the peripheral nervous system, composed of axons of sensory neurons, motor neurons, or both, encased in connective tissue. In the brain and spinal cord, similar cordlike bundles are called nerve tracts.

nerve impulse *See* action potential.

nerve tract A bundle of myelinated axons of interneurons inside the spinal cord and brain.

nervous system System of neurons oriented relative to one another in precise message-conducting and information-processing pathways.

nervous tissue Tissue composed of neurons and (in the central nervous system) neuroglia.

neural tube Embryonic forerunner of the brain and spinal cord.

neuroendocrine control center The parts of the hypothalamus and pituitary gland that interact to control many body functions.

neurofibromatosis Genetic disorder that occurs when a transposable element is inserted in a particular location in a gene.

neuroglia (nur-oh-GLEE-uh) Cells that structurally and metabolically support neurons. They make up about half the volume of nervous tissue in the human body.

neuromodulator A signaling molecule that influences the effects of transmitter substances by enhancing or reducing membrane responses in target neurons.

neuromuscular junction Chemical synapse between axon terminals of a motor neuron and a muscle cell.

neuron A nerve cell; the basic unit of communication in the nervous system. Neurons collectively sense environmental change, integrate sensory inputs, then activate muscles or glands that initiate or carry out responses.

neurotransmitter Any of the class of signaling molecules that are secreted from neurons, act on adjacent cells, and are then rapidly degraded or recycled.

neutron Unit of matter, one or more of which occupies the atomic nucleus. Neutrons have mass but no electric charge.

neutrophil Phagocytic white blood cell that takes part in inflammatory responses against bacteria.

niche (nitch) [L. *nidas,* nest] The full range of physical and biological conditions under which members of a species can live and reproduce.

night blindness Reduced visual capacity in dim light, caused by vitamin A deficiency.

nitrification (nye-trih-fih-KAY-shun) A process in which certain bacteria strip electrons from ammonia or ammonium present in soil. The end product, nitrite (NO_2^-), is broken down to nitrate (NO_3^-) by different bacteria.

nitrogen cycle Biogeochemical cycle in which gaseous nitrogen is captured by nitrogen-fixing microorganisms and then moves through organisms and ecosystems before being returned to the atmosphere. The atmosphere is the largest reservoir of nitrogen.

nitrogen fixation Process by which a few kinds of bacteria convert gaseous nitrogen (N_2) to ammonia.

nociceptor A receptor, such as a free nerve ending, that detects stimuli causing tissue damage.

nondisjunction Failure of one or more chromosomes to separate properly during mitosis or meiosis.

nongonococcal urethritis (NGU) An inflammation of the urethra; often caused by infection by the bacterium that causes chlamydia and considered a sexually transmitted disease.

non-Hodgkin lymphoma Lymphoma consisting of a group of malignant tumors of B or T lymphocytes.

nonpoint source A source of pollution not tied to a particular location.

nonrenewable resource A natural resource that exists in a finite amount and cannot be replenished.

nonsteroid hormone A type of water-soluble hormone, such as a protein hormone, that cannot cross the lipid bilayer of a target cell. These hormones enter the cell by receptor-mediated endocytosis, or they bind to receptors that activate membrane proteins or second messengers within the cell.

nosocomial infection An infection that is acquired in a hospital, usually by direct contact with a microbe.

nuclear envelope A double membrane (two lipid bilayers and associated proteins) that is the outermost portion of a cell nucleus.

nucleic acid (noo-CLAY-ik) A long, single- or double-stranded chain of four different nucleotides joined at their phosphate groups. Nucleic acids differ in which nucleotide base follows the next in the sequence. DNA and RNA are examples.

nucleolus (noo-KLEE-oh-lus) [L. *nucleolus,* a little kernel] Within the nucleus of a nondividing cell, a site where the protein and RNA subunits of ribosomes are assembled.

nucleosome (NOO-KLEE-oh-sohm) Of chromosomes, one of many organizational units, each consisting of a small stretch of DNA looped twice around a "spool" of histone molecules, which another histone molecule stabilizes.

nucleotide (NOO-klee-oh-tide) A small organic compound having a five-carbon sugar (deoxyribose), nitrogen-containing base, and phosphate group. Nucleotides are the structural units of adenosine phosphates, nucleotide coenzymes, and nucleic acids.

nucleotide coenzyme A protein that transports hydrogen atoms (free protons) and electrons from one reaction site to another in cells.

nucleotide sequence The order of nucleotides in a gene; it codes for a specific polypeptide chain.

nucleus (NOO-klee-us) Of atoms, the central core consisting of one or more positively charged protons and (in all but hydrogen) electrically neutral neutrons. In cells, a membranous organelle that physically isolates and organizes the DNA, out of the way of cytoplasmic machinery.

nutrient Element with a direct or indirect role in metabolism that no other element fulfills.

nutrition All those processes by which food is ingested, digested, absorbed, and later converted to the body's own organic compounds.

obesity An excess of fat in the body's adipose tissues, often caused by imbalances between caloric intake and energy output.

olfactory receptors Receptors in the nasal epithelium that detect water-soluble or volatile substances.

oligosaccharide A carbohydrate consisting of a short chain of two or more covalently bonded sugar units. One subclass, disaccharides, has two sugar units. Compare *monosaccharide; polysaccharide*.

omnivore [L. *omnis,* all, and *vovare,* to devour] An organism that feeds on a variety of food types, such as plant and animal tissues. Most humans are omnivores.

oncogene (ON-coe-jeen) A gene that has the potential to induce cancerous transformations in a cell.

oocyte An immature egg.

oogenesis (oo-oh-JEN-uh-sis) Formation of a female gamete, from a germ cell to a mature haploid ovum (egg).

oral cavity The mouth.

orbital Volume of space around the nucleus of an atom in which electrons are likely to be at any instant.

organ A body structure of definite form and function that is composed of more than one tissue.

organ of Corti Region of the inner ear that contains the sensory hair cells involved in hearing.

organ system Two or more organs that interact chemically, physically, or both in performing a common task.

organelle In cells, an internal, membrane-bounded sac or compartment that has a specific, metabolic function.

organic compound A compound having a carbon backbone, often with carbon atoms arranged as a chain or ring structure, and at least one hydrogen atom.

organogenesis Stage of development in which organs form and acquire specialized chemical and physical properties.

orgasm The culmination of the sex act that involves muscle contractions and sensations of warmth, release, and relaxation.

origin The end of a muscle that is attached to the bone that remains relatively stationary when the muscle contracts.

osmoreceptor Sensory receptor that detects changes in water volume (solute concentration) in the fluid bathing it.

