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The Core Concepts of Physiology

A New Paradigm for Teaching Physiology

Published on behalf of The American Physiological Society by Springer

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This book is dedicated to Ann Wright (1952–2016), a dear friend and colleague for many years. Ann contributed in many different ways to the conceptual assessment project from which this book arose. She was always quick to lend a hand when something needed to be done. With her typical positive attitude, she was always certain that we could overcome whatever the current problem was. She made significant contributions to the writing of this book. We will miss her friendship and her professional contributions.

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Part I
Introduction

Chapter 1
Reforming Science Education/Reforming Physiology Education

Abstract Calls for reform of American science education go back at least to the early twentieth century, and in recent years there has been a plethora of reports and recommendations about how to "fix" the problems that have been identified. One notable problem is the continued focus on breadth versus depth of understanding in STEM disciplines. In part, this reflects the enormous expansion of knowledge in all fields of science. One consequence is that more is known than can possibly be mastered by students.

All recent reports calling for significant change in American science education have included recommendations that learning objectives focus on the mastery of core concepts as opposed to the mere accumulation of ever more facts.

Physiology faces the same challenges as all of the other STEM disciplines. However, it also faces a number of additional challenges that call for changes in the way we teach. Physiology is hard for students to learn because more is known than they can learn. In addition, the very nature of the disciplines poses problems for students. Physiology is hard to teach because the wide spectrum of students taking physiology courses, the inherent nature of the discipline, and because the goal of physiology teaching is meaningful learning, not the accumulation of facts.

A focus on core concepts of physiology can help students achieve meaningful learning and can help teachers facilitate the acquisition of meaningful learning.

Keywords Education reform • Core concepts • Knowledge explosion • Physiology learning • Causal reasoning • Prerequisite knowledge • Knowledge transfer • Student diversity

Calls for the reform of American science education have a long history. In 1910, the noted American philosopher and educator John Dewey published a paper in the journal *Science* (Dewey 1910) entitled "Science as subject-matter and as method" in which he had this to say; "...science has been taught too much as an accumulation of ready-made material with which students are to be made familiar, not enough as a method of thinking, an attitude of mind, after the pattern of which mental habits are to be transformed." This plea for reform certainly foreshadows more recent calls for reform and on much the same grounds, and it occurred before the enormous post-World War II explosion of scientific research!

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1.1 The Need for Reform of American Science Education

“Vision and Change” (American Association for the Advancement of Science 2011) has captured the recurrent calls for reform in science education with capsule summaries of 20 reform documents issued between 1986 and 2010. We will not review each of them, but will focus on a few that most directly relate to our proposed changes in physiology education.

1.1.1 Calls for Reform in the 1980s and 1990s

In its report “A Nation at Risk,” the United States National Commission on Excellence in Education (1983) took a broad look at American primary education (K-12) and found much to be wanting. It highlighted many failings in almost every discipline, but it was particularly critical about what today we would call Science, Technology, Engineering, and Mathematics (STEM) education. It called for better-prepared teachers and higher standards for student achievement. It called for many other reforms, but had little or nothing to say about pedagogy. Nevertheless, it did galvanize change and at least some of these changes have persisted until today.

A year later, the GPEP report—General Professional Education of Physicians—appeared (Association of American Medical Colleges 1984). This document addressed both admission requirements for applicants to medical school (thus reflecting undergraduate preparation in science) and basic science teaching and learning in medical schools. Like “A Nation at Risk,” it too called for significant reform in American science education.

In 1990, the National Research Council (NRC) issued a report on the state of biology education in America’s primary (K-12) schools entitled “Fulfilling the Promise: Biology Education in the Nation’s Schools” (NRC 1990). This report called for reforms in curriculum, pedagogy and assessment, and the training and institutional support for teachers. It recognized that biology education at that time was not keeping up with changes in the science of biology and was not preparing students to meet the needs of the country.

1.1.2 More Recent Calls for Reform

The report “Vision and Change in Undergraduate Biology Education,” the product of a conference sponsored by the American Association for the Advancement of Science (2011), contains a comprehensive critique of essentially every facet of undergraduate biology education in the USA. Among its recommendation is one that calls for defining learning objectives that focus student learning of core concepts. “Vision and Change” also focused strongly on issues related to reforming classroom practice to create more student-centered learning. This report has had a strong impact on the biology education community and continues to help shape reform efforts at all levels.

"BIO2010: Transforming Undergraduate Education for Future Research Biologists" is a report produced by the National Research Council (2003) which specifically addressed the issue of training biology majors for future research careers in modern biology. In spite of its focus on a seemingly small fraction of undergraduates taking biology courses, its recommendations for change will impact all students. Like "Vision and Change," it recommends a curricular focus on biology concepts. The list of 18 concepts (referred to in that document as "central themes") overlaps significantly with the list of concepts defined in "Vision and Change."

The report "Scientific Foundations for Future Physicians," published by the American Association for the Advancement of Science and the Howard Hughes Medical Institute (2009), also called attention to the need for reforms in the undergraduate preparation of potential medical students. It recommended shifting the focus from courses and their contents to the development of wide-ranging competencies in the sciences.

1.1.3 Common Features of Reform Documents

These more recent calls for reform in science education have ***all*** included calls for a focus on "core concepts" in science, although the lists of these concepts contain different things (Table 1.1). In particular, concepts that physiologists would consider to be central to their discipline have not been well represented in these lists (AAAS 2011; National Research Council 2003; AAAS and HHMI 2009). In Part II of this book, we define what we believe to be the core concepts of physiology and expand on three of them.

Another common feature of ***all*** recent calls for reform is the recognition that the STEM community needs to develop assessments that can measure student mastery of the core concepts. Conventional science assessments test student knowledge of the "facts" of science and, perhaps, the ability to apply these facts in solving problems (National Research Council 2001). We will discuss the assessment of core concepts in physiology in Chap. 11.

1.1.4 Reforming Both Content and Pedagogy

It is clear that there is a need for reform of **content**, what is taught and what students are expected to learn, and **pedagogy**, how students are taught and how they are expected to learn. In Part II, we will discuss how to use a core concept approach to teaching physiology with the many approaches to student-centered teaching that have been implemented over the past 25–30 years (Michael 2006; Kay and Kibble 2016).

Table 1.1 A comparison of the core concepts defined in "Vision and Change" (AAAS 2011) and "BIO2010" (National Research Council 2003)

Vision and Change[a]	BIO2010[b]
Evolution	"Evolution"
Pathways and transformations of energy and matter	Biological systems obey the laws of chemistry and physics
Information flow, exchange, and storage	"Structural complexity and information content"
Structure and function	". . .reductionist and holistic thinking. . ."
Systems	"Living systems are far from equilibrium. . . no two cells are alike. . ."
	"Homeostasis"
	Cells are the fundamental units. . .
	"Living organisms have behavior. . ."
	DNA/RNA information coding
	Role of proteins
	Lipoprotein cell membrane
	Cell–cell communication
	Gene expression and cell differentiation
	Mechanisms of disease
	Nature of species
	Populations and ecosystems
	Humans and ecosystems

[a]The core concepts from "Vision and Change" are listed here exactly as they appear in the document
[b]The core concepts in "BIO2010" listed here are summaries since the original versions are often quite long

1.1.5 The Need for Reform and the Knowledge Explosion

The explosion of knowledge in all of the STEM disciplines exacerbates the problems identified in all of the STEM reform documents.

The existence of this explosion in knowledge can be documented in many ways. Bornmann and Mutz (2015) have done a detailed count of both the number of science journals and the number of cited papers from 1600 to 2012 and found that the rate of growth of science is currently 8–9% per year. This amounts to a doubling of the knowledge base of science approximately every 8 years!

Another approach to documenting this is to count the pages in recent editions of physiology and physiology and anatomy textbooks (Table 1.2). Textbooks have become encyclopedic in their content, with each new edition including the most recently established advances in the field. It is thus not surprising that textbooks get larger and larger (and, of course, more expensive).

Table 1.2 The number of pages in popular introductory and medical physiology textbooks (Michael et al. 2009)

Physiology textbooks (Authors)	Number of pages
Human anatomy and physiology	
Saladin	1248
Marieb and Hoehn	1296
Martini	1110
Undergraduate physiology	
Sherwood	801
Widmaier et al	738
Medical physiology	
Berne et al.	978
Boron and Boulpaep	1267
Guyton and Hall	1066

An obvious consequence of the enormous length of the textbooks we ask our students to buy is that they are confronted with more information to acquire, memorize, and understand than is possible during a single one or two semester course. This overabundance of information poses an additional problem; the sheer volume of information dilutes the important messages that students should understand! It also makes understanding the "big picture" very difficult.

The authors of the "Vision and Change" report (2011; page 58) made this point quite forcefully:

> As biology faculty, we need to put the "depth versus breadth" debate behind us. It is true today, and will be even more so in the future, that faculty cannot pack everything known in the life sciences into one or two survey courses. The advances and breakthroughs in the understanding of living systems cannot be covered in a classroom or a textbook. They cannot even be covered in the curriculum of life sciences majors. A more tenable approach is to recast the focus of biology courses and curricula on the conceptual framework on which the science itself is built and from which discoveries emerge. Such a focus is increasingly interdisciplinary, demands quantitative competency, and requires the instructor to use facts judiciously as a means of illustrating concepts rather than as items to be memorized in isolation.

Thus, another consequence of the knowledge explosion is that faculty now, more than ever, must directly confront the difficult task of deciding what to require their students to learn. This decision must address both the breath and the depth of their subject; how many topics about which systems (breadth) and at what level of organization (depth) should students be asked to understand. These decisions must obviously be made in the context of the particular course aimed at a particular group of students.

1.2 The Need for Reform of Physiology Education

Physiology is, of course, one of the STEM disciplines. As such it must deal with all of the issues described above. However, physiology education also must confront a number of additional challenges that call for new approaches to teaching physiology.

1.2.1 Physiology Is Hard for Students to Learn

Physiology is difficult for students at any academic level to learn. As teachers we hear this directly from at least some students. When teachers were asked directly what made physiology hard for students to learn, they offer many reasons (Michael 2007). The survey proposed three possible factors creating the difficulties that students report: (1) the intrinsic nature of the discipline, (2) how physiology is taught, and (3) how students approach the learning of physiology. Faculty indicated that the most important difficulty was the nature of the discipline, and what is thus required for students to master physiology. It is worth noting that a survey of students using essentially identical questions yielded a similar result (Sturges and Maurer 2013); student difficulties learning physiology arise primarily from the nature of the discipline.

The most important impediment to student success was identified as the need to **reason causally** about physiological mechanisms. Understanding physiology means not only having acquired an adequate knowledge base, but having the ability to use that knowledge base to solve problems (Michael and Rovick 1999). One mode of reasoning required to solve problems in physiology is causal reasoning, the ability to create a chain of cause-and-effect (causal) relationships between physiological entities (Michael and Rovick 1999; Evens and Michael 2006).

The second most important impediment was identified as **the need to apply knowledge of physics and chemistry** to understanding physiological mechanisms. Two problems were identified. First, students often lack the expected prerequisite knowledge of physics and chemistry (Rovick et al. 1999), and second, students have great difficulty transferring what they know about these subjects to the task of learning physiology (Perkins and Salomon 1994; Bransford et al. 1999).

Students also have a problem transferring knowledge even within the domain of physiology. For example, students learn about blood flow and the laws of hemodynamics in the cardiovascular section of a physiology course. Next, they are likely to encounter the flow of gas in the respiratory tree, which they typically approach as a totally new topic to be learned. That is to say, they do not recognize, and faculty often fail to point this out, that the laws are exactly the same even if the labels are different. What we have described here is, of course, the core concept of ***flow down gradients*** (see Chap. 6).

1.2.2 The Knowledge Explosion and Its Impact on Physiology Teaching and Learning

In Sect. 1.5 of this chapter, we discuss the problems caused by the knowledge explosion that has occurred in all of the sciences including physiology. More is known than it is possible for students to learn. Furthermore, it is difficult for students, and faculty too, to determine what things are most important. Textbooks often include features to aid students in determining what is important: (1) lists of learning outcomes or objectives, (2) pages of important points, and (3) questions related to mastery of these important facts. However, these aids are only partially successful. On the one hand, there is so much known that such lists are themselves daunting. On the other hand, conceiving and adequately describing learning objectives is a difficult task, and students are often left quite unsure about exactly what they are expected to learn.

It is important to acknowledge that physiology faculty, too, have similar problems coping with the amount of knowledge that is available. What are the essential things that their students should master? Vander (1998) raised this question about a number of topics in renal physiology, and Carroll (2001) addressed this question with regard to pressure-flow relationships. What do their students need to understand for the next physiology course they will take? What do they need to know for their future careers in a STEM or STEM-related field? What do they need to know to be well-informed citizens who will have to make personal and civic choices about STEM-related issues? What all as faculty recognize is that we must make choices about what to ask our students to learn since those students cannot learn it all.

1.2.3 The Spectrum of Students Taking Physiology

One of the greatest challenges facing the physiology teacher is the range of students who enroll in a physiology course. This spectrum includes differences in the reason for taking the course, differences in prior science background, and differences in the personal goals that students bring to the course.

The kinds of students taking physiology includes (1) lower division undergraduates who are not majoring in the sciences and who take a physiology course to fulfill a science requirement, (2) biology majors for whom physiology is a required course or an elective, (3) physiology majors or students enrolled in physiology related majors, (4) students who are preparing for careers in health care and biological research, and (5) those who are already graduate or professional students.

The various kinds of students taking physiology generally come into a physiology course with very different science backgrounds. Nonscience majors typically have received minimal training in high school sciences and have rudimentary quantitative and scientific thinking skills. At the other end, professional and graduate students generally already have strong undergraduate science training (chemistry, physics, biology) and seasoned analytical and scientific reasoning abilities. There are also considerable differences in science backgrounds among undergraduates who enroll in physiology course while majoring in the health or biological sciences. This includes students who are pursuing bachelor's degrees in the health sciences (e.g., allied health professions, nursing, exercise science, kinesiology, etc.), students who are preparing for doctoral programs in the health sciences (premedical, pre-dental, pre-veterinarian, pre-pharmacy, etc.), the biological sciences, or biomedical engineering. Students in these categories may have widely different degrees of intellectual and scientific preparedness for undertaking a study in physiology.

This diversity confounds an instructor's assumptions about the skills and understandings that students bring to their study of physiology. This in turn makes it difficult to set the foundational level of instruction required to facilitate student's mastery of the subject.

In addition to differences in preparedness for the study of physiology, students have different degrees of interest in the subject of physiology, as well as different motivations and expectations for taking a course in the subject. For example, some nonscience majors may have low interest in learning about physiology and may only be motivated to fulfill a distribution requirement. Others may be curious about health and fitness and want to learn how these phenomena are related to physiology. They enroll in a physiology course expecting to learn relevant aspects of how the body works.

Students who intend to pursue careers in the health professions may have greater interest in the life sciences but be motivated to take a physiology course primarily to fulfill a prerequisite for a health professional degree program or to prepare to perform well on a professional test (e.g., MCAT, DAT, PCAT, OAT, etc.). These types of students expect to learn aspects of human physiology that are relevant to their intended profession. This is also true of health professional students (e.g., medical, dental, pharmacy, veterinary) who wish to gain a scientific foundation for their clinical practice and to acquire competency in physiology sufficient to pass their licensing exams. Undergraduates majoring in the biological sciences may have a broader interest in organismal biology and expect to gain both depth and breadth in their study of the life sciences. Similarly, graduate students in the biomedical and biological sciences may wish to enhance their understanding of organismal biology to prepare for their thesis research and/or a career in the life sciences.

Each category of student approaches learning physiology with a different set of motives and expectations for successful outcome. This diverse set of reasons and goals for enrolling in physiology poses a challenge to the physiology teacher who wishes to engage a significant percentage of his/her students in meaningful study of the subject.

1.3 How Should We Attempt to Institute Reform in Physiology Education?

Physiology teachers are confronted by too much for their students to learn, a discipline that poses problems for students, and a great of diversity of student. How do we proceed?

"Vision and Change" and the many other reports referred to in Sect. 1.1 all recommend that science educators focus on student learning the core concepts of the particular STEM disciplines. As the title of this book states, teaching that is focused on the core concepts of physiology can contribute in different ways to meeting the challenges that we have discussed.

However, we must first deal with the question of what is meant by a "core concept."

1.4 What Do We Mean by "Core Concepts?"

The terms "concepts," "core concepts," "concept learning," and "foundational concepts" are all in common usage in the science education literature across all of the STEM disciplines and in all recent STEM reform recommendations. However, it is very difficult to find explicit definitions of what is meant by a "concept" in this now vast literature. Developers of "concept inventories" publish lists of what they regard as the "core concepts" to be tested, but such a list does not constitute a definition of a concept in that discipline. What is clear from examining these lists is that there are obvious differences in the nature and scope of what are defined as core concepts in different STEM disciplines.

It would be useful to have a working definition of what we mean by a "concept" so that we can recognize core concepts in our own field and in other science disciplines.

1.4.1 Definitions from Psychology and Philosophy

In both psychology (Colman 2006) and philosophy (Prinz 2005), a "concept" is a category such as "birds," "metals," or "organic compounds." Learning a "concept" is then a process of learning what features of an entity must be present for that entity to be considered a member of a particular category or concept. However, it does not appear that this is what science educators mean when they use the term "concept."

1.4.2 Definitions in the Field of Education

There is another term, “big ideas,” that frequently appears in the education literature. This term is used in ways that seem to us to be synonymous with the term “core concept.” Descriptions of what is meant by a “big idea” have been provided by a number of authors.

Duschl et al. (2007) have offered the following description:

“Each [BIG IDEA] is well tested, validated, and absolutely central to the discipline. Each integrates many different findings and has exceptionally broad explanatory scope. Each is the source of coherence for many key concepts, principles and even other theories in the discipline.”

Wiggins and McTighe (2005; page 69) have offered the following description of a “big idea.”

“More generally, then, big ideas can be thought of as:

- Providing a focusing conceptual ‘lens’ for any study
- Providing breath of meaning by connecting and organizing many facts, skills, and experiences; serving as the linchpin of understanding
- Pointing to ideas at the heart of expert understanding of the subject
- Requiring ‘uncoverage’ because its meaning or value is rarely obvious to the learner is counterintuitive or prone to misunderstanding
- Having great transfer value; applying to many other inquires and issues over time—‘horizontally’ (across subjects) and ‘vertically’ (through the years in later courses) in the curriculum and out of school”

Finally, Harlen (2010), in a comprehensive discussion of the use of “big ideas” in science education, offers the following definition.

> “We define big ideas as ideas that can be used to explain and make predictions about a range of related phenomena in the natural world. However, ideas come in different sizes; there are moderately big ideas that can be linked into bigger ideas and some of these can be subsumed into even bigger, more encompassing ideas.”

There are several features that seem common to these definitions of “big ideas” (or concepts) that are relevant to our use of “core concepts” in physiology. “Big ideas” or core concepts:

- Are applicable to many sub-domains within the field (they are transferable).
- Provide coherence or structure to the domain (they foster retention).
- Provide tools for solving problems (thus advancing student understanding).
- Have utility in the future (when the “details” have been forgotten).

1.4.3 Core Concepts and General Models in Physiology Education

Modell (2000) described a set of "general models" that he argued could be applied to explain and understand many different physiological phenomena. As we will see later, there is a significant overlap between Modell's "general models" and our "core concepts" and both function in much the same way.

Feder (2005) also described a set of "core ideas or concepts" that he attempted to convey to students in his course. These core ideas or concepts also overlap with our set of core concepts, although in many ways they serve as an outline of the subject matter he wants his students to master.

1.5 Defining the Core Concepts of Biology: The Conceptual Assessment in Biology (CAB) Workshops

So what might be the core concepts that students in physiology courses should learn? An approach to defining this was initiated by the National Science Foundation (NSF) in 2007. NSF sponsored a workshop titled "Conceptual Assessment in the Biological Sciences" which was held at the University of Colorado in Boulder, CO (Michael 2007; Garvin-Doxas et al. 2007). A group of 20–25 biologists and biology educators was brought together to begin a conversation on how to assess students' understanding of biology concepts. There was considerable discussion about the meaning of the term "concept" (see above), and the group recognized that it must first decide what the core concepts in biology might be before attempting to develop a means to appropriately assess student's understanding.

Although the participants worked in a large number of different biology subdisciplines, it took very little time for the group to agree on a set of core concepts. The list of these core concepts of ***biology*** with some explanation can be seen in Table 1.3.

It was understood by all of the participants that the different subdisciplines of biology emphasize different sets of these core concepts to differing degrees. It was also recognized that these core concepts are not independent ideas; there are clear overlaps and connections between various sets of concepts.

Having defined a set of core concepts in biology, the CAB group could then turn to a discussion of how to develop and implement a conceptual assessment tool for widespread use (see Chap. 11).

A comparison of the core concepts from "Vision and Change" (AAAS 2011) and "BIO2010" (National Research Council 2003) seen in Table 1.1 and the core concepts from the CAB meeting seen in Table 1.3 reveals a significant overlap. It is clear that there are STEM concepts that all biologists regard as essential for students to understand.

Table 1.3 The core concepts (big ideas) of ***biology*** defined at the 2007 CAB workshop (Michael 2007)

Core concepts	Definition
The cell is the basic unit of life	The organism is made up of tissues composed of ***cells*** with specialized structures and functions. Cells in the organism must cooperate with one other (exchange information, exchange matter) because no individual cell can "do it all"
Information flow	Life requires ***information flow*** in and between cells and between the environment and the organism. The transmission of genetic information is a major determinant of the structure and function of each cell. Information flow between cells (cell–cell communications) is essential to coordinate the activity of the myriad of cells making up the organism. Information flow from the environment is required so that the organism can react appropriately to things happening in the environment
Matter and energy	Living organisms must obtain matter and energy from the external world to continue to exist. That ***matter and energy must be transferred and transformed*** in a variety of ways in order to build the organism and to perform work (from the cellular to the organismal levels)
Homeostasis	***Homeostasis*** (and "stability" in a more general sense) maintains the internal environment of living systems in a more or less constant state. Important system parameters are measured and the measured value is compared to a predetermined set-point (desired) value. The difference is used to generate signals that alter the functions of the organism to return the regulated variable toward its preset determined value. Stability is also a property of ecosystems (although the mechanisms are probably quite different)
Structure and function	To understand the behavior of the organism requires understanding the relationship between the ***structure and the function*** of the organism, since function is dependent on structure and structure must match the functional needs of the organism
Causal mechanisms	Living organisms are ***causal mechanisms*** whose functions are to be understood by applications of the laws of physics and chemistry. Understanding physiological systems requires the ability to think causally
Ecosystem	All life exists within an ***ecosystem*** composed of the physicochemical world and the total biological world
Evolution	***Evolution*** provides a scientific explanation for the history of life on Earth and the mechanisms (at the molecular level and at the level of species, etc.) by which changes have occurred to the biota

1.6 What Are the Core Concepts of Physiology and How Should They Be Used to Teach Physiology?

Even a cursory look at Table 1.3 makes clear that each of the core concepts of *biology* has some relevance to *physiology* and to the teaching of physiology. Some are ideas that are heavily represented in the usual physiology course taught at any level, while others may appear only in advanced course (300-, 400-level courses,

Table 1.4 The core concepts of physiology described by Michael and McFarland (2011)[a]

Core concepts in physiology
Evolution
Homeostasis
Causality
Energy
Structure/function
Cell theory
Levels of organization
Cell–cell communication
Cell membrane
Flow down gradients
Genes to proteins
Interdependence
Mass balance
Physics/chemistry
Scientific reasoning

[a]In Chap. 3 we will fully describe how we generated this list and what each of the core concepts means.

graduate courses) or in specialized courses (e.g. comparative physiology). The obvious applicability of these core concepts of *biology* to *physiology* led us to ask whether we could generate a list of core concepts that would specifically address the needs of *physiology* instructors. In Part II of this book, we will address this issue, discussing how we arrived at a list of core concepts in physiology, and how we analyzed these concepts to determine their smaller, more easily testable ideas. For the moment, Table 1.4 lists the 15 core concepts that we have identified. In Part III, we will present our ideas about how physiology instructors can use these core concepts to improve student meaningful learning and understanding of physiology.

1.7 How Can a Focus on Core Concepts Help?

In what ways can a focus on teaching physiology from a core concepts perspective help to make physiology less difficult for students? How can this approach help teachers do a better job of helping the learner to learn? We think that there are several ways that a focus on core concepts can help.

1.7.1 Selectively Reduce the Body of Knowledge to be Acquired

A focus on core concepts can help to limit the amount of knowledge students are expected to acquire. For example, if students understand homeostasis and the regulation of mean arterial pressure, it may be enough to require some knowledge about the carotid baroreceptors without also requiring them to know about the aortic arch baroreceptors. An understanding of cell–cell communication as a core concept means that not every signaling molecule (transmitter, hormone, growth factor, etc.) needs to be memorized.

Furthermore, if the student understands the core concepts, each new system in which those core concepts are applicable will be easier to learn because the student is not starting from a zero base.

1.7.2 Focus on the Generalities and that Which Is Most Transferable

One of the key points in the definition of core concepts or big ideas is that they are applicable in many areas of the domain in question (Wiggins and McTighe 2005). Thus, if a student understands ***flow down gradients***, learning about hemodynamics (blood flow in the circulation) requires only the learning of new labels for components and ideas already understood. Once the student understands blood flow in the circulation, understanding gas flow in the airways is not a new topic to be mastered (Modell 2000).

Because core concepts are general in scope and apply in many different areas within physiology, if students understand them they can be helped to learn how to transfer this understanding as they move through the course.

This should also apply as students advance from course to course in the biology or physiology curriculum. They will encounter new topics and be expected to master these topics at a deeper level, but the core concepts, once mastered, will always apply to the new systems they are learning.

1.7.3 Provide the Scaffolding for Learning New Things Later

Perhaps most importantly, an understanding of the core concepts of physiology will provide students with a scaffold for all their future learning about physiology, whenever and wherever that learning occurs. The frameworks are knowledge structures on which the student can add newly acquired information so that it is not just part of a laundry list of memorized facts but is now part of a knowledge structure. With conceptual frameworks in place, learning about cellular or molecular mechanisms of muscle contraction in a later course becomes easier because of the organized framework already available. Problems involving more complex disturbances to a system are easier to solve (predictions or explanations about altered behavior) because runnable causal models of relevant core concepts are available to be used in a new context.

1.8 Organization of this Book

In the next chapter (Chap. 2), we provide an overview of the new paradigm we are proposing. In Part II (Chaps. 3–7), we briefly describe each of the core concepts of physiology and then expand on three of them. In Part III (Chaps. 8–12), we discuss a number of aspects of implementing the core concepts paradigm in the classroom. Finally, in Part IV (Chaps. 13 and 14), we provide some concluding thoughts about physiology teaching and the new paradigm.

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Chapter 2
What Is the New Paradigm and What Is New About It?

Abstract With the publication of Thomas Kuhn's *The Structure of Scientific Revolutions* in 1962, the term "paradigm" took on several specialized meanings. It is our contention that the changes to physiology education that we are recommending constitute a new paradigm in the Kuhnian sense.

In this chapter, we first discuss Kuhn's use of the term "paradigm." We then describe the overarching features of our new paradigm and offer an overview of the application of this new paradigm to classroom teaching, the building of physiology courses, and the creation of a physiology curriculum.

Keywords Paradigm • Physiology education • Physiology course • Physiology curriculum

The title of this book refers to a "new paradigm." Before we describe our new paradigm, we must first define the term "paradigm" and explain the significance of our use of it. Merriam-Webster.com defines "paradigm" as "a model or pattern for something that may be copied" and "a theory or a group of ideas about how something should be done, made, or thought about." Both of these definitions describe the ideas we are advancing in this book. However, the term has acquired a special meaning in science, and this meaning most closely reflects our use of the term.

2.1 Thomas Kuhn and the Meaning of a "Paradigm"

In 1962, Thomas Kuhn introduced the notion of "paradigm shifts" in the history of science (Kuhn 1962). What he meant by a "paradigm" was thought by many to be unclear, and in a postscript added to the second edition, Kuhn (1970) attempted to clarify his use of this term.

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2.1.1 What Did Kuhn Mean by the Term "Paradigm?"

In one context, Kuhn used the term "paradigm" to mean the way a community of scientists looks at or thinks about the domain of science in which they work. The term encompasses, is shorthand for, the way in which this community "does" science. It is how the community of scientists working in this domain behaves as scientists.

Kuhn posited that paradigm shifts, changes in the dominant world view in a particular field of science, occur when developments in that field result in the accumulation of anomalies that cannot be explained by the current way of thinking about things. Eventually, a new way of thinking appears that can accommodate not only the old established science but also these anomalies. Although it may take many years for it to be fully adopted, a new paradigm is said to have arisen.

However, Kuhn also uses the term "paradigm" in a different way to refer to "shared examples" or exemplars of types of problems to be solved in a domain. Kuhn offers an example of what he means by this. Newton's Second Law of Motion, $f = ma$, which relates force (f), mass (m), and acceleration (a), can be used to solve problems about the motion of objects. Kuhn then shows how solving problems in a variety of physics domains requires students to, first, recognize the applicability of the Second Law and, second, figure out how to recast it using the symbols, etc., appropriate to the nature of the problem. The Second Law is thus an exemplar of a wide variety of similar relationships.

2.1.2 How and Why Have We Used the Term "Paradigm" in a Book About Physiology Education?

We would argue that both meanings of Kuhn's term "paradigm" are applicable to what we are proposing in this book.

One use of the term paradigm by Kuhn is to describe the way in which a particular field of science is practiced. It is a term that describes a community that shares ideas, methods, theories, and techniques in order to advance understanding in that particular field.

