Introduction to Nanotechnology

- Textbook：
  Nanophysics and Nanotechnology
  by:
  Edward L. Wolf

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Classroom: A209
Time: Thursday; 13:20 -16:10 PM
Office hour: Thur., 10:00-11:30 AM or by appointment

Sep 15	Introduction	Hossein
Sep 22	Systematic of Making Things Smaller	Hossein
Sep 29	What are limits to smallness	Hossein
Oct 6	Quantum Nature of the Nanoworld	CW Chen
Oct 13	Quantum Consequence for the Macroworld	CW Chen
Oct 20		
Oct 27	Self-Assmbled Nano-Strauctur e in Nature and Industry	Hossein
Nov 3		
Nov 10	**Midterm**	
Nov 17	Physics-based Experimental Approaches to Nanofabrication and Nanotechnology	Hossein
Nov 24		
Dec 1	Quantum Technologies based on Magnetism, Electron and Nuclear Spin, and Superconductivity	KH Chen
Dec 8		
Dec 15	Silicon Nanoeletronic and Beyond	Hossein
Dec 22		
Dec 29	Looking into the Future	LC Chen
Jan 5		
Jan 12	**Final Exam**	

Objective of the course

The course, Introduction to Nanotechnology (IN), will focus on understanding of the basic molecular structure principals of Nano-materials. It will address the molecular structures of various materials. The long term goal of this course is to teach molecular design of materials for a broad range of applications. A brief history of biological materials and its future perspective as well as its impact to the society will be also discussed.

Evaluation; Score: 100%:

Mid-term Exam: 30%
Final Exam: 30%
Scientific Activity: 40 % (Home work, Innovation Design)

Contents

- Introduction (*Prof. Hossein*)
- Systematic of Making Things Smaller (*Prof. Hossein*)
- What are limits to smallness (*Prof. Hossein*)
- Quantum Nature of the Nano-world (*Prof. CW Chen*)
- Quantum Consequence for the Macro-world (*Prof. CW Chen*)
- Self-Assembled Nano-Structure in Nature and Industry (*Prof. Hossein*)
- Physical-based Experimental Approaches to Nanofabrication and Nanotechnology (*Prof. Hossein*)

- Mid-term Exam

Contents

- Quantum Technologies based on Magnetism, Electron and Nuclear Spin, and Superconductivity (*Prof. KH Chen*)
- Silicon Nanoeletronic and Beyond (*Prof. Hossein*)
- Looking into the Future (*Prof. LC Chen*)

- Final Exam

Systematic of Making Things Smaller- Pre-Quantum

1. Mechanical Frequencies increase in Small System

2. Thermal Time Constants and Temperature Differences *Decrease*

3. Viscous Forces Becomes Dominant for Small Particles in Fluid Media

4. Fractional Forces can Disappear in Symmetric Molecular Scale Systems

Thermal Time Constants and Temperature Differences *Decrease*

heat energy flow:
dq/dt: kAT/L

dq/dt : CVdT/dt

We can write:

$dT/T : -(kA/LCV)dt \longrightarrow T=T(0)\exp(-t/\tau_{th})$

$\tau_{th} : LCV/kA$

Thermal time constant decrease as the size is reduced.

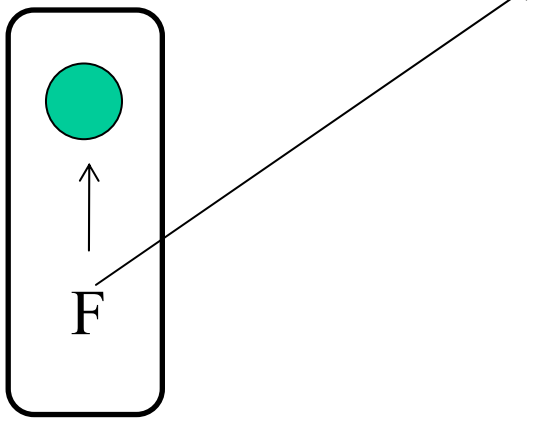
Viscous Forces Becomes Dominant for Small Particles in Fluid Media

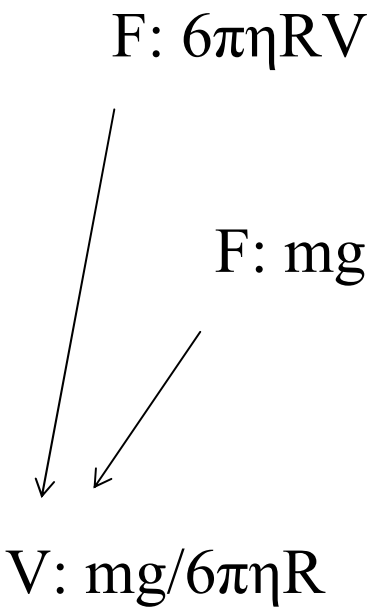
The force needed to move a sphere of radius R and velocity V

