“Nanos” Greek: “Dwarf“

1 nm = 10^{-9} \text{ m}

Earth

Euro Coin

\phi = 16 \text{ mm}

Nanotechnology

is the design, characterization, production and applications of structures, devices and systems by controlling shape and size at the nanometer scale.
A property describes how a material acts under certain conditions.

- **Types of properties:**
  - Optical (e.g. color).
  - Electrical (e.g. conductivity).
  - Physical (e.g. melting point).
  - Chemical (e.g. reaction rate).

- Properties are usually measured by looking at large (~$10^{23}$) aggregations of atoms or molecules.
What’s interesting about the nanoscale?

• Nanosized particles exhibit different properties than larger particles of the same substance.

• Nanosized particles exhibit size & shape dependent properties.
Three important ways in which Nanoscale materials may differ from macro scale materials

1. Gravitational forces become negligible and electromagnetic forces dominate.
2. Quantum mechanics is the model used to describe motion and energy instead of the classical mechanics model.
3. Greater surface to volume ratios.
Gravitational force is a function of mass and distance and is weak between (low-mass) Nano sized particles.

Electromagnetic force is a function of charge and distance is not affected by mass, so it can be very strong even when we have Nano sized particles.
Classical mechanical models that we use to understand matter at the macro scale **break down** for…

• The very small (Nanoscale) systems.

Quantum mechanics better describes phenomena that classical physics cannot, like…

• The colors of Nano gold
• The probability (instead of certainty) of where an electron will be found.
• Below a certain length scale (that depends on interaction strengths) systems must be described using quantum mechanics.
At the nanoscale, the physical, chemical, and biological properties of materials differ in fundamental and valuable ways from the properties of individual atoms and molecules or bulk matter.

Nanotechnology R&D is directed toward understanding and creating improved materials, devices, and systems that exploit these new properties.
Working at the atomic, molecular and supra-molecular levels, in the length scale of approximately $1-100 \text{ nm}$ range, through the control and manipulation of matter at the atomic and molecular level in order to design, create and use materials, devices and systems with fundamentally new properties and functions because of their small structure.

Small photonic crystals: titanium dioxide micro-sphere 1-50 $\mu\text{m}$ in diameter

Courtesy: National Science Foundation
Credit: S. Klein, F. Lange and D. Pine, UC Santa Barbara
Two main Reasons: Difference in materials properties at the Nanoscale

➢ **First**, Nanomaterials have a relatively larger surface area when compared to the same mass of material produced in larger form.

逦 Nanoparticles can make materials more chemically reactive and affect their strength or electrical properties.

➢ **Seconds**, quantum effects can begin to dominate the behavior of matter at the Nanoscale.
Specific Area: Surface Area to Volume Ratio

in dependence upon particle size

$L^3 = V_o$

$n_{L} = 1$

$S_o = 6L^2$

$S_{L/2} = 6(L/2)^2 \times (2 \times 2 \times 2) = 12L^2$

$S_{L/4} = 6(L/4)^2 \times (4 \times 4 \times 4) = 24L^2$

$n_{L/2} = 2 \times 2 \times 2 = 8$

$n_{L/4} = 4 \times 4 \times 4 = 64$

$S_{L/8} = 6(L/8)^2 \times (8 \times 8 \times 8) = 48L^2$

$\frac{S}{V} = \frac{S_o}{V_o}$

$= \frac{6L^2}{L^3}$

$= \frac{6}{L}$

$n_{L/8} = 8 \times 8 \times 8 = 512$
## Specific Area: Surface Area to Volume Ratio

<table>
<thead>
<tr>
<th>Size of cube side (m)</th>
<th>Number of cubes</th>
<th>Total Surface Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>$10 \times 10 \times 10$ (= $10^3$)</td>
<td>$60$ (=6 x 10)</td>
</tr>
<tr>
<td>$10^{-2}$ (= 1 cm)</td>
<td>$100 \times 100 \times 100$ (= $10^6$)</td>
<td>$600$ ($6 \times 10^2$)</td>
</tr>
<tr>
<td>$10^{-3}$ (= 1 mm)</td>
<td>$10^9$</td>
<td>$6,000$ ($6 \times 10^3$)</td>
</tr>
<tr>
<td>$10^{-6}$ (= 1 μm)</td>
<td>$10^{18}$</td>
<td>$6 \times 10^6$</td>
</tr>
<tr>
<td>$10^{-9}$ (= 1 nm)</td>
<td>$10^{27}$</td>
<td>$6 \times 10^9$</td>
</tr>
</tbody>
</table>

The ratio increases dramatically when the nanoparticle diameter drops **below about 100 nm**.