In this sense of the term, "paradigm" has a very similar meaning as the term "community of practice" (Wenger 2009). In education, teachers who teach in a certain way, or want to learn to teach in a certain way, interact with one another, sharing ideas, theories, techniques, and information about outcomes as they attempt to do a better job of helping their students to learn. This is one meaning of the term "community of practice." What we are proposing here is a new paradigm, a new approach to teaching physiology that is based on a consideration of the core concepts of physiology. We are proposing a new paradigm for the physiology teaching community.

We would also observe that physiology education is currently going through a protracted paradigm shift in which active learning (Michael and Modell 2003; Michael 2006; Kay and Kibble 2016) and the pursuit of meaningful learning is being recognized as the necessary approach to improving science education.

If we consider the term "paradigm" as "an exemplar," we would argue that the core concepts of physiology work in a way that is analogous to $f = ma$. The core concepts are each widely applicable throughout the domain of mammalian physiology, and each can thus serve as a unifying construct that will help students to integrate their knowledge of physiological mechanisms and better apply that knowledge to solving problems.

In Part III of this book, we will be describing a new paradigm, a new mode of practice, which is based on different assumptions than the old paradigm. Below we will describe both the old and the new paradigms.

2.2 The Current Paradigm Shift Underway in Physiology Education

We believe that education, and particularly science education, is in the midst of a paradigm shift in which the teacher-centered, passive learning paradigm is being replaced by a student-centered, active learning paradigm.

Since John Dewey's call for reform of science teaching (1910), it has been recognized that students' passive accumulation of facts does not lead to the kind of understanding of scientific phenomena that is desirable for the individual and for society. Nevertheless, the model of students as empty vessels to be filled with as many facts as possible continues well into the beginning of the twenty-first century. This paradigm is fact oriented, and students are seen as passive and expected to merely store away for later retrieval all the facts viewed as relevant.

However, in the 1990s, it became increasingly evident that this paradigm was failing in an important way. Members of the physics education community began to collect data that clearly demonstrated that students taking, and succeeding in, conventional physics courses nevertheless did not understand the basic concepts of physics (Halloun and Hestenes 1985)! Chemistry students have been found to have many misconceptions (Ozmen 2004; Barke et al. 2009). Michael (1998) and his colleagues (Michael et al. 1999, 2002) have found misconceptions about respiratory and cardiovascular physiology across large, diverse groups of students. This is the kind of anomaly that Kuhn discussed; students who are demonstrably "successful" in our course nevertheless do not understand the important concepts of the field!

At the same time, cognitive psychologists and learning scientists were expanding on the thinking of Piaget, Dewey, Vygotsky, and Bruner to build an approach to learning referred to as constructivism (Mintzes and Wandersee 1997; Bransford et al. 1999). This approach to understanding learning is built on two ideas. First, learners construct their understanding of a topic on a foundation of what they already know (even though some of their prior knowledge is wrong). This, of course, means that the learner is not an empty container that is being filled by the lecturer or the textbook. Second, the notion that learning requires the learner to build his or her own understanding means that learning with understanding is always an active process.

The effectiveness of active learning approaches to teaching and learning science has been well documented in STEM disciplines. Michael and Modell (2003) described many facets of an active learning approach to teaching the sciences, and Michael (2006) reviewed much of the literature on learning applicable to physiology. Kay and Kibble (2016) have presented some of the findings of the learning sciences and have discussed the application of these ideas to the classroom.

Thus, classroom practice in the middle decades of the twentieth century has been changing from a passive and teacher-centered approach to a more active and student-centered approach. Nevertheless, teaching has remained heavily fact based, and in too many cases, the goal continues to be "coverage" of the material.

2.3 The Concept-Based Paradigm

The concept-based paradigm we will describe is predicated on the constructivist idea that knowledge is built on existing knowledge (Michael and Modell 2003; Mintzes and Wandersee 1997). The learner builds mental models of that which is being learned, tests these models, and refines the models as needed (Michael and Modell 2003). We are arguing that helping the physiology student to understand the core concepts of physiology will provide the learner with a foundation, or perhaps it would be better to describe it as a skeleton, on which all subsequent learning about physiological mechanisms can be attached. This paradigm also provides a set of tools with which students' problem solving can be facilitated.

What are these core concepts? In Chap. 3, we describe in great deal what they are and how we generated the list with the help of a large cohort of colleagues. Table 2.1 below is a list of the 15 core concepts of physiology around which we are proposing a new paradigm for teaching physiology.

This emphasis on core concepts is not meant to deny the importance of the student learning the "facts" of physiology. Learning any discipline requires the learning of the language with which the discipline carries out its discourse. It goes without saying that learning any language requires the acquisition, the memorization, of the words used in that language. Furthermore, to understand the physiological mechanisms being studied requires the acquisition of a large body of knowledge about the structures and the functions involved. Finally, it is well recognized that while there are generic problem-solving processes, the solving of actual problems requires both skill at employing these processes and a body of knowledge to be used in applying these processes.

Table 2.1 The core concepts of physiology. In Chap. 3, we describe the process that generate this list and what is meant by each of the items

Core concepts in physiology (Michael and McFarland 2011)
Evolution
Homeostasis
Causality
Energy
Structure/function
Cell theory
Levels of organization
Cell–cell communication
Cell membrane
Flow down gradients
Genes to proteins
Interdependence
Mass balance
Physics/chemistry
Scientific reasoning

2.4 Implementing the New Paradigm in Physiology Courses

In Chaps. 8, 9, and 10, we describe in detail how one might implement a physiology course based on the core concepts. Here, let us just observe that the key to using the core concepts to help student learn physiology is to make explicit the nature of the core concepts and their applicability to the physiology being learned. This requires consistency and repetition. It also requires learning outcomes and learning objectives that focus on the core concepts. Finally, if the core concepts and their application are important, if they are incorporated in the learning outcomes, then they must be tested.

2.5 Implementing the New Paradigm in the Curriculum

A curriculum is a sequence of courses, the successful completion of which leads to a degree in the particular field of study. It is assumed that there is a connection between the courses that are required and that, in some sense, they build on one another. As we describe further in Chap. 12, a focus on the core concepts of physiology provides a structure with which to construct a physiology curriculum. Progress through such a curriculum would involve learning to understand and use additional core concepts. Progress would also require being able to solve more complex problems using the core concepts and the growing knowledge base about physiology.

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Part II
The Core Concepts of Physiology

Chapter 3
What *Are* the Core Concepts of Physiology?

Abstract What are the core concepts of physiology? Michael et al. (Adv Physiol Educ 33:10–16, 2009) defined nine core concepts in physiology. As a result of surveying physiology faculty at a wide variety of institutions in the USA and elsewhere, Michael and McFarland (Adv Physiol Educ 35:336–341, 2011) expanded this list to a set of 15 core concepts for physiology.

We will first describe the process by which we arrived at our list of core concepts in physiology. Then, we will briefly describe each of the core concepts identified at the NSF-sponsored CAB meetings, the 15 core concepts of physiology we have developed, and their relationship to Modell's general models. We will also describe the overlap and interrelationship between the core physiology concepts.

In Chaps. 5, 6, and 7, we present our unpacking of the three most important core concepts that physiology faculty have helped us identify.

Keywords Core concepts • Physiology • Big ideas

Following the CAB meetings in 2007 (Michael 2007) and 2008 (Michael et al. 2008)—which we previously discussed (Sect. 1.5)—a group of physiology educational researchers began working together to determine how we might take the work of the CAB meeting and apply it to physiology teaching. Our initial goal was to develop a concept inventory for physiology. We thought of ourselves as the Conceptual Assessment in Physiology (CAP) group and quickly concluded that a concept inventory could only be written if we had a definition of the core concepts of physiology. This book is one product of our pursuit of this goal over the past 10 years.

3.1 The Process by Which We Defined the Core Concepts of Physiology

Before listing and explaining the core concepts of physiology, it is important to describe the process that we used to arrive at this list. It was not simply the product of five or six of us sitting around a table and deciding what we thought was most

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Table 3.1 Time line for the generation of a list of core concepts in physiology

Date	Activity	Described in
March, 2007	CAB workshop participants define eight big ideas in biology	Michael (2007)
2007–2008	CAP group defines core concepts of physiology, starting with the big ideas from the CAB workshop	Michael et al. (2009)
2008–2010	Physiology faculty surveyed by CAP group	Michael and McFarland (2011)
November 2008	Faculty asked (free response) to define core concepts	
March 2009	Faculty asked to rank order list of 15 core concepts and to identify the three most important core concepts	Michael and McFarland (2011)
January, 2010	Faculty asked for feedback about unpacking of one of the core concepts	Michael and McFarland (2011)

important, although it did start this way. Rather, after developing our first list of concepts, we enlisted the physiology teaching community in a process of defining and ranking the importance of these core concepts. Table 3.1 describes the time line for this project.

3.1.1 *The Core Concepts of* Biology *Defined at the First CAB Meeting*

As described in Chap. 1 (see Table 1.3), the participants at the first Conceptual Assessment in Biology meeting (Michael 2007) generated a list of big ideas in biology. This list contained five entries that would clearly appear on a list of core concepts in physiology: (1) living systems are causal mechanisms, (2) information, (3) matter and energy, (4) homeostasis, and (5) structure/function relationships.

3.1.2 *The Core Concepts of* Physiology *Derived from the Biology Concepts*

Michael et al. (2009) took the list of biology big ideas and generated a list of nine big ideas in physiology. This list was the result of discussions that the authors and other members of the CAP team had had over the year following the first CAB meeting. In this paper, we defined each of the core concepts, provided a description of the context within physiology where the concept would apply, and provided an example of such an application. This list contained the following core concepts: (1) evolution, (2) ecosystems and environments, (3) causal mechanisms, (4) the cell, (5) structure/function relationships, (6) levels of organization, (7) information flow, (8) matter/energy transfer and transformation, and (9) homeostasis. Table 3.2 displays a side-by-side comparison of the core concepts of biology/physiology as they evolved.

Table 3.2 The evolution of identified core concepts in biology/physiology (the wording of some entries in the table has been edited for consistency)

Core concepts in biology (Michael 2007)	Core concepts in physiology (Michael et al. 2009)	Core concepts in physiology (Michael and McFarland 2011)
Ecosystems/ environments	Ecosystems and environments	
Evolution	Evolution	Evolution
Homeostasis	Homeostasis	Homeostasis
Information flow	Information flow	
Living systems are causal mechanisms	Causal mechanisms	Causality
Matter/energy transfer/ transformation	Matter/energy transfer/ transformation	Energy
Structure/function relationships	Structure/function relationships	Structure/function
The cell	The cell	Cell theory
	Levels of organization	Levels of organization
		Cell–cell communication
		Cell membrane
		Flow down gradients
		Genes to proteins
		Interdependence
		Mass balance
		Physics/chemistry
		Scientific reasoning

3.1.3 Polling our Colleagues for Their Idea About Core Concepts

Although our group is a diverse one with members teaching at a variety of educational institutions, we were concerned that our list might be too idiosyncratic and that we were missing important core concepts.

Thus, in November 2008, Michael and McFarland (2011) surveyed the physiology teaching community using four different listservs to enlist respondents. We asked the respondents to tell us, in their own words, what they believed to be the "core principles" or "big ideas" (both terms were defined in the survey) of physiology. We received 81 responses from faculty at every level of post-second education in the USA, Canada, and nine other foreign countries.

We received 73 useable responses (not all the respondents answered the question we asked). Michael and McFarland individually read all the responses and extracted all the core concepts that were described. When we compared the lists that each of us had extracted from the surveys, they were virtually identical and contained 15 core concepts. Furthermore, the list of faculty-generated core concepts was virtually identical to the list that we had just published (Michael et al. 2009).

In March 2009, we again surveyed the 81 individuals who had responded to our first survey (Michael and McFarland 2011). We asked them to indicate, using a Likert scale (1 = strongly disagree to 5 = strongly agree), how important it was that their students master each of the 15 core concepts. In a separate section of the survey, they were asked to select the three most important core concepts. Sixty-one of the 81 responded to this survey. The results of this survey are briefly described below.

3.2 The Core Concepts of Physiology

The result of the iterative process of consultation with our colleagues (described above) was a list of core concepts. While they are not viewed as equally important in all courses, all were recognized as describing much of what is important to the teaching of physiology.

3.2.1 The 15 Core Concepts of Physiology and a Brief Explanation of Each

Below, in alphabetical order, are the 15 core concepts of physiology (adapted from Michael and McFarland 2011) that resulted from the process described above. The list can also be seen in Table 3.2 where they can be compared with the earlier version of the core concepts.

Causality: Living organisms are causal mechanisms ("machines") whose functions are explainable by a description of the cause-and-effect relationships that are present. What we attempted to capture in this core concept is the idea that the functions of the body arise from the interaction of atoms, ions, and molecules as described by the law of chemistry and physics. It follows then that an "explanation" for a physiological phenomenon or mechanism must be a set of statements outlining the cause-and-effect relationships (the causal relationships) between entities.

Cell–cell communication: The function of the organism requires that cells pass information to one another to coordinate their activities. These communication processes include endocrine and neural signaling. This concept describes the mechanism by which cells pass information to one another, thus making possible the coordinated activity of all of the cells of the body. Modell (2000) included this as one of the general models he described. The unpacked conceptual framework for ***cell–cell communication*** is presented in Chap. 7.

Cell membrane: Cell plasma membranes are complex structures that determine what substances enter or leave the cell. They are essential for cell signaling, transport, and other processes. Every cell has a membrane separating the constituents of the cell from the extracellular compartment. The properties of membranes are thus an important determinant of the functions of the cell.

Cell theory: All cells making up the organism have the same DNA. Cells have many common functions but also many specialized functions that are required by the organism. Cell theory is one of the oldest concepts in modern biology, and it is often assumed that students understand it. However, it has important implications that are not obvious to students but are, nevertheless, very important.

Energy: The life of the organism requires the constant expenditure of energy. The acquisition, transformation, and transportation of energy are essential functions of the body. While this core concept plays a major role in biochemistry, physiological mechanisms are all ultimately dependent on the availability of biological energy.

Evolution: The mechanisms of evolution act at many levels of organization and result in adaptive changes that have produced the extant relationships between structure and function. This core concept occupies a somewhat strange position in physiology; ***evolution*** is usually acknowledged but rarely invoked to explain the functions of the body.

Flow down gradients: The transport of "stuff" (ions, molecules, blood, and gas) is a central process at all levels of organization in the organism, and a simple model describes such transport. Ions crossing a cell membrane, blood flowing in blood vessels, gas moving in airways, and chyme moving down the gastrointestinal tract are all processes that result from the interaction of an energy gradient and the resistance to flow that is present. Modell (2000) also included this as a general model. The unpacked conceptual framework for ***flow down gradients*** is presented in Chap. 6.

Genes to proteins: The genes (DNA) of every organism code for the synthesis of proteins (including enzymes). The genes that are expressed determine the functions of every cell. This is the central dogma of molecular biology, and it plays out in a large number of situations in physiological systems.

Homeostasis: The internal environment of the organism is actively maintained constant by the function of cells, tissues, and organs organized into negative feedback systems. The role of negative feedback in regulating the functions of the body is a particularly powerful core concept in that it describes so much of organ system physiology. Modell (2000) proposed negative feedback as a general model. We present the unpacked conceptual framework for ***homeostasis*** in Chap. 5.

Interdependence: Cells, tissues, organs, and organ systems interact with one another (are dependent on the function of one another) to sustain life. The respondents to our first survey referred to this core concept often. However, it is difficult to know exactly what this means since, in one sense, it is a truism. What is probably the most important idea here is that one cannot focus on a single system in attempting to understanding physiological phenomena or trying to solve real problems.

Levels of organization: An understanding of physiological functions requires understanding the behavior at every level of organization from the molecular to the social. As the science of physiology has advanced, our understanding of physiological phenomena has expanded to encompass many different levels of organization. While we cannot yet explain everything at the molecular level, we are rapidly expanding the list of phenomena understood at that level.

Mass balance: The quantity of "stuff" in any system, or in a compartment in a system, is determined by the inputs to and the outputs from that system or compartment. This is a simple general model (Modell 2000) that has wide applicability in the body and explains a great many phenomena.

Physics/chemistry: The functions of living organisms are explainable by the application of the laws of physics and chemistry. This core concept is clearly related to the core concept of ***causality***. Physics and chemistry are perquisite to an understanding of all physiological phenomena, and physiologists, and students of physiology, must be able to transfer that understanding to the living organism.

Scientific reasoning; Physiology is a science. Our understanding of the functions of the body arises from the application of the scientific method; thus, our understanding is always tentative. It is scientific reasoning, the experimental method that has generated the information that fills our textbooks. To fully understand, physiology students must understand how the results they are reading about were generated and how future results will be generated.

Structure/function: The function of a cell, tissue, or organ is determined by its form. Structure and function (from the molecular level to the organ system level) are intrinsically related to each other. When applied to human designed and constructed artifacts this is a truism. But it is equally true of biological systems. An understanding of a physiological mechanism requires some understanding of the structures that involved.

It is interesting to note that of the 18 "Concepts of Biology: Central themes" listed in BIO2010 (NRC 2003), nine of them are essentially the same as the ones found in our list of core concepts.

3.2.2 Faculty Feedback About the 15 Core Concepts

In the March 2009 survey (Michael and McFarland 2011), we asked the respondents to indicate the importance of each of the 15 core concepts for their students. On a separate survey page, we also asked that they indicate the three most important core concepts. The ranking of the 15 core concepts, and the top 5, are shown in Table 3.3. Note that the responses we received led us to expand our analysis from the top 3 to the top 5 core concepts.

Of the five most important core concepts, one of them, ***Interdependence***, came from the faculty we had polled. Intense scrutiny of the written comments about this idea has failed to clarify for us a single concept that we can work with and we have not pursued this core concept any further. We have continued working with ***cell–cell communication***, ***homeostasis***, and ***flow down gradients***, and we will have much to say about these in the next three chapters.

Table 3.3 The ranking of the 15 core concepts in physiology by surveyed faculty (Michael and McFarland 2011)

	Ranking	Top five
Causality	14	
Cell–cell communication	3	X
Cell membrane	1	X
Cell theory	9	
Energy	6	
Evolution	15	
Flow down gradients	5	X
Genes to proteins	11	
Homeostasis	1	X
Interdependence	4	X
Levels of organization	12	
Mass balance	13	
Physics/chemistry	10	
Scientific reasoning	8	
Structure/function	7	

3.3 Characteristics of the Core Concepts

On even casual inspection of the list of core concepts in physiology (Table 3.3), it is clear that the 15 concepts differ from one another in significant ways. It is also clear that the 15 core concepts are not isolated, independent ideas.

3.3.1 The Nature of the Core Concepts

The 15 core concepts are all "big ideas" according to the definitions by Wiggins and McTighe (2005), Duschl et al. (2007), and Harlen (2010). But they seem to be "big ideas" about different kinds of things.

For example, ***flow down gradients*** and ***mass balance*** are examples of concepts that apply everywhere in the physical world, animate as well as inanimate. That is to say, they are core concepts that are not specifically about biological organisms, although they certainly apply to organisms.

On the other hand, ***homeostasis*** and ***cell–cell communication*** are big ideas that specifically describe biological phenomena. ***Interdependence***, ***levels of organization***, and ***structure/function*** all have applications of one sort or another in the world of man-made objects, but clearly also have very direct applications to living organisms. However, they are core concepts which appear to be difficult to unpack in the same way we have unpacked ***homeostasis***, ***flow down gradients***, and ***cell–cell communication*** (see Chaps. 4, 5, 6, and 7).

The existence of these differences should not obscure the fact that all of the core concepts, whichever "category" they belong to, can serve as tools in the processes of teaching and learning physiology.

3.3.2 The Intersecting Nature of the Core Concepts

The 15 core concepts that have been identified are related to one another or overlap with one another in obvious and not so obvious ways; they are certainly NOT independent ideas. This should not be surprising since, by definition, these are "big ideas" with widespread application across the whole domain of physiology.

We have already mentioned the overlap between the core concept of ***causality*** and the core concept of ***physics/chemistry***. Although the overlap is considerable, each of the separate concepts has different implications for student learning of physiology. Since physiological systems are causal mechanisms, students must learn to construct, critique, and run causal models (see Michael and Rovick 1999). The applicability of the laws of physics and chemistry to understanding physiological phenomena means that students must be able to transfer knowledge gained elsewhere to their learning of physiology, a task which many students find difficult.

Another obvious overlap involves ***cell membrane*** and ***cell–cell communication***. Cell membranes contain proteins, some on the exterior, some on the interior, and some that span the membrane. All of these proteins play a role in the response of one cell to chemical signals produced by other cells.

Finally, there is an obvious overlap between ***homeostasis*** and ***cell–cell communication***. Many homeostatically regulated mechanisms use hormonal signals to alter effector function. Many others use neural signaling to communicate both signals for neural receptors and effector control signals. Both types of mechanism are examples of ***cell–cell communications***.

In Chap. 1, we tried to make it clear that the purpose of defining the core concepts in physiology was to make available to teachers of physiology tools that might help their students understand physiology. Thus, the focus is on pedagogy. In light of this, it is important to point out that each physiology teacher deals with a specific class and with specific course objectives. Which core concepts are emphasized and which overlaps between core concepts become topics for discussion will clearly depend on the teacher and the course. In this book, we are describing tools, NOT a course or a curriculum for physiology.

3.4 Core Concepts and General Models

In describing the 15 core concepts that were identified, we have noted that four of them (***cell–cell communication***, ***flow down gradients***, ***homeostasis***, and ***mass balance***) are essentially identical to four of the general models identified by Modell (2000). Core concepts *are* "general models" in that they have wide applicability across all areas of physiology.

3.5 What Can You Do with the Core Concepts?

Core concepts, or big ideas, are by their very nature big. They are built up from many smaller concepts or ideas. The charge from NSF to the participants at the three CAB meetings was to think about how to do conceptual assessment in a robust way. The three of us who attended these meetings shared this interest, as did the other members of our research group. We wanted to write a concept inventory to assess students' understanding of one or more of the core concepts of physiology (see Chap. 11). However, it quickly became obvious to us that it was impossible to assess student's understanding of a complete core concept using multiple-choice questions. The complexity of each core concept was too great to be captured in a realistic number of multiple-choice questions.

Thus, we concluded that we needed to break a core concept into its constituent parts and then determine whether students understood the smaller, constituent concepts. The process of "unpacking" or deconstructing a core concept into its parts yields a conceptual framework. This process is the subject of the next chapter.

The first thing we sought to do with the core concepts we identified is to begin the process of writing a conceptual assessment instrument. However, we quickly realized that core concepts could be used as a central theme in all physiology teaching. We will be elaborating on these uses in Part III of this book.

3.6 Organization of the Next Four Chapters

Chapter 4 describes the process we have developed for unpacking the core concepts into conceptual frameworks. In Chaps. 5, 6, and 7, we present the conceptual frameworks, the unpacking, of the three core concepts that we selected for our initial development work: ***homeostasis***, ***flow down gradients***, and ***cell–cell communication***. For each of these core concepts, we discuss the elements of the framework, define the key terms that are used in each framework, present a visual representation of the concept, and, finally, discuss some of the issues that arise in helping students understand each concept.

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Chapter 4
What Does It Mean to "Unpack" a Core Concept?

Abstract Core concepts are sometimes called "big ideas." As such, each core concept is built up from a set of component ideas. Thus, understanding a core concept—being able to use it to solve a problem—requires an understanding of each of these smaller components. We have referred to the process of deconstructing a core concept into its critical components as "unpacking," and the result of unpacking is a conceptual framework.

The process that we have used to unpack core concepts results in a set of "critical components" that must be understood by physiology students at all educational levels. The "constituent ideas" will vary for different educational levels (along the novice to expert continuum) and purposes.

We will describe the process that we have used to "unpacking" the core concept of ***homeostasis*** into a logical, legitimate, and useful conceptual framework. We will also describe the process we used to validate these conceptual frameworks using a Delphi method. Finally, we briefly mention the many ways in which conceptual frameworks can be used in teaching and learning physiology.

Keywords Core concepts • Big ideas • Causal models • Unpacking • Conceptual frameworks

The core concepts of physiology (Chap. 3) are all "big ideas," although they clearly vary in their "size." ***Evolution*** is a "larger" concept than ***flow down gradients***, but even the smallest of the core concepts are made up of many component parts (concepts, ideas). Understanding a core concept then requires an understanding of these component parts.

4.1 What Does It Mean to "Unpack" a Core Concept?

Core concepts, or big ideas, are complex assemblages of interconnected smaller ideas. For example, the core concept of ***homeostasis*** is made up of concepts about sensors, effectors, set points, error signals, and controllers (see Chap. 5). Each of

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these subsidiary ideas may be made up of still smaller ideas. "Unpacking," a core concept, is the process of systematically deconstructing a "big idea" into the set of smaller ideas needed to understand the core concept. The resulting hierarchically structured statements make up a conceptual framework (McFarland et al. 2016).

Khodor et al. (2004) developed the Biology Concept Framework and organized their unpacking in a hierarchical structure. Feder (2005) described a framework-like description of "essential core ideas" for undergraduate physiology, and his organization is also hierarchical.

There is no single right way to unpack a core concept and no one right way to construct a conceptual framework. The ultimate goal of constructing a conceptual framework is to provide students with a learning resource that will help them achieve the learning goals for their course or curriculum. To the extent that courses vary in their coverage of the various domains of physiology, and the breadth and depth of understanding expected, any core concept can be usefully represented by a number of different conceptual frameworks. As we are using the term, a conceptual framework is not a description of the known science that makes up a discipline like physiology (although it must never violate that understanding). Rather, it is an organizational tool to help students learning that science.

4.1.1 Conceptual Assessment and Conceptual Frameworks in Biology

As was noted in Chap. 1, in 2007, the National Science Foundation sponsored the first workshop on Conceptual Assessment in Biology. CAB participants argued, we believe convincingly, that the first step in constructing a conceptual assessment instrument, a concept inventory, must be the definition of the concepts to be assessed and hence the building of a conceptual framework.

At the time of this meeting, there were already a number of groups working in different areas of biology to develop concept inventories. The literature describing the various assessment instruments is large and growing rapidly. However, the authors often do not define what they mean by a "concept," and it is often unclear exactly what set of "concepts" is being assessed. That is to say, there are conceptual inventories for which there is no clearly defined conceptual framework.

For example, Anderson et al. (2002) have developed a concept inventory on natural selection, but it was not based on a conceptual framework for this subject. Knudson et al. (2003) have developed a concept inventory for biomechanics and have defined a set of competencies but no list of concept as such. A genetics concept inventory, which is based on a conceptual framework, has been published by Bowling et al. (2008). Smith et al. (2008) described a genetics concept inventory based on a set of course learning goals, but they do not present a conceptual framework. Marbach et al. (2009) have developed a concept inventory for host–pathogen interactions based on a list of concepts but with no conceptual framework. Shi et al. (2010) described a concept inventory for introductory molecular and cell biology based on course learning goals but with no conceptual framework. Villafane et al. (2011) have developed a concept inventory about foundational concepts of biochemistry based on a simple list of concepts. Perez et al. (2013) described a concept inventory on evolutionary developmental biology based on a “flat” conceptual framework. Finally, Abraham et al. (2014) described a concept inventory on genetics with a list of core concepts but without unpacking these concepts.

4.1.2 Hierarchical Levels of Our Conceptual Frameworks

In unpacking the three core concepts described in Chaps. 5, 6, and 7 we have created hierarchical structures of the component concepts that make up these core concepts. The structure of one of our conceptual frameworks can be seen in the table below (see Table 4.1 below).

Our conceptual frameworks vary in their hierarchical depth. There are four hierarchical levels in the ***cell–cell communication*** conceptual framework, two levels for the ***homeostasis*** conceptual framework and three levels for the ***flow down gradients*** framework. The depth of a conceptual framework depends on two things, the complexity (which is not the same thing as the degree of difficulty) of the physiology described by the core concept and the use to be made of it. Since we are developing conceptual frameworks and conceptual assessments for introductory physiology students, the depth we employed is appropriate for that audience. A conceptual framework written for advanced undergraduates or graduate students might very well have greater depth.

Table 4.1 A description of the hierarchical organization of our conceptual frameworks with an example (Michael et al. 2016)

Level	Example
Core concept (big idea)	***Cell–cell communication*** (see Chap. 7)
Critical components	CC4 binding of the messenger molecule to its receptor gives rise to signal transduction
Constituent ideas	CC4.3 There are two basic mechanisms for transduction, both of which result in amplification
Elaborations	CC4.3.3 The speed of the response of the two systems is different
Amplifications	CC4.3.3.1 The speed of response in a second messenger system is fast

4.1.3 Conceptual Frameworks and Physiological (Causal) Models

A conceptual framework is a text-based, hierarchically organized representation of the ideas that taken together describe a core concept (McFarland et al. 2016). A causal model is another device for organizing the information describing a core concept (Michael and Rovick 1999). While these two representations clearly overlap, they do have different purposes as learning resources.

Conceptual frameworks are compact verbal descriptions of a core concept. They provide a structure or a scaffold that students can use to associate the facts and details of physiological mechanisms. When used in this way, frameworks should aid in retention and recall. They can also function as a scaffold to which attach (associate) new knowledge as they acquire it.

Physiological (causal) models are visual representations of the critical components of a core concept arranged in a way that illustrates the connections between these components. A model is "runnable" in the sense that it can be used to make predictions about how the system in question will respond to perturbations (Michael and Rovick 1999; Evens and Michael 2006; Michael et al. 2008). The visual components of the model, the "boxes" that make it up, can also be viewed as folders in which all the ideas about that critical component can be stored for retrieval and used in solving problems.