F: $6\pi\eta RV$

Stokes's Law

Viscosity Index of the medium





Falling particle of mass of m
under gravity

A particle of 10 um radius and density 2000 kg/m3 falls
In air at V of 23 mm/s

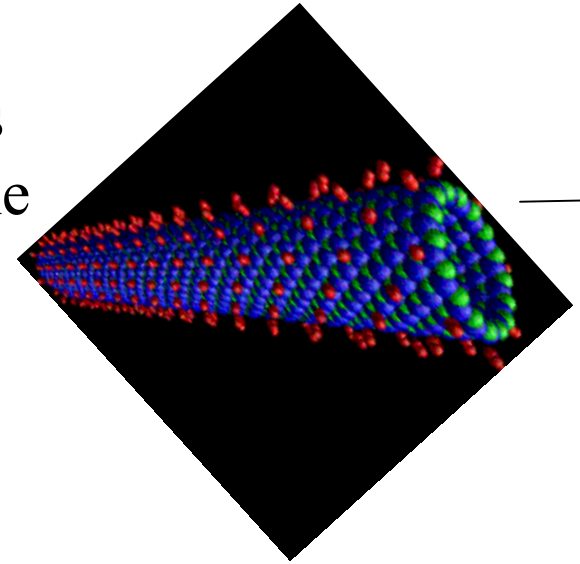
A particle of 15 nm and density 500 kg/m3 fall in air
At V of 13 nm/s.

Fractional Forces can Disappear in Symmetric Molecular Scale Systems

Viscous and Fractional forces are nearly "0" in nano-scale system.

Carbon nano-tubes:
They are rolled sheets of Graphite

There are no molecules at all between the layers of Graphite and the same In Nano-tubes.



The medium between the very close space moving elements is vacuum

What are limits to smallness

1. Particles

Atoms ⟶ ~ 0.1 nm

Photons ⟶ Particles of light

E: hv

Light frequency in Hz

Planck's constant : 6.6x10-34 J.s

Molecules ⟶ Combine of at least two atoms

2. Limited size of device

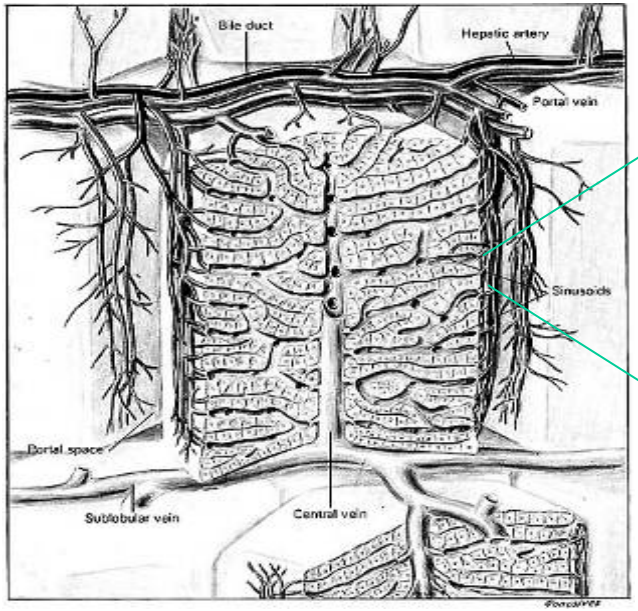
↓

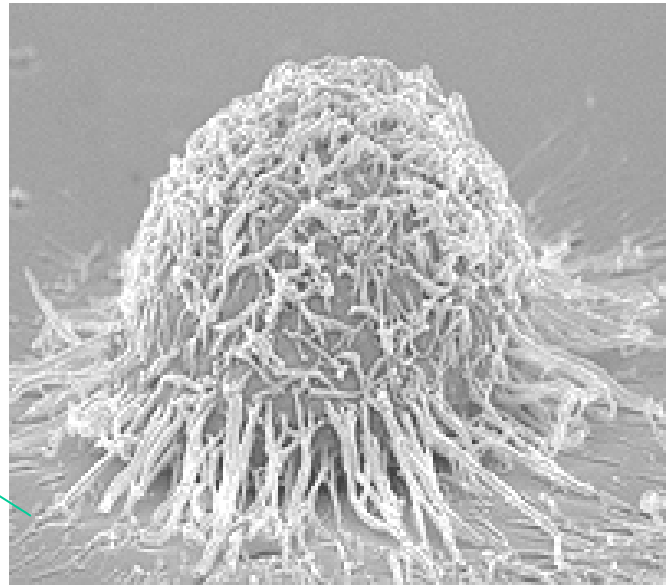
It is so hard to make device smaller than millimeter