osmosis (oss-MOE-sis) [Gk. *osmos,* act of pushing] The tendency of water to move across a cell membrane in response to a concentration gradient.

osteoblast A cell that forms bone.

osteoclast A bone cell that breaks down the matrix of bone tissue.

osteocyte A living bone cell.

osteon A set of thin, concentric layers of compact bone tissue surrounding a narrow canal carrying blood vessels and nerves; arrays of osteons make up compact bone.

ovarian cycle Cycle during which a primary oocyte matures and is ovulated.

ovary (OH-vuh-ree) The primary female reproductive organ, where eggs form.

oviduct (OH-vih-dukt) Duct through which eggs travel from the ovary to the uterus. Also called Fallopian tube.

ovulation (ahv-you-LAY-shun) During each turn of the menstrual cycle, the release of a secondary oocyte (immature egg) from an ovary.

ovum (OH-vum) A mature female gamete (egg).

oxaloacetate A four-carbon compound with roles in metabolism (e.g., the point of entry into the Krebs cycle).

oxidation-reduction reaction An electron transfer from one atom or molecule to another. Often hydrogen is transferred along with the electron or electrons.

oxidative phosphorylation (foss-for-ih-LAY-shun) Final stage of aerobic respiration, in which ATP forms after hydrogen ions and electrons (from the Krebs cycle) are sent through a transport system that gives up the electrons to oxygen.

oxygen debt Lowered O_2 level in blood when muscle cells have used up more ATP than they have formed by aerobic respiration.

oxyhemoglobin A hemoglobin molecule that has oxygen bound to it.

ozone thinning Pronounced seasonal thinning of Earth's ozone layer, as in the lower stratosphere above Antarctica.

P (parent) generation The designation for the parent generation in a genetic cross.

palate Structure that separates the nasal cavity from the oral cavity. The bone-reinforced hard palate serves as a hard surface against which the tongue can press food as it mixes it with saliva.

pancreas (PAN-cree-us) Gland that secretes enzymes and bicarbonate into the small intestine during digestion, and that also secretes the hormones insulin and glucagon.

pancreatic islets Any of the two million clusters of endocrine cells in the pancreas, including alpha cells, beta cells, and delta cells.

pandemic A situation in which epidemics of a disease break out in several countries around the world within a given time span.

paralysis Loss of sensation and/or motor function, often due to spinal cord injuries.

parasite [Gk. *para,* alongside, and *sitos,* food] An organism that obtains nutrients directly from the tissues of a living host, which it lives on or in and may or may not kill.

parasympathetic nerve Of the autonomic nervous system, any of the nerves carrying signals that tend to slow the body down overall and divert energy to basic tasks; parasympathetic nerves also work continually in opposition with sympathetic nerves to bring about minor adjustments in internal organs.

parathyroid glands (pare-uh-THY-royd) Endocrine glands embedded in the thyroid gland that secrete parathyroid hormone, which helps restore blood calcium levels.

Parkinson's disease Degenerative brain disorder that impairs normal muscle function.

parturition Birth.

passive immunity Temporary immunity conferred by deliberately introducing antibodies into the body.

passive transport Diffusion of a solute through a channel or carrier protein that spans the lipid bilayer of a cell membrane. Its passage does not require an energy input; the protein passively allows the solute to follow its concentration gradient.

pathogen (PATH-oh-jen) [Gk. *pathos,* suffering] An infectious, disease-causing agent, such as a virus or bacterium.

PCR *See* polymerase chain reaction.

pectoral girdle Set of bones, including the scapula (shoulder blade) and clavicle (collarbone), to which the long bone of each arm attaches. The pectoral girdles form the upper part of the appendicular skeleton and are only loosely attached to the rest of the body by muscles.

pedigree chart A chart of genetic connections among individuals, as constructed according to standardized methods.

pelvic cavity Body cavity in which the reproductive organs, bladder, and rectum are located.

pelvic girdle Set of bones including coxal bones that form the pelvis; the lower part of the appendicular skeleton. The upper portions of the two coxal bones are the hipbones; the thighbones (femurs) join the coxal bones at hip joints. The pelvic girdle bears the body's weight when a person stands.

pelvic inflammatory disease (PID) Generally, a bacterially caused inflammation of the uterus, oviducts, and ovaries. Often a complication of gonorrhea, chlamydia, or some other sexually transmitted disease.

penetrance In a given population, the percentage of individuals in which a particular genotype is expressed (that is, the percentage of individuals who have the genotype and also exhibit the corresponding phenotype).

penis Male organ that deposits sperm into the female reproductive tract; also houses the urethra.

pepsin Any of several digestive enzymes that are part of gastric fluid in the stomach.

pepsinogen A precursor to the digestive enzyme pepsin.

peptide hormone A hormone that consists of a short chain of amino acids.

perception The conscious interpretation of some aspect of the external world created by the brain from nerve impulses generated by sensory receptors.

perforin A type of protein secreted by a natural killer cell of the immune system, and which creates holes (pores) in the plasma membrane of a target cell.

peripheral nervous system (per-IF-ur-uhl) [Gk. *peripherein,* to carry around] The nerves leading into and out from the spinal cord and brain and the ganglia along those communication lines.

peripheral vasoconstriction The reduction in blood flow to capillaries near the body's surface to retain body heat.

peripheral vasodilation The dilation of blood vessels in the skin that allows excess heat in the blood to dissipate.

peristalsis (pare-ih-STAL-sis) Rhythmic contraction of muscles that moves food forward through the gastrointestinal tract.

peritoneum Lining of the coelom that also covers and helps maintain the position of internal organs.

peritubular capillaries The set of blood capillaries that threads around the tubular parts of a nephron; they function in reabsorption of water and solutes and in secretion of hydrogen ions and some other substances as urine is formed.

peroxisome Enzyme-filled vesicle in which fatty acids and amino acids are digested first into hydrogen peroxide (which is toxic), then to harmless products.

PGA Phosphoglycerate (foss-foe-GLISS-er-ate). A key intermediate in glycolysis.