In Chaps. 5, 6 and 7, we present the conceptual frameworks and causal models for the three core concepts that we describe.

4.2 How Did We Construct and Validate a Conceptual Framework?

In his report about the first CAB meeting, Michael (2007) provided the first example of an unpacking of the core concept of homeostasis. At that time, he identified seven critical components (see Table 4.1). Michael et al. (2009), in addition to defining nine core concepts, unpacked each of them into a hierarchical framework.

The members of the CAP team carried out these initial attempts at identifying and unpacking core concepts. As was the case with identifying the core concepts, we were concerned that our attempts at unpacking did not necessarily reflect the needs of the wider physiology teaching community. We thus went to this community and elicited feedback from them on the unpacking of "homeostasis" and "flow down gradients."

As previously described, during our surveying of physiology teachers to elicit their views of the core concepts of physiology (Michael and McFarland 2011), we also asked our respondents for feedback on the unpacking of flow down gradients (fully described in Chap. 5) using a Likert scale. Respondents showed strong agreement with what we had done. Comments they provided were very supportive and did not suggest that we had missed anything.

We pursued an even more rigorous validation process for our unpacking of ***homeostasis*** (McFarland et al. 2016). The CAP group produced a proposed unpacking. We then asked survey respondents to provide us with feedback on each element of the conceptual framework. We also presented the homeostasis conceptual framework to participants in workshops at national meetings and elicited valuable feedback in this way. We presented the framework as a poster at EB 2015 and received additional feedback. The conceptual frame for ***homeostasis*** discussed in Chap. 5 is the final product of this iterative process.

4.3 Why the Particular Three Core Concepts We Unpacked?

We have been asked why we picked ***flow down gradients***, ***homeostasis***, and ***cell–cell communication*** to unpack. There were two criteria that played a role in making our choices.

We first unpacked and validated ***flow down gradients*** (Michael and McFarland 2011) because we had had experience using Modell's general models (2000) in our own teaching and because of its obvious widespread applicability. It also seemed to us that the conceptual framework that would be created would be relatively small (only a few items) and relatively simple (only a few hierarchical levels). In Chap. 6, you can see what this conceptual framework looks like.

We next attempted to unpack and validate ***homeostasis***. Michael (2007) and Michael et al. (2009) contained simple unpackings of this core concept, but no attempt was made to validate them. McFarland et al. (2016) generated a more complex conceptual framework and rigorously validated it. This was the second core concept we chose, and the reasons for selecting it were simple; ***homeostasis*** is the most commonly cited big idea in physiology, and it was a concept whose structure had been well established by many biomedical engineers and system physiologists. In Chap. 5 we present this conceptual framework.

The reasons for electing to unpack ***cell–cell communication*** were very similar. In validating our selection of core concepts (Michael and McFarland 2011), our survey respondents had told us that this was one of the top five most important concepts. We thought we understood the pieces of this core concept and believed that we could produce a useful conceptual framework even though it might be large (many items) and complex (many levels in the hierarchy). The resulting conceptual framework confirmed our predictions (Michael et al. 2016). In Chap. 7, we present this conceptual framework.

What about the other 12 core concepts? They do need to be unpacked (see Chap. 13), and we would urge others to begin the work of generating conceptual frameworks for these concepts. They too will represent useful tools for helping students learn physiology.

Finally, we must emphasize two things. There is no single, uniquely correct conceptual framework for any of the core concepts. Although our survey respondents have told us that our frameworks are correct, this does not mean that no other correct and useful frameworks can exist. We can certainly imagine frameworks tailored for specific courses or physiology curricula that would differ from ours.

In this book, we are attempting to provide examples of how to use the core concepts of physiology to teach physiology. We will be using the three core concepts that we have unpacked because we have them and because they have been validated. Other core concepts, if unpacked, would have worked just as well. So, what we are offering is a description of how to use a kind of tool that is available for helping students to learn. We are not prescribing what tools must be used nor how they must be used.

4.4 What Are the Uses of Conceptual Frameworks?

In Part III of this volume, we describe more fully the uses of core concepts and conceptual frameworks in teaching physiology. Here, we simply mention some of the ways in which conceptual frameworks can be used.

4.4.1 Student Learning of Physiology

Both conceptual frameworks and causal models are tools that can be used by students to acquire an understanding of core concepts.

Conceptual frameworks can simultaneously serve two purposes. A framework can serve to define for students what is important and therefore what needs to be understood. At the same time, the conceptual framework makes clear the relationships between the various pieces of knowledge that are encompassed by the framework. Finally, the framework provides the student with a structure with which to relate new knowledge as they acquire it; the framework is thus a kind of scaffolding.

Causal models are often drawn in a way that makes them "runnable." That is, if a change is present somewhere in the system, it is possible to propagate that change around the system to determine how the function of each system component will change. Problem solving in physiology often involves this kind of reasoning (Michael and Rovick 1999). In addition, such visual representations of a system or phenomenon are compact ways of keeping track of the accumulating knowledge about the system; the boxes become pointers to or addresses for all of the knowledge about a particular component of the system.

4.4.2 Teaching Physiology

Conceptual frameworks define the essential components of a core concept. The systematic unpacking of a core concept makes it possible for an instructor to explicitly define what she or he expects their students to know and be able to do. Thus, the design of courses, the preparation of learning resources, and the planning of classroom activities can all benefit from a focus on the core concepts. In Chaps. 8, 9, and 10, we discuss all of these at some length.

4.4.3 Assessment

If the core concepts are important, and we have certainly argued that they are, then it is essential that we assess whether our students understand these concepts. The first step in this process must be defining the concepts we want our students to master. Developing conceptual frameworks is the first step in developing a conceptual assessment instrument. In Chap. 11, we describe the process we have pursued in developing a conceptual assessment for the core concept of homeostasis.

4.4.4 Curriculum Design

A curriculum (or academic major or academic minor) is a sequence of courses, some required and other elected, that is intended to prepare students to some level of competence in a discipline. Ideally, the courses making up a curriculum should build on one another, with each successive course increasing the breadth and depth of the students' understanding. The core concepts and their conceptual frameworks provide a framework with which a faculty can build a curriculum in a systematic way. This will be discussed further in Chap. 12.

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Chapter 5
The "Unpacked" Core Concept of *Homeostasis*

Abstract We define ***homeostasis*** to be the maintenance of a constant internal environment by active functioning of cells, tissues, and organs organized into a negative feedback system.

In this chapter, we present a conceptual framework of the core concept of ***homeostasis***. We provide a visual representation of the critical components that make up ***homeostasis*** and provide definitions for all of the important terms that appear in the unpacking. We describe specific physiological variables to which this core concept is applied in mammals. Finally, we discuss some of the aspects of this core concept that are known to be difficult for students to master.

Keywords Core concept • Conceptual framework • Homeostasis • Sensor • Set point • Effector • Regulated variable

5.1 A Conceptual Framework for *Homeostasis*

In Chap. 3, we defined what we mean by the core concept of ***homeostasis*** as follows. ***Homeostasis:*** *The internal environment of the organism is actively maintained constant by the function of cells, tissues, and organs organized into negative feedback systems.*

The conceptual framework for the core concept of ***homeostasis*** is found in Table 5.1. It is important to note two constraints on our discussion of homeostasis. First, although other mechanisms may contribute to homeostasis (including feed-forward processes), this conceptual framework is limited to the concept of ***homeostasis*** via negative feedback mechanisms, because these are most often encountered in undergraduate physiology. Second, this framework specifically addresses ***homeostasis*** at the level of the organism (e.g., an animal) and does not address cellular or ecosystem homeostasis.

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Table 5.1 A conceptual framework for ***homeostasis*** (From McFarland et al. 2016)

H1.	The organism maintains a stable internal environment in the face of a fluctuating external environment.	
	H1.1.	The organism's internal environment differs from its external environment.
	H1.2.	The external environmental variables may change.
	H1.3.	A limited number of variables (i.e., regulated variables) of the internal environment are maintained stable via homeostatic processes in order to sustain cell function (if these variables change too much, cells cannot function normally and may die).
	H1.4.	Not all variables that remain within a normal range over time are homeostatically regulated variables (e.g., blood hematocrit, testosterone).
	H1.5.	Depending on the particular system, the regulated variable may be kept within a very narrow range or within a much wider range.
	H1.6.	Homeostatic (i.e., regulatory) mechanisms operate all the time to determine the value of the regulated variable (they do not turn "on" or "off"; they are not like a "light switch," they are like a "volume control knob").
H2.	A substantial change to a regulated variable will result in a physiological response to restore it toward its normal range.	
	H2.1.	The regulated variable is held stable by a negative feedback system.
	H2.2.	Not all negative feedback systems are homeostatic.
	H2.3.	The process of responding to a perturbation requires an action by a sensor, a control center, and an effector (the components of a negative feedback system).
	H2.4.	The sensor, control center, and effectors may be physically far from or near to each other in the body and can even exist in the same cell.
H3.	Homeostatic processes require a sensor inside the body ("what can't be measured can't be regulated").	
	H3.1.	Sensors detect the regulated variable and respond by transducing that stimulus into a different signal.
	H3.2.	Sensors respond within a limited range of stimulus values.
	H3.3.	Sensors generate an output whose value is proportional to the magnitude of the input to the sensor (i.e., the stimulus).
	H3.4.	Sensors are constantly active (not just active when the regulated variable is not at the set-point value).
	H3.5.	An organ system may employ a variety of types of sensors (e.g., chemoreceptors, baroreceptors, mechanoreceptors, etc.) to regulate variables associated with that organ system.
H4.	Homeostatic processes require a control center (which includes an integrator).	
	H4.1.	The control center is part of the endocrine and/or the nervous system.
	H4.2.	The integrator receives a signal from the sensor.
	H4.3.	The integrator is a component of the control center.
	H4.4.	Physiological systems have a normal range for a regulated variable (a so-called set point).
	H4.5.	The integrator determines the difference between the signal from the sensors and the set point (i.e., the normal range of the regulated variable).
	H4.6.	The value of the difference (between the signal from the sensor and the set point) is used by the control center to calculate a change in the signals going to the effectors (i.e., targets).

(continued)

Table 5.1 (continued)

	H4.7.	It is possible in some circumstances and in some systems for the set point to change.
H5.	Homeostatic processes require target organs or tissues, i.e., "effectors".	
	H5.1.	Physiological targets or effectors are cells, tissues, or organs (unlike "effector molecules" in biochemistry).
	H5.2.	The action of the targets (i.e., effectors) causes physical or chemical changes that alter the regulated variable.
	H5.3.	Effectors result in changes in nonregulated variables that in turn alter the regulated variable (e.g., the regulated variable, blood pressure, can be changed by altering heart rate (HR) and systemic resistance (SVR), which are not regulated).

5.2 A Visual Representation of the Core Concept of *Homeostasis*

Visual representations of physiological phenomena—causal diagrams—can be useful learning resources (Weaver et al. 2002; Luckie et al. 2011). As is the case with terminology, completeness and consistency in the use of visual representations are essential.

We have proposed two visual representations of homeostatic mechanisms (Modell et al. 2015) that can be seen here. Figure 5.1 depicts a generic homeostatic mechanism. It, or figures like it, appears in at least some advanced textbooks. A somewhat simplified version of this representation is seen in Fig. 5.2; similar figures are found in introductory level textbooks. The labels used in any version of a visual representation of homeostatic mechanisms should be consistent with the terminology used in the text.

It should be noted that this figure is a visual representation of most of the information that is found in the conceptual framework. The conceptual framework (Table 5.1) and the causal diagram (Fig. 5.1) are thus complementary but are used in different ways (McFarland et al. 2016). The causal diagram (Fig. 5.1) can be "run" to enable predictions to be made about the consequence of various changes in the system (Michael and Rovick 1999; Evens and Michael 2006; Michael et al. 2008).

5.3 *Homeostasis*: Terminology

The concept of ***homeostasis*** poses many difficulties for both instructors and students (Modell et al. 2015). One source of some of this difficulty is the terminology that is used to describe and explain ***homeostasis***. The treatment of this concept in widely used textbooks is often incomplete and inconsistent (Michael et al. 2013). We have published (Modell et al. 2015) a set of terms that are used in discussing

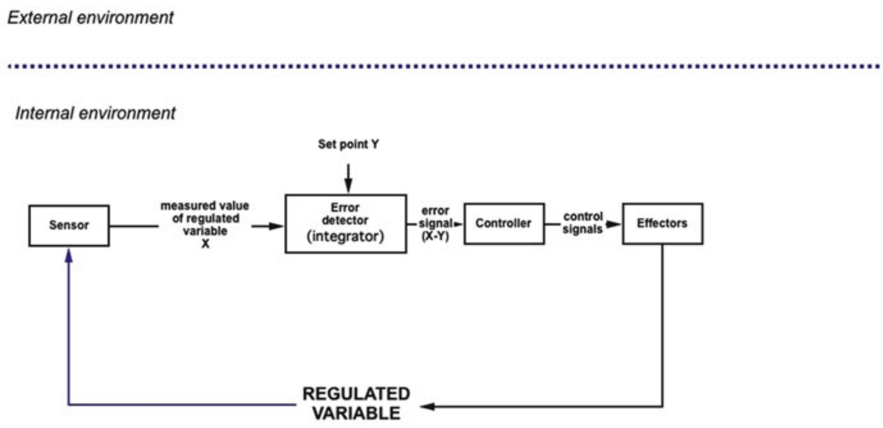

Fig. 5.1 A complete representation of homeostatic mechanisms (Modell et al. 2015)

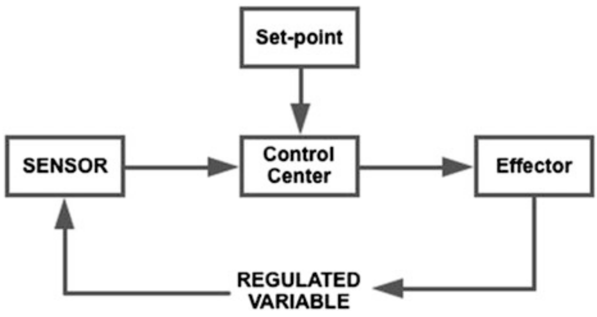

Fig. 5.2 A simplified representation of a homeostatic mechanism (from Modell et al. 2015)

homeostasis and their definitions (see Table 5.2) as a way of assisting instructors (and textbook authors) to maintain the use of a consistent terminology.

The terminology used to describe homeostatic regulation is general; it describes an abstract concept about how system components are arranged to carry out a function. In learning physiology, students will encounter many physiological variables that are regulated. In each specific system, the names for the components will differ, but the generic labels are useful as they convey the homeostatic system function that is being described. It is, thus, important that a consistent terminology is employed; this will help students understand the generality of the concept of regulation.

Table 5.2 Definitions of terms used in the ***homeostasis*** conceptual framework (Adapted from Modell et al. 2015)

Term	Definition
Control Center (or Integrating Center)	The control center consists of an error detector and controller. It receives signals (information) from sensors, compares information (value of regulated variable) with the set point, integrates information from all sensors, and sends output signals (sends instructions or commands) to increase or decrease the activity of effectors The control center determines and initiates the appropriate physiological response to any change or disturbance of the internal environment
Controller	The component of the control center that receives signals (information) from the error detector and sends output signals (instructions or commands) to increase or decrease the activity of effectors. The controller initiates the appropriate physiological response to an error signal resulting from a change or disturbance of the regulated (sensed) variable
Effector	A component whose activity or action contributes to determining the value of any variable in the system. In this model, the effectors determine the value of the regulated (sensed) variable.
Error detector	The component in the control center that determines (calculates) the difference between the set-point value and the actual value of the regulated (sensed) variable. The error detector generates the error signal that is used to determine the output of the control center.
Error signal	A signal that represents the difference between the set-point value and the actual value of the regulated variable. The error signal is one of the input signals to the control center.
External environment	The world outside of the body and its "state." The state or conditions in the outside world can determine the state of many internal properties of the organism.
Integrator	Another term for the control center. The integrator processes information from the sensor and those components that determine the set point, determines any error signal present, and sends output signals (instructions or commands) to increase or decrease the activity of effectors.
Internal environment	The internal environment is the extracellular fluid compartment (ECF). This is the environment in which the body's cells live. It is what Bernard meant by the "internal milieu."
Homeostasis	The maintenance of a relatively stable internal environment by an organism in the face of a changing external environment and varying internal activity using negative feedback mechanisms to minimize an error signal.
Negative feedback	A control mechanism in which the action of the effector (which generates a response) opposes a change in the regulated variable and returns it back toward the set-point value.

(continued)

Table 5.2 (continued)

Term	Definition
Nonregulated variable (Controlled variable)	A variable whose value changes in response to effector activity but whose value is not directly sensed by the system. Controlled variables contribute to determination of the regulated variable. For example, heart rate and stroke volume (controlled variables) contribute to determining cardiac output (another controlled variable) that contributes to arterial blood pressure (a regulated variable).
Perturbation (Disturbance)	Any change in the internal or external environment that causes a change to a homeostatically regulated variable. Physiologically induced changes in the set point would not be considered a perturbation.
Regulated variable (Sensed variable)	Any variable for which sensors are present in the system and the value of which is kept within limits by a negative feedback system in the face of perturbations in the system. A regulated variable is any property or condition of the extracellular fluid that is kept relatively constant in the internal environment in order to ensure the viability (survival) of the organism.
Response	The change in the function or action of an effector.
Sensor (Receptor)	A "device" that measures the magnitude of some variable by generating an output signal (neural or hormonal) that is proportional to the magnitude of the stimulus. A sensor is a measuring "device." For some regulated variables, sensors are specialized sensory cells or "sensory receptors," e.g., thermoreceptors, baroreceptors, or osmoreceptors. For other regulated variables, sensors are cellular components, e.g., the calcium-sensing receptor (a G-protein coupled receptor that senses blood calcium ion in the parathyroid gland).
Set point	The range of values (range of magnitudes) of the regulated variable that the system attempts to maintain. Set point refers to the "desired value." The "set point" is generally not a single value; it is a range of values.

5.4 Where Is the Core Concept of *Homeostasis* Applicable?

Homeostasis, the maintenance of a more or less constant internal environment, is essential for health and the continued viability of the organism. Homeostatic mechanisms affect the function of all of the body's organ systems. Table 5.3 (edited from Modell et al. 2015) contains a description of 10 homeostatically regulated variables about which we know a great deal and the system components that are involved in keeping them more or less constant. As can be seen, a great many organs and organ systems are involved in maintaining ***homeostasis***.

Table 5.3 A list of the physiological variables that are regulated by homeostatic mechanisms (modified from Modell et al. 2015)

Regulated variable (normal range)	Sensors (Location of control center)	Effectors
Arterial PO_2 (75–100 mm Hg)	Chemosensors (brain stem)	Diaphragm, Respiratory muscles
Arterial PCO_2 (34–45 mm Hg)	Chemosensors (brain stem)	Diaphragm, Respiratory muscles
$[K^+]$ (3.5–5.0 meq/L)	Chemosensors (adrenal cortex)	Kidneys
$[Ca^{2+}]$ (4.3–5.3 meq/L)	Chemosensors (parathyroid gland)	Bone, kidneys, intestine
$[H^+]$/pH (35–45 nM; 7.35–7.45)	Chemosensors (brain stem, kidneys)	Diaphragm, respiratory muscles, kidneys
[Glucose] (70–110 mg/dL fasting)	Fed state: chemosensors (pancreas) Fasting state: chemosensors (hypothalamus and pancreas)	Liver, adipose tissue, skeletal muscle
Core body temperature (98.6 °F)	Thermosensors (hypothalamus)	Blood vessels, sweat glands, skeletal muscle
Mean arterial pressure (80–100 mm Hg)	Mechanosensors (medulla)	Heart, blood vessels
Blood volume (5 L)	Mechanosensors	Hypothalamus, atria, kidneys
Blood osmolality	Osmoreceptors (hypothalamus)	Kidneys

5.5 Topics that Cause Confusion for Students and Instructors: Sticky Points

Modell et al. (2015), in describing our current understanding of ***homeostasis,*** discussed several pieces of the homeostasis conceptual framework that are problematic for students and instructors. Some of these difficulties arise from the complexity of the topic. Others are the results of apparently counterintuitive aspects of the system under consideration. The inconsistent use of terminology or visual representations of homeostatic mechanisms can also create a problem. Finally, some are the consequences of faulty mental models (misconceptions). Here, we will focus on only a few of these sticky points.

We have acquired information about student misconceptions about ***homeostasis*** from a number of sources. In validating the questions making up our ***homeostasis*** concept inventory (see Chap. 11), we have obtained responses from more than 600 students. An examination of the choices that students selected in taking the inventory reveals misconceptions. Interactions with physiology faculty at Human Anatomy and Physiology Society (HAPS) workshops have provided us with misconceptions seen in the classroom. Finally, our experiences as classroom teachers of physiology have revealed student misconceptions.

We have discussed 10 of these misconceptions with workshop participants at the HAPS 2012 meeting (Wright et al. 2013, 2015). Here, we will focus on only three of the most common student misconceptions about homeostasis.

In Chaps. 9 and 10, we address the creation of learning resources and the various classroom practices that can help students correct their flawed mental models of ***homeostasis*** and the other core concepts.

5.5.1 Everything Is Regulated

One of the more common misconceptions is that the body regulates ***all*** physiological variables in order to keep the body "in balance." This would mean that there are sensors (receptors) for ***all*** physiological variables since a physiological variable can only be regulated if the body has a sensor that can measure the value of that variable.

This is, of course, not the case. To consider just one organ system, the body cannot measure heart rate (although it can be controlled), stroke volume, or cardiac output.

The source of this misconception is probably the very emphasis that we place on the existence of homeostatic regulation of some physiological variables and the natural tendency to generalize to all those variables that do not get discussed in the course.

5.5.2 Homeostasis Is an ON/OFF Switch

Another common misconception is that ***homeostasis*** is like an ON/OFF switch that is only turned on when the regulated variable is not at its set-point value. This represents a serious flaw in the students' mental model since the output of the effectors that determine the value of the regulated variable are continually being determined by the output of the controller.

This misconception is often the consequence of using the home heating system as a model for temperature regulation; such systems almost always do operate in an ON/OFF fashion.

5.5.3 How Constant Is "Relatively Constant?"

Students often find it difficult to understand exactly what we mean when we say that homeostatic mechanisms hold the regulated variable "more or less constant over time." This difficulty is compounded when they compare a graph of a normal subject's blood pressure over time with a similar graph for blood glucose concentration. The variations in blood pressure are very small, while for a normal individual the swings in the concentration of blood glucose over the course of a day are very large. So, what does that "relatively constant" mean?

Students need to understand that homeostatic mechanisms (1) result in swings in the regulated variable that are smaller than would occur if the homeostatic mechanism was not operating, and (2) even when the swings in the value of the regulated variable seem large, the regulated variable is being held within a range consistent with normal functioning of the body.

5.5.4 The Set Point Can Change

Having been told that the set point is the value at which the regulated variable is to be held, students may be confused when they encounter situations in which the set point itself changes. For example, when an individual develops a fever, the increase in body temperature is the result of the temperature set point being increased by some pathology that is present. Similarly, there are conditions in which the set point for blood pressure regulation is elevated leading to hypertension.

The explanation for these phenomena and others like them is that the set point is the product of some physiological mechanism, and such mechanisms can have their function altered in many different ways.

5.5.5 Not All Examples of Negative Feedback Are Homeostatic

As students learn physiology, they encounter many examples of mechanisms that contain negative feedback. However, not all of these examples of negative feedback represent a homeostatic mechanism. A homeostatic system must contain all of the elements we identified earlier in this chapter. In Sect. 9.4, we discuss a system with multiple negative feedback loops, only some of which are examples of homeostasis.

5.5.6 The Hierarchy of Homeostatic Regulation

Many effectors play a role in more than one homeostatic mechanism. For example, the respiratory muscles (the diaphragm and the intercostal muscles) are the effectors that determine alveolar ventilation ($\dot{V}_A$) and hence the alveolar partial pressure of carbon dioxide (P_ACO_2). P_ACO_2 in turn determines arterial partial pressure of carbon dioxide (P_aCO_2). P_aCO_2 is a regulated variable, and changes in the activity of the respiratory muscles maintain P_aCO_2 within the normal set-point values.

However, arterial hydrogen ion concentration is also a homeostatically regulated variable, one with a number of effectors. Metabolic disturbances that alter arterial hydrogen ion concentration thus generate compensatory changes to the activity of the respiratory effectors and cause P_aCO_2 to change its value outside of the normal respiratory set-point values.

Thus, we can say that as far as the respiratory muscle effectors are concerned, there is a hierarchy of regulation with preservation of a normal hydrogen ion concentration taking precedence over maintaining the set-point value of P_aCO_2.

5.6 Summing Up: *Homeostasis*

Homeostasis allows complex multicellular organisms to maintain an internal environment (the extracellular compartment) that allows normal cellular function in the face of changes in the external environment and changes in internal function. An understanding of the core concept of ***homeostasis*** will provide students with a tool for understanding the many homeostatic mechanisms that they will encounter as they learn physiology.

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Chapter 6
The "Unpacked" Core Concept of *Flow Down Gradients*

Abstract The core concept of ***flow down gradients*** is also a general model of how things, whether animate or inanimate, move in the physical world.

In this chapter, we present a conceptual framework of the core concept of ***flow down gradients***. We provide a visual representation of the critical components that make up ***flow down gradients*** and provide definitions for all of the important terms that appear in the unpacking. We describe specific examples in which this core concept is applied in physiological systems. Finally, we discuss some of the aspects of this core concept that are known to be difficult for students to master.

Keywords Flow • Pressure • Resistance • Gradient • Core concept • Conceptual framework

6.1 The Conceptual Framework for *Flow Down Gradient*

The conceptual framework for the core concept of ***flow down gradient*** is found in Table 6.1 (Michael and McFarland 2011). Note that we have described the particular physiological phenomena to which each of the component ideas applies.

6.2 *Flow Down Gradients*: Terminology

Flow down gradients is a core concept, but it is also what Modell (2000) called a "general model." This term perhaps best describes the very important idea that the phenomenon being referred to is applicable to an essentially all of the transport process that are encountered in the body. Unfortunately, in each specific area of applicability, the student is likely to encounter different terms for ideas that she already understands. The result is the student begins a process of learning something she already understands. For this reason, it is particularly important that great care be given to using an appropriate terminology in discussing this core concept. In Table 6.2 (seen below), we have provided a glossary of the terms used in the conceptual framework for ***flow down gradients***.

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Table 6.1 Unpacking the core concept of ***flow down gradients*** (Michael and McFarland 2011)

F1.	Flow is the movement of “substances” from one point in the system to another point in the system.		
	F1.1	Molecules and ions can diffuse through a solution.	
	F1.2	Fluid (blood, chyme) and gases (air) are transported through tubes.	
	F1.3	Heat can move through objects.	
F2.	Flow occurs because of the existence of an energy gradient between two points.		
	F2.1	Differences in concentration (concentration gradients) cause molecules and ions in solution to move down a gradient from high to low concentration.	
	F2.2	Differences in electrical potential (potential gradient) cause ions in solution to move from high to low electrical potential.	
	F2.3	Differences in pressure (pressure gradient) between two points in a system cause substances to move toward a region of lower pressure.	
	F2.4	Differences in temperature (temperature gradients) between two points cause heat to flow from the hotter to the cooler location.	
F3.	The magnitude of the flow is a direct function of the magnitude of the energy gradient that is present—the larger the gradient, the greater the flow.		
F4.	More than one gradient can determine the magnitude and direction of flow.		
	F4.1	Osmotic (concentration gradient for water) and hydrostatic pressure gradients together determine flow across the capillary wall.	
	F4.2	Concentration gradients and electrical gradients determine ion flow through channels in cell membranes.	
F5.	There is resistance or opposition to flow in all systems.		
	F5.1	Resistance and flow are reciprocally related—the greater the resistance, the smaller the flow.	
	F5.2	The resistance to flow is determined by the physical properties of the system.	
	F5.3	Some resistances can be varied and can be actively (physiologically) controlled.	
		F5.3.1	Ion channels in a membrane can open and close changing resistance (decreasing and increasing, respectively).
		F5.3.2	Arterioles and bronchioles can constrict (increasing resistance) and dilate (decreasing resistance).
		F5.3.3	Pilo-erection can increase the resistance to heat flow in many animals.

6.3 A Visual Representation of the Core Concept of *Flow Down Gradients*

Figure 6.1 is a representation of the ***flow down gradients*** core concept. The plus sign (+) indicates that the relationship between the energy gradient and flow is a direct one; as the gradient increases, the flow will increase. The minus sign (−) indicates that the relationship between resistance and flow is an inverse one; as resistance increases, the flow decreases.

The simplicity of the model for ***flow down gradients*** (Fig. 6.1) belies the great power of this core concept to explain many important phenomena described in physiology. What students need to recognize as they move from the topic of cell membranes and ion transport to the cardiovascular system and blood flow and on to the respiratory system and air-flow is that these are all the same phenomenon although the labels are different.

Table 6.2 Definition of terms used in the ***flow down gradient*** core concept

Term	Definition
Bulk flow	The movement of a solution in a system driven by pressure gradient. Any solutes in the solution are carried in the solution as it moves.
Concentration	The amount of a solute in a unit volume of solution. Changes in either amount of solute, volume of solvent, or both will change the concentration of the solution.
Diffusion	The movement of solutes through a solution driven by the random motion of the solutes. In the presence of a gradient, there will be a net movement of the solute down the gradient.
Electrical potential	The result of a charge gradient (difference in charge at two points). It is a measure of electrical potential energy.
Energy	A measure of a system's ability to do work.
Flow	The movement of substances from one point in the system to another point in the system. The units of flow are thus amount of substance per unit time
Gradient	A difference in the magnitude of the concentration, electrical potential, pressure, or temperature between two points in a system. Changes in the magnitude of a gradient can occur because a change in the "upstream" and/or the "downstream" value or both
Hydrostatic pressure	Pressure in a fluid (liquid or gas) created by a vertical column (gravity) or by a pump. Fluid flow in tubes is driven by hydrostatic pressure gradients.
Osmosis	The movement of water down its concentration gradient. An osmotic pressure gradient is commonly defined by the gradient of solute particles (molecules or ions) in the two compartments.
Resistance	The opposition to flow in a system. The resistance that is present is always a function of the properties of the system. Resistances can vary as the physiological state of the system changes.