↓

Small devices in nature

Cells: Nano-motors in biological system



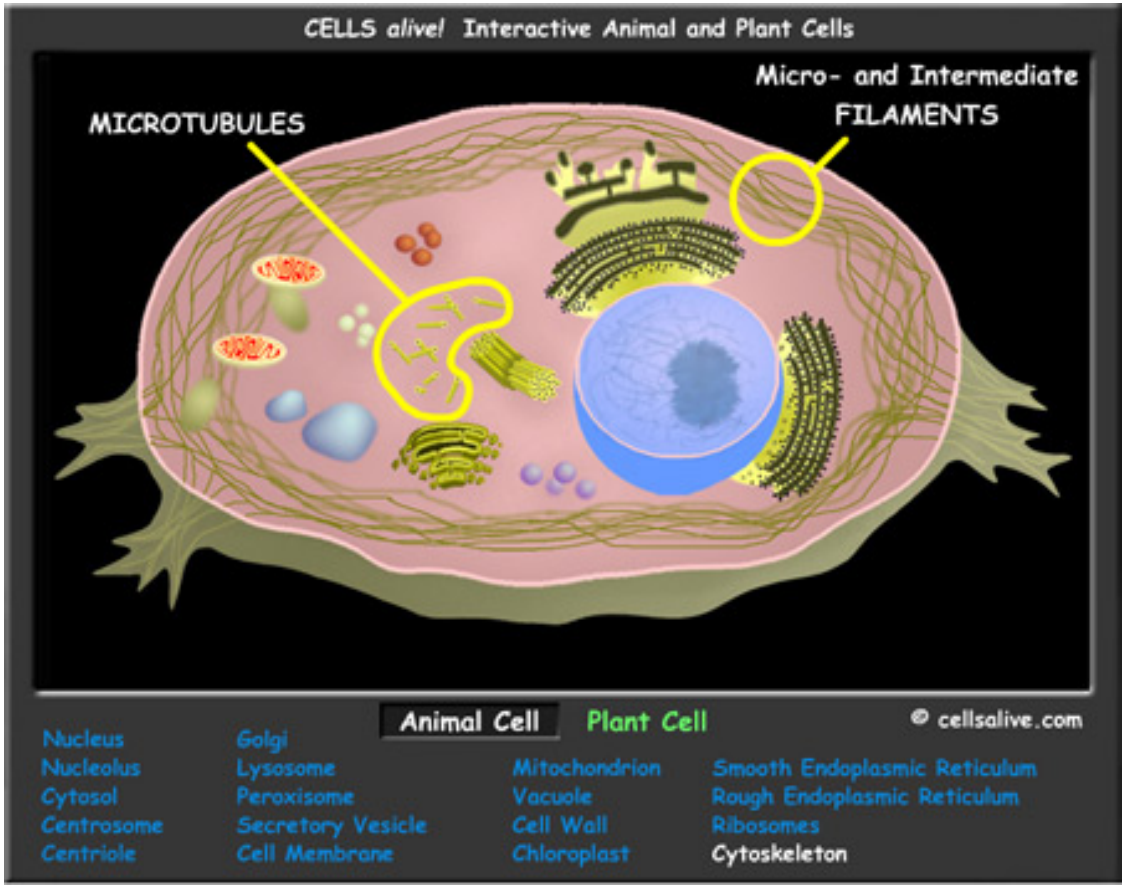


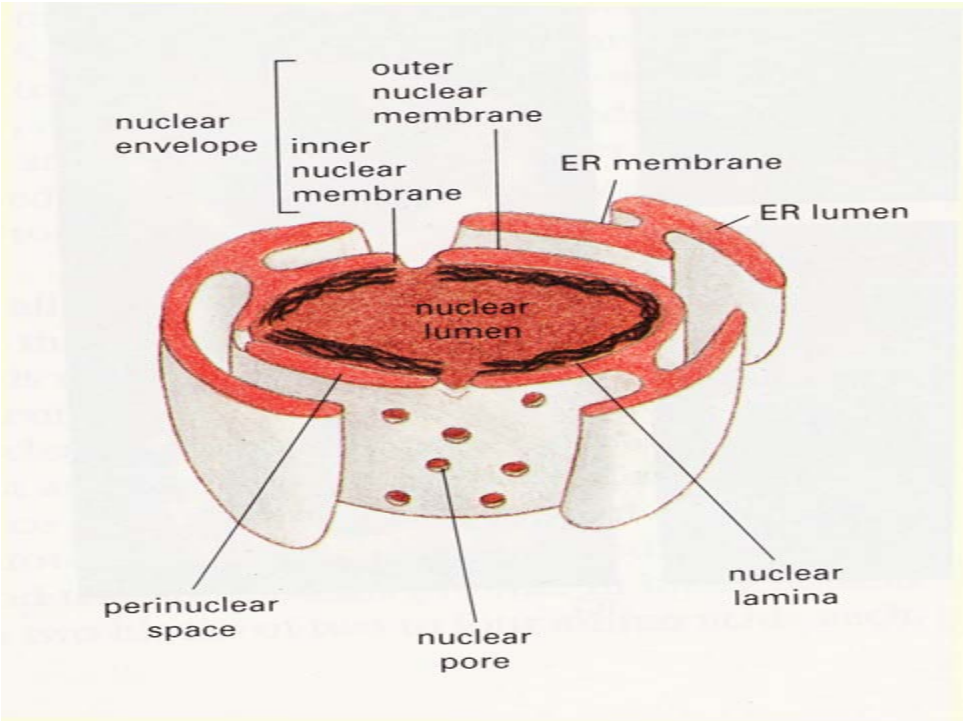
Human Lung

A walking Avogadro being

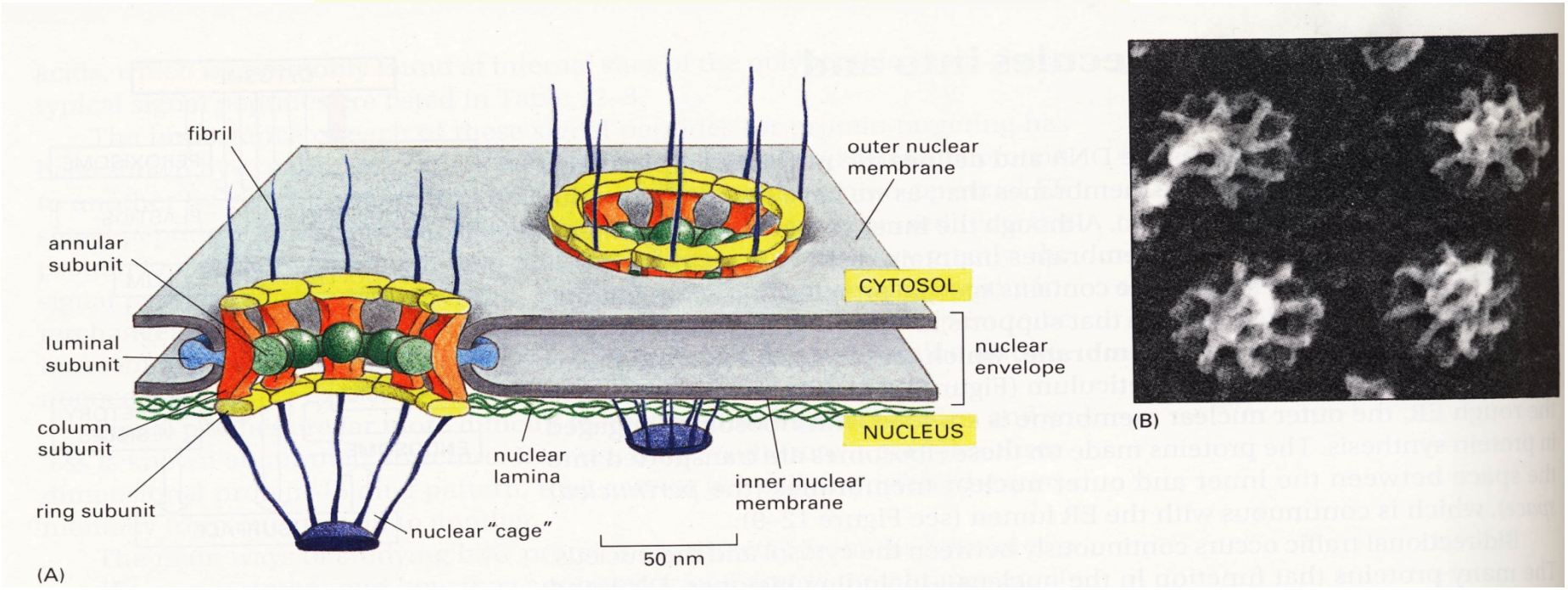