PGAL Phosphoglyceraldehyde. A key intermediate in glycolysis.

pH scale A scale used to measure the concentration of free hydrogen ions in blood, water, and other solutions; pH 0 is the most acidic, 14 the most basic, and 7, neutral.

phagocyte (FAYG-uh-sight) [Gk. *phagein,* to eat, and *-kytos,* hollow vessel] A macrophage or other white blood cell that engulfs and destroys foreign agents.

phagocytosis (fayg-uh-sigh-TOE-sis) [Gk. *phagein,* to eat, and *-kytos,* hollow vessel] Engulfment of foreign cells or substances by specialized white blood cells by means of endocytosis.

pharynx (FARE-inks) A muscular tube by which food enters the gastrointestinal tract; the dual entrance for the tubular part of the digestive tract and windpipe (trachea).

phenotype (FEE-no-type) [Gk. *phainein,* to show, and *-typos,* image] Observable trait or traits of an individual; arises from interactions between genes, and between genes and the environment.

phenylketonuria (PKU) Genetic disorder in which the amino acid phenylalanine builds up abnormally in the affected person.

pheromone (FARE-oh-moan) [Gk. *phero,* to carry, and *-mone,* as in hormone] A type of signaling molecule secreted by exocrine glands that serves as a communication signal between individuals of the same species.

phospholipid A type of lipid that is the main structural component of cell membranes. Each has a hydrophobic tail (of two fatty acids) and a hydrophilic head that incorporates glycerol and a phosphate group.

phosphorus cycle Movement of phosphorus from rock or soil through organisms, then back to soil.

phosphorylation (foss-for-ih-LAY-shun) The attachment of unbound (inorganic) phosphate to a molecule; also the transfer of a phosphate group from one molecule to another, as when ATP phosphorylates glucose.

photoreceptor A light-sensitive sensory cell.

pigment A light-absorbing molecule.

pilomotor response Contraction of smooth muscle controlling the erection of body hair when outside temperature drops. This creates a layer of still air that reduces heat losses from the body. (It is most effective in mammals that have more body hair than humans do.)

pineal gland (PY-neel) A light-sensitive endocrine gland that secretes melatonin, a hormone that influences reproductive cycles and the development of reproductive organs.

pituitary dwarfism Underproduction of growth hormone, causing an affected adult to be abnormally small.

pituitary gland An endocrine gland that interacts with the hypothalamus to coordinate and control many physiological functions, including the activity of many other endocrine glands. Its posterior lobe stores and secretes hypothalamic hormones; the anterior lobe produces and secretes its own hormones.

placenta (pluh-SEN-tuh) Of the uterus, an organ composed of maternal tissues and extraembryonic membranes (the chorion especially); it delivers nutrients to the fetus and accepts wastes from it, yet allows the fetal circulatory system to develop separately from the mother's.

plasma (PLAZ-muh) Liquid portion of blood; consists of water, various proteins, ions, sugars, dissolved gases, and other substances.

plasma cell In adaptive immunity, an effector B cell that quickly floods the bloodstream with antibodies.

plasma membrane The outermost cell membrane. Proteins in its lipid bilayer carry out most functions, including transport across the membrane and reception of extracellular signals.

platelet (PLAYT-let) A cell fragment in blood that releases substances necessary for blood clotting.

pleiotropy (pleye-AH-troe-pee) [Gk. *pleon,* more, and *trope,* direction] A type of gene interaction in which a single gene exerts multiple effects on seemingly unrelated aspects of an individual's phenotype.

pleura plural pleurae. Thin, double membrane surrounding each lung.

pneumonia Infection that causes inflammation in lung tissue, followed by buildup of fluid in the lungs and difficulty in breathing.

point source A single place where a form of pollution begins.

polar body Any of up to three cells that form during the meiotic cell division of an oocyte; the division also forms the mature egg, or ovum.

pollutant Any substance with which an ecosystem has had no prior evolutionary experience in terms of kinds or amounts, and that can accumulate to disruptive or harmful levels. Can be naturally occurring or synthetic.

polycystic kidney disease An inherited disorder in which cysts form in both kidneys and eventually destroy kidney function.

polygenic trait Trait that results from the combined expression of several genes.

polymer (PAH-lih-mur) [Gk. *polus,* many, and *meris,* part] A molecule composed of three to millions of small subunits that may or may not be identical.

polymerase chain reaction (PCR) DNA amplification method; DNA containing a gene of interest is split into single strands, which enzymes (polymerases) copy; the enzymes also act on the accumulating copies, multiplying the gene sequence by the millions.

polymorphism (poly-MORE-fizz-um) [Gk. *polus,* many, and *morphe,* form] Of a population, the persistence through the generations of two or more forms of a trait.

polypeptide chain Three or more amino acids joined by peptide bonds.

polyploidy (PAHL-ee-ployd-ee) A case of somatic cells having three or more of each type of chromosome.

polysaccharide [Gk. *polus,* many, and *sakharon,* sugar] A straight or branched chain of covalently bonded monomers of the same or different kinds of sugars. The most common polysaccharides are cellulose, starch, and glycogen.

pons Hindbrain traffic center for signals between centers of the cerebellum and forebrain.

population A group of individuals of the same species occupying a given area.

population density The number of individuals of a population that are living in a specified area or volume.

population size The number of individuals that make up the gene pool of a population.

positive feedback mechanism Homeostatic mechanism by which a chain of events is set in motion that intensifies a change from an original condition.

precapillary sphincter A ring of smooth muscle that regulates the flow of blood into a capillary.

prediction A statement about what one can expect to observe in nature if a theory or hypothesis is correct.

primary immune response Activity of white blood cells and their products elicited by a first-time encounter with an antigen; includes both antibody-mediated and cell-mediated responses.

primary productivity Of ecosystems, *gross* primary productivity is the rate at which the producer organisms capture and store a given amount of energy during a specified interval. *Net* primary productivity is the rate of energy storage in the tissues of producers in excess of their rate of aerobic respiration.

primate A type of mammal; primates include prosimians, tarsioids, and anthropoids (monkeys, apes, and humans).

primer A laboratory-made short nucleotide sequence designed to base-pair with any complementary DNA sequence; later, DNA polymerases recognize it as a start tag for replication.

principle of sustainability The idea that to survive and thrive on Earth, humans must control their population growth, use resources wisely, develop and use more renewable resources, and protect the natural habitats of other species.

prion (PREE-on) Small infectious protein that causes rare, fatal degenerative diseases of the nervous system.

probability With respect to any chance event, the most likely number of times it will turn out a certain way, divided by the total number of all possible outcomes.

producer, primary Of ecosystems, any of the organisms that secure energy from the physical environment, as by photosynthesis or chemosynthesis. Green plants are Earth's main primary producers.

progesterone (pro-JESS-tuh-rown) Female sex hormone secreted by the ovaries.

prokaryotic cell (pro-carry-OH-tic) [L. *pro,* before, and Gk. *karyon,* kernel] A single-celled organism that has no nucleus or any of the other membrane-bound organelles characteristic of eukaryotic cells. Bacteria are prokaryotic.

promoter Of transcription, a base sequence that signals the start of a gene; the site where RNA polymerase initially binds.

prophase Of mitosis, the stage when each duplicated chromosome starts to condense, microtubules form a spindle apparatus, and the nuclear envelope starts to break up.