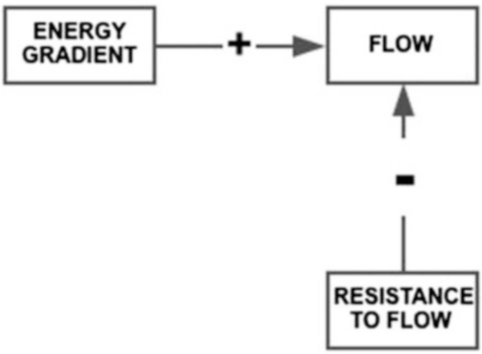

Fig. 6.1 A visual representation of the core concept of ***flow down gradients***. Note that the *plus* sign indicates a direct relationship between two variables and the *minus* sign indicates an inverse relationship

Table 6.3 Physiological phenomena to which the ***flow down gradients*** core concepts applies

What is moving	Nature of gradient	Source of resistance	Quantity of flow	Examples
Molecules (uncharged)	Concentration difference	Area available for diffusion Number of channels, pores, or transporters	Flux: mM/min for uncharged molecules or mEq/min for charged molecules	Oxygen Glucose Na^+
Ions (atoms or molecules with a net charge)	Electrical potential; charge concentration	Number of channel through which ions can pass	Current: μA/s	Na^+ and K^+
Fluids	Difference in hydrostatic pressure; difference in osmotic pressure	The properties of the medium and the structure	Flow: ml/s L/min	Blood Oxygen Chyme
Heat	Temperature difference	Thermal properties of tissues	Cal/min	Heat loss at skin

6.4 In What Physiological Systems Does *Flow Down Gradients* Apply?

Essentially, every physiological system at every level of organization exhibits phenomena that involve the movement of things down gradients. The movement of "stuff" into and out of cells as well as the movement of biological fluids in tubes and vessels can all be described by the same relationship. Table 6.3 contains a brief list of some of the phenomena for which the core concept of ***flow down gradients*** applies.

6.5 Topics that Cause Confusion for Students and Instructors: Sticky Points

Michael et al. (2002) assessed undergraduate students' understanding of cardiovascular phenomena. They found that across a large and diverse population of students, there were identifiable misconceptions (faulty mental models) about pressure-flow–resistance relationships (***flow down gradients***) in the circulation.

6.5.1 Problems with Flow Down Gradients in the Circulation

In applying flow down gradients to the circulation, students encounter a number of difficulties.

One problem that students have is attending to ONLY the upstream pressure (or energy) and not the pressure (or energy) gradient. By failing to recognize the downstream pressure, they ignore the fact that it is the gradient that determines flow and not the absolute pressure.

Another common problem is assuming that flow is an important determinant of resistance in a blood vessel. This error arises from the assumption that increasing flow means the vessels will get larger, and hence resistance will decrease. However, increasing flow through a vessel does not necessarily result in a change in vessel volume or radius. Hence, this phenomenon is not an important determinant of resistance to flow in the arterial compartment.

Students may also fail to understand that the downstream pressure is determined by the resistance to flow that is present. Furthermore, the likelihood of these misconceptions about cardiovascular phenomena being present was affected by the students' ability to apply a pressure-flow–resistance general model (Modell 2000) to non-physiological systems.

6.5.2 Failure to Take into Account the Presence of Multiple Gradients

There are many situations in which the flow of something is determined by two different gradients. These two gradients may cause flow in the same direction (in which case the flow is greater than would be present if only one gradient was acting) or they can promote flow in opposite directions (in which case the direction and magnitude of the resulting flow are determined by the difference between the gradients).

For example, the flow of ions across a membrane is always determined by both the concentration gradient across the membrane and the electrical potential gradient that is present (the electrochemical gradient). At the capillary, the balance between a hydrostatic gradient and the oncotic gradient that are present determines the direction and the magnitude of the flow of water across the wall of capillary.

Students often disregard one or the other of these gradients in thinking about how the substance under consideration will behave.

6.5.3 Recognizing Osmosis as an Example of a Core Concept

Osmosis is the movement of water between two compartments through a semipermeable membrane from a region of low concentration of solutes (high concentration of water) to a region of high concentration of solutes (low concentration of water). In osmosis, water is diffusing down its own concentration gradient. Osmosis is thus one example of ***flow down gradients***. However, students frequently simply memorize a definition of osmosis without recognizing that it is simply one example of a core concept. Thus, students may fail to recognize all of the features of ***flow down gradient*** (see Table 6.2) that apply to osmosis.

6.5.4 Molecules Diffuse Independently of One Another

Many students believe that oxygen crosses the alveolar–capillary barrier coupled to the movement of carbon dioxide in the opposite direction. The error has two possible sources: (1) it is often said that there is an exchange of oxygen and carbon dioxide which students think implies a coupling mechanism and (2) failure to recognize that each gas is diffusing down its own concentration (partial pressure) gradient. Molecules in solution and the gases making up air diffuse independently of one another.

6.5.5 The Presence of a Gradient Does Not Mean that Flow Will Occur

Movement of things into and out of cells (ions, amino acids, glucose, etc.) does not always occur in the presence of a concentration gradient. If the cell membrane is impermeable to the substance (equivalent to the resistance to flow being infinite), no flow can occur. In the case of ions, flow down gradient may require the presence of open channels; in the case of glucose or amino acids, flow requires the presence of transporters in the membrane. Students must think about both the gradient and the opposition to flow (resistance, permeability).

6.6 Summing Up: *Flow Down Gradients*

Flow down gradients is a concept that describes how things move in the world, whether inanimate or animate. It is a core concept of physiology that applies to every level of the organism, from transport across cell membranes to the flow of blood in the circulation and the flow of gas in the airways. Students will encounter this concept in systems that seem very different. If they understand the core concept, understanding each of these seemingly disparate systems will be much easier.

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Chapter 7
The "Unpacked" Core Concept of *Cell–Cell Communication*

Abstract ***Cell–cell communication*** focuses on how cells generate and receive messages from other cells. Cells do not live in isolation. Cell survival and normal functions depend on collecting and responding to information from other cells. Only in this way can a complex, multicellular organism carry out all of its many functions.

In this chapter, we present a conceptual framework of the core concept of ***cell–cell communication***. We provide a visual representation of the critical components that make up ***cell–cell communication*** and provide definitions for all of the important terms that appear in the unpacking. We describe specific examples in which this core concept is applied in physiological systems. Finally, we discuss some of the aspects of this core concept that are known to be difficult for students to master.

Keywords Communications • Information • Receptors • Cells • Chemical messengers

7.1 A Conceptual Framework for *Cell–Cell Communication*

Cell–cell communication was ranked the third most important core concept in the study reported by Michael and McFarland (2011).

Table 7.1 is the conceptual framework for ***cell–cell communication***. We propose the conceptual framework as a way to organize material to enhance teaching and learning. This framework is hierarchical in that it places details in context and nests related concepts. The framework can be used to help physiology students to form their own accurate mental models (Modell 2000) and to create enduring understanding of component ideas.

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Table 7.1 The conceptual framework for the core concept of ***cell–cell communication*** (Michael et al. 2016)

CC1	A cell synthesizes and releases a chemical messenger.		
	CC1.1	A cell synthesizes a messenger molecule.	
	CC1.2	Messenger molecules can be proteins (or peptides), steroids, or amines.	
	CC1.3	The rate of release of a messenger from a cell is determined by the “sum” of the stimuli for release and the stimuli that inhibits release.	
	CC1.4	Chemical messengers are present at very low concentrations in the blood compared to other biologically active molecules such as ions and nutrients.	
	CC1.5	The greater the net stimulus for release, the higher the rate of release of the messenger.	
	CC1.6	Cells release messengers by exocytosis or diffusion across the cell membrane.	
	CC1.7	Cells that release messengers can be anywhere in the body.	
CC2	Transport of messenger molecules is determined by the chemical nature of the messenger.		
	CC2.1	The solubility of the molecule determines how it is transported to its target cells.	
		CC2.1.1	Protein/peptide and amine messengers are generally water soluble and are transported in solution.
		CC2.1.2	Steroid messengers are lipid soluble and are transported bound to protein carrier molecules in the blood.
		CC2.1.3	Some amine messengers are transported bound to transport proteins, and others are carried in solution.
	CC2.2	The extracellular fluid concentration of a messenger molecule depends on the balance between production/release and elimination of the messenger.	
	CC2.3	Only the messenger in solution and free to diffuse is biologically active.	
CC3	The messenger must bind to a receptor protein in or on its target cell to produce a response.		
	CC3.1	Each messenger molecule can only bind to a specific receptor molecule. Binding of a messenger to its receptor is a probabilistic event.	
	CC3.2	A cell can only respond to a messenger for which it has receptors.	
	CC3.3	The solubility of the messenger determines the location of its receptor protein in/on the target cell.	
		CC3.3.1	Water-soluble messengers have receptors that are on the target cell membrane.
		CC3.3.2	Lipid soluble messenger have receptors that are inside the target cell, usually in the nucleus but in some cases in the cytoplasm as well.
	CC3.4	The number of receptors for a particular messenger can be relatively small or relative large and is variable.	
	CC3.5	There can be more than one type of receptor for the same messenger on different target cells.	
	CC3.6	Thus, the same messenger can produce different responses in the same type of target cells wherever they may be in the body.	
	CC3.7	Cells have a large variety of different receptors, thus enabling them to respond to a large number of different messengers.	

(continued)

Table 7.1 (continued)

CC4	Binding of the messenger molecule to its receptor gives rise to signal transduction.			
	CC4.1	A single messenger molecule bound to its receptor can activate or alter many more molecules in the target cell; this is called amplification.		
		CC4.1.1	Because target cell response is a multistep process and amplification occurs at each step, a single molecule can activate or alter many more molecules; the more steps in the intracellular signaling process, the greater the amplification can be.	
		CC4.1.2	Given that messenger molecules are scarce, if the signal is not amplified, it will have little physiological effect.	
		CC4.1.3	Because the target cell response is a multistep process, there are many points at which different inputs (other messengers) can modify the outcome/response. This is referred to as integration.	
	CC4.2	Because the target cell response is a multistep process, a particular messenger molecule can have more than one effect in a target cell.		
	CC4.3	There are two basic mechanisms for transduction, both of which result in amplification.		
		CC4.3.1	Binding of a messenger molecule to its receptor can activate a cascade of intracellular second messengers which result in altered enzyme activity.	
		CC4.3.2	Binding of a messenger molecule to its receptor can alter the processes of translation and transcription in the cell nucleus, thus altering the concentration of a specific enzyme in the cell.	
		CC4.3.3	The speed of the response of the two systems is different.	
			CC4.3.3.1	The speed of response in a second messenger system is fast since second messenger molecules are already present in the cell.
			CC4.3.3.2	The speed of response in transcription and translation systems is slower because new molecules have to be synthesized.
		CC4.3.4	Persistence of the response to messenger molecules also differs.	
			CC4.3.4.1	In second messenger systems, the half-life of the molecules that get activated is short, and the response can be terminated quickly.
			CC4.3.4.2	In translation-/transcription-based systems, the half-life of the molecule (proteins) produced is longer, so the responses persist longer.
CC5	Binding of the messenger molecule to its receptor alters cell function.			
	CC5.1	The response of the target cell is a function of the target cell and not the messenger molecule. That is to say, the response to a given messenger is determined by the physiology of the target cell.		
	CC5.2	Alteration of target cell function is always the result of altering enzyme activity, whether caused by second messenger alteration of enzyme activity or by changes in translation/transcription causing the appearance of more enzyme molecules.		
CC6	Termination of a messenger signal is accomplished in several ways.			
	CC6.1	The messenger signal goes away because the messenger molecule is no longer released or it is broken down.		
	CC6.2	The messenger molecule is removed from the receptor.		
	CC6.3	The receptor+messenger complex is internalized and ceases to generate a signal.		

(continued)

Table 7.1 (continued)

CC7	Some cells can communicate with neighboring cells electrically; they are electrically coupled.	
	CC7.1	Electrically coupled cells have gap junctions that span their two membranes.
	CC7.2	Current can flow from one cell, when electrically excited, to neighboring cells.
	CC7.3	These currents then electrically excite the second cell.

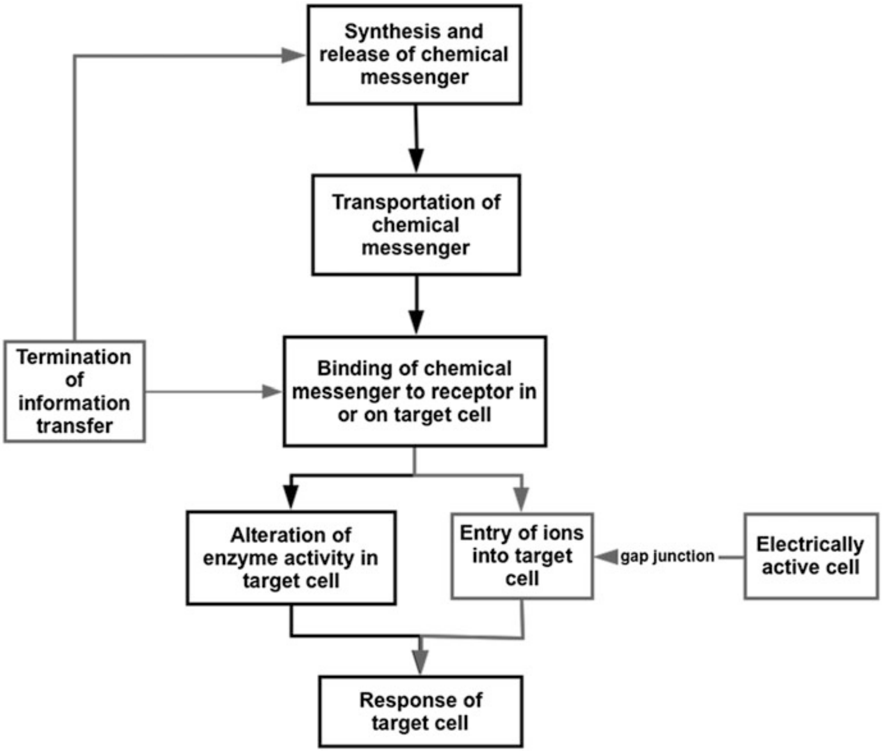

Fig. 7.1 A visual representation of the core concept of ***cell–cell communication***

7.2 A Visual Representation of the Core Concept of *Cell–Cell Communication*

Figure 7.1, below, illustrates a model of ***cell–cell communication***. This model, like all general models (Modell 2000), applies in a great many physiological contexts. It makes no attempt to encompass all of the details, but it does show the relationships between the major ideas. As with the other two models (Chaps. 5 and 6), the boxes can serve as folders in which students can associate the new information they acquire with the relevant components of the system. Students can also use the model to solve problems.

7.3 *Cell–Cell Communication*: Terminology

Cell–cell communication is a core concept in physiology (Michael and McFarland 2011). As was pointed out in Chap. 5 (***homeostasis***) and Chap. 6 (***flow down gradients***), it is essential that a clearly defined set of terms be used in teaching and using this core concept.

Cell–cell communication describes the very important idea of how cells communicate with one another, which is necessary for the survival of the organism.

This topic draws on many disciplines for its foundational ideas and in turn contributes to many disciplines. As a consequence of this, the student is likely to encounter different terms used to describe the same idea in different contexts. Since this is the case, instruction must include the use of the appropriate terminology in discussing this core concept, and the same terminology must be used throughout the course. Table 7.2 is a glossary of the terms used in the conceptual framework for ***cell–cell communication***.

7.4 Where Is *Cell–Cell Communication* Applicable?

It has been reported (Bianconi et al. 2013) that the human body is made up of 37.2 trillion cells and that there are hundreds of different types of cells (Mescher 2016). Each of these types of cells, while they have the same DNA, expresses different genes and carries out different functions. This myriad of functions must be coordinated so that the organism is able to maintain a more or less constant internal environment. That is to say, life can only be maintained through the coordinated activity of all the cells of the body. This coordination takes place via the transmission of messages between cells. The ***cell–cell communication*** conceptual framework describes the components of this kind of information processing system.

In the human body, ***cell–cell communication*** commonly occurs by the nervous system (in which neurons release transmitters that alter the function of adjacent cells that have receptors for those transmitters) or by the endocrine system (in which hormones are produced and released and travel throughout the body to bind to receptors on target cells).

Thus, the answer to the question of where the core concept of cell–cell communications is applicable is EVERYWHERE!

Table 7.2 Terminology for ***cell–cell communication*** core concept

Term	Definition
(Chemical) Messenger	A molecule produced and released by a particular cell that carries information to target cells. The binding of the messenger molecule to a receptor on or in the target cell causes a change in the function of that cell.
Amplification	Binding of a messenger molecule to a cell receptor gives rise to a cascade of second messengers in the cell, or the production of many enzymes, that alters cell function. One molecule thus engages a great many molecules in altering target function.
Biological response	The change in target cell function that is initiated by the receipt of the messenger. This may include the generation of a new function, the cessation of an existing function, or a change in the magnitude of an existing function.
Cell function	All of the myriad of processes that are ongoing in a cell. Many are general to all cells and many represent specialized processes. Cell functions are altered in response to chemical messengers, thus giving rise to a biological response.
Enzyme	Enzymes are biological catalysts; the activity of which is essential for the chemical reactions that make up a cell's metabolism to proceed. The activity of an enzyme is a function of its concentration (how much is in the cell) and the state of the enzyme molecule (which can be altered by second messengers).
Receptor	A protein molecule in the target cell membrane or nucleus to which a particular messenger molecule can bind. When the messenger binds to a receptor, signal transduction and amplification occur. A change in cell function, a biological response, then occurs.
Second messenger	Molecules that relay signals received at receptors on the cell surface (the binding of messenger molecules) to other molecules in the cytosol and/or nucleus that ultimately alter enzyme activity.
Signal transduction	The process by which incoming messages are conveyed to the target cell's interior where amplification can occur.
Target (Target cell)	A cell that has receptors for a particular chemical messenger molecule and can thus respond (change its function) when the message is received.
Termination (of signal)	For proper control of signaling, there must be a means of terminating the signaling. In all cases, once the messenger molecule dissociates from the receptor, the signal ends.
Transcription	Process of building a RNA copy of a gene sequence on DNA. The copy is, simply put, a messenger RNA (mRNA) molecule. mRNA leaves the nucleus and in the cytoplasm is involved with assembling proteins that function as enzymes.
Translation	Process of translating the sequence of a transcribed messenger RNA (mRNA) molecule to a sequence of amino acids during protein synthesis. The proteins assembled are often enzymes that produce the biological response triggered by the messenger.
Transport	The chemical messenger molecules that are synthesized and released from cells must reach their targets. In some instances, this occurs by simple diffusion through the extracellular compartment. In other instances, the messenger is transported around the body in the blood. Messenger molecules that are lipid (not water) soluble are transported in the blood bound to transport proteins.

7.5 Topics that Cause Confusion for Students and Instructors: Sticky Points

The study of ***cell–cell communication*** occurs in many different biological disciplines, such as developmental biology, neurobiology, endocrinology, and physiology. Students will learn many component ideas (see Table 4.1) of ***cell–cell communication*** in a number of different courses. It is thus important that instruction about this core concept is accurate and consistent across the curriculum. We will have more to say about the use of core concepts in building the curriculum in Chap. 12.

7.5.1 What Is Information?

Both the endocrine and the nervous systems are information processing systems. "Information" is a term with a precise scientific meaning and a much looser meaning in everyday conversation. As a consequence, students are often confused by what is meant by information in the organism.

The signals that pass from cell to cell are examples of "information." The presence of the messenger molecule attached to a receptor "means something" to the target cell. For example, when a molecule of insulin binds to the receptor on the membrane of a skeletal muscle cell, it "means" that blood glucose is higher than it ought to be (higher than the set point). That information directs the cell to incorporate glucose transporters into its membrane metabolism, increasing the influx of glucose into the cell, thereby causing blood glucose concentration to decrease.

The insulin molecule does not itself alter cell metabolism, it does not provide a substrate used by the cell's metabolism, and it does not itself provide metabolic energy for use by the cell. Insulin simply tells the cell that something has happened.

As with many of the other difficult topics we have discussed here, teachers can help students by explicitly addressing this issue and clarifying the issues that arise. We will discuss in later chapters how teachers can accomplish this in the classroom.

7.5.2 The Central Role of Enzymes

The final common pathway for most cell–cell communications systems is the alteration or modulation of the activity of intracellular enzymes. When enzyme activity changes, metabolism changes in some way, and these changes in metabolism constitute the biological response that the target cell generates when stimulated by the messenger.

Thus, it is essential that students have some understanding (perhaps only a limited one) of enzymes, what they are, how they work, and why they are important.

Enzymes are molecules that speed up a specific chemical reaction. Some molecule called the substrate undergoes a change (a chemical reaction) because of the presence of an enzyme. The resulting molecule is called the product. Second messengers are enzymes that can alter other enzymes. These changes then cause the metabolic pathways in the target cells to change. These changes are the response of the target cell to the messenger molecule.

Because enzymes are usually protein molecules whose complex shape determines their function, very small structural changes to an enzyme will change their function.

7.5.3 What Is a Response?

Students are likely to see the contraction of a muscle, the lowering of blood glucose after a meal, increased activity of osteoblasts, and the secretion of gastric acid as categorically different events. However, they share two things: (1) the occurrence of each is the result of the communications of information via some kind of cell–cell interaction, and (2) each is the result of changes in enzyme activity in the target (responding) cell.

Teachers, like all people, tend to assume that what they know everyone else knows. That is to say, teachers often assume that students see the common features of things just as they see them. Here too, then, the key is for teachers to be as explicit as possible in order to help students see the commonalities where they exist and to help students look at these commonalities on their own.

7.5.4 Properties of Receptors

Students are often confused when they encounter the term "receptor" because that word is used to describe two fundamentally different kinds of structures. In studying functions of the nervous system, they learn about several different kinds of cells that function to convert some physical stimulus into a neural signal (depolarization or action potential): mechanoreceptors, stretch receptors, touch receptors, etc. Each of these is a discrete cell.On the other hand, the term "receptor" also is used to refer to protein molecules in cell membrane or in the nucleus that bind specific chemical messengers and thereby trigger a response from the target cell. These two kinds of receptors are functionally quite different, and they have very different properties.

In talking about cell–cell communications, we are, of course, talking about receptors as proteins that bind specific messenger molecules. These receptors have some important properties that must be understood. First, their function is dependent on their shape, and this can be altered in a variety of ways so that the receptor does not function normally.

In addition, there are many receptor molecules of a particular kind on every target cell, and the strength of a response depends on the number of receptors available that bind a messenger molecule. But receptor expression is *usually* dynamic—chronic stimulation of receptors often results in decreased numbers of receptors (downregulation), while under-stimulation causes an increase in the number of receptors (upregulation). There are many practical examples of this process, for example, long-term stimulation of beta-1 and beta-2 adrenergic receptors causes their numbers to decrease (with profound effects on asthmatics and people in heart failure), while denervation of some structures may cause upregulation and modification of receptors to a point where even mild stimuli cause substantial responses (e.g., in achalasia and also in spinal cord injury).

7.5.5 The Number of Receptors on a Target Cell Is Small (1 to Few)

Students commonly respond to questions or problem as if they believe that cells have small number of receptors, in some cases implying that there is a single receptor for each chemical messenger. This misconception probably arises from the fact that few textbooks explicitly discuss the binding of a messenger molecule to a receptor is a probabilistic event, and that number of receptors that are present for any system, even when they describe processes of up- and downregulation that can change that number.

7.5.6 The Response to a Messenger Is a Property of the Messenger Itself

In spite of the fact that teachers and textbooks list the many different responses that can be elicited by a particular autonomic transmitter (acetylcholine) or hormone (cortisol), students often retain the misconception that it is only the nature of the messenger molecule that determines the response that will be generated. A consequence of this misconception is that students then find it difficult to understand the varied responses to insulin that are involved in the regulation of blood glucose concentration.

7.5.7 Chemical Messengers Act Independently of One Another

Students may believe that each chemical messenger generates a unique response in each of its target cells. They think that if a tissue is innervated by sympathetic and the parasympathetic neurons, then each type of input produces a unique response. They might also believe that if a cell responds to many hormones (has receptors for many hormones), then each hormone produces a distinctive response in the target cell.

What students fail to understand is that each postsynaptic cell is a device that adds up the inputs it receives from multiple messengers, and the net result determines whether the postsynaptic cell fires an action potential or not. Similarly, a skeletal muscle cell has receptors for many hormones that alter the cell's metabolism, and hence the results of stimulation depend on a summing up of all of the inputs it is receiving.

7.5.8 Responses to Messengers Are All-Or-None

Perhaps because students know that the action potential is all-or-nor, they assume that the responses to all chemical messengers are all-or-none. This is, of course, incorrect even for neurons. While action potentials ***are*** all-or-none, the response of neurons to synaptic inputs is graded; spatial and temporal summation of synaptic inputs is required to excite a neuron. Similarly, the responses generated by hormones acting on their target cells are graded; the more the receptors occupied (which usually means the higher the concentration of hormone reaching the target), the bigger the response.

7.5.9 The Nervous System and the Endocrine System Operate in Fundamentally Different Ways

For many students, the obvious differences, anatomical, histological, and functional, between neural systems and endocrine systems obscure the similarities in function between the two systems. This is, of course, the message that is meant to be conveyed by the core concept of cell–cell communications. Both systems operate by sending out chemical messenger molecules that, if they bind to a specific receptor, trigger a response in the target cell.

7.6 Summing up: *Cell–Cell Communication*

The many cells making up the body must coordinate their functions in order to maintain the life of the organism. ***Cell–cell communication*** is a core concept of physiology that describes the complex processes that underlie this interaction between cells. Whatever physiologic topic the students attempt to understand, their understanding of this core concept will provide a tool to facilitate their learning.

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Part III
Implementing the New Paradigm for Teaching Physiology

Chapter 8
Organizing an Introductory Physiology Course Based on Core Concepts

Abstract We begin by defining a typical sequence of topics that make up an introductory physiology course. We then describe how one might introduce students in the course to the core concepts and general models. We then discuss how to revisit the core concepts as they occur in the physiology being learned. What is essential is the use of consistent terminology and visual representations of the core concepts. It is also essential that the learning objectives (the definition of what is required for student mastery) include the recognition and use of the core concepts. We end with a discussion of the time constraints that are associated with every course while at the same time adding an emphasis on the core concepts.

Keywords Physiology course • Core concepts

Whether you teach a first-year introductory anatomy and physiology course, a medical physiology course for first-year medical students, or a course somewhere in the middle, focusing your course on the core concepts of physiology will require changes be made to the way you think about your current course.

The issue is not about the physiology content of the course, although we will address this below. It is about building into your course the consistent use of the core concepts as learning tools for your students. The steps to be taken may not directly change your course content, but they will result in changes to the way in students learn (master) the content you expect them to master.

8.1 Organizing an Introductory Physiology Course

It will perhaps be most useful to illustrate the processes we are talking about by describing how an introductory physiology course can be organized in order to incorporate a focus on the core concepts of physiology (see Chap. 3).

Typical courses of this kind, and the textbooks that are assigned, follow a more or less common sequence of topics: chemistry of the body, cells and their functions, the nervous system, muscle, cardiovascular physiology, respiratory system, the kidneys, digestive system, endocrine system, regulation of metabolism, and reproductions. Not every textbook or course is organized in exactly this way; topics such

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as the endocrine may come early or late in the sequence or there may be other deviations from the pattern we are assuming. However, for our purposes, the sequence defined here will provide us the structure we need to discuss how to incorporate the core concepts of physiology.

8.2 Introducing the Core Concepts of Physiology

We, and a cohort of physiology teachers, identified 15 core concepts of physiology (see Chap. 3). While it is clear that all of the core concepts are of some importance, this same cohort told us that ***homeostasis*** (Chap. 5), ***flow down gradients*** (Chap. 6), and ***cell–cell communication*** (Chap. 7) were the three most important ones. Thus, we will be describing how we would incorporate these three core concepts into a physiology course.

It is unlikely that you will want to incorporate all of the 15 core concepts in your course. Thus, the first task is to select which of the core concepts (in addition to the first three) you will introduce in your course. It is worth noting that the three identified as being most important appear, in one way or another, in essentially every physiology textbook and course. If others are to be introduced as well, they will have to be selected to meet the learning needs of your students in your course.

The next issue is how to introduce your students to the set of core concepts you have selected. There are two ways in which one might do this.

8.2.1 Introduce the Core Concepts at the Beginning of the Course

It is not uncommon for physiology textbooks and courses to begin with an introductory unit that focuses on broad biological topics. ***Homeostasis*** is one such topic that is likely to be included in such a section. The issue, though, is how to introduce this and the other core concepts in a way that will help students gain an understanding of them.

There are two answers to this question. First, the core concepts, like everything else you want your students to master, must be taught in an active learning environment. Second, if you expect students to achieve some particular level of mastery of the core concepts (whichever ones you select), this must be clearly communicated in your learning objectives/learning outcomes. It follows, then, that you must assess student's mastery of whatever you have included in your learning outcomes.