Each adult human is made of ~ 100 trillion cells (10^{14} cells) !

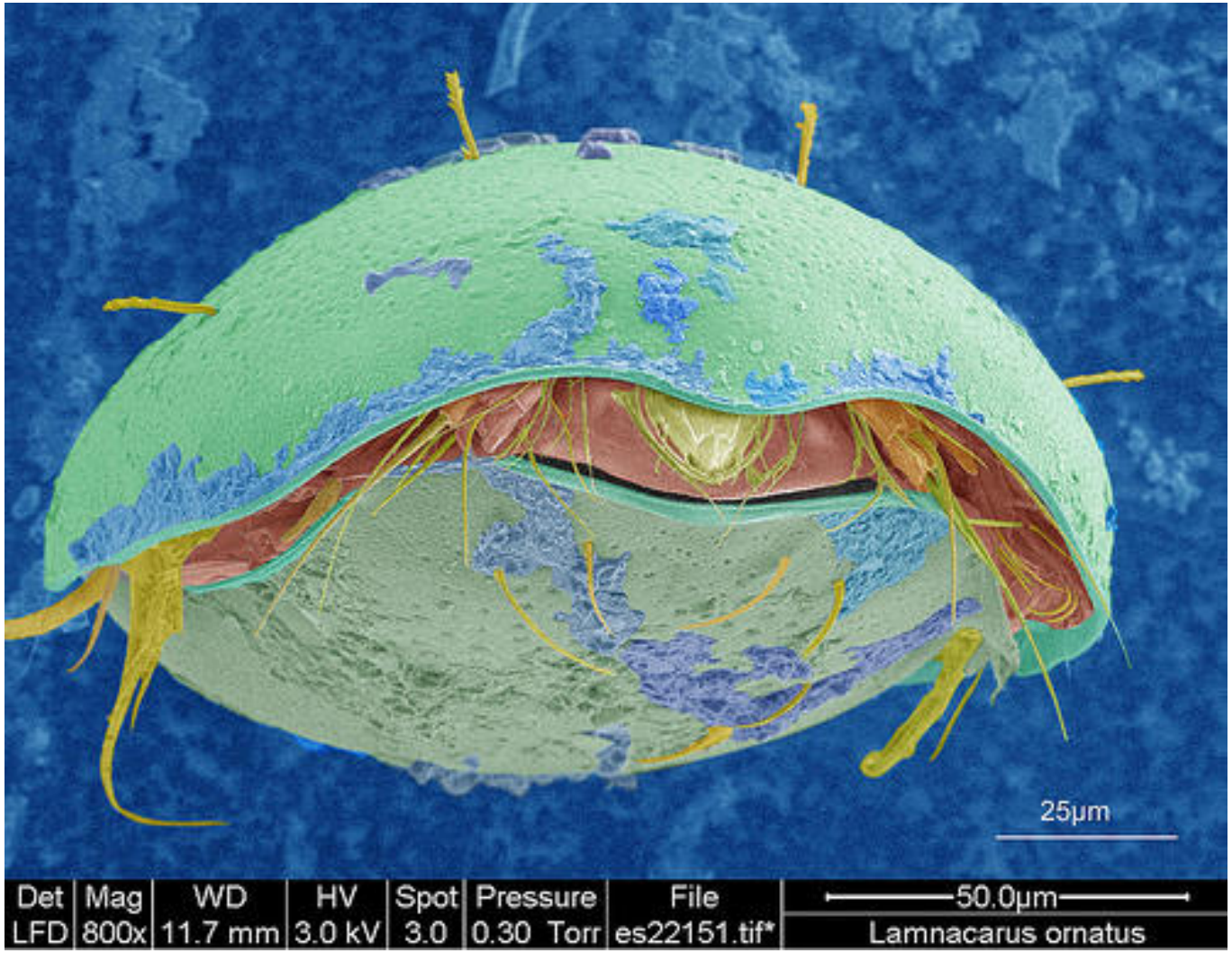
(Guyton, A.C. & Hall, J.E. (2000) Text Book of Medical Physiology 10th ed. W.B. Saunders.