prophase I Of meiosis, the stage at which the spindle starts to form, the nuclear envelope starts to break up, and each duplicated chromosome condenses and pairs with its homologous partner. At this time, their sister chromatids typically undergo crossing over and genetic recombination.

prophase II Of meiosis, a brief stage during which each chromosome still consists of two chromatids.

prostaglandin Any of various local signaling molecules that typically cause smooth muscle to contract or relax, as in blood vessels, the uterus, and airways.

prostate gland Gland in males that wraps around the urethra and ejaculatory ducts; its secretions become part of semen.

protein A large organic compound composed of one or more chains of amino acids held together by peptide bonds. Proteins have unique sequences of different kinds of amino acids in their polypeptide chains; such sequences are the basis of a protein's three-dimensional structure and chemical behavior.

protein hormone A hormone that consists of a long amino acid chain.

proto-oncogene A gene similar to an oncogene but that codes for a protein required in normal cell function; may trigger cancer, generally when mutations alter its structure or function.

proton Positively charged subatomic particle in the nucleus of all atoms.

proximal tubule The region of a nephron tubule that receives water and solutes filtered from the blood.

psychoactive drug A chemical that acts on the central nervous system, altering the activity of brain neurons and associated mental and physical states.

puberty Period of human development that marks the onset of sexual maturity as the reproductive organs begin to function.

pulmonary circuit Blood circulation route between the heart and lungs.

pulse Rhythmic pressure surge of blood flowing in an artery, created during each cardiac cycle when a ventricle contracts.

Punnett square method A method to predict the probable outcome of a mating or an experimental cross in a simple diagram.

purine Nucleotide base having a double ring structure. Adenine and guanine are examples.

pyelonephritis Inflammation of the kidney usually resulting from a bladder infection.

pyrimidine (pie-RIM-ih-deen) Nucleotide base having a single ring structure. Cytosine and thymine are examples.

pyruvate (pie-ROO-vate) A compound with a backbone of three carbon atoms that is the end product of glycolysis.

radiation therapy Cancer treatment that relies on radiation from radioisotopes to damage or destroy cancer cells.

radioisotope An unstable atom that spontaneously decays to a new, stable atom that is not radioactive.

radiometric dating A method of dating fossils that tracks the radioactive decay of material in the specimen.

radius One of two long bones of the forearm that extend from the humerus (at the elbow joint) to the wrist. The radius runs along the thumb side of the forearm, parallel to the ulna.

reabsorption In the kidney, the diffusion or active transport of water and usable solutes out of a nephron and into capillaries leading back to the general circulation; regulated by ADH and aldosterone.

receptor, sensory A sensory cell or cell part that may be activated by a specific stimulus.

recessive (allele or trait) [L. *recedere,* to recede] Allele whose expression in heterozygotes is fully or partially masked by expression of its partner; fully expressed only in the homozygous recessive condition.

recognition protein One of a class of glycoproteins that project above the plasma membrane and identify a cell as nonself (foreign) or self (belonging to one's own body tissues).

recombinant DNA A DNA molecule that contains genetic material from more than one organism of the same species or from different species.

recombinant DNA technology Procedures by which DNA (genes) from different species may be isolated, cut, spliced together, and the new recombinant molecules multiplied in quantity in a population of rapidly dividing cells such as bacteria.

rectum Final region of the gastrointestinal tract, which receives and temporarily stores undigested food residues (feces).

red blood cell Erythrocyte; an oxygen-transporting cell in blood.

red-green color blindness Vision problem in which the retina lacks cone cells that normally respond to light of red or green wavelengths.

red marrow A substance in the spongy tissue of many bones that serves as a major site of blood cell formation.

reductional division The mode of cell division represented by meiosis, in which daughter cells end up with one-half the normal diploid number of chromosomes.

reflex [L. *reflectere,* to bend back] A simple, stereotyped movement in response to a stimulus. Sensory neurons synapse on motor neurons in the simplest reflex arcs.

reflex arc [L. *reflectere,* to bend back] A neural pathway in which signals from sensory neurons directly stimulate or inhibit motor neurons.

refractory period Of neurons, the period following an action potential at a given patch of membrane when sodium gates are shut and potassium gates are open, so that the patch does not respond to stimulation.

regulatory protein A protein that enhances or suppresses transcription of a gene.

releasing hormone A hormone released from the hypothalamus that stimulates or slows down secretion by target cells in the anterior lobe of the pituitary gland.

renewable resource A natural resource that can, in theory, be tapped indefinitely if replenished.

reproduction In biology, processes by which a new generation of cells or multicellular individuals is produced. Sexual reproduction requires meiosis, formation of gametes, and fertilization. Asexual reproduction refers to the production of new individuals by any mode that does not involve gametes.

reproductive base The number of actually and potentially reproducing individuals in a population.

reproductive isolating mechanism Any aspect of body structure, function, or behavior that restricts gene flow between two populations.

reproductive isolation An absence of gene flow between populations.

reproductive success Production of viable offspring by an individual.

reproductive system An organ system consisting of a pair of gonads (testes in males, ovaries in females). Its sole function is the continuation of the species.

respiration [L. *respirare,* to breathe] The exchange of oxygen from the environment for carbon dioxide wastes from cells by way of circulating blood. Compare *aerobic cellular respiration; cellular respiration.*

respiratory bronchiole Smallest airway in the respiratory system; opens onto alveoli.

respiratory cycle One inhalation, one exhalation of air into and out of the lungs.

respiratory surface In alveoli of the lungs, the thin, moist membrane across which gases diffuse.

respiratory system An organ system specialized for bringing in oxygen and carrying away carbon dioxde wastes; human lungs and airways.

resting membrane potential Of neurons and other excitable cells that are not being stimulated, the steady voltage difference across the plasma membrane.

restriction enzymes Class of bacterial enzymes that cut apart foreign DNA injected into them, as by viruses; also used in recombinant DNA technology.

reticular formation A major network of interneurons in the brain stem that helps govern activity of the whole nervous system.

retina A thin layer of neural tissue in the eye that contains densely packed photoreceptors.

retinal detachment Separation of the retina from the underlying choroid.

retinoblastoma A cancer of the retina; usually hereditary.

retrovirus An RNA virus that infects animal cells and with reverse transcriptase creates an RNA template to synthesize a DNA molecule that integrates itself into the host's DNA.

reverse transcription Assembly of DNA on a single-stranded mRNA molecule by viral enzymes.

RFLPs ("riff-lips") Restriction fragment length polymorphisms. Of DNA samples from different individuals, slight but unique differences in the banding pattern of fragments of the DNA that have been cut with restriction enzymes.