![Graph showing the relationship between particle diameter [nm] and specific area/volume ratio (SA:Vol Ratio = nm²/nm³)](image)
Some example calculations for volume and surface area of nanoparticles. These calculations use nm as unit of length.

<table>
<thead>
<tr>
<th>Nanoparticle Diameter (nm)</th>
<th>Volume (nm³)</th>
<th>Surface Area (nm²)</th>
<th>SA:Vol Ratio (nm²/nm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.524</td>
<td>3.14</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>524</td>
<td>314</td>
<td>0.6</td>
</tr>
<tr>
<td>100</td>
<td>523598</td>
<td>31416</td>
<td>0.06</td>
</tr>
<tr>
<td>1000</td>
<td>5.24E+08</td>
<td>3.14E+06</td>
<td>0.006</td>
</tr>
<tr>
<td>10000</td>
<td>5.24E+11</td>
<td>3.14E+08</td>
<td>0.0006</td>
</tr>
<tr>
<td>100000</td>
<td>5.24E+14</td>
<td>3.14E+10</td>
<td>0.00006</td>
</tr>
<tr>
<td>1000000</td>
<td>5.24E+17</td>
<td>3.14E+12</td>
<td>0.000006</td>
</tr>
</tbody>
</table>

\[ V_p = \frac{4}{3} \pi r^3 = \frac{4}{3} \pi \left( \frac{D}{2} \right)^3 = \frac{\pi D^3}{6} \]

\[ S = 4\pi r^2 = 4\pi \left( \frac{D}{2} \right)^2 = \pi D^2 \]

\[ S : V \text{ Ratio} = \frac{\pi D^2}{\frac{\pi D^3}{6}} = \frac{6}{D} \]
Bohr Radius

\[ L = \frac{\hbar}{2\pi} \]

but \[ L = mvr \]

So

\[ mvr = \frac{\hbar}{2\pi} \]

\[ r = \frac{\hbar}{2\pi mv} \]

\[ r = \frac{nh}{2\pi mv} \]

Putting

\[ v = \frac{e}{\sqrt{4\pi \varepsilon_0 m r}} \]

\[ r = \frac{2 \hbar^2 \varepsilon_0}{\pi m e^2} \]

This is called the Bohr radius, represented by the symbol \( a_0 \).

\[ a_0 = \frac{\varepsilon_0 \hbar^2}{\pi m e^2} \approx 5.29 \times 10^{-11} \text{ m} \]
The diameter of the hydrogen atom for stationary states is

\[ r_n = \frac{4\pi \varepsilon_0 n^2 \hbar^2}{me^2} \equiv n^2 a_0 \]

Where the **Bohr radius** is given by

\[ a_0 = \frac{4\pi \varepsilon_0 \hbar^2}{me^2} = \frac{(1.055 \times 10^{-34} \text{ J} \cdot \text{s})^2}{8.99 \times 10^9 \frac{\text{N} \cdot \text{m}^2}{\text{C}^2}} \left(9.11 \times 10^{-31} \text{ kg})(1.6 \times 10^{-16} \text{ C})^2 = 0.53 \times 10^{-10} \text{ m} \]

The smallest diameter of the hydrogen atom is

\[ 2r_1 = 2a_0 \approx 10^{-10} \text{ m} \]

\( n = 1 \) gives its lowest energy state (called the “ground” state)
• Bohr radius = 0.529 Å ≈ 0.05 nm
• C atom (VdW radius) = 0.17 nm
• In a 1 nm line: 3C atoms
• In a 1 nm x 1 nm surface: 9C atoms
• In a 1 nm x 1 nm x 1 nm cube: 27 C atoms
• In a 100 nm x 100 nm x 100 nm cube: 27 x 10^6 C atoms
• In a 1 m x 1 m x 1 m cube: 2.7 x 10^28 C atoms
A typical material possesses:

\(~10^{23} \text{ atoms/cm}^3\) (volume density)
\(~10^{15} \text{ atoms/cm}^2\) (surface density)

Assume that we have a cube with side of length = 1 cm.