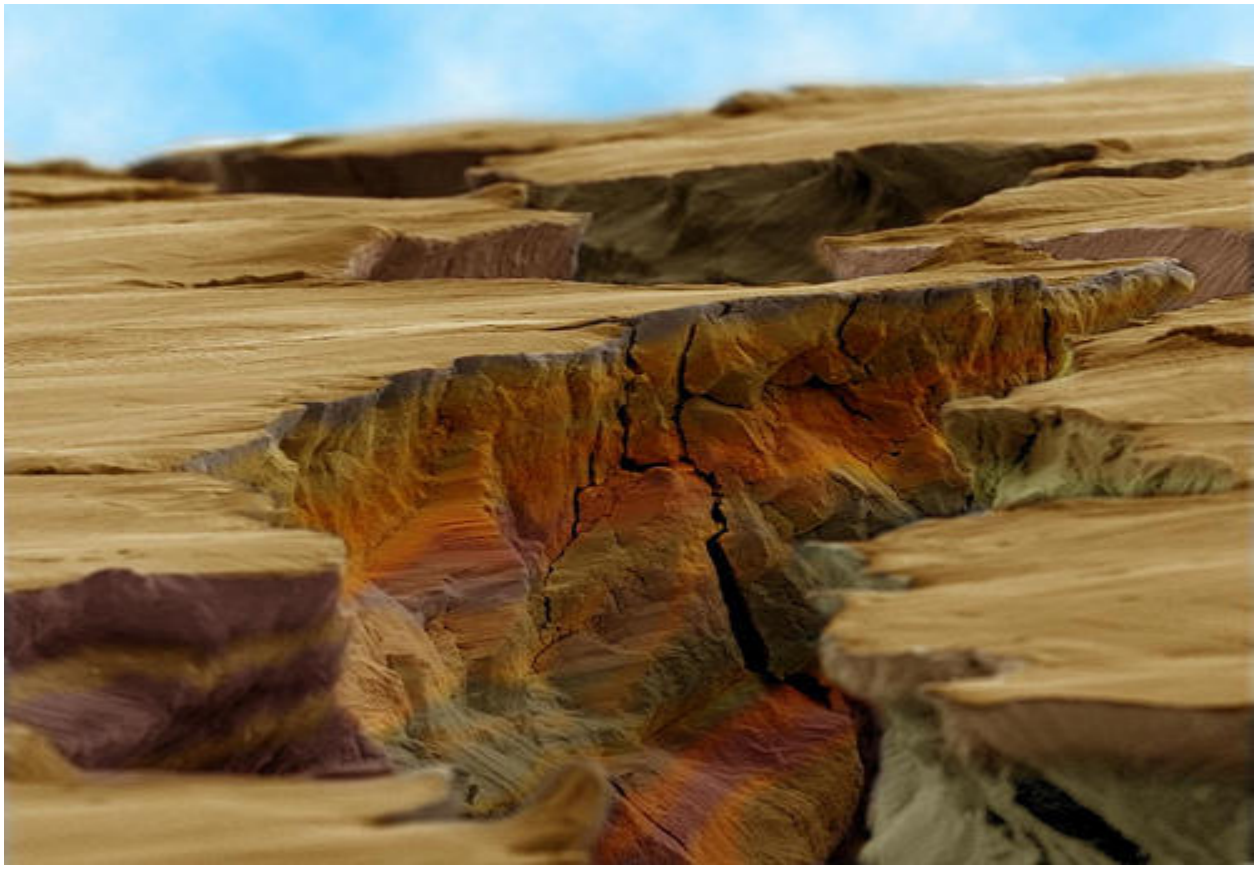


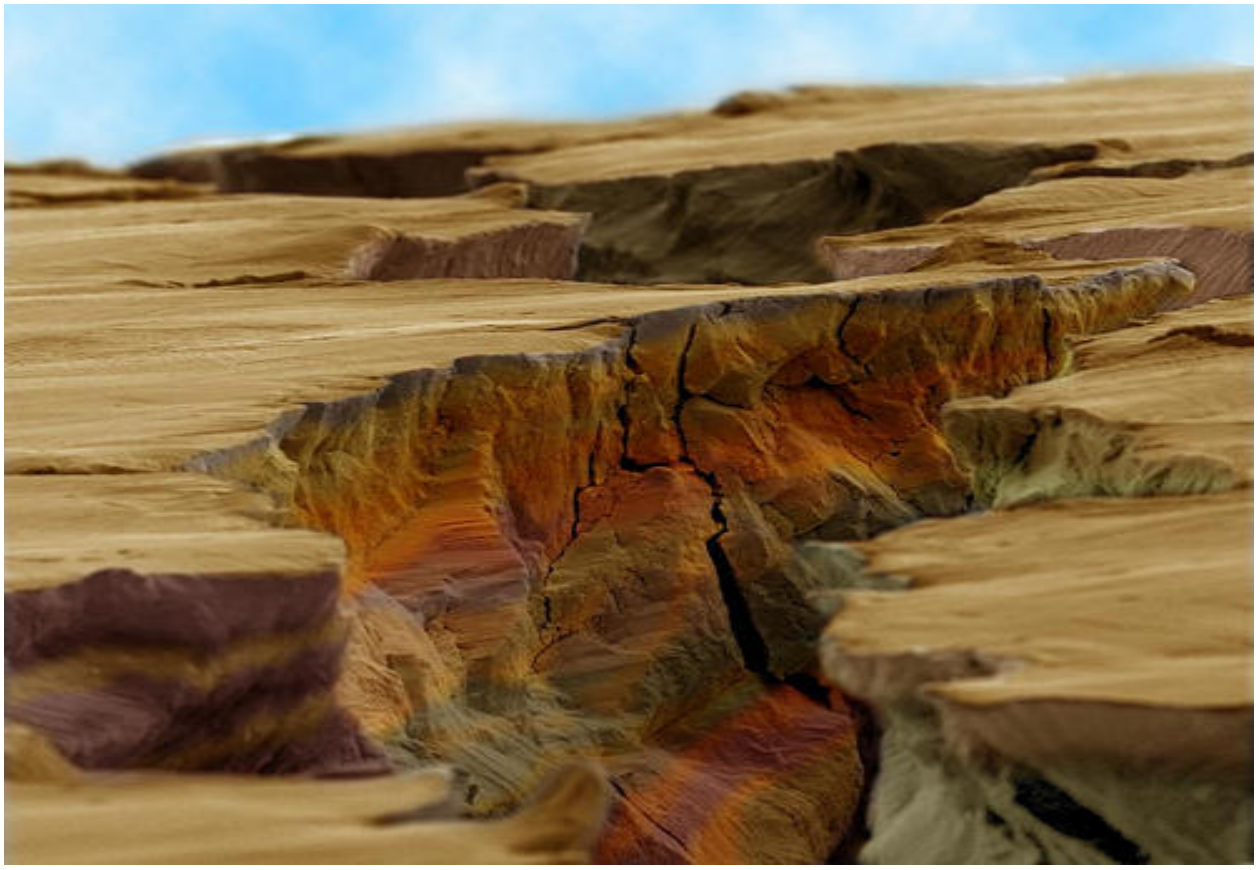
Nuclear Pore Structure





A bacteria: Mayte





SEM photo of cracking of a thin layer of a metal under Shear stress.

Devices in Nano-scale

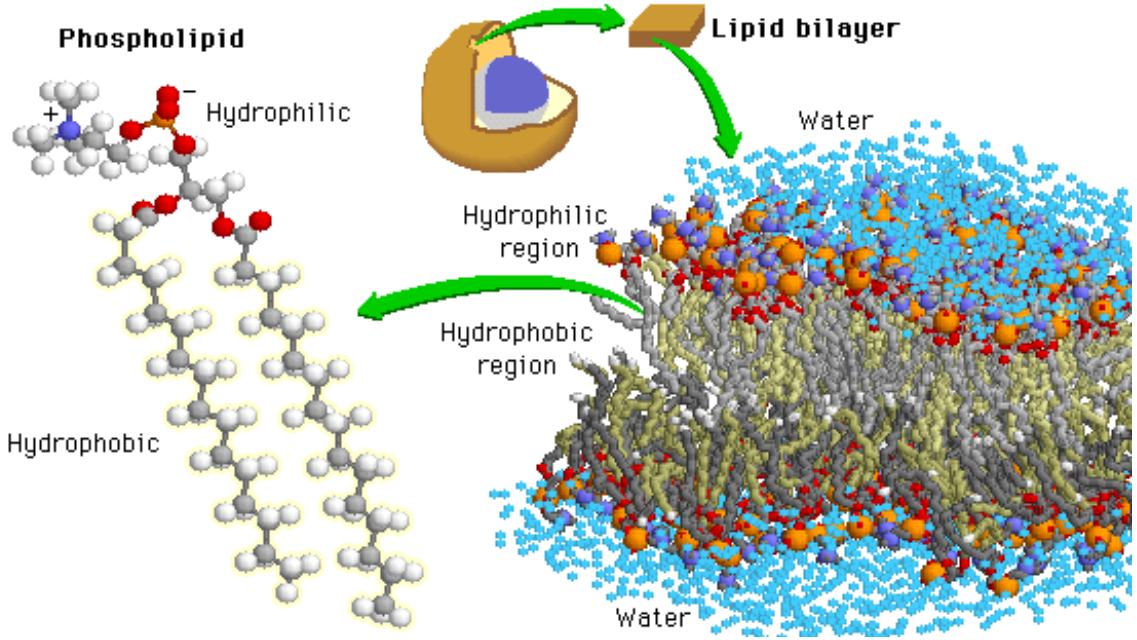
Biological cells:

Nano-meter scale motors and electrical devices

Limits of smallness

Ion Channels: Electrically controlled valves in biology
Voltage-gated potassium channel

In phospholipids, the two fatty acids are hydrophobic, or insoluble in water. But the phosphate group is hydrophilic, or soluble in water. When phospholipids are mixed with water, they spontaneously rearrange themselves to form the lowest free-energy configuration. This means that the hydrophobic regions find ways to remove themselves from water, while the hydrophilic regions interact with water.