Rh blood typing A method of characterizing red blood cells on the basis of a protein that serves as a self marker at their surface; Rh^+ signifies its presence and Rh^-, its absence.

rhodopsin Substance in rod cells of the eye consisting of the protein opsin and a side group, cis-retinal. When the side group absorbs incoming light energy, a series of chemical events follows that result in action potentials in associated neurons.

ribosome The cell structure at which amino acids are strung together to form the polypeptide chains of proteins. An intact ribosome consists of two subunits, each composed of ribosomal RNA and protein molecules.

ribosomal RNA (rRNA) Type of RNA molecule that combines with proteins to form ribosomes, on which the polypeptide chains of proteins are assembled.

ribs Twelve pairs of bones that form the rib cage of the axial skeleton and help support the upper torso.

rigor mortis A stiffening of skeletal muscles caused when a person dies and body cells stop making ATP.

RNA Ribonucleic acid. A category of single-stranded nucleic acids that function in processes by which genetic instructions are used to build proteins.

RNA polymerase Enzyme that catalyzes the assembly of RNA strands on DNA templates.

rod cell Of the retina, a photoreceptor sensitive to very dim light that contributes to coarse perception of movement.

rugae The crumpled wall folds of an empty stomach.

S-shaped curve A curve characteristic of logistic growth; it is obtained when population size is plotted against time.

salinization A salt buildup in soil as a result of evaporation, poor drainage, and often the importation of mineral salts in irrigation water.

salivary amylase Starch-degrading enzyme in saliva.

salivary gland Any of the glands that secrete saliva, a fluid that initially mixes with food in the mouth and starts the breakdown of starch.

salt Compound that releases ions other than H^+ and OH^- in solution.

saltatory conduction In myelinated neurons, rapid, node-to-node hopping of action potentials.

sampling error Error that develops when an experimenter uses a sample (or subset) of a population, an event, or some other aspect of nature for an experimental group that is not large enough to be representative of the whole.

sarcoma Cancer of connective tissues such as muscle and bone.

sarcomere (SAR-koe-meer) The basic unit of muscle contraction; a region of myosin and actin filaments organized in parallel between two Z bands of a myofibril inside a muscle cell.

sarcoplasmic reticulum (sar-koe-PLAZ-mik reh-TIK-you-lum) In muscle cells, a membrane system that takes up, stores, and releases the calcium ions required for cross-bridge formation in sarcomeres, hence for contraction.

scapula Flat, triangular bone on either side of the pectoral girdle; the scapulae form the shoulder blades.

Schwann cell A specialized neuroglial cell that grows around a neuron axon, forming a myelin sheath.

scientific method A systematic way of gathering knowledge about the natural world.

second messenger A molecule inside a cell that mediates and generally triggers an amplified response to a hormone.

secondary immune response Rapid, prolonged response by white blood cells, memory cells especially, to a previously encountered antigen.

secondary oocyte An oocyte (unfertilized egg cell) that has completed meiosis I; it is this haploid cell that is released at ovulation.

secondary sexual trait Trait associated with maleness or femaleness, but not directly involved with reproduction. Beard growth in males and breast development in females are examples.

secretion In general, release of a substance by one or more gland cells. In digestion, the release of enzymes and other substances into the digestive tube. In the urinary system, the step of urine formation in which unwanted substances in peritubular capillaries are moved to the urine forming in nephron tubules.

sedimentary cycle A biogeochemical cycle in which an element having no gaseous phase moves from land, through food webs, to the seafloor, then returns to land through long-term uplifting.

segmentation In the digestive system, an oscillating movement produced by rings of muscle in the tube wall.

segregation, genetic principle of [L. *se-,* apart, and *grex,* herd] The principle that diploid organisms inherit a pair of genes for each trait (on a pair of homologous chromosomes) and that the two genes segregate during meiosis and end up in separate gametes.

seizure disorder Also known as epilepsy; disease characterized by recurring seizures.

selective permeability The capacity of a cell membrane to let some substances but not others cross it at certain times. The property arises as an outcome of the membrane's lipid bilayer structure and its transport proteins.

semen [L. *serere,* to sow] Sperm-bearing fluid expelled from the penis during male orgasm.

semicircular canals Fluid-filled canals positioned at different angles within the vestibular apparatus of the inner ear and that contain sensory receptors that detect head movements, deceleration, and acceleration.

semiconservative replication [Gk. *hemi,* half, and L. *conservare,* to keep] Reproduction of a DNA molecule when a complementary strand forms on each of the unzipping strands of an existing DNA double helix, the outcome being two "half-old, half-new" molecules.

semilunar valve A valve in each half of the heart that opens and closes during each heartbeat in ways that keep blood flowing in one direction, from the ventricle to the arteries leading away from it.

seminal vesicle Part of the male reproductive system; secretes fructose that nourishes sperm.

seminiferous tubules Coiled tubes inside the testes where sperm develop.

senescence (sen-ESS-cents) [L. *senescere,* to grow old] Sum total of processes leading to the natural death of an organism or some of its parts.

sensation The conscious awareness of a stimulus.

sensory adaptation In a sensory system, a state in which the frequency of action potentials eventually slows or stops even when the strength of a stimulus is constant.

sensory neuron Any of the nerve cells that act as sensory receptors, detecting specific stimuli (such as light energy) and relaying signals to the brain and spinal cord.

sensory receptor A sensory cell or specialized cell adjacent to it that can detect a particular stimulus.

sensory system An organ system consisting of sensory receptors (such as photoreceptors), nerve pathways from the receptors to the brain, and brain regions that process sensory information.

septic shock Sudden and dangerous decline in blood pressure.

septum Of the heart, a thick wall that divides the heart into right and left halves.

serous membranes Membranes that occur in paired sheets and anchor internal organs and reduce friction between organs.