Below, we will discuss how you can build on this initial exposure to the core concepts as the course moves from topic to topic.

8.2.2 Introduce the Core Concepts as the Students First Encounter Them

An alternative approach to introducing the core concepts is to focus on each one as they first become applicable to the physiology being studied. Since most courses begin with a consideration of basic cell function, ***flow down gradients*** is probably the first core concept that students will encounter. The passive movement of molecules into and out cells is driven by a concentration gradient (energy gradient). The passive movement of ions is driven by the electrochemical gradient that is present. In either case, the opposition to flow, the permeability or resistance, determines the flux that will result for any given gradient. As this core concept is developed, it is essential to point out that exactly the same relationship describes the movement of blood in the circulation and the movement of gas in the airways. It is also important to help students recognize that many core concepts (e.g., flow down gradients) are encountered in everyday life.

Where you choose to introduce each of the core concepts you have selected for incorporation in your course will clearly depend on the sequence of topics you present in your course and where you think it will be didactically most useful to your students.

8.3 Revisiting the Core Concepts Wherever They Apply to a Physiology Topic

Perhaps the most important tactic in helping students develop an understanding of, and the ability to apply, the core concepts is explicit and consistent repetition of their use.

8.3.1 Consistent Terminology

One problem that students encounter in every textbook is the lack of consistency in the terminology that they encounter as they move from organ system to organ system. Some of this simply reflects the fact that different domains in physiology use different terms to describe the different systems being studied, and some differences reflect historical conventions that have arisen. Take the core concept of ***homeostasis*** as an example. After the initial development of the concept and the introduction of terms such as sensor and error signal (see Chap. 5), later discussions of specific homeostatic mechanisms (i.e., regulation of blood pressure, regulation of blood glucose) generally present students with different terminologies. In talking about blood pressure regulation, students do not necessarily recognize that the carotid baroreceptor is the sensor in a homeostatic mechanism. Thus, it is not hard to understand why students usually do not see the connection between the core concept of ***homeostasis*** that they learned earlier in the course and the phenomenon of blood pressure regulation.

It is therefore important that the teacher uses a consistent terminology in discussing phenomena where one or more of the core concepts are applicable. It is also essential that the teacher explicitly relate new, system-specific terms to the more generic terminology used in discussing core concepts.

8.3.2 Consistent Visual Representations

A similar problem arises when we think about the visual representations that are used in describing different systems. Each of the core concepts we have discussed can be represented visually (see Chaps. 5, 6 and 7), and for many students such visual representations are powerful learning tools.

But as with terminology, the visual representations the students are likely to see as they study the various organ systems are different from the canonical representations they saw initially. Thus, it is hard for the students to see that the system they are now studying is like the system they saw several weeks ago.

Thus, it is important for the teacher to either generate visual representations that make clear the connection between the physiology being described and the canonical version or at least call to the students' attention that the systems are essentially identical.

Michael et al. (2013) and Wright et al. (2014) have discussed the visual representations of ***homeostasis*** that are found in common textbook (and presumably used by faculty) and discussed the problems that these representations create. In Chap. 5, you can see the representations created by Modell et al. (2015) that we believe are more correct and more useful.

8.3.3 Requiring the Students to Actively Recognize Where the Core Concepts Apply

The learning phenomenon we have been discussing is referred to as the transfer problem in the learning sciences (Perkins and Salomon 1992; Bransford et al. 1999; Wiggin and McTighe 2005). It is a general problem in teaching and learning at all educational levels and in all disciplines.

How does one facilitate students' learning to transfer what they have learned in one context into a second, different context? One answer is practice (with appropriate feedback)! We need to create learning resources (see Chap. 10) with which students are required to practice recognizing core concepts or general models and then using them to solve a problem. We also need to be sure that our learning outcomes include requiring a demonstration of this skill and that we then assess whether our students have achieved the level of competence that we define.

8.3.4 Requiring Students to Use the Core Concepts

If students are to develop the ability to use core concepts as an aid to learning and understanding physiology, we have to explicitly expect them to learn to recognize where they are applicable and learn to use them. This means that we must provide them with opportunities to practice these skills. In Chap. 10, we discuss how to go about writing such resources and present some examples of exercises that help students accomplish this.

8.4 Aligning Your Learning Outcomes and Learning Objectives with the Focus on Core Concepts

If you want your students to become proficient at using core concepts to understand physiology, it is essential that your learning objectives (what students need to know) and learning outcomes (what students can do) clear descriptions of which core concepts are to be mastered and how the students are expected to use them.

It is also essential that your learning objectives and outcomes incorporate the use of the core concepts into their mastering of the physiology content of your course.

8.5 Assessing Student Mastery of the Core Concepts

Having established your learning objectives and learning outcomes, it is essential that your assessments, whether formative or summative, determine whether students have mastered the core concepts and their application in physiology. We will have more to say about assessment in Chap. 11.

8.6 The Long-Term Goal

In Chap. 1, we discussed what we mean by core concepts or "big ideas." One point that we made is that mastery of the core concepts can be expected to have a benefit long after the students have completed your course. This should be evident in subsequent physiology courses where students should be able to apply what they have learned in your course to the new and more complex material they are being asked to master in more advanced courses (see Chap. 12 on core concepts and the physiology curriculum).

If students truly master the core concepts of physiology, we can hope that in 5 years or more, long after they have forgotten the details of many physiological mechanisms, they will still be able to think about physiology and use that understanding.

8.7 How to Do It All in the Available Time and with the Existing Constraints?

We recognize that the above recommendations, and those to be found in the next chapter, would seem to require additional course time, when you already are facing the task of accomplishing everything that needs to be accomplished in too little time.

However, the power of the core concepts as learning tools lies in their generalizability, the fact that they apply to a great many of the physiological phenomena that you are asking your students to learn. Having learned about ***flow down gradients*** in the section on cells and their properties, learning about the ***flow*** of blood ***down a*** pressure ***gradient*** should be easier and quicker. And when they have to learn about the ***flow*** of gas ***down a*** pressure ***gradient*** in the airways this should be easier still. There will be new structures to learn about and perhaps some additional wrinkles that are relevant, but the basic idea is the same in all three instances. Similarly, if your students understand ***homeostasis*** as a core concept, then learning about the regulation of [K^+] or [Ca^{2+}] does not require them to learn a totally new set of mechanisms.

Similarly, your students will be able to learn to solve physiological problems quicker since the core concepts provide a set of tools for approaching even difficult problems. With a greater command of the facts and a greater facility at using the facts to solve problems, students will be able to advance toward mastery of your learning goals and outcomes more quickly.

In short, we are proposing that an approach to teaching physiology that is focused on the core concepts your students will become more effective and more efficient learners.

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Chapter 9
Teaching Physiology Using the New Paradigm: Three Examples

Abstract In this chapter, we illustrate how three important topics included in every introductory course can be taught using the new paradigm. The three topics are (1) short-term regulation of blood pressure, (2) generating a tidal volume, and (3) the hypothalamic-anterior pituitary axis.

For each of these topics, we will (1) describe the context within the course of this topic, (2) describe the content of this topic, (3) define the learning objectives or learning outcomes, (4) discuss how one can assess student understanding of the material, and (5) discuss how to help students master this topic.

Keywords Conceptual framework • Blood pressure • Tidal volume • Hypothalamic-pituitary axis

In this chapter, we illustrate the core concepts paradigm by showing how it can be used to teach three topics found in every introductory physiology course. We will do this by first defining a topic and then providing a description of how one can teach this topic using core concepts as the organizing scaffolding.

Our examples will be structured according to the backwards design paradigm (Wiggins and McTighe 2005). We will explain the context in which it might occur in a typical course. Next, we will describe the content of the topic. We will then describe the learning outcomes and learning objectives for the topic and what the students are expected to know and be able to do at the conclusion of the topic. Then we will discuss how to assess whether students have mastered the described learning outcomes. Finally, we will describe some learning activities to help students build the required mental models based on the application of core concepts.

9.1 The Foundations of Our Approach to Teaching

How we teach is informed by our belief—our mind-set—that the goal in our classrooms must be meaningful learning, that students must learn in a setting that allows them to build, test, and refine their mental models, and all this must occur in an active learning environment (Michael and Modell 2003).

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9.1.1 Meaningful Learning

Meaningful learning (Michael 2001; Simon 2001)—learning with understanding—has occurred when the learner can use what they have learned to do something. In a physiology course, this typically means solving problems (Michael and Rovick 1999). Meaningful learning requires both the acquisition of knowledge and the development of the skills needed to use that knowledge. Memorization and the ability to recognize or recall acquired knowledge is an important component of learning physiology, but it is not per se the desired learning goal.

9.1.2 Active Learning: Build–Test–Refine Mental Models

Meaningful learning is most likely to occur in an active learning environment (Michael and Modell 2003). In such an environment, students are challenged to build mental models of the phenomena being learned, test their models by solving problems, and then refine or correct their models. An active learning environment is one in which students engage the content while interacting with one another and with the instructor. It is a student-centered environment. Such learning environments have been repeatedly demonstrated to facilitate student learning (Michael 2006).

9.1.3 Learning Outcomes for this Topic

What exactly do we mean by learning outcomes and learning objectives? The Teaching & Learning Laboratory of MIT provides a useful definition on their website (tll.mit.edu):

> "It may be best to start with what intended learning outcomes aren't. They aren't simply a list of the topics to be covered in the course. Certainly, there will be a body of knowledge that students should know and understand by the time the course is complete. But if the goals for what students should achieve stops there, there may be many missed opportunities for providing them with a more productive learning experience.
>
> An intended learning outcome should describe what students should know or be able to do at the end of the course that they couldn't do before. Intended learning outcomes should be about student performance. Good intended learning outcomes shouldn't be too abstract ("the students will understand what good literature is"); too narrow ("the students will know what a ground is"); or be restricted to lower-level cognitive skills ("the students will be able to name the countries in Africa.").
>
> Each individual intended learning outcome should support the overarching goal of the course, that is, the thread that unites all the topics that will be covered and all the skills students should have mastered by the end of the semester. Best practice dictates that intended learning outcomes be kept to no more than half a dozen. [Emphasis in the original text]

Learning outcomes, then, define both *knowledge* to be acquired and the *skills* needed to accomplish certain tasks. We will be using the term "learning objectives" for the cataloging of the facts that students are expected to acquire and the term "learning outcomes" to describe what students should be able to do with what they have learned. As an example, Table 9.1 describes a possible set of learning objectives and learning outcomes for the topic of short-term regulation of blood pressure. We must emphasize that our lists is **NOT** intended to be a universal prescription for what all students ought to know and be able to do. Each instructor must establish learning objectives and outcomes for his or her students.

9.1.4 Learning Environments

Any teaching space can be an active learning environment, and in every space, we can maintain a focus on the core concepts of physiology.

If you deliver conventional **lectures**, they should be organized around the core concepts (or ask the students to do this for you). It is important that in doing this you, and the students, use the standard terminology and visual representations consistently (Chaps. 5, 6, and 7). This is essential if students are to come to understand the transferability of these concepts to many different physiological phenomena.

For example, in describing the autonomic innervation of the heart and blood vessels, it is important that you remind the students that these systems are examples of ***cell–cell communication*** and that they will be seeing similar systems elsewhere in the body. In describing the baroreceptor reflex, it is important to use visual representations that map onto the standard representation of a homeostatic mechanism.

If you use **clicker questions** (or do think-pair-share exercises) in your lectures, it is essential that you not only ask questions about the baroreceptor reflex but that you ask students to demonstrate their understanding of the core concept of ***homeostasis*** that is involved. This is one way to determine how well your students are doing in acquiring the content of the lessons and whether they are acquiring the skills to use the core concepts.

You can ask a question about the core concept of ***homeostasis*** (What happens to the error signal when the output of the sensor is interrupted?) and then ask how the blood pressure will change if the nerve from the baroreceptors to the medulla is cut. The students' answers to these questions will help them assess their knowledge about the system and will help you gauge the extent to which your efforts are helping your students to learn.

If you implement a **flipped classroom**, the same considerations apply. In addition, you should incorporate core concept-based exercises into the classroom activities that occur after your students have viewed the online material.

Workshops should offer opportunities for the students to practice applying core concepts to the physiological mechanisms being studied and to practice using their understanding of the physiological mechanisms to solve problems. As with every activity that makes up the course, standard terminology and visual representations should be used consistently.

An example of the kind of exercise that can be used in a workshop is to present a brief scenario of a patient with a myocardial infarction and then ask the students to predict how cardiovascular function will change and how blood pressure will change (Michael and Rovick 1999).

Laboratories, whether actual (human or animal models) or virtual, should present the students with problems that can be solved through application of the core concepts and their understanding of the physiology involved.

As we describe our approach to teaching of the three topics we have selected, we will describe some active learning exercises that address the physiology involved and the underlying core concepts.

9.2 Teaching Short-Term Regulation of Blood Pressure

This is a topic that occurs in every introductory physiology textbook and in every course. It occurs in the context of the cardiovascular system block. The essential core concept that this topic illustrates is ***homeostasis***, although ***cell–cell communication*** and ***flow down gradients*** also play major roles.

9.2.1 Context Within the CV Block and the Course

As we discussed in Chap. 8, the cardiovascular block typically follows units on the core concepts of physiology, the autonomic nervous system, and sensory receptors (and possibly other topics). Within the CV block, students will have studied pressure-flow and resistance in the cardiovascular system, the heart and cardiac muscle, the heart as a pump, and the properties of the circulation. All of these are topics that the students are expected to have mastered ***before*** dealing with the regulation of blood pressure

9.2.2 The Content of This Topic

What follows is **NOT** intended to be a prescription for what should be taught about the regulation of blood pressure. It is one example of how core concepts can be used to succinctly tell the story of why regulation of blood pressure is important and how this is brought about. You may feel that some parts of this story can be omitted or minimized for your students. You may choose to deliver this story in a different sequence than the one found here, and your assumptions about what your students already know when they come to this topic may differ from our assumptions.

One central feature of the new paradigm is its attention to the core concepts while at the same time attending to those details that are required for the students to master your intended learning outcomes.

The cardiovascular system transports to every cell in the body those substances necessary for their health and function. It must do this in the face of varying levels of activity in the cells, tissues, and organs and, hence, varying needs for perfusion. To accomplish this task, mean arterial pressure, the driving force for tissue perfusion, is maintained relatively constant over time in the face of changes in the state of the organism (disturbances), both internal and external. With blood pressure more or less constant, appropriate distribution of blood flow (cardiac output) can be accomplished by varying the resistance to flow in the many circuits of the body. Thus, to accomplish its fundamental task, the cardiovascular system uses a mechanism that is one example of the core concept of ***homeostasis***.

An elevated pressure in the arterial compartment, blood pressure or mean arterial pressure, can be thought about as arising in two different ways. The heart is a pump whose activity causes a flow of blood out of the heart, the cardiac output. Flow through the circulation is opposed by the systemic vascular resistance (SVR), often referred to as the total peripheral resistance. Thus, the pressure in the arterial compartment, the mean arterial pressure, is determined by the cardiac output (CO) pumped by the heart and the SVR. The central core concept here is clearly ***flow down gradients***.

The pressure in the arterial compartment can also be viewed as being the result of the volume of blood in the arterial compartment (determined by flow in–flow out) and the compliance of the arterial compartment. Here, the relevant core concept (and a general model—Modell 2000) is ***mass balance*** in *elastic structures* (another general model).

Cardiac output is, by definition, determined by heart rate and stroke volume (the volume of blood ejected from the left ventricle each beat).

Both heart rate and stroke volume are controlled, in part, by the autonomic nervous system. The SA node, which establishes the intrinsic heart rate, is innervated by both the sympathetic (increases HR) and the parasympathetic (decreases HR) nervous systems. The ventricles are innervated by the sympathetic nervous system that determines the inotropic state (contractility) of the heart (note that stroke volume is also determined by the length–tension relationship of cardiac muscle, an intrinsic, not neutrally controlled, property). Thus, the heart, which comprises two different effectors, is controlled by the ANS. Here, the core concept of ***cell–cell communication*** is applicable.

The resistance to flow of the arterioles (the major component of the SVR) is determined, in part, by the sympathetic nervous system. Here too ***cell–cell communication*** is the applicable core concept.

Regulation of a physiological variable requires a sensor to measure that variable. Blood pressure is measured by the baroreceptors located in the carotid sinus and in the arch of the aorta. At normal blood pressure, these receptors have a tonic firing rate. As pressure increases, these receptors increase their firing rate, and as pressure decreases they decrease their firing rate. The applicability of the homeostasis core concept is obvious here.

The baroreceptor reflex (a homeostatic mechanism) maintains blood pressure more or less constant over time (see Fig. 9.1). The baroreceptors are the sensors in the control system. The SA node, the ventricular myocardium, and arteriolar smooth muscle are the effectors whose outputs determine blood pressure. The mechanism defining a set point and control centers is located in the medulla.

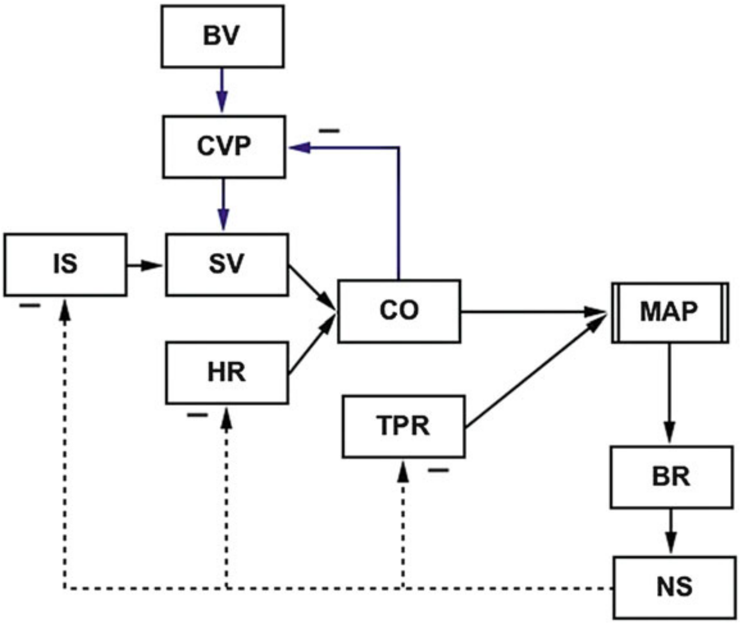

Fig. 9.1 This diagram is a visual representation of the baroreceptor reflex, an example of ***homeostasis***. The *minus signs* (−) indicate an inverse or inhibitory relationship between the connected variables. The dotted connections represent neural signals and the solid connections represent physical relationships. Such a model is useful to students in solving problems about the regulation of blood pressure. *BV* blood volume, *CVP* central venous pressure, *IS* inotropic state, *SV* stroke volume, *HR* heart rate, *CO* cardiac output, *TPR* total peripheral resistance (also known as systemic vascular resistance), *MAP* mean arterial pressure, *BR* baroreceptors, *NS* nervous system

9.2.3 Learning Outcomes and Learning Objectives for This Topic

Given the overarching goal of meaningful learning, it is essential that the learning outcomes defined for this topic define what kinds of problems the student will be expected to be able to solve at the conclusion of this particular topic. In Table 9.1, two different kinds of problems are described and the nature of the expected solution is described. To accomplish these learning outcomes, the student will need to have mastered the learning objectives defined in the table.

Table 9.1 Learning outcomes for the topic of short-term regulation of blood pressure

Learning outcome (performance goal)	Relevant core concepts
1. Predict the consequence of perturbations to the organism on blood pressure and the response of the components that make up the baroreceptor reflex to the perturbation.	***Homeostasis*** ***Flow down gradients*** ***Cell–cell communication***
2. Given a description of the signs and symptoms of a patient, explain the physiological mechanisms that gave rise to them.	***Homeostasis*** ***Flow down gradients*** ***Cell–cell communication***
Learning objectives for regulation of blood pressure	**Relevant core concept**
1. List the two parameters that determine mean arterial pressure and write the equation that relates them.	***Flow down gradients***
2. State the two parameters that determine cardiac output and write the equation that relates these parameters.	***Flow down gradients***
3. Name the receptors that measure blood pressure and state their locations.	***Homeostasis***
4. Describe the relationship between baroreceptor firing rate and blood pressure.	***Homeostasis***
5. Describe the neural controls of heart rate, cardiac contractility, and arteriolar resistance.	***Cell–cell communication***
6. Draw a causal diagram of the baroreceptor reflex and identify the location in the body of each component.	***Homeostasis***
7. Describe the function of each component of the baroreceptor reflex as an example of the core concept of *homeostasis*.	***Homeostasis***
8. Describe the ANS control of the heart and blood vessels and relate the mechanisms to the core concept of ***cell–cell communication***.	***Cell–cell communication***

9.2.4 Assessing Student Mastery of the Regulation of Blood Pressure

Assessment of students' mastery of this topic must follow from whatever learning outcomes and objectives you have set for your students. These outcomes and objectives should encompass knowledge acquisition, the ability (the skill) to integrate the information acquired, and finally the ability to use the knowledge and skills acquired to solve problems.

It is important to remember that the outcomes and objectives define mastery of the topic, regulation of blood pressure, as well as evidence of the ability to use the core concepts that are relevant here.

We will have more to say about assessment in Chap. 11, but let us note here that assessing the students' understanding of the core concepts and the mechanisms of blood pressure regulation **as defined in the learning outcomes** is an essential step.

In a large class setting in which grading written work is problematic, there are multiple choice questions that can be used to test the performance goals defined here. Rovick and Michael (1992) described a type of problem format, the prediction table, that tests students' ability to carry out causal reasoning to solve a problem about the regulation of blood pressure, and Michael and Rovick (1999) provide many examples of the sorts of perturbations that can be used in assessing this learning outcome.

Below are two examples of questions that can be machine scored. An important feature of the question is that it describes a situation novel to the students. That is, it is a situation that they have not previously encountered in class. Thus, the answer is not likely to have been memorized, and the student must engage in causal reasoning to arrive at an answer. Another feature of this question format is that the distractors (incorrect answers) can be selected to represent common student misconceptions. We will have to say about writing assessment items in Chap. 11.

The question seen in Table 9.2 illustrates a prediction table question about the behavior of the baroreceptor reflex. To correctly answer this question, the student must understand the core concept of homeostasis and know the homeostatic mechanism that regulates blood pressure.

Question 1 (Table 9.2) requires students to apply an understanding of the core concept of ***homeostasis*** to a specific homeostatic mechanism, the baroreceptor reflex. It is equally important to determine student understanding of core concept itself. The questions in Table 9.3 do this in a different format.

9.2.5 How We Might Help Students Master This Topic

Here, we suggest an approach to teaching about the regulation of blood pressure using core concepts. The focus is on the pedagogy to be employed, not on the content that you decide your students need to master.

Table 9.2 An example of a multiple-choice question to test students' ability to reason causally about the baroreceptor reflex

Question 1: An Iron-Man triathlon is being conducted under conditions of high temperature and high humidity. One of the competitors becomes extremely ***dehydrated***. Predict the effects of this condition on the state of his cardiovascular system.

	A	**B***	**C**	**D**	**E**
Inotropic state (IS)	NC	I	I	I	NC
Central Venous Pressure (CVP)	D	D	D	D	NC
Stroke Volume (SV)	D	D	D	I	NC
Heart Rate (HR)	NC	I	I	I	NC
Cardiac Output (CO)	D	D	I	I	NC
Total Peripheral Resistance (TPR)	NC	I	I	I	NC
Mean Arterial Pressure (MAP)	D	D	I	I	NC

I increase, *D* decrease, *NC* no change
*The correct answer

Table 9.3 The questions here test student understanding of the core concept of homeostasis in a format that is easily scored by a computer

You are driving down the highway with the cruise control set to 65 miles/hour. One cylinder in your engine stops working. Predict the changes that will occur to the following components of cruise control system.
Question 1
The output of the sensor will:
a. increase
b. decrease*
c. not change
Question 2
The value of the set-point will:
a. increase
b. decrease
c. not change*
Question 3
The signal to the effector will:
a. increase*
b. decrease
c. not change

*The correct answers

As Wiggins and McTigue (2005) have reminded us, we must start with defining what it is we expect our students to be able to do with what they learn. We have proposed a set of learning outcomes and objectives above, but you will have to determine what learning outcomes and objectives are appropriate for *your* students and *your* course. It is also essential to determine what specific learning objectives your students will have been expected to learn in previous portions of the course.

The question, then, is how can I best help my students to learn (Michael and Modell 2003); how can I help them build a mental model of the topic with which they can solve whatever problems you expect them to solve.

Our answer to this question is to scaffold everything that occurs in the course around the core concepts of physiology. The mechanisms involved here can be scaffolded by considerations of the core concepts of (1) ***homeostasis***, (2) ***cell–cell communication***, (3) ***flow down gradients***, (4) ***mass balance***, and (5) the general model of elastic structures.

How does one do this?

It must start with a mind-set that recognizes the importance of the core concepts as learning tools. This must be followed by a diligent effort to incorporate the relevant core concepts into everything that you do in your course.

The single most important thing that you can do is to assist your students in incorporating the core concepts into their understanding and mental models of the physiology they are learning. Thus, you must use the core concepts in what you do, and the student must be asked to use the core concepts in what they do. Students must learn to recognize where core concepts are relevant and useful and learn to use core concepts to advance their learning and to solve problems.

Several examples of the kinds of challenges to students' understanding of the regulation of blood pressure ***and*** the relevant core concepts are presented in Table 9.4. These problems can be used in any kind of classroom activity or as homework problems.

Each of these exercises provides opportunities for students to cooperatively solve problems, thus learning from one another. These problems also offer the faculty opportunities to determine what aspects of the physiology are causing student difficulties. The first step in helping students repair their mental model is to determine what problems are present in the students' models.

Exercises like these can be combined into problem sets in which students in small groups solve the first problem, discuss the solution, and then go on to the next problem (Michael and Rovick 1999). At each step, the instructor can intervene as needed to help students correct their mental models or solution algorithms.

9.3 Teaching Respiratory Mechanics: Generating a Tidal Volume

Respiratory physiology is covered in most courses as three broad topics, respiratory mechanics, gas exchange between the atmosphere and tissues, and regulation of ventilation. Students find respiratory mechanics especially challenging for a number of reasons including system-specific terminology, the quantitative nature of the topic, and the application of simple physics concepts to the system. However, if we examine the lung and chest wall in terms of a simple everyday model and applying several core concepts and general models, the challenges may be minimized.

Table 9.4 Exercises to help students build mental models of short-term regulation of blood pressure using the related core concepts

Exercise	Core concepts/General models
The arterial compartment can be considered an elastic structure. Briefly describe the factors that contribute to the pressure in this compartment.	*Elastic structures*
Pressure receptors (sensors) are essentially stretch receptors. Predict how the pressure receptors in arterial walls will respond to changes in arterial blood pressure. Explain the basis for your prediction.	***Homeostasis***
Based on your model of the cardiovascular system, predict the location(s) where you expect to find the receptors measuring arterial blood pressure that send signals to the control center. Explain the basis for your predictions.	***Homeostasis***
Based on your study of the heart and the concept of mass balance (reservoir model), predict how changes in cardiac function can change the pressure in the arterial compartment. Explain the basis for your predictions.	***Mass balance***, *elastic structures*
Based on the flow model and elastic structure model, predict how changes in arteriolar resistance can change the pressure in the arterial compartment. Explain the basis for your prediction.	***Flow down gradients***, *elastic structure*, *mass balance*
Based on your model of cardiac function, predict how changes in venomotor tone of the great veins will lead to changes in pressure in the arterial compartment. Explain the basis for your predictions.	***Homeostasis*** ***Flow down gradients*** *Elastic structures*
Draw a causal diagram that shows how your homeostatic control model will respond in the face of blood loss.	***Homeostasis*** *Elastic structures*, ***mass balance***
Draw a causal diagram that shows how your homeostatic control model will respond to an increase in sympathetic nervous system activity.	***Homeostasis*** ***Cell–cell communication*** ***Flow down gradients***
Predict response of the components of the baroreceptor reflex to various perturbations of MAP or of the system itself (computer lab or paper and pencil workshop).	
Predict changes to cardiovascular function and MAP as a result of alterations of ANS function; i.e., administration of agonists or antagonists.	

9.3.1 Context Within the Respiratory Block

Examining the mechanical properties of the lung and chest wall generally occurs at the beginning of the respiratory block, but some instructors choose to deal with this topic later in the sequence. Whichever is the case, we will assume that the student has not had prior experience with respiratory physiology topics. However, we will assume that the student is familiar with the core concepts of ***flow down gradients*** and the general model of and elastic structures. We will also assume that the student is familiar with the universal gas law (PV = nRT).

9.3.2 Content of this Topic

The role that the respiratory apparatus (lungs and chest wall) plays in gas exchange between the atmosphere and tissues is that of moving air from the atmosphere to the alveoli and moving alveolar gas from the lungs to the atmosphere. This is accomplished through the interaction of forces generated by the respiratory muscles and elastic components of the lungs and the chest wall.

When, during a resting tidal volume, the muscular force is greater than the elastic recoil force, air moves from the atmosphere to the alveoli. When these forces are balanced, airflow ceases marking the end of inspiration. Relaxation of the respiratory muscles results in the recoil forces becoming greater than the muscular force, and gas flows from the alveoli to the atmosphere (expiration). The end of expiration occurs when the muscular force is zero, and the internal elastic forces of the respiratory system (lung and chest wall) are balanced. A simple analysis of this process may be achieved by applying the ***flow down gradients*** core concept and the general model of *elastic structures* to the respiratory apparatus (see Sect. 9.3.5).