Total number of atoms \(~10^{23} \text{ atoms/cm}^3 \times (1 \text{ cm})^3 \sim 10^{23}\)

Total number of surface atoms \(~10^{15} \text{ atoms/cm}^2 \times 6 \times (1 \text{ cm})^2 \sim 6 \times 10^{15}\)

Ratio of surface to total atoms \(~6 \times 10^{15}/10^{23} \sim 6 \times 10^{-8}\)

6\times10^{-8}
A typical material possesses:
\( \sim 10^{23} \text{ atoms/cm}^3 \) (volume density)
\( \sim 10^{15} \text{ atoms/cm}^2 \) (surface density)

Assume that we have a cube with side of length = 1 nm = 10\(^{-7}\) cm.

Total number of atoms \( \sim 10^{23} \text{ atoms/cm}^3 \times (10^{-7} \text{ cm})^3 \sim 100 \)

Total number of surface atoms \( \sim 10^{15} \text{ atoms/cm}^2 \times 6 \times (10^{-7} \text{ cm})^2 \sim 60 \)

Ratio of surface to total atoms \( \sim 60/100 \sim 0.6 \)

\[ \begin{array}{c}
\text{cm Scale} \\
6 \times 10^{-8} \\
\rightarrow \\
10^7 \\
\rightarrow \\
\text{nm Scale} \\
6 \times 10^{-1}
\end{array} \]
• Magic Number = Cluster has a complete, regular outer geometry
• Formed by successively packing layers around a single metal atom.
• Number of atoms \( y \) in shell \( n \): \( y = 10n^2 + 2 \) \( n = 1, 2, 3 \ldots \)
• Maximum number of nearest neighbors (metal-metal hcp packing)
• Decreasing percentage of surface atoms as cluster grows
The number of surface atoms increases with reducing size of the particles.
Generally accepted material properties are derived from the bulk, where the percentage of atoms at the surface is miniscule. These properties change at the nanoscale.

As the surface area to volume ratio increases so does the percentage of atoms at the surface and surface forces become more dominant.

**Surface Energy**

Surface atoms possess more energy than bulk atoms.

Consequently, surface atoms are more chemically reactive.

Nanoparticles possess enhanced chemical reactivity.
The Surface

…is where the interactions that result in changes in physical and chemical properties occur.

…is where chemical reactions take place.
What factors account for the increase in reaction rates of chemical processes at the nanoscale level?

As the size of nanoscale particles decreases, the surface area to volume ratio increases.

Therefore, the surface energy increases!

Increase the rates of chemical reactions
Unique Characteristics of Nanoparticles

• Large surface to volume ratio
• High percentage of atoms/molecules on the surface
• Surface forces are very important, while bulk forces are not as important.

• Semiconductor nanoparticles may exhibit confined energy states in their electronic band structure (e.g., quantum dots)
• Can have unique chemical and physical properties
• Same size scale as many biological structures
The gold we know:

Material properties don’t change with size
- resistivity
- melting point
- optical absorption

The gold we are discovering:

Material properties (such as optical Absorption, shown here) change with the size of the gold nanoparticle.
As the percentage of atoms at the surface increases, the mechanical, optical, electrical, chemical, and magnetic properties change.