Sertoli cell A type of cells in seminiferous tubules that nourish and otherwise aid the development of sperm.

severe combined immune deficiency (SCID) Genetic disorder in which stem cells in the affected person's bone marrow fail to make lymphocytes; affected children must live in germ-free isolation tents.

sex chromosome A chromosome that determines a new individual's gender. Compare *autosomes.*

sexually transmitted disease (STD) Infection passed from person to person through sexual contact.

shell model Model of electron distribution in atoms in which orbitals available to electrons occupy a nested series of shells.

sickle-cell anemia An inherited disorder in which red blood cells are shaped like sickles, impeding their ability to carry oxygen.

simple goiter Enlargement of the thyroid gland due to an iodine-deficient diet.

sinoatrial (SA) node Region of conducting cells in the upper wall of the right atrium; the cells generate periodic waves of excitation that stimulate the atria to contract.

sinus In the skull, an air-filled space lined with mucous membrane that reduces the weight of the skull.

sister chromatid Of a duplicated chromosome, one of two DNA molecules (and associated proteins) that remain attached at their centromere during nuclear division. Each ends up in a separate daughter nucleus.

skeletal muscle Type of muscle that interacts with the skeleton to bring about body movements. A skeletal muscle typically consists of bundles of many long cylindrical cells encapsulated by connective tissue.

skeletal system The organ system consisting of bones of the skeleton along with cartilages, joints, and ligaments.

sliding filament model Model of muscle contraction in which myosin filaments physically slide along and pull actin filaments toward the center of the sarcomere, which shortens. The sliding requires ATP energy and the formation of cross-bridges between the actin and myosin.

small-cell carcinoma Type of lung cancer that spreads rapidly and kills most victims within five years.

small intestine The portion of the digestive system where digestion is completed and most nutrients are absorbed.

smog A general term for air pollution; originally the term meant "*fog*" infused with "*sm*oke" and other pollutants.

smooth muscle One of the three main muscle types; occurs in the walls of internal organs and generally is not under voluntary control.

sodium–potassium pump A transport protein spanning the lipid bilayer of the plasma membrane. When activated by ATP, its shape changes and it selectively transports sodium ions out of the cell and potassium ions in.

solute (SOL-yoot) [L. *solvere,* to loosen] Any substance dissolved in a solution. In water, this means spheres of hydration surround the charged parts of individual ions or molecules and keep them dispersed.

solvent Fluid in which one or more substances is dissolved.

somatic cell (so-MAT-ik) [Gk. *soma,* body] Any body cell that is not a germ cell; that is, a body cell that does not give rise to gametes.

somatic nerve Nerves leading from the central nervous system to skeletal muscles.

somatic sensation Awareness of touch, pressure, heat, cold, pain, and limb movement.

somatosensory cortex Part of the gray matter of the cerebral hemispheres that controls somatic sensations.

somatostatin Hormone that inhibits the secretion of insulin in beta cells and glucagen in alpha cells.

somites In a developing embryo, paired blocks of mesoderm that will give rise to most bones and to the skeletal muscles of the neck and trunk.

special senses Vision, hearing, olfaction, or other sensation that arises from a particular location, such as the eyes, ears, or nose.

speciation (spee-cee-AY-shun) The evolutionary process by which species originate. One speciation route starts with divergence of two reproductively isolated populations of a species. They become separate species when accumulated genetic differences prevent them from interbreeding successfully under natural conditions.

species (SPEE-ceez) [L. *species,* a kind] A unit consisting of one or more populations of individuals that can interbreed under natural conditions to produce fertile offspring that are reproductively isolated from other such units.

sperm [Gk. *sperma,* seed] A mature male gamete.

spermatogenesis (sperm-at-oh-JEN-ih-sis) Formation of a male gamete, from a germ cell to a mature sperm.

sphere of hydration A clustering of water molecules around the individual molecules of a substance placed in water. Compare *solute.*

sphincter (SFINK-tur) Ring of smooth muscle between regions of a tubelike system (as between the stomach and small intestine).

spina bifida Birth defect in which the neural tube doesn't close properly.

spinal cavity Body cavity that houses the spinal cord.

spinal cord The portion of the central nervous system threading through a canal inside the vertebral column. It provides direct reflex connections between sensory and motor neurons, as well as communication lines to and from the brain.

spindle A structure that forms during mitosis or meiosis and that moves the chromosomes. It consists of two sets of microtubules that extend from the opposite poles and that overlap at the spindle's equator.

spleen The largest lymphoid organ; it is a filtering station for blood and a reservoir of lymphocytes, red blood cells, and macrophages.

spongy bone Type of bone tissue in which hard, needle-like struts separate large spaces filled with marrow. Spongy bone occurs at the ends of long bones and within the breastbone (sternum), pelvis, and bones of the skull.

sporadic disease A disease that breaks out irregularly and affects relatively few people.

squamous cell carcinoma Type of lung cancer that affects squamous epithelium in the bronchi.

start codon Of protein synthesis, a base triplet in a strand of mRNA that serves as the start signal for mRNA translation.

stem cell Unspecialized cell that can give rise to descendants that differentiate into specialized cells.

sternum Elongated flat bone (also called the breastbone) to which the upper ribs attach and so form the rib cage.

steroid (STAIR-oid) A lipid with a backbone of four carbon rings and with no fatty acid tails. Steroids differ in their functional groups. Different types have roles in metabolism, intercellular communication, and cell membranes.

steroid hormone A type of lipid-soluble hormone synthesized from cholesterol. Many steroid hormones move into the nucleus and bind to receptors there; others bind to receptors in the cytoplasm, and the entire complex moves into the nucleus.

sterol A type of lipid with a rigid backbone of four fused carbon rings. Sterols occur in cell membranes; cholesterol is the main type in human tissues.

stimulus [L. *stimulus,* goad] A specific change in the environment, such as a variation in light, heat, or mechanical pressure, that the body can detect through sensory receptors; a form of energy that activates receptor endings of a sensory neuron.

stomach A muscular, stretchable sac that receives ingested food; the organ between the esophagus and intestine in which considerable protein digestion occurs.

stop codon Of protein synthesis, a base triplet in a strand of mRNA that serves as the stop signal for translation, so that no more amino acids are added to the polypeptide chain.

strep throat Common bacterial infection of the throat and tonsils; short for *Streptococcus*.

substrate A reactant or precursor molecule for a metabolic reaction; a specific molecule or molecules that an enzyme can chemically recognize, briefly bind to, and modify in a specific way.

substrate-level phosphorylation The direct, enzyme-mediated transfer of a phosphate group from the substrate of a reaction to another molecule. An example is the transfer of phosphate from an intermediate of glycolysis to ADP, forming ATP.

succession, primary and secondary (suk-SESH-un) [L. *succedere,* to follow after] Orderly changes from the time pioneer species colonize a barren habitat through replacements by various species until the climax community, when the composition of species remains steady under prevailing conditions.

suppressor T cell Any of the cells that produce chemical signals that help shut down an immune response.

surface-to-volume ratio A mathematical relationship in which volume increases with the cube of the diameter, but surface area increases only with the square. In growing cells, the volume of cytoplasm increases more rapidly than the surface area of the plasma membrane that must service the cytoplasm. Because of this constraint, cells generally remain small or elongated, or have elaborately folded membranes.

sympathetic nerve Any of the nerves of the autonomic nervous system; generally concerned with increasing overall body activities during times of heightened awareness, excitement, or danger; sympathetic nerves also work in opposition with parasympathetic nerves to bring about minor adjustments in internal organs.

synaptic integration (sin-AP-tik) The moment-by-moment combining of excitatory and inhibitory signals arriving at a trigger zone of a neuron.