9.3.3 Learning Outcomes and Learning Objectives for This Topic

Several learning outcomes (performance goals) can be stated for this topic depending on the level of the student. For the beginning student, the performance goal is to predict how changes in the mechanical properties of the respiratory system components (lung and chest wall) will alter overall respiratory system function. At a more advanced level, the performance goal is similar but focused on changes in regional mechanics and their effect on distribution of ventilation. In this case, the goal would be to predict how changes in the regional mechanical properties of the lung (compliance and airway resistance) will alter the distribution of ventilation in the lung. At both levels, the student should also be able to explain the reasoning behind his/her prediction.

The "learning objectives" define for the student the scope of information required to complete the topic. Table 9.5 presents both the learning outcome and the learning objectives for this topic along with the relevant core concept/general model.

9.3.4 Assessing the Outcome (Performance) Goals: Generating a Tidal Volume

The performance goal for this topic is to predict how changes in the elastic properties of the respiratory system components (lung and chest wall) will alter overall respiratory system function. The easiest way to assess this performance goal is to

Table 9.5 Learning objectives for unit on generating a tidal volume

Learning outcomes	**Course level**	**Relevant core concept or general model**
Be able to predict how changes in the mechanical properties of the respiratory system components (lung and chest wall) will alter overall respiratory system function.	Introductory	Elastic structures ***Flow down gradients*** Universal gas law
Learning Objectives		
1. Define the characteristics of an elastic structure.	Introductory and advanced	Elastic structures
2. Explain why the intrapleural pressure is sub-atmospheric when the respiratory system is at its unstressed volume.	Introductory and advanced	Elastic structures
3. Explain how the lung and chest wall interact during a breath.	Introductory and advanced	Elastic structures, ***flow down gradients***, universal gas law
4. Describe the forces that cause gas flow into and out of the respiratory system.	Introductory and advanced	***Flow down gradients***
5. Describe how surfactant and alveolar interdependence affect lung function.	Advanced	Elastic structures
6. Describe the factors that contribute to airway resistance.	Advanced	Elastic structures, ***Flow down gradients***
7. Describe the determinants of gas flow during a forced expiration.	Advanced	Elastic structures, ***Flow down gradients***
8. Define the Forced Expiratory Volume in 1 second ($FEV_{1.0}$), and explain its clinical significance.	Advanced	Elastic structures, ***Flow down gradients***

provide the student with a problem in which alterations in lung or chest wall mechanics have occurred and ask him or her to predict how these changes will affect function. An important feature of the assessment is to have the student explain the basis for the prediction.

The complexity of the problem should match the complexity of understanding of the system by the student. The examples shown in Table 9.6 illustrate the type of problem that might be presented to an introductory student and the type of problem that might be presented to an advanced student. The problem may be stated as a theoretical change in mechanics or in the context of a clinical situation.

9.3.5 How We Might Help Students Master This Topic

A simple model that is often used at the introductory level to examine the interaction between the lung and chest wall consists of a balloon within a second balloon (see Fig. 9.2). The inner balloon represents the lung that communicates with the

Table 9.6 Below are some examples of questions that test students' understanding of both the core concepts and the physiological mechanisms underlying the process of generating a tidal volume

Example 1 (Introductory): A normal subject develops a cold with a productive cough. The cold has not affected the elastic properties of the lung but has increased the resistance to gas flow. Assume the measurements are made in the subject before and during the cold. Also assume that the breathing frequency and tidal volume remain the same for both measurement periods. **Predict how the intrapleural pressure changes occurring during the cold will compare to those when the subject was normal. Be sure to explain the basis of your prediction.**
Example 2 (Introductory): Over a period of time, a normal subject is exposed to an irritant and, as a consequence, develops interstitial fibrosis. As a result, the lung recoil of the subject increases. Data obtained before the onset of the disease are compared to those obtained after the lung recoil is increased. **Predict how the intrapleural pressure changes occurring after development of the disease will compare to those when the patient was normal.** (Assume that breathing frequency and tidal volume were same in both the cases.) **Be sure to explain the basis for your prediction.**
Example 3 (Advanced): Consider a 2-compartment lung that is exposed to the same changes in intrapleural pressure. Compartment 1 of this lung has twice the airway resistance as that found in compartment 2. **Predict how the ventilation arriving at compartment 1 will compare to the ventilation arriving at compartment 2. Be sure to explain the basis for your prediction.**
Example 4 (Advanced): Pulmonary function tests in which the time course of changes in intrapleural pressure and lung volume is conducted on a series of patients. The volume changes observed in patients A and B are the same, but the intrapleural pressure change in Patient B is much larger than that recorded in Patient A. **Predict how the elastic properties of the two patient's lungs compare to each other. Be sure to explain the basis for the prediction.**

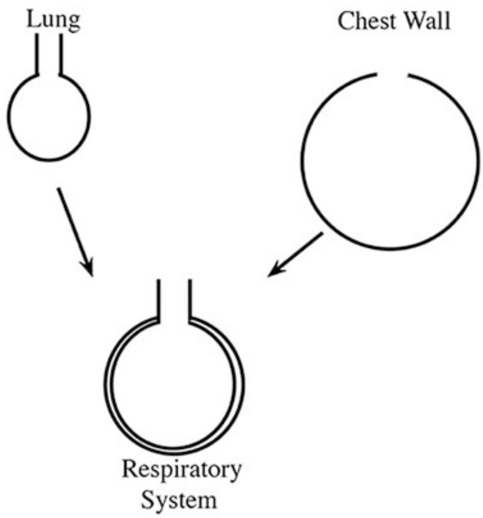

Fig. 9.2 The model representing the interaction of the chest wall (the outer balloon) with the lungs (the inner balloon)

atmosphere. The outer balloon is connected to the inner balloon by a thin liquid film. The outer balloon does not communicate with the outside world.

Before dealing with a model further, it is helpful to review briefly the characteristics of an elastic structure. If the elastic structure contains a volume, then that structure has a resting or unstressed volume that occurs when no outside forces are applied to the wall. When the structure is displaced from its resting or unstressed volume (i.e., a transmural pressure is applied), the structure exhibits recoil that opposes the applied force and tends to return the structure to its resting or unstressed volume. The degree to which structure recoils toward its resting volume is often referred to in terms of compliance. The greater the compliance of the structure, the smaller the recoil generated by the structure.

Returning to the model, the inner balloon has a low resting volume, and the outer balloon has a much higher resting volume. Hence, when the two structures are connected by the thin liquid film between them, the outer balloon exerts a distending force on the inner balloon, and the inner balloon exerts a force in the opposite direction on the outer balloon. As a result, a positive transmural pressure develops across the inner balloon, and a negative intrapleural pressure develops across the outer balloon. Because the inside of the inner balloon communicates with the atmospheric, the pressure inside the inner balloon is atmospheric or zero. The volume of the inner balloon is greater than its resting volume and so the transmural pressure is positive. If the pressure inside the balloon is atmospheric, the pressure outside the balloon in the liquid film must be subatmospheric.

By applying the core concept/general models of elastic structures, pressure–flow relationships, and the universal gas law to this model, the introductory student can easily examine the mechanisms responsible for generating a tidal volume. At an advanced level, the model can be extended by adding more inner balloons having different compliances and/or adding resistances between the airways and the atmosphere. With this model, the student can study how a distribution of ventilation occurs within the lung.

The following exercise is intended to show one approach to helping students use the core concepts and general models to explain the mechanisms involved in generating a tidal volume. The exercise can be run in the classroom as an individual or group exercise. It can be run as an independent study exercise. It can also be conducted as a role-play in which the students generate the forces and act as elements of the model.

The purpose of the exercise, which can be seen in Table 9.7, is to have the students work through the mechanisms generating inspiration and expiration in a step-by-step fashion. At the completion of the exercise, students should be able to draw a causal diagram of the steps involved and use this diagram to predict what will happen if the lung compliance changes or if the airway resistance changes. The model illustrated in Fig. 9.2 serves as the reference for this exercise.

Table 9.7 Examples of an exercise that facilitate student mastery of the learning outcomes and the learning objectives

Part 1: The exercise begins with the volume of the system at the end of expiration. At this volume, the muscles of the chest wall are relaxed, and alveolar pressure is atmospheric. Question 1: How does the volume of the lung (inner balloon) compare to its resting volume when the system is at this beginning volume? Question 2: How does the volume of the chest wall (outer balloon) compare to its resting volume when the system is at this beginning volume? At this point, is the pressure between the two balloons greater than atmospheric pressure, equal to atmospheric pressure, or less than atmospheric pressure? Explain the basis for your prediction.
Part 2: Consider what happens if the respiratory muscles now exert a force tending to pull on the outer balloon. Assume that this change occurs before any volume can enter the system. Remember, the liquid film connecting the inner and outer balloon still contains the same number of molecules. Question 3: If the outer balloon pulls on this liquid film, what will happen to the volume of the liquid film? Will this change be a micro-change or a macro-change? Question 4: According to the universal gas law (PV = nRT), what will happen to the pressure in the liquid film? How will this pressure change act on the inner balloon? If we again assume that the time frame of this change is such that no volume has entered the lung (inner balloon), what will happen to the volume of air in the lung (inner balloon)? Will this change be a micro-change or a macro-change? Again, think about the universal gas law and the fact that the number of gas molecules has not yet changed. What will happen to the pressure inside the lungs (alveolar pressure, pressure in the inner balloon)? What will happen to the flow through the airways as a result of this pressure change? (Hint: think about the pressure-flow-resistance model.) Now, what will happen to the number of gas molecules in the inner balloon? Will the ensuing volume change be a micro-change or a macro-change? What determines how fast gas flows into the balloon? When will gas stop flowing into the balloon? At this point, what force is opposing the force in the intrapleural space (in the liquid film) acting on the lung (inner balloon)?
Part 3: Think about a quiet, resting, inspiration. The muscles of inspiration continue to act on the elastic elements of the chest wall, developing more force until the respiratory center stops stimulating the inspiratory muscles. Repeat steps Part 2 until you think a tidal volume has entered the lung. On the axes provided, plot the intrapleural pressure, gas flow, and lung volume as functions of time for one inspiration.
Part 4: Now consider quiet expiration from the end-inspiratory volume that you chose. In this case, assume that the respiratory muscles begin to relax. Using your model, the core concepts of elastic structures, pressure–resistance-flow, and the universal gas law predict the changes that will occur in intrapleural pressure, alveolar pressure, and gas flow as expiration continues. What causes the observed changes in alveolar pressure? What happens to the volume of the chest wall as expiration continues? When will flow out of the lung stop? Explain why alveolar pressure is atmospheric at this point? At this point, how do the volumes of the lung, chest wall, and respiratory system compare to their resting (unstressed) volumes? On the axes provided, plot, for one expiration, the intrapleural pressure, gas flow, and lung volume as functions of time.
Part 5: Draw a causal diagram of the mechanism responsible for one tidal volume.

9.4 Teaching the Hypothalamic-Anterior Pituitary Hormones and Their Control

The hypothalamus and anterior pituitary together constitute an endocrine system that determines the concentrations of many different hormones. The system contains many negative feedback loops, although these do not constitute a homeostatic system per se. This is an important distinction that will be considered below.

9.4.1 Context Within Course

A major topic within the endocrine physiology block is the role of the hypothalamic-anterior pituitary-target endocrine gland axis in regulating various physiological parameters. In some cases, this axis represents the effectors in the homeostatically regulated system. As a result, many students find the relationships within this axis confusing, and they interpret the control of hormone secretion within this axis to be an example of homeostatic regulation. Examining these relationships within the context of the cell–cell communication core concept can provide clarity to these mechanisms.

9.4.2 Content of Topic

The hypothalamic-pituitary axis (HPA) controls secretion of multiple peripheral endocrine glands. This is accomplished through a cascade of secretions arising from various groups of cells within the hypothalamus and anterior pituitary. Fig. 9.3 provides a general scheme for the hormonal systems involving the hypothalamus and anterior pituitary. In this scheme, there are several possible mechanisms for feedback loops that act on different elements in the pathway.

As this diagram indicates, one feedback loop is integral to the homeostatic regulatory mechanisms that involve the HPA. However, there are negative feedback loops that are part of the effector systems that lead to changes in the regulated variables. Because many students believe that all mechanisms that include negative feedback loops are homeostatic, they mistakenly believe that hormone levels that act on the final target tissues (e.g., thyroid hormone, cortisol) are homeostatically regulated.

Using the core concept of cell–cell communication to view this model can help students recognize the role that these feedback loops play in this effector system.

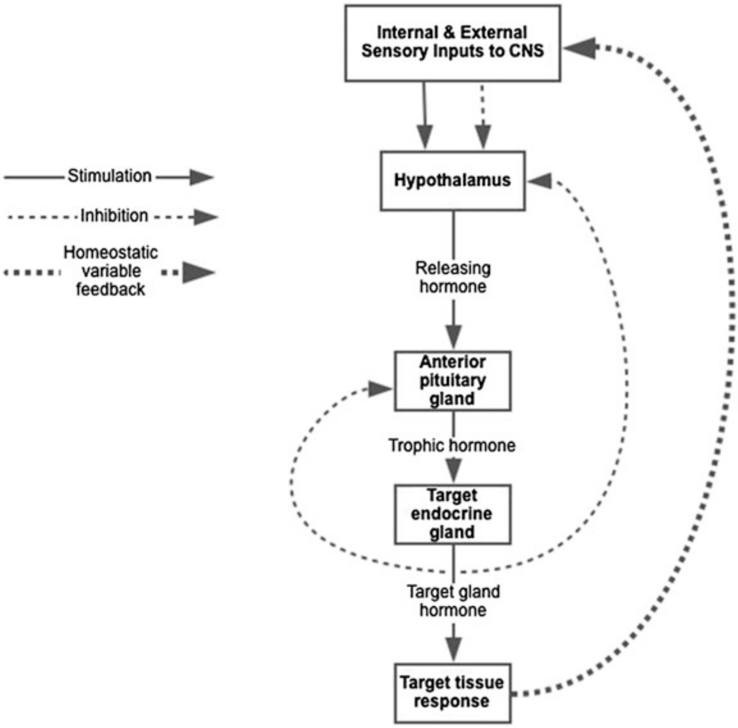

Fig. 9.3 The figure below is a general scheme for the hormonal systems involving the hypothalamus and anterior pituitary

9.4.3 Learning Outcomes and Performance Outcomes for This Topic

The learning outcomes and learning objectives for this topic will depend on exactly where in the course the topic appears. Endocrine physiology is a one of those systems that can appear early in a course in conjunction with some discussion of the nervous system. It can also appear much later in the course when the target organs for hormones have already been discussed. Table 9.8 contains learning outcomes and objectives for this subject matter presented early in the course.

9.4.4 Assessment

Assessment of the performance goals for this general model of the Hypothalamic-Anterior Pituitary axis can be achieved by providing the students with a case problem of hypo- or hyperfunction involving a specific hormone (e.g., thyroid hormone, cortisol). Along with the signs and symptoms, laboratory data related to

Table 9.8 Learning outcomes (performance goals) for the hypothalamic-anterior pituitary axis

Learning outcomes (Performance goals)
1. Predict the physiological consequences of alterations in the hypothalamic-anterior pituitary axis and explain the rationale behind the prediction(s).
2. Predict the site of dysfunction in the hypothalamic-anterior pituitary axis given a set of pathophysiological signs and symptoms and explain the rationale behind the prediction(s).
3. Predict how the range of variables values homeostatically regulated by the hypothalamic-anterior pituitary system will change (increase, decrease, no change) if the hormonal feedback loops are blocked. Explain the basis for your predictions.
Learning objectives
1. Describe the functional–anatomical relationship between the hypothalamus and the anterior pituitary.
2. Describe the nature, action, and control of the hormones secreted by the anterior pituitary.

Table 9.9 An example of a scenario-based assessment of student understanding of the HPA

Assessing student understanding of the HPA
A 34-year-old woman has a 3-month history of nervousness, tremor, palpitations, increased sweating, and discomfort with heat. She has lost 15 pounds despite increased food intake. She also noted muscle weakness and easy fatigability with exercise to which she was ordinarily accustomed. A. What do these data suggest about thyroid hormone levels? B. Explain how you used your model to arrive at your prediction?
On physical examination, pulse was 110 beats/min at rest and increased to 150 beats/min with 30 s of rapid stair climbing. Blood pressure was 150/60 and respirations were 20/min. Her skin was warm and moist, and her speech was rapid. She exhibited a tremor and very rapid reflexes (e.g., knee-jerk reflex), and she was unable to rise without assistance from a squatting position. The thyroid gland was diffusely enlarged. A. Do the additional physical findings support your initial hypothesis? Explain. B. Based on your model of thyroid hormone secretion, what are the possible sites of pathophysiology that could produce this endocrine abnormality? How would you distinguish between these possible sites?
Laboratory studies: Total serum T_4 level: 26 μg/dl (normal: 5–12 μg/dl), free T_4 level: 4.1 ng/dl (normal: 0.8–2.4 ng/dl), serum TSH: 0.01 mIU/ml (normal: 0.5–5 mIU/ml), and 24-h radioactive iodine uptake (what does this measure?): 70% (normal: 20%–30%) C. What is the difference between total serum T_4 and free T_4? D. What does the low serum TSH concentration suggest? E. How do the lab results support your hypothesis? F. What is the most likely site of pathophysiology in this patient?

Note: This case also assesses the student's model of thyroid function

plasma concentrations of the trophic hormone (e.g. TSH, ACTH) and final target tissue hormone (e.g., T_3, T_4, cortisol) are provided (see Table 9.9). The task for the student is to determine the most likely site of the pathophysiology and explain the basis for the prediction.

9.4.5 How Might We Help Students Master This Topic?

Table 9.10 below contains an example of an exercise that can be used to help students recognize the impact of negative feedback loops within the Hypothalamic-Anterior Pituitary-target endocrine gland axis on the control of target endocrine gland hormone (e.g., thyroid hormones, cortisol) secretion. The exercise can be used as an independent study exercise (individual, group) as a preview for an interactive classroom discussion, a small group exercise in a classroom setting, or a series of think-pair-share activities in a large group (classroom) setting. It is assumed that the student is familiar with the core concepts of homeostasis and cell–cell communication including the graphic representations of the homeostasis (Modell et al. 2015) and the HPA axis (Fig. 9.3 above) model. In addition, it is assumed that the student has studied a homeostatic mechanism (e.g., the baroreceptor reflex) previously.

Table 9.10 Exercises to help students understand the Hypothalamic-Anterior Pituitary Axis

Purpose of the exercise: To examine the impact of negative feedback loops within the HPA effector system on the control of final hormone secretion.
Step 1: Review of ***homeostasis*** Recall the mechanisms involved in the baroreceptor reflex. Answer the following questions: What is the regulated variable? What is the "set point" (reference value)? What is the "error signal?" What role does the "error signal" play in the integrator's control of the actions of the effectors? How does this action of the effectors influence the regulated variable? Over time, what happens to the error signal? What happens to the activity of the effectors as the error signal changes?
Step 2: Applying the ***homeostasis*** model to the HPA axis Examine the general figure representing the hormonal control by the hypothalamic-anterior pituitary axis. In this figure, how are the regulated variables represented? In which box would you locate the integrator (control center)? *For this step, ignore the negative feedback loops that involve hormones.* Which boxes represent the effectors in this model? In the diagram, what determines release of hormones from the hypothalamus? What determines release of hormone from the anterior pituitary? What determines release of hormone from the target endocrine gland? Based on the core concept of cell–cell communication, how would you explain the increase in hormone concentration secreted by glands later in the cascade? What determines which tissues are affected by the target gland hormone? What determines the actions that these hormones will have on these target tissues? When will the CNS decrease stimulation of Releasing Hormone from the hypothalamus?
Step 3: Comparing the two models. *Continue to ignore the endocrine feedback loops for this step.* The communication in the effector components of the baroreceptor reflex is neuronal. Those in the HPA system are hormonal. In view of this, in which system would you expect the fastest response to a perturbation? Explain the basis for your expectation. How do you think the time course of the response to a perturbation in the two systems would compare? Now consider the nature of the hormones involved in the HPA effector system. The Releasing Hormones in this system (e.g., TRH, CRH) are water soluble. The trophic hormones in this system (e.g., TSH, ACTH) are also water soluble. Based on this information, what would you predict about the time course of the target cell (e.g., anterior pituitary cells, thyroid cells, adrenal cortex cells) response to stimulation by these hormones? How long do you think the response would last? The

(continued)

Table 9.10 (continued)

hormones released by the target endocrine gland in this system (e.g., thyroid hormone, cortisol) are lipid soluble. Based on this information, how do you think the response time of the target endocrine gland to stimulation will compare to the response of the anterior pituitary cells? How quickly do you think the actions of the hormonal action on the final target tissue will become evident? Explain the basis for your prediction. When a decrease in the levels of the trophic hormone to basal levels occurs, will there continue to be circulating hormone affecting the final target tissues? As a result, how do you think the "regulated variable" value will compare to the reference value ("set point") at this time? As a consequence of the continued action of the final target gland hormone, the homeostatic regulatory system will exhibit oscillation. That is, the regulated variable value will "overshoot" the "set point" causing an error signal in the direction opposite direction from the original perturbation.
Step 4: Examining the influence of the negative feedback loops on the effector system *For this step, consider the entire model* ***including*** *the endocrine feedback loops.* In this step, we will compare the predictions from Step 3 (without feedback loops) with predictions resulting from the system with functioning feedback loops. In this model, hormone-secreting cells in the hypothalamus and anterior pituitary have receptors for the final target tissue hormone (e.g., thyroid hormones, cortisol). In this model, what determines the secretion rate of the hormone from the hypothalamus (e.g., TRH, CRH) and the hormone secretion rate of the hormone from the anterior pituitary (e.g., TSH, ACTH)? How will these secretion rates compare with those in Step 3 (without feedback loops)? How will the release rate of the final target tissue hormone (thyroid hormones, cortisol) compare to that in Step 3 (without feedback loops)? What factors determine the level of circulating final target tissue hormone? (Hint: think about the mass balance core concept.) In this model, as the regulated variable value approaches the reference ("set point") value, how does the level of circulating final target tissue hormone compare with that you predicted in Step 3? To what extent would you expect this model to exhibit oscillation compared to the model in Step 3? Explain the basis for your prediction.
Problem: Consider a situation in which an antibody is produced in an autoimmune response that binds to receptors on the cell surface of the target endocrine gland (e.g., thyroid gland). As a result, the gland is stimulated to release hormone. Describe what you would measure and what results expect to distinguish between this condition and one in which a tumor in the anterior pituitary secretes trophic hormone (e.g., TSH).

9.5 How to Use These Examples

Each of the three examples we have presented is merely one way to incorporate the core concepts of physiology into a consideration of an important physiology topic. Our goal here is to stimulate your thinking about your particular physiology course. To the extent that your course is different than the ones we have imagined here, your solutions to how to incorporate core concepts will differ from our examples. Your learning objectives and learning outcomes will differ, your assessments will look for different things, and the learning environments you create will aim at facilitating student construction of different models and the development of different problem solving skills.

Hopefully, these examples will serve to stimulate your imagination about how to begin implementing the new paradigm into your approach to teaching physiology.

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Chapter 10
Using Core Concepts of Physiology in Designing Learning Resources

Abstract Learning resources are materials used by students to assist in mastering the learning objectives and learning outcomes assigned by the instructor. There are many different kinds of learning resources. Most learning resources can be used in a variety of learning environments.

All of the learning resources to be used in a course should focus on the core concepts of physiology, whatever learning context they will be used in.

Keywords Core concepts • Learning resources

Learning resources are materials that student use to assist in meeting the learning outcomes or learning goals of the course. Some learning resources are produced by the instructor, and some are produced by others and recommended or assigned for student use by the instructor.

In this chapter, we discuss some of the issues that arise in developing and implementing learning resources to help students (1) understand the core concepts of physiology and (2) maintain a focus on the core concepts as they learn the assigned physiology.

10.1 What Do We Mean by Learning Resources?

All teachers make use of some sort of learning resources, and many teachers make use of a great many different kinds of resources. Table 10.1 contains a list of some of the commonly used resources in physiology courses and the context in which they are most often used.

It is important to note that we are distinguishing the learning resource, an "object," from the context or setting in which it is used. For example, a clinical problem (a brief scenario, physical exam results, or laboratory results) can be used in a problem-based learning session, in a team-based learning session, in small group discussion setting, and in a think-pair-share exercise in the lecture hall. In each of these settings, the "task" assigned to the students and/or the protocol for using the resource will differ, but the students will be using the same learning resource.

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DOI 10.1007/978-1-4939-6909-8_10

Table 10.1 A partial list of learning resources used in physiology courses

Learning resource	Context in which it is typically used
Animations	Lecture hall, laboratories, online
Computer simulations	Laboratories, online
Problems to be solved	Lecture hall, discussion groups, online
Laboratories ("wet" or human)	Laboratory
Laboratories (simulated)	Laboratory, online
Textbooks	Anywhere
Journal articles	Discussion groups, individually, online
Role-play games	Lecture hall, discussion groups, laboratories

10.2 Principles Guiding Development of Learning Resources

The overarching goal for any course is that students engage in meaningful learning (Michael 2001; Michael and Modell 2003). This requires the student to acquire the information needed to solve problems (use the information) and the skills to successfully do so.

Given the goals described above, we can describe the general principles that should govern the development of learning resources.

10.2.1 The Student Is Responsible for His or Her Own Learning

Herbert Simon (2001) cogently observed that "The long-established first principle, the foundation stone of the entire enterprise [the learning sciences/cognitive science], is that *learning takes place inside the learner and only inside the learner*." The "helping the learner to learn" mind-set (Michael and Modell 2003) follows directly from that observation; all that we as teachers can do is help.

An equally direct conclusion is that students are ultimately responsible for their own learning. One of the jobs of the teacher is to help the learner accept this responsibility. Equally important is making clear and explicit what it is that the students are expected to learn and be able to do.

10.2.2 The Learning Resource Should Support Meaningful Learning, an Active Process

Meaningful learning, or learning with understanding, is achieved when a student can use the knowledge that has been acquired from all sources to do something. In physiology, this means solving a problem.

10.2.3 The Learning Resource Should Help Students Recognize Their Current Mental Models

When anyone acquires new knowledge, they form a mental model from that information or they modify an existing mental model. While this process is essentially automatic, students need help to become aware of the exact nature of their models. The learning resources that we make available to students should provide opportunities to do just that.

10.2.4 The Learning Resource Should Help Students Test Their Current Mental Models

Once students have become aware of their mental models about some physiological phenomenon, they need to be given opportunities to test the validity of those models. To do this, students need to use their mental models to solve some sort of problem. A correct solution suggests that their model is correct, while errors suggest that their models need to be repaired.

10.2.5 The Learning Resource Should Guide Students in Revising Their Current Mental Models

A faulty mental model cannot be fixed by telling a student that it is faulty or by giving him or her the correct model (McDermott 1993). Repairing a mental model first requires that the learner recognize that use of his or her model has yielded an incorrect answer. Then they must examine their model to identify missing elements or elements that need to be revised.

10.3 Incorporating Core Concepts in Your Learning Resources

We are advocating for teachers to focus on the core concepts of physiology in all aspects of their courses. Thus, all learning resources that are developed for a course should contribute to the students' understanding of and use of the core concepts as tools for learning.

Students can be introduced to core concepts by learning resources developed for that purpose (see the examples described in Sect. 10.3). Appropriate learning resources can reinforce the use of core concepts to understand physiological mechanisms as students learn about physiology (see Sect. 10.4).

10.4 Learning Resources for Introducing Core Concepts

In Chap. 8, we described two approaches to introducing the core concepts to be emphasized in your course: (1) explore the core concepts at the beginning of the course or (2) introduce each core concept when it is first relevant to understanding a physiological phenomenon.

We will describe three different kinds of learning resources to introduce students to core concepts. Each of these makes use of an everyday model or analogy for the core concept being discussed. Not all of the core concepts lend themselves to this approach.

10.4.1 Introducing Students to the Core Concept of Homeostasis

Although physiology textbooks routinely use a heating system as a model (analogy) for a homeostatic mechanism, a better model is an automobile cruise control system. (As we discussed in Sect. 5.5.2, home heating systems almost always work in an ON/OFF fashion although this is NOT how homeostatic mechanisms work.)

The cruise control mechanism found in most automobiles is a much more appropriate analogy. There are many ways to introduce students to a cruise control system. One is to use the role-playing game described here.

One student is selected to determine the desired speed (thus acting like the set point), one student measures the speed (acting like the sensor, a speedometer), one person decides whether the actual speed is too high or too low (the error detector), and one person operates the gas pedal (controlling the effector).

Other students are asked to suggest possible perturbations (the automobile begins to climb a hill), and other students are then asked to decide how the "actors" are to behave. Playing this game with several perturbations will give students the opportunity to begin building a mental model of the core concept of ***homeostasis***.

10.4.2 Introducing Students to the Core Concept Flow Down Gradients

Here is a simple exercise that will introduce students to the core concept of ***flow down gradients***. Small groups of students are presented with a number of scenarios describing seemingly unrelated events from "everyday" life. Their task is to explain the mechanisms underlying the observations described.

A set of observations illustrating ***flow down gradients*** may include water flowing through a garden hose, diffusion of an ink drop in a glass of water, the heating of a pair of tongs placed on a barbeque, airflow through a heating/air conditioner vent, watching a river flow, and flow through a bathroom shower before and after a "flow restrictor" is placed in the shower head. In each case, the answer to the question "What causes the flow?" is the same regardless of what is flowing (water, air, heat).

10.4.3 Introducing Students to the Core Concept of Mass Balance

A bathtub is a simple, everyday model of the core concept of ***mass balance***. The level of water in the tub (or the amount of water) is determined by the rate at which water enters from the faucet and the rate at which it leaves via the drain. Students can be presented with various scenarios and asked to predict what will happen to the level of the water.