- For example, optical properties (color) of gold and silver change when the spatial dimensions are reduced and the concentration is changed.
Size Effect: Color

Color Control by QD Particle Size

- **Core Size**
  - 2 NM
  - 3 NM
  - 4 NM
  - 5 NM
  - 7 NM

- **Number of Active Centers**
  - 15 ATOMS
  - 30 ATOMS
  - 50 ATOMS
  - 80 ATOMS
  - 150 ATOMS

Depending on size, quantum dots emit different color light due to quantum confinement. Illustrated is the range of QDs with emission gradually stepping from violet to red.
Shape Effect: Color

A Sampling of Different Shaped Gold NanoParticles

Gold NanoSpheres  Gold NanoRods

Gold NanoStars  Gold NanoTriangles

Scattering cross section [nm]

Wavelength [nm]

50nm
Figure 10. Transmission electron micrographs and UV—Vis spectra of gold nanoparticle colloids with various geometries: (top) spheres, (middle) decahedra and (bottom) rods. (Image credit: Reprinted from: Borja Sepúlveda et al., "LSPR-based Nanobiosensors", Nano Today (2009), 4 (3), 244-251, with permission from Elsevier).
The band gap is increases with reducing the size of the particles.
Figure 8. Schematic illustration of the valence and conduction bands in the three kinds of materials, insulator, semiconductor and conductor. (Image credit: L. Filipponi, iNANO, Aarhus University, Creative Commons ShareAlike 3.0)
**Figure 9.** The image compares the energy of the bandgap (arrow) in a bulk semiconductor, in a quantum dot and in an atom. As more energy states are lost due to the shrinking size, the energy bandgap increases. (Image credit: L. Filipponi, iNANO, Aarhus University, Creative Commons ShareAlike 3.0)
The melting point decreases dramatically as the particle size gets below 5 nm.

Particle Volume Fraction

\[ \phi_p = \frac{\pi D^3 / 6}{L^3} \cdot \# \text{ of particles} \]
Why Nanocomposites?

„Nanos“ Greek: „Dwarf“

50,000x smaller than human hair radius

Particle size: 10 µm  1 µm  100 nm

Number of particles: 3  3000  3,000,000

Small but Great Effect!

3 Vol.-%
Specific Volume = $\frac{\text{Effective Volume Fraction}}{\text{Particle Volume Fraction}} = \frac{\phi_E}{\phi_p} = \left(1 + \frac{6\delta}{D}\right)$

Effective Volume:

$V_E = V_p + V_I$
Particle Volume: \( V_p = \frac{4}{3} \pi r^3 = \frac{4}{3} \pi \left( \frac{D}{2} \right)^3 = \frac{\pi D^3}{6} \)

Particle Volume Fraction: \( \phi_p = \frac{\pi D^3 / 6}{L^3} \)

Interface (Influence Zone) Volume:
\[
V_I = \frac{4}{3} \pi \left( \frac{D}{2} + \delta \right)^3 - \frac{\pi D^3}{6} = \frac{4}{3} \pi \left( \frac{D^3}{8} + \frac{3}{4} D^2 \delta + \frac{3}{2} D \delta^2 + \delta^3 \right) - \frac{4}{3} \pi \left( \frac{D}{2} \right)^3 = \pi D^2 \delta
\]

\( V_I = \pi D^2 \delta \)

Effective Volume: \( V_E = V_p + V_I \)

Effective Volume Fraction: \( \phi_E = \frac{V_p + V_I}{L^3} = \frac{\pi D^3 / 6 + \pi D^2 \delta}{L^3} = \phi \left( 1 + \frac{6 \delta}{D} \right) \)

Specific Volume = \( \frac{\text{Effective Volume Fraction}}{\text{Particle Volume Fraction}} = \frac{\phi_E}{\phi_p} = \left( 1 + \frac{6 \delta}{D} \right) \)
A structure with at least 1 dimension less than 100nm.

Examples:
- Sphere-like particles
  - Ag nanoparticles, buckyballs
- Rod-like particles
  - Si & Ni nanowires
- Tube-like particles
  - Carbon nanotubes
  - TiO$_2$ nanotubes
Based on the **size** and **shape**, the **Nanomaterials** are classified as follows:

- Nanoparticles
- Nanocapsules
- Nanofibers
- Nanowires
- Fullerenees (carbon 60)

- Nanotubes
- Nanosprings
- Nanobelts
- Quantum dots
- Nanofuidies
Nanowires
What are Nanofluids?