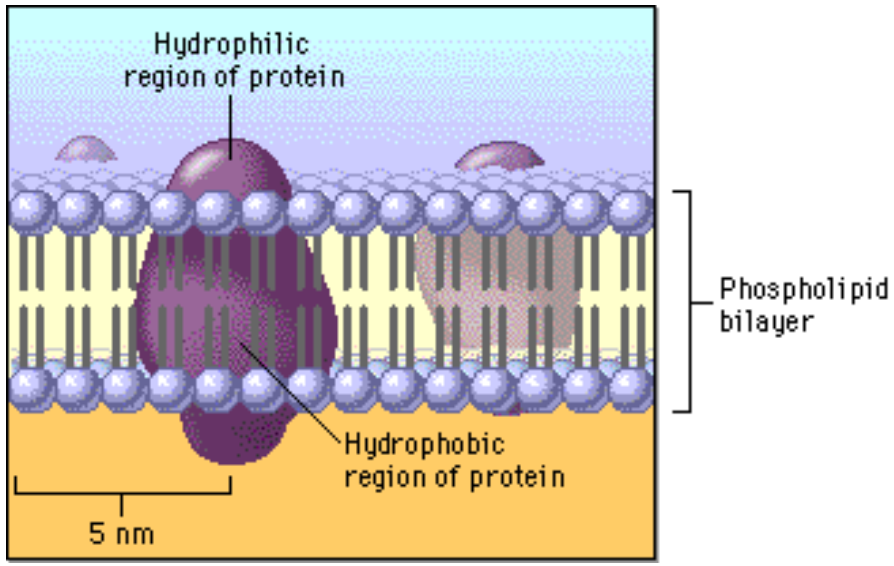


The resulting structure is called a lipid bilayer. All biological membranes (except for those found in certain unusual bacteria, members of the Archaea) contain lipid bilayers, as well as proteins, which provide membranes with stability and specialized functions.

The image above is based on original work by H. Heller, M. Schaefer, & K. Schulten, "Molecular dynamics simulation of a bilayer of 200 lipids in the gel and in the liquid-crystal phases", J. Phys. Chem. 97:8343-60, 1993.

Concept 1: Membrane Structure

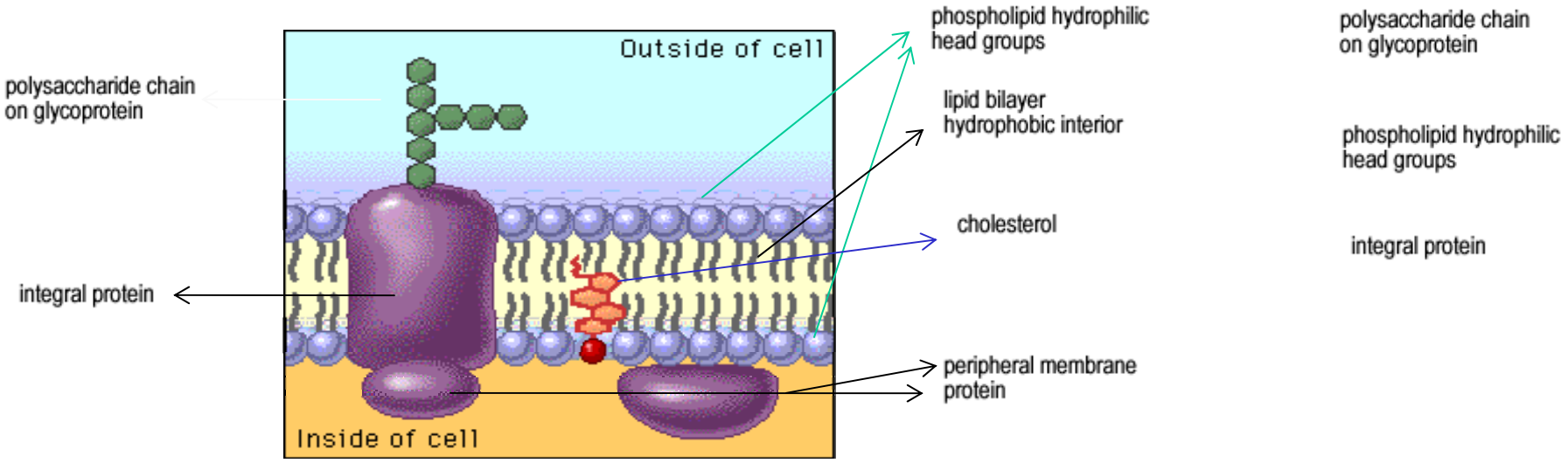
Membranes consist of a phospholipid bilayer combined with a variety of proteins in a fluid mosaic arrangement.



Hydrophilic molecules tend to interact with water and with each other. Hydrophobic molecules avoid interaction with water and tend to interact with other hydrophobic molecules.

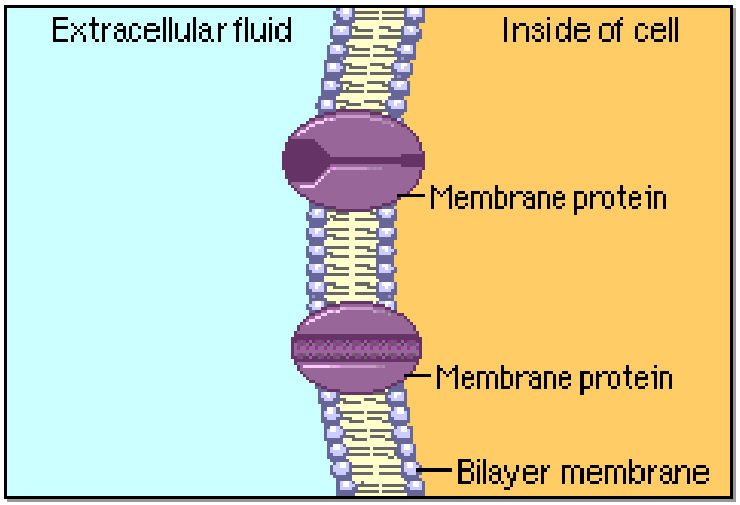
Concept 1 Review: Components and Properties of Biological Membranes