10.5 Learning Resources to Help Students Master Physiology

In Chap. 9, we described some learning resources incorporating core concepts that could be used to help students master three important topics in physiology. Here, we will present additional examples of a variety of different kinds of learning resources to help students build useful, appropriate mental models of physiological systems.

Table 10.2 An exercise about temperature regulation as an example of ***homeostasis***

A hospitalized patient comes down with a fever of unknown origin. Consider the period during which the patient's temperature is still rising. Identify the physiological components of the temperature regulating system and the role they play as a component in a homeostatic mechanism. Indicate how the function of each of the components has changed relative to the period before the fever began. How does this system differ in it operation from the simple thermostat-furnace system in a house?

10.5.1 Temperature Regulation as an Example of Homeostasis

Temperature regulation is often presented as the introductory example of homeostatic mechanism. Disturbances to temperature regulation occur naturally (exposure to a cold ambient environment) and when pathology is present. Table 10.2 contains an example of an exercise that requires students to explore temperature regulation during the onset of a fever. It also requires students to think about how the physiological system differs from the simple heating system found in most homes.

10.5.2 The Action Potential and Flow Down Gradients

One of the earliest examples of the application of ***flow down gradients*** is present in any consideration of the action potential (whether in nerve, skeletal muscle, or cardiac muscle). The distribution of ions across the membrane at rest (the resting potential) and the movement of ions during the action potential both result from movement down gradients (concentration and electrical). In Sect. 10.8, we describe exercises that can be used to help students understand the core concept and relate it to important physiological mechanisms.

10.5.3 Three Examples of the Application of Mass Balance to Important Physiological Phenomena

After a core concept has been introduced with a simple analogy as described above, a set of questions/problems can be presented applying the analogy to physiological situations. A brief explanation may be necessary to introduce the physiology if the student has not studied the particular system previously. However, this introduction need not be any more complex than necessary to relate it to the analogy.

For example, the following three problems (Table 10.3) illustrate mass balance in three different systems. The goal of the exercise is to help students recognize that the vocabulary may be system specific, but the underlying concept is the same.

Table 10.3 Three examples of problems using the core concept of ***mass balance*** to facilitate students learning of important physiological mechanisms

Example from the respiratory system Carbon dioxide enters the alveoli from the blood as blood passes through the pulmonary capillaries. Carbon dioxide leaves the alveoli when exhalation causes alveolar gas to leave the lung. (Note: atmospheric air contains essentially no carbon dioxide [0.03%]). What will happen to the concentration of carbon dioxide in the alveoli if the breathing rate doubles and the carbon dioxide production rate remains constant?
Example from renal physiology: Creatinine is a metabolic waste product that is eliminated from the body by being filtered at the kidney. It is produced at a fairly constant rate by muscle metabolism. Plasma creatinine concentration is used clinically as an indicator of glomerular filtration rate. Use the mass balance core concept to explain the basis for using plasma creatinine concentration as an indicator of glomerular filtration rate. Predict what will happen to plasma creatinine concentration if glomerular filtration decreases. Explain the basis for your predictions.
Example from cardiovascular physiology: Blood flows through a metabolizing tissue bed. Using the core concept of mass balance, explain what measurements you would make, and how would you use the results to determine how much oxygen the tissue is consuming in one minute.

Hence, as presented, the problems might be included in an introductory discussion of the mass balance core concept. These problems can, of course, be used in a variety of different settings.

10.6 Creating Online Resources

As technology has progressed, a growing number of instructors are putting "learning" resources online. Frequently, these take the form of video presentations or demonstrations, voice-over PowerPoint presentations, research papers, or problem sets. Unfortunately, these formats do not require that the learner test his/her mental model and, hence, do not promote active or meaningful learning.

To promote active or meaningful learning, online resources should follow the governing principles that were discussed above. To accomplish this, the resource must help students address their current state of understanding (mental model), make a prediction on the basis of that model, evaluate the prediction, and provide feedback to help the student revise the current model, if necessary.

Many institutions use learning management systems (e.g., Moodle, Blackboard) that include features that allow development of interactive lessons. Website design software can also be used for the purpose. However, it is not necessary to learn these systems to develop effective resources.

Interactive lessons can be developed using readily available software. For example, narrative frames (screens) with embedded graphics can be created with a word processor (e.g., MS Word) or with desktop publishing software (e.g., InDesign) that can convert the document to PDF format. Navigation links, video

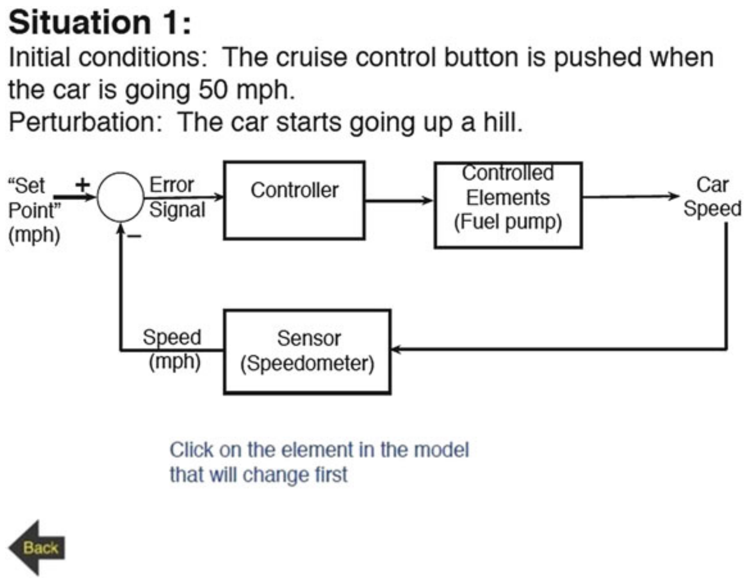

Fig. 10.1 A screen illustrating the use of a graphic as a basis for program–student interaction

clips, or audio clips can then be inserted using Acrobat Pro. With this approach, a variety of interactive activities can be produced (Modell and Michael 2013).

The following examples provide a sampling of strategies used in online resources that follow the governing principle for promoting meaningful learning.

10.6.1 An Interactive Tutorial

This example, drawn from an introductory homeostasis tutorial (Modell and Michael 2013), illustrates student–program dialogue based on a graphic representation of a model. The program moves from defining homeostasis to helping the student build a simple model of a "homeostatic" mechanism from "everyday life." The mechanism is a cruise control feature in an automobile. Figure 10.1 presents the resulting model and asks the student to apply it to a simple problem.

In this interaction, the student is asked to predict, by clicking on it, which element in the model will exhibit a change when a perturbation is applied. The ensuing dialogue is based on the choice made by the student. The dialogue provides more feedback than a simple yes/no. It discusses the role of the chosen element and why, in that context, the response is either correct or incorrect. The student is then either redirected to this screen in the event that she or he has made an incorrect choice, directed to the next screen in the conversation.

The range of images that can be used with this type of interaction is considerable, from that of an actual picture to a cartoon-type illustration to a causal diagram,

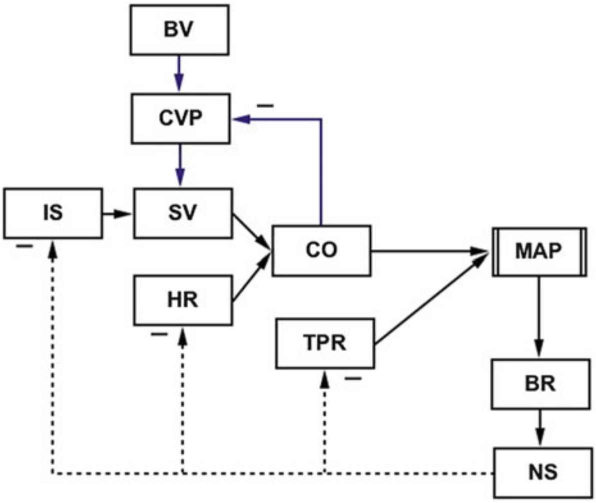

Fig. 10.2 The model of the baroreceptor reflex from which the predictions requested by CIRCSIM are derived. The dotted line is meant to represent neural signals. The solid lines are physical interactions. (Adapted from Evens and Michael 2006). *BV* blood volume, *CVP* central venous pressure, *IS* inotropic state, *SV* stroke volume, *HR* heart rate, *CO* cardiac output, *TPR* total peripheral resistance (also known as systemic vascular resistance), *MAP* mean arterial pressure, *BR* baroreceptors, *NS* nervous system

etc. Use of an image in this way can provide more insight into the students' mental models than a set of words.

10.6.2 A Qualitative Simulation

CIRCSIM (Evens and Michael 2006) is a qualitative simulation of the baroreceptor reflex, the mechanism that provides short-term regulation of blood pressure. The model on which it is based can be seen in Fig. 10.2.

Students using CIRCSIM are presented with a set of problems, each describing a perturbation to the subject that will alter blood pressure in some way. The students' task is to predict the changes that will occur to eight physiological parameters presented in an interface called the prediction table (Rovick and Michael 1992). The prediction table can be seen in Table 10.4.

The program detects student errors and patterns of errors that reflect common misconceptions. These errors trigger explanations that assist students to refine their mental model about blood pressure regulation. The effect of using CIRCSIM has been investigated, and it has been determined that CIRCSIM does help students to better understand the baroreceptor reflex (Rovick and Michael 1992; Evens and Michael 2006).

Table 10.4 The prediction table used in CIRCSIM

Parameter	DR	RR	SS
Inotropic State (IS)—contractility			
Central venous pressure (CVP)			
Stroke volume (SV)			
Heart rate (HR)			
Cardiac output (CO)			
Total peripheral resistance (TPR)			
Mena arterial pressure (MAP)			

DR is the direct response to the perturbation (with no reflexes operating), RR is the reflex response, and SS is the new steady state. Students are asked to predict whether the parameter increases, decreases, or shows no change.

10.7 Textbooks and the Focus on Core Concepts

Textbooks continue to be one of the most commonly used learning resources by students in higher education. However, textbooks pose certain problems in a learning environment that focuses on achieving meaningful learning and on the use of core concepts. We will address some of these issues in this section.

10.7.1 Challenges Posed by Textbooks

Our new paradigm emphasizes meaningful learning and the building of mental models of physiological mechanisms that are applicable to a spectrum of physiological systems. A focus on the core concepts of physiology should provide students with tools that will help them achieve the breadth and depth of understanding we are seeking.

To reach this goal, it is important that all resources begin with models to which students can readily relate and use those models as scaffolding when more complexity is added during students' study of specific systems.

Unfortunately, current textbooks do not promote this approach. Although many texts begin with describing core concepts or general models in the introductory chapter, they do not refer the student back to these descriptions as specific physiological systems are discussed. In addition, there seems to be no attempt to adopt a consistent terminology that helps students make appropriate connections to the core concepts/general models. Another inconsistency of current texts exists in the choice of pictorial representations of mechanisms. Rather than adopting a common set of design criteria that help students make conceptual connections among mechanisms, illustrations appear to show relationships as situationally specific (e.g., specific to cardiovascular physiology, specific to digestive physiology, specific to renal physiology, etc). Michael et al. (2013) have described some of these problems with textbook descriptions of ***homeostasis***.

In addition to not providing a framework of core concepts or general models, textbooks also fail to offer opportunities for readers to challenge their mental models. In the absence of such challenges, students' initial, naïve mental models (their misconceptions) usually fail to be corrected. The intrinsic difficulties of achieving meaningful learning (conceptual learning) of physiology (Michael 2007) can be compounded by reliance on a learning resource—the textbook—that does not offer the supports needed for success.

The deficiencies in current physiology (and anatomy and physiology) textbooks lead to the question of how we can best help students use the existing textbooks we assign.

10.7.2 How to Use Current Textbooks to Help Your Students

Textbooks are a source for the "facts" that represent our current understanding of physiology. To the extent that your learning objectives (see Chap. 9) include some set of these facts, textbooks can serve to make these available to your students.

In the build–test–refine paradigm described by Michael and Modell (2003), the test of a student's mental model always requires that the student compare his or her predictions of how the model will behave with the known responses of the system. The textbook can be an important reference for that comparison.

The deficiencies of textbooks can only be overcome by the instructor's consistent reference to and use of the core concepts wherever they are applicable. Consistent terminology needs to be used, even when it is different than the terminology encountered in the textbook; it is, of course, incumbent on the instructor to help the students with the "translation" problem. Consistent visual representations of the core concepts should also be used; here too it is important that instructors explain the differences between the figures students will see in the textbooks and the representations being used by the instructor.

10.7.3 Textbooks Which Have Attempted to Incorporate Core Concepts

Rhoades and Pflanzer (2003) attempted to address this challenge in the fourth edition of their text. A section of chapter one of the text was devoted to explaining the general models proposed by Modell (2000). An icon was presented to represent each of the general models. The intent was to place these icons within the text whenever the narrative described a mechanism to which the general model applied. However, due to a publisher's error, the icons were only placed in one chapter. Consequently, it was not possible to assess the impact of adding the icon to the text.

A second feature added to this text attempted to help students approach their reading as an active learner. Immediately following a heading in the text, a question was presented to help students examine their current understanding of the topic discussed in the ensuing narrative. The question also helped students look for answers to specific questions rather than passively reading the narrative. For example, the narrative describing the chemistry of hormones includes the heading "Most Hormones Can Be Characterized as Belonging to One of Three Chemical Classification." Before the narrative begins, the following question is proposed. "What characteristics do various hormones have in common?"

Michael (2011) employed a similar approach. Eight general models were described, and wherever a general model was applicable, an inset box identifying and discussing the application of that general model was presented. Repeated explicit invocation of these general models wherever they appear should help students generalize these models.

In addition, each section of the book (essentially each organ system) was started with a clinical scenario and questions related to the case were present in each chapter. These questions served as a vehicle for getting students to think about their mental models, the core concepts that are related to it, and how both can be used to explain the case.

10.7.4 How to Incorporate Core Concepts in Physiology Textbooks

One solution to the challenges of current textbook design extends the approach attempted by Rhoades and Pflanzer (2003) and Michael (2011) to include the following features:

(1) Include a general graphic representation for each core concept/general model early in the text. These general representations would then be used as a first step throughout the text whenever a specific model of the core concept/general model is presented.
(2) Define a set of terminology early in the text and used consistently throughout the text.
(3) Use uniform diagrams when applying core concepts/general models to specific physiological systems.
(4) Provide exercises within the text similar to those illustrated in the learning guide examples above to help students examine their current mental models.

The physiology education community needs to ask textbook authors and publishers to make their products a better learning resource for students.

10.8 Scaffolding Conceptual Learning with Appropriate Learning Resources

One strategy for using core concepts to reinforce understanding of physiological mechanisms is to present a model of the mechanism and ask students what core concepts apply to the mechanism under study. Once the students have identified the applicable core concepts, they can be presented with problems related to the physiology being studied that can be solved using those core concepts.

However, conceptual learning is difficult (Sinatra and Pintrich 2003), and the provision of scaffolding as students progress to that end point can be very helpful (Bransford et al. 2000). A structured series of exercises to guide student learning, beginning with the relevant core concepts, and providing opportunities for the students to test and refine their mental models can help students achieve the meaningful learning we expect. Exercises may take a variety of approaches. Some may be interactive computer exercises. Some exercises may pose questions for students to think about and provide resources to help them articulate what they are thinking. Some exercises are designed to prepare students to engage in discussions that will take place in subsequent workshops. This approach is based on a constructivist model of learning that recognizes that learning is built on prior knowledge (Bransford et al. 2000).

This approach to scaffolding conceptual learning can yield a "learning guide" (Modell and Modell 2004). Such learning guides focus on the process of testing and refining mental models that is essential to meaningful learning. The exercises first help students make their current mental models "visible." They then present situations or problems in which students use those models to predict how the system will respond to the situation. The sequence of problems provides a scaffolding to incrementally build a more comprehensive model of the mechanism. Finally, the guide provides information for the students to determine if their predictions are correct. This information often takes the form of selected reference reading in standard textbooks. Note that, in this design, the reference reading is identified after the exercises are performed. It is assumed that students will generate questions for themselves while going through the exercises. Thus, when approaching the reference reading, they will be seeking answers to questions raised and, therefore, approach the reading in a more active learning mode than if they used the reading as an introduction to the topic.

An example of this approach can be seen in the sequence of exercises that deal with membrane potentials in a variety of cell types shown in Table 10.5. The exercises presented are distributed among a number of content areas that include nerve and skeletal muscle, cardiac pacemaker cells, and ventricular muscle cells. However, the list could be extended to include smooth muscle and other situations that involve ion movement across cell membranes. These topics might be taught in a single block in an academic term or might occur at different times in a multi-term course.

Table 10.5 A sequence of learning guide exercises dealing with membrane potentials in a variety of cell types. The primary core concept being dealt with is ***flow down gradients***

Course topic	Exercise	Description
Introduction to core concepts	Determinants of flow	Interactive computer tutorial focused on flow down gradients core concept.
Introduction to core concepts	Membrane transport	Interactive computer tutorial focused on membrane transport mechanisms.
Excitable cells	Membrane potentials	Interactive computer tutorial focused on factors contributing to the membrane potential and applying flow down gradients core concept to determine membrane potential.
Nerve–Skeletal muscle	Prediction of membrane potential changes resulting from ion concentration changes or relative permeability changes	Students use computer simulation of squid giant axon to predict changes in membrane potential resulting from changes in extracellular ion concentrations or changes in relative membrane ion permeability resulting from opening or closing specific ion channels. Students generate a membrane potential pattern consistent with an action potential in the neuron. Reference reading allows students to relate results with the mechanism of action potential generation in an axon or skeletal muscle.
Nerve–skeletal muscle	Problem set for group discussion	Predict how changing experimental conditions in a squid giant axon preparation will affect characteristics of an action potential.
Nerve–skeletal muscle	Propagation of an action potential along the axon or sarcolemma	Apply the flow down gradients core concept to examine propagation of the action potential using the "view from the inside" approach (Modell 2007).
Nerve	Initiation of an action potential in the neuron	Apply the flow down gradients core concept to examine ion movement in the neuronal cell soma. Students examine summation and membrane length constant contributions to depolarization of the axon hillock.
Nerve–skeletal muscle	Synapse—Neuromuscular junction	Interactive computer tutorial focused on core concept of conservation of mass followed by application of this concept and flow down gradient to events at the synapse/neuromuscular junction.

(continued)

Table 10.5 (continued)

Course topic	Exercise	Description
Cardiac muscle	Excitation of cardiac pacemaker cells	Given the relative permeability changes for K^+, Na^+, and Ca^{++} over time, students use the flow down gradients core concept to predict the changes that occur in the membrane potential of SA node cells. Reference reading allows students to relate results with the mechanism of action potential generation in a pacemaker cell in the SA node.
Cardiac muscle	Excitation of cardiac contractile (ventricular muscle) cells	Given the relative permeability changes for K^+, Na^+, and Ca^{++} over time, students use the flow down gradients core concept to predict the changes that occur in the membrane potential of cardiac contractile (ventricle muscle) cells. Reference reading allows students to relate results with the mechanism of action potential generation in a ventricular muscle cell.

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Chapter 11
Conceptual Assessment of Student Learning

Abstract In this chapter, we first discuss the roles that assessment plays in any learning environment. We then discuss the problem of aligning assessment with learning objectives. We then turn to the particular problem of assessing conceptual understanding as opposed to assessing information acquisition. We conclude with a discussion of the special characteristics of concept-based questions.

Keywords Formative assessment • Summative assessment • Conceptual assessment

Teachers, educators, and educational researchers frequently say "assessment drives learning." While this saying has many different implications, all point to the important, even essential, role of assessment in teaching and learning.

11.1 The Roles of Assessment in Teaching and Learning

Assessment has many roles to play in helping to enhance the learning environment. Assessments of any kind can provide information about the teaching and the learning that is occurring. It can also provide information for program evaluation.

11.1.1 Formative Assessment

"Formative assessment" is an idea in widespread use, although its definition is often rather elastic. Chappuis (2014) offers the following definition: "Formative assessment are formal and informal processes teachers and students use to gather evidence for the purpose of improving learning." Thus, by definition, formative assessment is not intended to measure student's achievement or to generate a grade.

Formative assessment provides feedback to both the teacher and the student. This information is then used by the teacher to appropriately alter what happens in the classroom and by the student to change what he has been doing to improve his learning. Research has shown that under the right conditions, formative assessment

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with appropriate feedback to the student can significantly increase learning (Kibble 2007; Marden et al. 2013). To be effective, feedback has to be immediate and has to engage the students' working mental models; in this way, having had their mental model challenged and finding it wanting, the student can repair their model.

Note that the definition of formative assessment does not in any way define the nature of the instrument used to provide feedback to teacher and/or students. Formative assessment is a matter of the use that is being made of the evidence generated, not the nature of the instrument being used.

11.1.2 Summative Assessment

Summative assessment is probably a more familiar process. Chappuis (2014) defines it as "assessment that provides evidence of student achievement for the purpose of making a judgment about student competence or program effectiveness." Certainly, assessment to enable the awarding of grades has long been a responsibility of the classroom teacher. End of term final exams, SAT and ACT exams, and the MCAT exams are all different examples of summative assessments.

11.1.3 Program Assessment

Program assessment is a process in which evidence is gathered to determine how well a program—a course or the curriculum—is succeeding in achieving its stated goals. Program assessments may be internally generated or it may use externally generated instruments.

11.2 Assessment Must Align with Learning Outcomes and Learning Goals

We believe that the overarching learning goal should be student meaningful learning (Michael 2001). We want our students to not only accumulate information but to be able to use that information to solve problems of varying kinds (Michael and Rovick 1999). Finally, we want our students to understand the core concepts of physiology and be able to use them in learning the physiology content for which they are being held accountable. It is therefore essential that in defining our learning outcomes (or learning objectives), we clearly define what it is we expect the students to know and what we expect them to be able to do.

It is equally critical that there is an alignment between what you have told students they should know and be able to do and what you ask them to demonstrate in the assessment you use (Wiggin and McTighe 2005). If your objectives include items requiring students to be able to solve certain problems but your exams only test the recall of information, students will not attempt to accomplish these higher-level goals since you do not seem to actually value them.

11.2.1 Assessing Knowledge Acquisition

Students learning any STEM discipline need to acquire some body of information about that discipline. This includes learning the language of the discipline (both the vocabulary and the syntax, how you say things in the language), the names of variables, and the causal links\ages that make up mechanisms, etc. Depending on the course, it may be important that students learn the normal values for important physiological variables.

Assessing student's acquisition of this information can employ any and all of the standard question formats; Michael and Modell (2003) have discussed many of the questions types that can be used. Which ones to use with your students will depend on what you want to accomplish, the number of students in your class, and the resources that are available for scoring assessments.

11.2.2 Assessing Understanding and Use of the Core Concepts

We have advocated that physiology teaching focuses on a set of core concepts as a way to help students master physiology. This, of course, means that the students must be able to demonstrate an understanding of the assigned core concepts and demonstrate an ability to use those concepts to understand physiological phenomena.

Assessing understanding of the core concepts usually requires writing new types of questions with important properties; the usual exam questions that you have employed in the past will not generally be suitable. In Sect. 11.3 (below), we will discuss our approach to writing conceptual assessment questions.

11.2.3 Assessing Meaningful Learning of Physiology

Meaningful learning involves the acquisition of information and the ability to use that information to do something, typically to solve a problem (Mintzes and Wandersee 1997; Michael and Rovick 1999; Michael 2001). Meaningful learning is usually equated with learning with understanding. Simon (2001, p. 214) has offered this definition: "... a person understands some information to the extent that he or she can use it in performing the tasks for which it is relevant."

Assessing whether students has achieved meaningful learning thus requires that you assess whether the student can solve relevant problems.

11.3 Problems of Doing Conceptual Assessment

Assessing whether students understand the concepts of a STEM discipline is difficult. McCloskey et al. (1980) determined that college students, even those who had completed a physics course, exhibited significant misconceptions about the laws of motion. Hestenes et al. (1992) developed the Force Concept Inventory (FCI) to assess whether students understood the concepts of force and motion independently of their ability to solve quantitative problems (the usual classroom or course assessment). To the surprise of many physics teachers, a high percentage of students successfully completing college physics course nevertheless made many errors on the FCI.

This points to the difficulty of determining whether your students do, in fact, understand the core concepts of physiology. The ordinary questions you write, whether formative or summative, usually do not allow you to assess conceptual understanding. That being the case, how do we determine whether our students understand and can use the core concepts of physiology?

11.3.1 Defining the Concepts

If you want to assess student's understanding of a set of core concepts, you have to first define which of these concepts you want your students to master. Our list contains 15 core concepts (see Chap. 3), although they are not all equally important. We also acknowledge that there may be other core concepts not on our list that nevertheless can serve important pedagogic purposes.

Selecting which core concepts to emphasize in a particular course or selecting core concepts to be incorporated in a curriculum or academic major will depend on the overall goals of the course or the curriculum. Thus, these choices are one that only you and your colleagues can make.

11.3.2 Unpacking the Concepts: Building the Conceptual Frameworks

In Chap. 4, we described the process of "unpacking" a core concept to generate a conceptual framework. In Chaps. 5, 6, and 7, we presented and discussed conceptual frameworks for three of core concepts: ***homeostasis***, ***flow down gradients***, and ***cell–cell communication***. While they vary considerably in size and complexity, all three contain those component ideas that students must understand if they are to be said to understand the particular core concept.

11.3.3 Writing Questions That Test Conceptual Understanding

All of the question types that are available for use in the classroom (multiple choice, true/false, short answer, essay, concept maps, etc.) can be employed to assess students' conceptual understanding. However, when class size is large or when resources are scarce, questions that can be objectively scored may be the only viable approach to testing conceptual understanding.

11.4 Writing Concept-Based Questions

Questions to assess students' understanding of concepts, regardless of their format, are different in some important ways from the usual multiple-choice questions used to assess knowledge acquisition. These differences include the avoidance of (scientific) jargon as much as possible, a focus on the "big picture" not individual knowledge elements, and the deliberate construction of distractors (wrong answers) that reflect known student misconceptions or misunderstandings.

11.4.1 Questions Should Be Free of Jargon

Physiology, like all disciplines, has a language that students must learn and be able to use with at least some minimal correctness. This language contains many specialized technical terms, some jargon, and some terms that are in common usage, but also have specialized meaning in physiology. If the purpose of a question is to determine whether a student understands a particular concept, it would not be useful if the student answers incorrectly due to a misunderstanding of a specialized piece of jargon.

This should not be interpreted to mean that questions must be written at an 8th grade reading level! Some technical language must be used to even ask the question and students would, of course, be expected to know those terms. Nevertheless, an effort should be made to eliminate, as much as possible, terminology, the meaning of which does not matter. The threshold for including technical language in concept questions obviously depends on the students and the course; more advanced students in advanced courses should be expected to deal with more technical language.

11.4.2 Questions Should Test the Concept or Its Application in Physiology

The usual multiple-choice questions used in classroom exams test whether students have acquired a particular piece of information. If the purpose of a question is to determine if the students understand a core concept or its application in physiology, then the question has to focus on the concept and not on the recall of a collection of facts.

For example, a question about the core concept of homeostasis as applied to the regulation of blood pressure should not require students to know the different properties of the carotid and the aortic baroreceptors; what the student needs to demonstrate is that they understand the need for, or the role of, a baroreceptor in the blood pressure regulating system.

11.4.3 Distractors Should Reflect Known Student Misconceptions

In assessing whether students understand the core concepts, it is particularly useful to write distractors that represent the misconceptions you have observed in your students' thinking or those described in the physiology education literature (Michael et al. 1999, 2002; Wright et al. 2015). When student select these distractors as correct answers, it provides you with useful insight into how they are thinking and thus how you might better help the learner to learn.

11.4.4 Two Examples from the Homeostasis Concept Inventory (HCI)

According to Smith and Tanner (2010) "Concept inventories are research-based instruments that measure students' conceptual understanding of topics for which

Table 11.1 Two sample questions from the Homeostasis Concept Inventory with the distribution of student responses ($N = 244$) from a pilot study. (McFarland et al. 2014)

Question	% of Responses ($N = 244$)
4. A homeostatic control mechanism functions to maintain the concentration of X at a relatively constant level. This mechanism is functioning	
A. when the concentration of X gets too high	0.8
B. when the concentration of X gets too low	0.8
C. when the concentration of X gets too high or too low	46.5
D. at all concentrations of X. ***CORRECT***	51.0
9. Baroreceptors detect blood pressure. Blood pressure is maintained relatively constant even when the internal or external environment changes. Under what conditions do the baroreceptors send signals to the brain?	
A. when blood pressure is not at its normal value	34.2
B. when blood pressure is increasing	5.3
C. when blood pressure is constant	1.2
D. at all levels of blood pressure ***CORRECT***	58.0

students share common alternative conceptions (also called “misconceptions”) and faulty reasoning” (Smith and Tanner 2010).

We have developed a concept inventory for ***homeostasis*** that is based on our conceptual framework for this core concept (see Chap. 5). The process by which this inventory was generated has been described (McFarland et al. 2014; McFarland et al. in preparation). The HCI has been extensively tested with a large diverse population of students, and its questions have demonstrated a lack of bias toward native English speakers, gender neutrality, and an appropriate level of difficulty.

Table 11.1 contains two sample questions from the HCI that we are developing (McFarland et al. 2014). The two questions selected from the HCI were administered to 244 undergraduate students at seven colleges and universities across the country. The correct answer is marked and the distribution of answers can be seen.

Several things about these two examples are worth noting. Both questions are testing student’s understanding of the idea that homeostatic mechanisms are active all the time, not just when the regulated variable is different than the set point (item H1.6 in Table 5.1). Question 4 poses an abstract question about homeostatic mechanisms containing no reference to any actual physiological system. Question 9 tests exactly the same idea in the context of a specific physiological mechanism, the baroreceptor reflex.