- A **Nanofluid** is a fluid containing nanometer-sized particles.
- These fluids are engineered *colloidal suspensions* of nanoparticles in a base fluid.
Magnetic Nanofluids: Ferrofluid
What is Nanofiber?

Human hair (~60 µm)  
PA6-Nanofiber (~50nm)

Large specific area and high aspect ratio!
What a nanofiber can mean?

3 g (polymer) = V • ρ = (πr²L)ρ = π (50nm)² • L • (1g/cm³)

L ≈ 381,972 km

Earth

380,400 km

Moon
How to produce Nanofibers?

Electrospinning Process

- Reservoir
- Polymer solution
- Capillary (Needle)
- Collector (Metal plate or Al foil)
- HV supply
How to produce Nanofibers?

Electrospinning Process

Reservoir

Polymer solution

Capillary (Needle)

Taylor Cone

HV supply

Collector (Metal plate or Al foil)
How to produce Nanofibers?

Electrospinning Process

- Straightforward
- Inexpensive
- Effective
Bone regeneration

Homo & Hetero Solution

Genes, Proteins & Cells

Biological Species (eg. HAp)

Drugs, Antibiotics, Antimicrobial & Antiseptic Agents

Control Morphology

Gene/Cell-therapy

Bone regeneration

Drug Delivery Systems

Diversity in Electrospinning Process

Multifunctional Nanofibers
### Potential Applications

#### Structural Application
- Reinforcing elements for composites
  - Improvement in stiffness-toughness balance
  - Super-light weight composites
  - Noise and vibration abater
  - Electrostatic discharge protection
  - Electromagnetic interference shielding
- Higher efficient and functional catalysts

#### Applications in Life Science
- Drug delivery/release systems
- Scaffolds for tissue engineering
  - Haemostatic devices
  - Wound dressing
  - Porous membrane for skin
  - Tubular shapes for blood vessels and nerve regeneration
  - 3D scaffolds for bone and cartilage regenerations

#### Filter media
- Liquid & gas filtration
- Molecules & bacteria filtration
- Clean room technology

#### Protective Clothing
- Minimal impedance to air
- Efficiency in trapping nanoparticles
- Anti-bio-chemical gases

#### Electro-optical Applications
- Sensor technology
  - Piezoelectric sensor
  - Chemical sensor
  - Florescence optical biochemical sensor
- Micro- & nanodivices
  - Single electron diode and transistor
  - Photovoltaic devices (nano-solar cell)
  - Fuel cells
  - Batteries
  - LCD devices

#### Cosmetic Skin Mask
- Skin cleansing, healing & therapy
Nanofiber Sensors

Exposure gas molecules

Bio-chemical Sensors
A quantum dot is a semiconductor nanostructure that confines the motion of conduction band electrons, valence band holes, or excitons (bound pairs of conduction band electrons and valence band holes) in all three spatial directions.

- Nanocrystals
- 2-10 nm diameter
- Semiconductors

Semiconductor Quantum Dots:
CdSe, ZnSe, ZnS, ZnO
Quantum Dots
Quantum Dots in Display

16 million colors
Red $2^8 \times$ Green $2^8 \times$ Blue $2^8$

64x more color than your average TV
Better light AND energy efficiency

1 billion colors
Red $2^{10} \times$ Green $2^{10} \times$ Blue $2^{10}$

Quantum dots
Blue LED
Quantum Dots

- Narrow tunable fluorescence emission
- Broad excitation profiles
- High surface-to-volume ratios
- High photostability

➢ In vitro
  - Cellular Imaging
  - Biomolecular tracking
  - Tissue staining

➢ In vivo
  - Biodistribution of QDs
  - Vascular imaging
  - Tracking of cells
  - Tumor imaging
Quantum Dots in Biomedical Applications

Sensitivity and multicolor capability of nanocrystal imaging in live animals. Left: a mouse with nanocrystal labeled organs. Right: nanocrystal labeled microbeads emitting green, yellow or red light depending on the size of the nanocrystal.
Nanoparticles: Different Dimensionality