syndrome A set of symptoms that may not individually be notable, but collectively characterize a disorder or disease.

synovial joint Freely movable joint in which adjoining bones are separated by a fluid-filled cavity and stabilized by straplike ligaments. An example is the ball-and-socket joint at the hip.

synovial membranes Connective tissue membranes that line the cavities of the body's movable joints.

syphilis The sexually transmitted disease caused by infection by the spirochete bacterium *Treponema pallidum.* Untreated syphilis can lead to lesions in mucous membranes, the eyes, bones, skin, liver, and central nervous system.

systemic circuit (sis-TEM-ik) Circulation route in which oxygenated blood flows from the lungs to the left half of the heart, through the rest of the body (where it gives up oxygen and takes on carbon dioxide), then back to the right side of the heart.

systole Contraction phase of the cardiac cycle.

target cell Any cell that has receptors for a specific signaling molecule (such as a hormone) and that may alter its behavior in response to the molecule.

taste receptors Chemoreceptors in the taste buds.

Tay-Sachs disease Genetic disorder in which an enzyme for lipid metabolism is missing; it results in neural degeneration and death in early childhood.

TCR Antigen-binding receptor of T cells.

tectorial membrane Inner ear structure against which sensory hair cells are bent, producing action potentials that travel to the brain via the auditory nerve.

telophase (TEE-low-faze) Of mitosis, the final stage when chromosomes decondense into threadlike structures and two daughter nuclei form. Of meiosis I, the stage when one of each pair of homologous chromosomes has arrived at one or the other end of the spindle pole. At telophase II, chromosomes decondense and four daughter nuclei form.

temporal summation The adding together (summing) of several muscle contractions, resulting in a single, stronger contraction, when stimulatory signals arrive in rapid succession.

tendon A cord or strap of dense, regular connective tissue that attaches a muscle to bone or to another muscle.

teratogens Agents that can cause birth defects.

test An attempt to produce actual observations that match predicted or expected observations.

testcross In genetics, an experimental cross to reveal whether an organism is homozygous dominant or heterozygous for a trait. The organism showing dominance is crossed to an individual known to be homozygous recessive for the same trait.

testicular feminizing syndrome Genetic disorder in which androgen receptors are defective; an affected XY embryo will develop as a female, but without uterus or ovaries.

testis plural testes. Male gonad; primary reproductive organ in which male gametes and sex hormones are produced.

testosterone (tess-TOSS-tuh-rown) In males, a major sex hormone that helps control reproductive functions.

tetanus Condition in which a muscle motor unit is maintained in a state of contraction for an extended period.

thalamus Coordinating center in the forebrain for sensory input and a relay station for signals to the cerebrum.

theory A testable explanation of a broad range of related phenomena. In modern science, only explanations that have been extensively tested and can be relied on with a very high degree of confidence are accorded the status of theory.

thermal inversion Situation in which a layer of dense, cool air becomes trapped beneath a layer of warm air; can cause air pollutants to accumulate to dangerous levels close to the ground.

thermoreceptor Sensory cell that can detect radiant energy associated with temperature.

thoracic cavity The chest cavity; holds the heart and lungs.

thirst center Cluster of nerve cells in the hypothalamus that can inhibit saliva production, resulting in mouth dryness that the brain interprets as thirst.

threshold Of neurons and other excitable cells, a certain minimum amount by which the voltage difference across the plasma membrane must change to produce an action potential.

thymine Nitrogen-containing base in some nucleotides; a building block of DNA.

thymus A lymphoid organ with endocrine functions; lymphocytes of the immune system multiply, differentiate, and mature in its tissues, and its hormone affect their functions.

thyroid gland An endocrine gland that produces hormones that affect overall metabolic rates, growth, and development.

tidal volume Volume of air, about 500 milliliters, that enters or leaves the lungs in a normal breath.

tight junction Cell junction where strands of fibrous proteins collectively block leaks between the adjoining cells.

tissue A group of cells and intercellular substances that function together in one or more specialized tasks.

T lymphocyte or **T cell** One of a class of white blood cells that carry out immune responses. The helper T and cytotoxic T cells are examples.

tonicity The relative concentrations of solutes in two fluids, such as inside and outside a cell. When solute concentrations are isotonic (equal in both fluids), water shows no net osmotic movement in either direction. When one fluid is hypotonic (has less solutes than the other), the other is hypertonic (has more solutes) and is the direction in which water tends to move.

total fertility rate (TFR) The average number of children born to the women in a given population during their reproductive years.

touch-killing Mechanism by which cytotoxic T cells directly release perforins and toxins into a target cell and cause its destruction.

toxin A normal metabolic product of one species with chemical effects that can hurt or kill individuals of another species.

trace element Any element that represents less than 0.01 percent of body weight.

tracer A substance with a radioisotope attached to it so that its pathway or destination in a cell, organism, ecosystem, or some other system can be tracked, as by scintillation counters that detect its emissions.

trachea (TRAY-kee-uh) The windpipe, which carries air between the larynx and bronchi.

trachoma A bacterial infection that damages the eyeball and the conjunctiva, sometimes resulting in blindness.

transcription [L. *trans,* across, and *scribere,* to write] Of protein synthesis, the assembly of an RNA strand on one of the two strands of a DNA double helix; the base sequence of the resulting transcript is complementary to the DNA region on which it was assembled.

transfer RNA (tRNA) Of protein synthesis, any of the type of RNA molecules that bind and deliver specific amino acids to ribosomes and pair with mRNA code words for those amino acids.

translation In protein synthesis, the conversion of the coded sequence of information in mRNA into a particular sequence of amino acids to form a polypeptide chain; depends on interactions of rRNA, tRNA, and mRNA.

translocation A change in a chromosome's structure following the insertion of part of a nonhomologous chromosome into it.

transport protein One of many kinds of membrane proteins involved in active or passive transport of substances across the lipid bilayer of a plasma membrane. Solutes on one side of the membrane pass through the protein's interior to the other side.

transposable element DNA element that can spontaneously "jump" to new locations in the same DNA molecule or a different one. Such elements often inactivate the genes into which they become inserted.

trichomoniasis Vaginal inflammation due to a parasite (usually sexually transmitted); symptoms include vaginal discharge, burning, and itching.

trigger zone The region of a motor neuron where proper stimulation can trigger an action potential (nerve impulse).

triglyceride (neutral fat) A lipid having three fatty acid tails attached to a glycerol backbone. Triglycerides are the body's most abundant lipids and richest energy source.

trisomy (TRY-so-mee) The abnormal presence of three of one type of chromosome in a diploid cell.

trophoblast Surface layer of cells of the blastocyst that secrete enzymes that break down the uterine lining where the embryo will implant.