The distractors (the incorrect choices) represent known misconceptions about this aspect of homeostatic mechanisms (Wright et al. 2015). Distractors 4C and 9A say essentially the same thing and both were collected from interactions with physiology teachers.

Note also the simple language used and the fact that Question 9 asks about a “generic” baroreceptor without regard to where it might be located (carotid or arch of the aorta) as this distinction is not relevant to the students' understanding of the homeostatic mechanism.

The process of writing questions like these and of then validating them is a complex one and we have developed only one concept inventory, the HCI. Concept inventories for the remaining core concepts need to be created.

But it is important to note that the type of questions we have illustrated here can be written and used in formative and summative assessments without formal research basis needed to establish their validity for use in a concept inventory. You will, of course, have to analyze these questions and the responses of your students as would do for any examination that you write.

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Chapter 12
Core Concepts and the Physiology Curriculum

Abstract We begin by defining what we mean by a "curriculum" and describing the critical features of a curriculum. We next describe the enormous diversity of students and programs in physiology and how the curricula reflect this diversity. We then propose how each of the three core concepts we have detailed can be sequenced through the courses that make up a curriculum. Finally, we consider how to assess student mastery of the core concepts across the courses that make up the curriculum.

Keywords Core concepts • Physiology curriculum

A "curriculum" is a set or sequence of required courses that, if successfully completed, results in the awarding of a degree in a particular discipline (Merriam-webster.com). As commonly used, the term is synonymous with a "major." In this chapter, we discuss how attention to the core concepts of physiology can help in the planning or organizing of a curriculum in which mastery of physiology is the goal.

12.1 The Undergraduate Physiology Curriculum: Varieties, Emphases, and Goals

Physiology is one of many biological sciences. There are relatively few undergraduate physiology departments, and physiology majors are often offered in Biology departments. There are also many other departments which may offer physiology majors or majors with a predominantly physiology content.

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12.1.1 Classification of Curricula by Undergraduate Programs: Physiology Major or Concentration Versus Other Biomedical Programs with Emphasis on Physiology

To speak of the impact of core concepts in physiology on the physiology curriculum presupposes that curricula exist whose specific purpose is to help students think and function as physiologists. In the USA, a relatively small percentage of colleges and universities offer an undergraduate program that emphasizes physiology as a major subject or concentration and that involves a defined series of physiology courses. According to Wehrwein et al. (2014), there are about 25 B.S. programs in the USA that afford an undergraduate curriculum that contains a course sequence in human physiology. Of these, 19 programs offer a degree in physiology (such as physiology, integrative physiology, human physiology) and six offer a degree in biology with a track or concentration that stresses physiology (Wehrwein et al. 2014). Our discussion of the relationship between core concepts and physiology curricula is mainly addressed to programs like these.

However, a variety of physiology courses also reside within the curricula of a much larger number of programs in exercise physiology, kinesiology, and general biomedical/health sciences. In this broader collection of undergraduate programs, physiology can be a core subject, and a specified sequence of physiology courses may be required. Even though a mastery of physiology is not the ultimate focus of teaching and learning in these programs, physiology instruction here would benefit from a deliberate effort to integrate the core concepts of physiology into the sequence of courses that are offered.

12.1.2 Curricular Requirements for Physiology Programs and Concentrations

In theory, the number of required physiology courses in a program or major sets the number of opportunities in which core concepts in physiology can be introduced and revisited in the curriculum. Wehrwein et al. (2014) determined that most physiology programs mandated a core of three semesters of physiology courses to fulfill degree requirements. This requirement was in addition to any instruction in physiology that might have been included in the introductory or general biology course sequence. The three-course core varied from three specified physiology courses, a single-semester anatomy and physiology course and two additional specified physiology courses, or a two-semester anatomy and physiology sequence and an additional specified course (Wehrwein et al. 2014). However, this core requirement does not include any required electives in physiology that may also have been stipulated by the program. At a minimum, such a core course requirement offers four opportunities (including general biology) to expose students to the core concepts of physiology. Moreover, the requirement presumably enables students to engage the core concepts at different levels of conceptual rigor and complexity (see below)

12.1.3 Classification of Curricula by Student Interest/ Progression Through Physiology Courses

The findings of Wehrwein et al. (2014) indicate that most general biology programs do not offer a specific track or concentration in physiology and therefore do not spell out a specified physiology curriculum. (This makes physiology different from physics and chemistry where there are standard curricula that have been prescribed.) Nevertheless, it is not uncommon to find that students take definite pathways through the physiology-related course offerings even in a general biology program. These pathways, when viewed from the perspective of student's interest in physiology, sort themselves out into at least three distinct "curricula" and can be recognized in the different sequences of courses that students select to fulfill their degree requirements. These "curricula" or pathways can be identified as: (1) biomedical/human, (2) animal/comparative/environmental/ecological, and (3) exercise.

Given the significant interest in the health professions (Wehrwein 2016), the first track is undoubtedly the most popular. Students who follow this pathway see their progression through a series of courses in physiology and other basic and biomedical sciences as a means to prepare for professional training. As a result, the physiology "curricula" of this population of students is dominated by systems-based**,** human or mammalian, physiology and is rounded out by electives in specialty topics (e.g., endocrinology, physiology of nutrition, cardiorespiratory physiology, physiology of aging) and subjects related to human health and disease (e.g., pathophysiology, pharmacology, toxicology).

The second track is not so narrowly defined by the target goals of the students. Many students who follow this sequence are interested in animal biology—whether for professional reasons (e.g., to become animal scientists or veterinarians) or because of a personal interest in learning how different animals function and how this function is influenced by the animal's environment. These students will seek out courses in comparative or animal physiology and related courses in the animal sciences (e.g., animal behavior, animal nutrition). Others pursuing this pathway have an interest in environmental biology or ecology and wish to combine it with an understanding of organismal biology. These students will also take courses in comparative or animal physiology. In addition, they will gravitate to course offerings in environmental physiology or ecophysiology (or physiological ecology). Given the diversity of interests in students following this pathway, it is not surprising that the only common thread that runs through the curricula is animal physiology.

Students in the third group, if they are not enrolled in a school that has a program in exercise science, will follow a curriculum that begins with systems-based human physiology. From here, students will choose among different electives and specialty courses (e.g., musculoskeletal physiology) that best suit their interests in exercise physiology, biomechanics, or kinesiology.

Even though these pathways through the general biology curriculum are self-selected and do not have the cohesion (breadth, depth, sequencing) of true curriculum, they nevertheless constitute a progression through a sequence of physiology-related courses. As such they represent an opportunity to progressively engage a considerable number of students with the core concepts of physiology.

12.1.4 Sequencing of Courses and Goals

Most undergraduate biology programs offer an introductory course that broadly surveys the biological sciences and is required of students from a variety of majors in the life sciences. In such a survey course, the introductory sequence typically features an instructional block or module that focuses on organismal biology and/or human physiology. This module or course component usually presents an overview of the major body systems and often emphasizes aspects of human physiology. Here is where the opportunity presents itself to introduce students to the core concepts of physiology and expose them to some of the critical components and fundamental constituent ideas.

Intermediate level courses in physiology are required by the physiology major or concentration and are often required electives in the general biology curriculum. These courses typically provide a general survey of physiological processes at the organizational level of the cell or the body systems. In this setting, system specific examples illustrating the core concepts occur repeatedly and the critical components and constituent ideas underlying the core concepts can be examined and reexamined in greater detail.

A variety of advanced courses in physiology are typically offered to satisfy diverse interests of students and to explore specialized topics in greater detail. For students who have progressed to this point in the curriculum, these courses offer an opportunity where advanced ideas and theories relevant to the core concepts can be addressed, exceptions to the general principles analyzed, and more specialized applications of the core concepts investigated. Table 12.1 outlines a hypothetical physiology major (sequence of courses).

As students pursue such a curriculum, they should be expected to develop increasingly complex mental model of the core concepts (see below). They would be expected to develop the skills needed to solve increasingly complex problems.

Table 12.1 Sequence of courses across three levels of subject rigor and complexity in a physiology curriculum

Introductory (Required)	Intermediate (Required)	Advanced (Elective)
Introductory Biology	Cellular Biology/ Physiology	Endocrinology
Organismal Biology/Physiology block or component	Systems Physiology (Anatomy & Physiology)	Neurophysiology
	Animal Physiology	Reproductive Physiology
		Mammalian Physiology
		Ecophysiology
		Integrative Physiology
		Immunology
		Etc.

12.2 Sequencing of Core Concepts in the Curriculum

Even with the variation between different course sequences in physiology and notwithstanding the diverse interests of students (and faculty) in physiology, it is reasonable to propose a sequence for how core concepts ought to be unfolded within different physiology curricula. Core concepts are by definition widely applicable, and the mental models that underlie them are uniform regardless of the particular curricular context in which they are learned. Moreover, core concepts have widespread applicability and therefore do not depend on the particular stress or emphasis that is placed on the physiology being learned.

Our proposal for sequencing the core concepts of physiology across the curriculum is grounded on the construct of science learning progressions (Duncan and Rivet 2013). Put simply, science learning progressions are "cognitive models of how learning of scientific concepts and practices unfolds over time" (Duncan and Rivet 2013). They purport to describe the "paths by which students might develop more sophisticated ways of reasoning over extended periods of time" (Duncan and Rivet 2013). As a way of approaching teaching and learning, learning progressions are distinguished by at least four characteristic properties (Duncan and Hmelo-Silver 2009). First, learning is focused on the "big ideas" or core concepts of the discipline. Second, the scope of a learning progression is delimited by the prior knowledge and skills of the incoming students at the onset and by the outcome goals expected of students at the end. Third, intermediate levels of achievement within the progression are derived from existing research on student learning as well as from empirical studies of the progression itself. Fourth, learning progressions are accomplished by targeted instruction that scaffolds student learning with appropriate learning activities and resources.

For a number of reasons, this approach to mapping the progress students ought to make as they advance through a scientific discipline is helpful for proposing how different core concepts ought to be learned as students move through the physiology curricula. Most obviously, the construct of science learning progressions focuses on the big ideas of a domain. Furthermore, learning progressions place an emphasis on defining both the input and output states of student understanding that bound the progression.

It should be emphasized that progress in learning of the core concepts of physiology ought to occur in parallel. Since each core concept is foundational to achieving a meaningful understanding of the discipline, it would be counterproductive for students to learn the core concepts of physiology in series—e.g., ***homeostasis*** first, ***flow down gradients*** second, ***cell–cell commuunication*** third, etc. Thus, progression through the core concepts of physiology will occur as set of parallel, intertwining learning pathways whereby students gain more sophisticated understanding of each of the concept over the course of their studies.

At the outset, we admit the limitations facing the construction of legitimate learning progressions around the core concepts in physiology. Very little is known about the prior knowledge and skills that undergraduates bring to their learning of the core concepts of physiology and even experienced teachers are not very accurate in their predictions about this (Rovick et al. 1999). Furthermore, while output goals have been defined for individual courses of instruction, there is no widespread consensus (in the form of standards) about what constitutes satisfactory achievement of the learning outcomes associated with the core concepts. Therefore, much more needs to be uncovered about the prior knowledge that students bring to their college-level learning of physiology before we can satisfactorily define our input state. Further delineation of the expected outcomes with regard to understanding each of the core concepts need to be made. Thirdly, the existing literature relevant to instruction in the core concepts of physiology needs to be called upon to determine suitable levels of intermediate achievement for progression through the core concepts. Finally, appropriate instructional strategies need to be identified that will enable students to develop more sophisticated ways of reasoning about the core concepts over the course of their undergraduate education.

Despite these limitations, we think it worthwhile to attempt to create a framework for meaningful learning progressions about core concepts in physiology. Following Duncan et al. (2009), we will ground our learning progressions on (1) the limited research literature that exists about student thinking and learning of the core concepts in physiology, (2) an analysis of physiology as a knowledge domain itself, and (3) some of the expectations set by relevant national science standards (AAAS 2011; AAMC 2009). Admittedly, much of our efforts here will be conjectural since empirical validation of student understanding of the big ideas of physiology is rudimentary.

In this process, we are assisted by the unpacking of the core concepts into conceptual frameworks (Chaps. 5, 6, 7) and guided by the experience and expertise of the instructors who have helped students to learn physiology at different levels of the discipline. We are also informed by the preliminary identification of misconceptions about the core concepts (Wright et al. 2013). This unpacking, together with our experience in helping students learn core concepts, helps us begin to determine the foundational ideas within each core concept and to distinguish them from more advanced or complex ideas. From here, calling upon the expertise of experienced instructors, we can arrange the foundation and advanced ideas into a reasonable sequence for learning. Recognition of the student misconceptions enables us to identify where and when in the sequence of learning, special attention needs to be applied to helping students overcome misconceptions and therefore continue to progress satisfactorily in their learning of the core concepts.

In this chapter, we restrict our development of learning progressions to those core concepts that have been most thoroughly unpacked into conceptual frameworks (Chaps. 5, 6, 7). Each core concept was deconstructed into a series of statements that describe features, requirements, and behaviors of the necessary processes that underlie the core concept (McFarland et al. 2016). These so-called "critical components" (see Table 4.1) are essential for the specification of the complete mental model of each concept (McFarland et al. 2016). Each critical component was in turn deconstructed into a set of constituent ideas. These ideas are necessary to develop a working understanding of each critical component (McFarland et al. 2016). Being essential for building an accurate model of the core concept, an understanding of the critical components is vital at all stages of the learning progression. However, constituent ideas can be assigned to different levels of the progression based on their perceived contribution to building increasingly sophisticated models of the core concept. It should be noted that the original scope of the conceptual frameworks was fashioned to reflect the understanding of the core concepts that second and third year undergraduates in the life sciences would be expected to understand. Therefore, it is not surprising that most of the constituent ideas have been assigned to the intermediate level within the learning progressions.

12.2.1 Homeostasis

The learning progression for ***homeostasis*** is founded on the conception of internal stability (Table 5.1, Component H1). At the introductory level, the constituent ideas that must accompany this critical component are (1) an organism's internal environment differs from its external environment and (2) homeostatic processes work to maintain stability in the internal environment. As students move into intermediate levels of understanding about homeostasis, they gain more detailed pictures of which variables that are homeostatically regulated and the operational parameters of the systems involved. Advanced ideas related to the component of stability include the consideration of differences in the homeostatic ranges observed, the limitations of homeostatic mechanisms, and the extension of the idea of physiological stability into more complex conceptions of feedforward and allostasis.

The second critical component of ***homeostasis*** is the notion of negative feedback (Table 5.1, Component H2). Since this conception is foundational to meaningful understanding of homeostasis, it is not surprising that most of its constituent ideas are required at the introductory level of the learning progression. This includes the idea that a negative feedback system of any sort, including a physiologic homeostatic system, consists fundamentally of a sensor, control center, and effector. More complex ideas concerning the anatomical arrangement of these components and the functional hierarchy of negative feedback systems are assigned to higher levels of the learning progression (Table 5.1).

Critical components H3, H4, and H5 (Table 5.1) emphasize that homeostatic processes require the operation of three essential components of a regulatory system (sensor, control center, effector). Introductory learning begins with a basic understanding of how each component works. Intermediate learning develops this basic functional understanding to include more detailed conceptions of component operation, and how each component contributes to the maintenance of homeostasis. Advanced learning of homeostatic system requirements extends the understanding of the mechanisms to include environmentally induced alterations in the performance of the system.

12.2.2 Flow Down Gradients

At the introductory level, the learning progression for ***flow down gradients*** is grounded in a fundamental understanding of flow—that particular substances (individual molecules, volumes of fluid and bulk gas) and heat move from one point in a system to another (Component F1, Table 6.1). This corresponds to the notion of flow as expressed in the general model of mass and heat flow (Modell 2000). Critical components F2 and F3 describe the second significant element of mass and heat flow—the relationship between flow and an energy gradient. At the introductory level, students should understand that the driving force for flow is the existing energy gradient for any particular substance or heat and that the magnitude of the flow (flow rate) is directly proportional to the magnitude of the energy gradient (Table 6.1). The notion that more than one type of energy gradient acting together can drive the flow of ions and water (Critical Component F4) is then addressed at the intermediate level and builds on the understanding of how a single gradient can drive flow. Learning that multiple gradients can influence the movement of ions and water across membranes is important for the application of these conceptions to the intermediate level understanding of the mechanism of the action potential and of fluid movement across the capillary wall. The third significant element of the mass and heat flow model is the notion of resistance or opposition to flow. At the introductory level, it is enough that students understand that resistance and flow are reciprocally related (Table 6.1, Critical Component F5). The physical determinants of resistance and the specific mechanisms for controlling resistance in different physiological systems can then be explored when system-specific physiology is addressed at the intermediate level.

12.2.3 Cell–Cell Communication

The learning progression for cell–cell communication builds on the fundamental understanding of the general model of a control system (Modell 2000) or a stimulus response pathway. At the introductory level, students are expected to develop a basic understanding of cell–cell communication that involves the release of a messenger molecule, binding to a receptor protein, intracellular signal transduction and amplification, and the target cell response (Table 7.1, Critical Components CC1, CC3, CC4, CC5, Introductory Level). Beginning with these understandings, students continue to build their mental models at the intermediate level to include mechanisms of transport of the message molecule and termination of the message signal (Table 7.1, Critical Components CC2, CC6, Intermediate Level). Students further refine their mental models of how messenger molecules are released, how message molecules are transported, how message molecules bind to receptors, how amplification and integration occur, and the mechanisms of message termination (Table 7.1, Critical Components CC1, CC2, CC3, CC4, Intermediate Level).

12.2.4 Learning Progressions for the Core Concepts of Physiology

Table 12.2 describes possible learning progressions for the core concepts of ***homeostasis***, ***flow down gradients***, and ***cell–cell communication*** across courses at three different levels in a curriculum. It should be obvious that as students advance from one course to the next, they should be held accountable for all of the previous component ideas they have already mastered. These progressions are meant to illustrate how one might build into the curriculum (the sequence of courses) a gradual unfolding of the core concepts.

The details of how a learning progression might occur in any particular program, and even the sequence of the components of the core concepts, will obviously depend on many local factors.

12.3 Assessing Student Mastery of Core Concepts Across the Curriculum

The planned learning progressions described in the previous section should be reflected in the learning outcomes and learning objectives for the courses making the sequence of courses. It follows, then, that assessment in each of these successive courses must look for a mastery of more complex mechanisms and more complex mental models. One way of accomplishing this is to use novel scenarios (stems of questions) of increasing depth and complexity.

Table 12.2 Suggested learning progressions for three different levels of courses. The topics listed make up those pieces of the core concepts. These topics do not correspond exactly to the items in the conceptual frameworks, but where they do correspond the "item number" has been listed. Students are expected to understand and be able to use component ideas already mastered in subsequent courses. Tables 5.1 (***homeostasis***), 6.1 (***flow down gradients***), and 7.1 (***cell–cell communication***) contain the full conceptual frameworks

Core Concept	Introductory	Intermediate	Advanced
Homeostasis	Sensor (H3) Control Center (H4) Effector (H5) Negative Feedback (H2.1)	Regulation vs Control Variables (H5.3) Integrator (H4.2,4.3,4.5) Error Signal (H4.6) Controller (H4) Changing Set Points (H4.7) Hierarchy of Controls	Feedforward Allostasis Acclimatization
Flow Down Gradients	Flow (F1) Energy Gradient (F2) Resistance (F5)	Determinants of Flow Multiple Energy Gradients (F4) Determinants of Resistance (F5.3) Control of Resistance (F5.3)	2° Active Transport Solvent Drag Ion Selectivity Gating Behavior (F5.3.1) Poiseuille's Law Starling Equation
Cell–Cell Communication	Messenger Molecule (CC1) Biochemistry (CC1.1) Cell Release (CC1.3) Target Cell (CC3) Receptor Binding (CC3.1) Signal Transduction (CC4) Cell Response (CC5)	Determinants of Cell Release (CC1.3) Transport of Messenger Molecule (CC2) Determinants of Receptor Binding (CC3.1) Determinants of Signal Amplification (CC4.1) Signal Integration (CC4.1.3) Determinants of Cell Response (CC5.1, CC5.2) Mechanisms of Signal Termination (CC6)	

12.4 Core Concepts as a Framework for Organizing Physiology Curricula

An effective curriculum is based on a clearly defined sequence of learning outcomes and learning experiences embodies in some required sequence of courses. A curriculum is not simply an amalgamation of idiosyncratically selected courses.

What kind of curriculum (courses in some sequence) would we build if the organization of the curriculum were driven by learning progressions for the core concepts?

It is likely that it would not look much different than existing curricula; there would still be introductory, intermediate, and advanced courses. What would be different is emphases across the curriculum on helping students build increasingly complex mental models by recurring application and deepening of core (Duncan and Rivet 2013). There would also be less emphasis on mere accumulation of facts and more emphasis on learning to use the facts to solve problems.

In other words, what we would see is a focus on deepening students' understanding, even if there is a potential for less depth. This is, after all, what the recommendations in Vision and Change call for (AAAS 2011).

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Part IV
Concluding Thoughts

Chapter 13
Extending the Paradigm

Abstract In this chapter, we discuss the additional work that needs to be done to fully implement the core concepts paradigm in teaching physiology. One necessary step is the unpacking of more of the core concepts and validating the conceptual frameworks that result. We also need to better understand the relationships between the core concepts and how to utilize them to enrich the paradigm. We need to develop a library of conceptual assessment instruments that can be used by physiology teachers. We also need to continue developing and refining the pedagogical approaches, including the learning resources, that focus on core concepts. Finally, we need to develop means for collaborative work on all of these tasks.

Keywords Unpacking core concepts • Conceptual assessment • Learning resources • Physiology textbooks

The physiology teaching community has only just begun the process of reforming physiology education in the ways recommended in the Vision and Change report (AAAS 2011). That said, it is clear that much progress has been made. Active learning has begun to replace passive learning (Michael and Modell 2003; Michael 2006) and anyone reading *Advances in Physiology Education* can follow the evolving movement to experiment with and implement active learning experiences in the classroom. A search for "active learning" on the *Advances in Physiology Education* webpage yields over 300 articles published between 2006 and the present (July, 2016). However, there is clearly much still to be done.

In this book, we have proposed a new paradigm for teaching physiology that focuses on the core concepts of physiology. We recognize that what we have described is only a first step and much remains to be done. In this chapter, we explore the direction in which we believe continued development of this new paradigm needs to go.

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13.1 Complete Unpacking All of the Core Concepts of Physiology

We have unpacked and validated only three of the 15 core concepts that we have identified (see Chaps. 5, 6, and 7). To the extent that the other core concepts are important, and we firmly believe that they are, they too need to be unpacked. This is an enterprise that ought to involve the entire physiology teaching community.

Which of the other core concepts should be unpacked next?

We began our project by focusing on the three core concepts that we felt were most central to any level of physiology: ***homeostasis***, ***flow down gradients***, and ***cell–cell communication***. Each of these concepts is relevant to essentially every section of physiology and is applicable at every level of study. This is not to say that every item making up their concept frameworks is equally important at every level, but the main ideas certainly are.

Which of the remaining 12 core concepts should be unpacked next? There is no right answer to this question. As physiology teachers begin to implement a concept-based approach, they will determine what additional core concepts their students need for a particular course. These will then be the next core concepts to be unpacked. As additional conceptual frameworks are created, and eventually validated, they can be used as springboards to the development of additional concept inventories. This process, however, should be a community-wide one and we will have to say about this aspect below.

13.2 Develop a Library of Conceptual Assessments in Physiology

We have developed and validated only one conceptual assessment instrument, the HCI, that assesses students' understanding of ***homeostasis*** (McFarland, in preparation). If physiology teaching is to focus on ***all*** the core concepts, it is imperative that we should be able to assess whether students understand ***all*** of the core concepts.

As we have pointed out in Chap. 11, a concept inventory for a particular core concept can only be written when a conceptual framework has been developed. Thus, as additional core concepts are developed, it will be possible to write associated concept inventories.

The work involved in validating a concept inventory is great (see Chap. 11), and the entire teaching community must participate in the process. We will have to say about how to share the work involved in doing this below.

13.3 Developing Pedagogical Approaches that Support a Focus on Core Concepts

As the physiology education community acknowledges the validity of a focus on core concepts, there is a need to develop learning resources that will promote both deeper understanding of the core concepts while at the same time fostering a deeper understanding of physiology.

13.3.1 Textbooks

Regardless of the active learning modalities that may be implemented in classrooms, textbooks continue to be important resources for helping students learn physiology. However, we have already noted (see Table 1.1 in Chap. 1) that current physiology textbooks have become encyclopedic in their coverage of the discipline, even at the introductory level. In addition, there is rarely any attempt made to point out the commonalities, the core concepts, which span multiple organ systems. Finally, topics that are explicitly represented in multiple systems, homeostasis being one example, are not presented to the students in a correct and consistent way (Michael et al. 2013; Modell et al. 2015).

Thus, there is a real need for textbooks that will support the core concepts paradigm we have described here. Making this happen will require input from many physiology teachers to the textbook publishers.

13.3.2 Learning Resources

Physiology teachers use a variety of resources to help their students master the learning outcomes that have been defined for the course. When used in a classroom with a focus on the core concepts of physiology, such resources must facilitate the students' mastery of both the particular core concepts and the physiology being mastered.

Table 10.1 listed eight types of resources, each of them useable in a variety of settings. This list is clearly incomplete; there are many other resources that could be added to the list. Scanning through any issue of *Advances in Physiology Education* will reveal other possible resources that can be used.

It is unlikely to find all of these types of exercises used in a single course, but it is not at all uncommon to find a number of them used by any particular instructor. Whenever and wherever these exercises are employed, the goal is to encourage students to build, test, and refine their mental models (Michael and Modell 2003).

What is needed is the development of learning resources that focus on core concepts as well as on specific physiological mechanisms. We have provided brief description of such exercise in Chap. 11 but clearly the physiology teaching community needs to develop many more and more varied kinds of exercises.

There is also a need for the community to begin asking a new set of questions about active learning, concept-focused exercises. Are one or more types of exercises more effective than others at promoting meaningful learning? Do different groups of students (by levels or nature of program) benefit more from one type of exercise? And finally, we need to start asking questions about how, exactly, to get the greatest learning gains from the learning exercises we use.

13.4 Develop a "Public" Space to Facilitate Collaboration

Comprehensive implementation of the care concepts approach to teaching and learning physiology will be a major undertaking. Conceptual frameworks need to be developed and validated; concept inventories must be written and validated; and learning resources, including new textbooks, need to be developed and tested. This work will only be possible if as many members of the physiology teaching community as possible contribute to the work.

What is needed is a "public space" in which materials can be shared and critiqued; several such sites exist today, and the community needs to begin to use such sites to continue the development of the core concepts approach to teaching physiology.

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Chapter 14
Summing Up

Abstract In this final chapter, we review the arguments for reform of science education in general and physiology education in particular. We then summarize the key features of the new paradigm that we have described. Finally, we suggest that what is needed to realize the changes we have proposed is a change in the teacher's mind-set.

Keywords Physiology education • Core concepts

14.1 Summary of Arguments for the Need for Reform

In Chap. 1, we reviewed just a few of the many calls for reform of American education and particularly science education. Every level of education from kindergarten through graduate and medical school has been asked to make changes in a way that students learn science.

Among the problems identified is the fact that there is much more known than students can possibly learn. Students do not have the opportunity to develop an understanding of the "big picture" because so much time and effort are spent learning the facts. Finally, there is too little emphasis on students developing the ability to use the knowledge being accumulated to solve problems.

One result is that too few individuals in our society are equipped to deal with the myriad of issues having a biological component. Another easily identified consequence is that students in the healthcare professions are less prepared than they ought to be to deal with the additional learning that will occur throughout their careers. Lastly, graduate students in all the sciences, and particularly the biological sciences, are being trained in narrower and narrower domains, with consequences for both research and teaching.

We have proposed a new paradigm for teaching physiology that we believe will increase student learning, deepen their understanding, and improve long-term retention of this subject.

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14.2 Review of the Key Features of the New Paradigm We Are Proposing

- Learning must be student centered and active if students are to develop the appropriate mental models and develop the skills to use these models to apply their knowledge to solving problems.
- Teaching and learning should focus on core concepts and deep learning, not the accumulation of ever more facts.
- Assessments, formative and summative, must focus on students' attainment of meaningful learning about concepts and mechanisms, not just the ability to remember facts.
- We must build courses and curricula that focus on core concepts.
- The physiology teaching community must develop learning resources that actively engage students while focusing on core concepts.
- Physiology needs new textbooks that focus more on presenting and using core concepts and less on enumerating every longer list of facts.

14.3 It's a Mind-Set, Not a Prescription!

In the Preface to Michael and Modell (2003) the authors have this to say:

"This book is about 'helping the learner to learn.' While this phrase seems to merely describe all good teachers strive to do, it really describes something more than that. This phrase should be understood as a short-hand description of a ***mind-set*** that directs all aspects of a teacher's behavior." Michael and Modell then proceed to explain the implications of this ***mind-set*** for all the various tasks and challenges that a teacher must face. However, the active learning ***mind-set*** proposed by Michael and Modell addressed pedagogy or classroom practice, not the content of what students are asked to learn.

In this book, we have added an additional dimension to this ***mind-set***, one that asks the teacher to help the learner to ***learn the concepts*** of physiology and not just a collection of facts about physiology.

To help make this change, we have proposed a way to systematically think about what students in a physiology course need to understand, how to determine whether the student do understand, and how to build a course and a curriculum that will facilitate student understanding of physiology.

But remember, it is a ***mind-set***, not a prescription!

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