1-D

MWCNT

5 nm

2-D

Layed Silicate

200 nm

3-D

Silica

100 nm

1-10 μm

1 nm
Morphology by TEM

26 nm

relative frequency (a.u.)

particle size (nm)

26 nm

100 nm
Single and Multi-wall Carbon Nanotube

• Single wall nanotube:
  • SWNT
  • single atomic layer wall, diameter of 1-5 nm
  • excellent mechanical property
  • hot topic now

• Multi wall nanotube:
  • MWNT
  • Inner diameter: 1.5 – 15 nm
  • Outer diameter: 2.5 – 30 nm
  • ~50 layers
  • containing more structure defects
Properties of Nanotubes

• **Mechanical:**
  – Young’s Modulus: \( \sim 1 \text{TPa (SWNT), 1.25 TPa (MWNT)} \) (Steel: 230 GPa)
  – Density \( \sim 1.3 \text{ g/cm}^3 \) (SWNT: Wall-thickness: 0.34 nm, Diameter: 1.36 nm)

• **Thermal:**
  – Conductivity: 2000W/m.K (copper: 400W/m.K)

• **High Aspect Ratio:** Length \( \sim 1\mu\text{m} \), Diameter \( \sim 1\text{nm to 50nm} \)
• **Nanotubes are long, thin cylinders of carbon:**

Their electrical properties change with diameter, “twist”, and number of walls.

They can be either conducting or semi-conducting, their electrical behavior.
## The History of Nanotubes

<table>
<thead>
<tr>
<th>When</th>
<th>Who</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970s</td>
<td>Harry Kroto &amp; Dave Walton</td>
<td>Try to synthesize long carbon chains</td>
</tr>
<tr>
<td>Late 1980s</td>
<td>Scientists around the world</td>
<td>Buckyball was synthesized and confirmed as C60</td>
</tr>
<tr>
<td>1991</td>
<td>Japanese Scientist, Sumio Iijima</td>
<td>Discovery of multi wall carbon nanotubes</td>
</tr>
<tr>
<td>1993</td>
<td>S, Iijima and T, Ichihashi</td>
<td>Synthesis of single wall carbon nanotubes</td>
</tr>
<tr>
<td>1996</td>
<td>Robert F. Curl, Harry Kroto, Richard E. Smalley</td>
<td>Nobel Prize in Chemistry for the discovery of Buckyball</td>
</tr>
<tr>
<td>1999</td>
<td>Samsung</td>
<td>Flat Panel display prototype</td>
</tr>
<tr>
<td>2001</td>
<td>IBM</td>
<td>The first computer circuit composed of only one single carbon nanotube</td>
</tr>
</tbody>
</table>
The discovery of nanotubes comes from Buckyball.

The discovery of Buckyball is by accident, from Radio-astronomy.

Around 1970s
Allotropes of Carbon

Diamond
Graphite
C60
C70
SWCNT
MWCNT

Cutting line
(a) → (b)
(c) → (d) → graphene
Applications with CNTs

- **Transistor**
  - Field Effect transistor
  - Single electron transistor

- **SPM Tips**

- **Field Emission Display Device**

- **More Possible Applications**
• Nanotube sensors:
  • The electrical conductivities of SWNT change dramatically when they expose to gaseous molecules

• Hydrogen storage:
  • 5~10 wt% hydrogen storage density at room temperature for SWNT

• Light Elements:
  • Electrons from nanotube bombard a phosphor-coated surface to produce light
  • 2 times brighter, 8000h lifetime, can be used for giant outdoors displays

• Memory device:
  Capable to store single electronic charge
  • High mobility
Composite Materials: Carbon Nanotubes

- Reinforced materials
- Lighter materials
- Conductive polymers
- Radar absorbing materials
Synthesis of Nanomaterials

- Top-down method (Destruction)
- Bottom-up method (Construction)
Top-Down vs. Bottom-Up

Bulk → Fragments → Nanoscale Structures → Clusters → Atoms

Top-down

Bottom-up
Top-down approach refers to slicing or cutting of a bulk material to get nano sized material. This is similar to making a stone statue. You take a bulk piece of material and modify it by carving or cutting stone, until you have made the shape you want.