T tubules Tubelike extensions of a muscle cell's plasma membrane.

tuberculosis (TB) Serious bacterial lung infection that eventually destroys patches of lung tissue.

tumor A tissue mass composed of cells that are dividing at an abnormally high rate.

tumor marker A substance that is produced by a specific type of cancer cell or by normal cells in response to cancer.

tumor necrosis factor A chemical communication signal, secreted by white blood cells, that triggers inflammation and kills tumor cells.

tumor suppressor gene A gene whose protein product operates to keep cell growth and division within normal bounds, or whose product has a role in keeping cells anchored in place within a tissue.

Turner syndrome Genetic disorder in which one of two X chromosomes is missing; affected people are female, but are sterile and develop no secondary sexual traits.

tympanic membrane The eardrum, which vibrates when struck by sound waves.

type 1 diabetes Also called juvenile-onset diabetes; an autoimmune response that destroys beta cells in the pancreas.

type 2 diabetes A kind of diabetes where insulin levels are normal, but target cells don't respond properly; capillaries become damaged, resulting in less blood flow and eventual tissue death.

ulna One of two long bones of the forearm; the ulna extends along the little finger side of the forearm, parallel to the radius on the thumb side.

ultrafiltration Bulk flow of a small amount of protein-free plasma from a blood capillary when the outward-directed force of blood pressure is greater than the inward-directed osmotic force of interstitial fluid.

umami One of the five primary tastes; the brothy, savory taste associated with aged cheese or meats.

umbilical cord Structure containing blood vessels that connect a fetus to its mother's circulatory system by way of the placenta.

uracil (YUR-uh-sill) Nitrogen-containing base found in RNA molecules; can base-pair with adenine.

urea The main nitrogen-containing waste product when cells break down proteins.

ureter Channel that carries urine from each kidney to the urinary bladder.

urethra Tube that carries urine from the bladder to the body surface.

urinary bladder Storage organ for urine.

urinary excretion A mechanism by which excess water and solutes are removed by way of the urinary system.

urinary incontinence Urine leakage due to age-related weakening of the bladder and urethra.

urinary system An organ system that adjusts the volume and composition of blood and so helps maintain extracellular fluid.

urination Urine flow from the body; a reflex response to tension in the smooth muscle of a full bladder.

urine Fluid formed by filtration, reabsorption, and secretion in kidneys; consists of wastes, excess water, and unneeded solutes.

uterus (YOU-tur-us) [L. *uterus,* womb] Chamber in which the developing embryo is contained and nurtured during pregnancy.

vaccine Antigen-containing preparation injected into the body or taken orally; it elicits an immune response leading to the proliferation of memory cells that offer long-lasting protection against that particular antigen.

vagina Chamber of the female reproductive system that receives the male penis and sperm, forms part of the birth canal, and channels menstrual flow to the exterior.

variable In a scientific experiment, the only factor that is not the same in the experimental group as it is in the control group.

vas deferens Tube leading to the ejaculatory duct; one of several tubes through which sperm move after they leave the testes just prior to ejaculation.

vasoconstriction Decrease in the diameter of an arteriole, so that blood pressure rises; may be triggered by the hormones epinephrine and angiotensin.

vasodilation Enlargement of arteriole diameter, so that blood pressure falls; may be triggered by hormones including epinephrine and angiotensin.

veins Of the circulatory system, the large-diameter vessels that lead back to the heart.

ventricle (VEN-tri-kul) Of the heart, one of two chambers from which blood is pumped out. Compare *atrium.*

venule Small blood vessel that receives blood from tissue capillaries and merges into larger-diameter veins; a limited amount of diffusion occurs across venule walls.

vertebra plural vertebrae. One of a series of hard bones arranged with intervertebral disks into a backbone.

vertebrate Animal having a backbone of bony segments, the vertebrae.

vesicle (VESS-ih-kul) [L. *vesicula,* little bladder] One of a variety of small membrane-bound sacs in the cell cytoplasm that function in the transport, storage, or digestion of substances or in some other activity.

vestibular apparatus A closed system of fluid-filled canals and sacs in the inner ear that functions in the sense of balance. Compare *semicircular canals*.

villus (VIL-us), plural villi. Any of several types of absorptive structures projecting from the free surface of an epithelium.

virulence The relative ability of a pathogen to cause serious disease.

virus A noncellular infectious agent consisting of DNA or RNA and a protein coat; can replicate only after its genetic material enters a host cell and takes over its metabolic machinery.

vision Sensory reception of visual stimuli (especially light) followed by image formation in the brain.

visual cortex Part of the brain that receives signals from the optic nerves.

vital capacity Maximum volume of air that can move out of the lungs after a person inhales as deeply as possible.

vitamin Any of numerous organic substances that the body requires in small amounts for normal cell metabolism but generally cannot synthesize for itself.

vocal cords A pair of elastic ligaments on either side of the larynx wall. Air forced between them causes the cords to vibrate and produce sounds.

water (hydrologic) cycle The movement of water from oceans to the atmosphere, the land, and back to the ocean.

watershed Any region in which all precipitation drains into a single stream or river.

white blood cell Leukocyte; any of the macrophages, eosinophils, neutrophils, and other cells that are the central components of the immune system.

white matter Of the spinal cord, major nerve tracts so named because of the glistening myelin sheaths of their axons.

X chromosome A sex chromosome with genes that cause an embryo to develop into a female, provided that it inherits a pair of these.

X inactivation A compensating phenomenon in females that "switches off" one X chromosome soon after the first cleavages of the zygote.

X-linked gene Any gene on an X chromosome.

X-linked recessive inheritance Recessive condition in which the responsible, mutated gene occurs on the X chromosome.

Y chromosome A sex chromosome with genes that cause the embryo that inherited it to develop into a male.

Y-linked gene Any gene on a Y chromosome.

yellow marrow Bone marrow that consists mainly of fat and hence appears yellow. It can convert to red marrow and produce red blood cells if the need arises.

yolk sac One of four extraembryonic membranes. Part becomes a site of blood cell formation and some of its cells give rise to the forerunners of gametes.

zero population growth State in which the number of births in a population is balanced by the number of deaths over a specified period, assuming immigration and emigration also are balanced.

zona pellucida A noncellular coating around an oocyte.

zoonosis An infectious disease that mainly affects animals other than humans, but can also be passed on to humans.

zygote (ZYE-goat) The first cell of a new individual, formed by the fusion of a sperm nucleus with the nucleus of an egg (fertilization).

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INDEX

Note: figures and tables are indicated by an f *or* t *following the page number.*

APPLICATIONS INDEX

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