The process involves material wastage and is limited by the resolution of the tools you can use, causing significant crystallographic damage to the processed patterns.

Examples of this kind of approach include the various types of lithographic techniques.
Bottom-Up Approaches

- Assembling nano materials atom – by – atom or molecule – by – molecule (self assembling).
- This approach is much cheaper.
- Things become much larger.
- Examples of molecule self assembly are Watson–Crick basepairing and nano-lithography.

![Diagram of DNA structure and self-assembly process.](image-url)
Nanobiotechnology requires a new way of thinking ("change of paradigm") in order to make full use of its importance and potential value.

"Top-Down" - Strategy

Solid Materials

Goal:
Smallest Functional Units and Structures

Molecular Construction Kit

"Bottom-Up" - Strategy

Microlithography

Meso- and Macroscopic Scale

Self-Assembly

Solid Materials

Molecular Construction Kit

Goal:
Smallest Functional Units and Structures

Top-Down vs. Bottom-Up
The **spontaneous association of molecules** under equilibrium conditions into stable, structurally well-defined aggregates.

As opposed to the “**Top Down**” methods of the semiconductor industry, self-assembly exploits the naturally existing effects of Brownian Motion, Intermolecular Forces, and the 2nd Law of Thermodynamics to produce structures in a “**Bottom Up**” fashion.

- Biology uses a “bottom-up” assembled strategy
- The unique properties of the DNA and protein building blocks
- Introduction to molecular recognition and self-assembly
**Self Assembly**

Spontaneous change in a system from a more disordered state to an ordered or structured state.

- *e.g. DNA* - complementary strands

- *e.g. amphiphilic lipids* when placed in water will form bilayers, vesicles or micelles - cell membranes.
Self Assembly of Magnetic Nanoparticles

Techniques have been developed that use iron nano particles that self assemble into 3D arrays.

Fig. 1 Large Image
Schematics of (a) a three-dimensional superlattice crystal, (b) a magnetic superlattice of a nanoparticle self-assembly, and (c) a TEM image of a two-dimensional iron nanoparticle array.
Because of their small size, nanoscale devices can readily interact with biomolecules on both the surface of cells and inside of cells.

By gaining access to so many areas of the body, they have the potential to detect disease and deliver treatment.

Nanoparticles can deliver drugs directly to diseased cells in your body.

Nanomedicine is the medical use of molecular-sized particles to deliver drugs, heat, light or other substances to specific cells in the human body.
Greatly improved “directed therapies” for treating cancer using new nano-drug/gene delivery systems.

Tiny implantable devices to monitor health.

New point-of-care and home healthcare devices.

Tiny implantable devices with nanobiosensors to treat chronic diseases (diabetes, cardiovascular, arthritis, Parkinson’s disease, Alzheimer’s disease,…) with fewer side-effects.
NASA-funded scientists are crafting microscopic vessels that can venture into the human body and repair problems – one cell at a time.

January 15, 2002: It's like a scene from the movie "Fantastic Voyage." A tiny vessel -- far smaller than a human cell -- tumbles through a patient's bloodstream, hunting down diseased cells and penetrating their membranes to deliver precise doses of medicines.

Only this isn't Hollywood. This is real science.

Right: Tiny capsules much smaller than these blood cells may someday be injected into people's bloodstreams to treat conditions ranging from cancer to radiation damage. Copyright 1999, Daniel Higgins, University of Illinois at Chicago.
Voyage of the Nano-Surgeons

Cancer diagnosed → Programmed nanobots → Homing on the tumor → Recovery
Nanoshells are injected into cancer area and they recognize cancer cells. Then by applying near-infrared light, the heat generated by the *light-absorbing Nanoshells* has successfully killed tumor cells while leaving neighboring cells intact.
Nanoshells kill tumor cells selectively
Nanoparticles used for molecular imaging of malignant lesions
Nanowires as Medical Sensors

• **Nanosized sensing wires** are laid down across a micro-fluidic channel. As particles flow through the micro-fluidic channel, the Nanowire sensors pick up the molecular identifications of these particles and can immediately relay this information through a connection of electrodes to the outside world.

• They can detect the presence of altered genes associated with cancer and may help researchers pinpoint the exact location of those changes.

![Nanowire Sensor Diagram](image)
• Unfortunately, in some cases, the biomedical metal alloys may wear out within the lifetime of the patient. But Nanomaterials increases the life time of the implant materials.

• Nanocrystalline zirconium oxide (zirconia) is hard, wear resistant, bio-corrosion resistant and bio-compatible.

• It therefore presents an attractive alternative material for implants.

• Nanocrystalline silicon carbide is a candidate material for artificial heart valves primarily because of its low weight, high strength and inertness.
Potential Health Concerns

• Cause for concern:
  • Nanoparticles are similar in size to many biological structures → easily absorbed by the body.
  • Nanoparticles remain suspended in the environment for extended periods of time.

• Health Impacts of nanoparticles are expected to be dependent on composition and structure.

• The potential health concerns of nanomaterials are largely unknown.

• The EPA has started the National Nanotechnology Initiative which is providing funding to further investigate this issue.
Nanotechnologies and Healthcare

We have come a long way...

Art: Da Vinci’s
“Vitruvian Man” 1490

but we still have so far to go!
Military Battle Suits

- Enhanced nanomaterials form the basis of a state-of-the-art ‘battle suit’ that is being developed.
- A short-term development is likely to be energy-absorbing materials that will withstand blast waves;
- Longer-term are those that incorporate sensors to detect or respond to chemical and biological weapons (for example, responsive nanopores that ‘close’ upon detection of a biological agent).
The US Military has launched a program to design a new suit for elite forces.
The U.S. Special Operations Command is asking designers for ideas to produce a suit to protect soldiers of the future.

**Government requirements:**

**DISPLAYS**
Give wearer feedback information relevant to the environment from an array of sensors

**HEALTH STATUS**
Embedded systems monitor the body’s vital statistics such as oxygen levels and body heat

**LIGHTWEIGHT DESIGN**
Minimizes load and maximizes protection

**ARMOR**
Protects the head and body, especially from explosions, by using advanced materials

**POWER**
Built-in management systems along with wearable computers, antennas and a programmable radio

**MOBILITY**
Exoskeleton will be powered to enhance endurance and agility

*Screenshots from Army video*

*SOURCES: U.S. Special Operations Command, Chicago Tribune*
Nanomaterials: Other Applications

• Sunscreens and Cosmetics
  ✓ Nanosized \textit{titanium dioxide} and \textit{zinc oxide} are currently used in some sunscreens, as they absorb and reflect ultraviolet (UV) rays.
  ✓ Nanosized \textit{iron oxide} is present in some lipsticks as a pigment.

• Fuel Cells
• Displays
• Batteries
• Catalysts
• Magnetic Nanomaterials:
  \textit{Hard Disks with high storage capacity}
Artificial Ear: US soldier has new ear grown in her arm

The ear, grown to replace one lost in a car crash, will have functional blood vessels and nerve endings.

https://www.telegraph.co.uk/news/2018/05/10/us-soldier-has-new-ear-grown-arm/
A human ear from cartilage cells the back of a mouse,

Dr. Vacanti, a transplant surgeon
at Massachusetts General Hospital in Boston, USA
Artificial Ear
Artificial Ear
Growing a nose on a forehead is a revolutionary approach to surgical reconstruction.
A Fully-Implantable Bioartificial Tissue/Organ

Practical Procedure

1. Start with a porous scaffold
2. Mold to the shape of a tissue or organ
3. Seed with cells (autologous or allogeneic)
4. Culture the cells and grow a tissue or organs

Major Concerns

- Interconnecting pores
- Seeding cells
- Blood Vessel Ingrowth

Biomaterials: Metals, Ceramics, polymers