Biological membranes are thin, flexible surfaces separating cells and cell compartments from their environments. Different membranes have different properties, but all share a common architecture. Membranes are rich in phospholipids, which spontaneously form bilayer structures in water. Membrane proteins and lipids can diffuse laterally within the membrane, giving it the properties of a fluid mosaic. Membranes are asymmetric; interior and exterior faces carry different proteins and have different properties.



Concept 3: Selective Permeability of Membranes

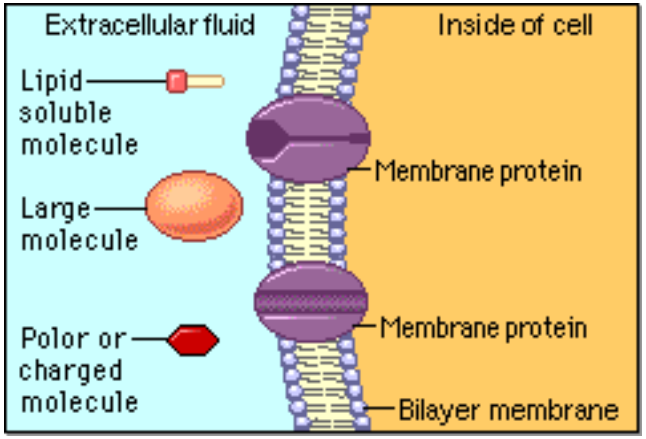
Cell membranes are selectively permeable. Some solutes cross the membrane freely, some cross with assistance, and others do not cross at all.



A few lipophilic substances move freely across the cell membrane by passive diffusion. Most small molecules or ions require the assistance of specific protein carriers to transport them across the membrane. Large molecules do not cross intact cell membranes, except in certain special cases.

Concept 3 Review: Mechanisms of Movement Across Cell Membranes

When a membrane separates two aqueous compartments, some molecules can move freely across the membrane, others cannot. This behavior can be seen with pure synthetic phospholipid membranes, which are analogous to biological membranes, but contain no proteins. In living organisms, the membrane proteins play a crucial role in directing the movement of solutes across cell membranes. Solutes fall into one of three groups:



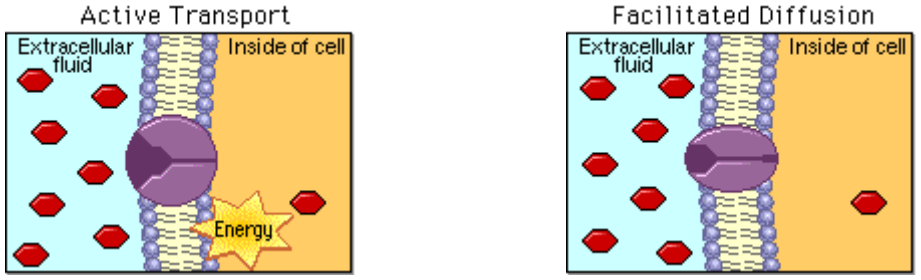
- Small lipophilic (lipid soluble) molecules that cross the membrane by diffusion alone

- Molecules that cross the membrane due to protein-mediated transport

- Molecules, usually of very large size, that do not cross the membrane at all

Concept 4: Passive and Active Transport

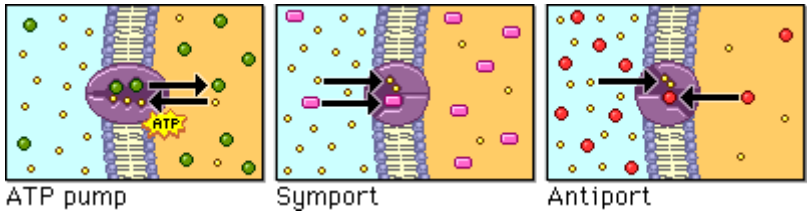
Most biologically important solutes require protein carriers to cross cell membranes, by a process of either passive or active transport.



Active transport uses energy to move a solute "uphill" against its gradient, whereas in facilitated diffusion, a solute moves down its concentration gradient and no energy input is required.

Concept 5: Mechanisms of Active Transport

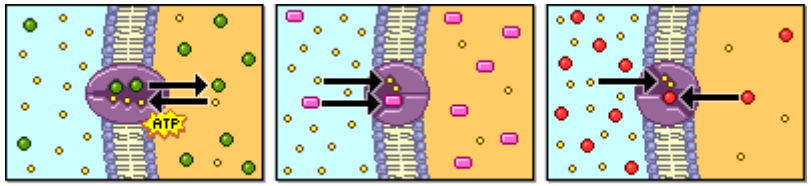
Active transport can occur as a direct result of ATP hydrolysis (ATP pump) or by coupling the movement of one substance with that of another (symport or antiport).



Active transport may move solutes into the cell or out of the cell, but energy is always used to move the solute against its concentration gradient.

Concept 5 Review: Active Transport

Most living cells maintain internal environments that are different from their extracellular environment, as well as concentration differences between the cytosol and internal compartments. In human tissues, for example, all cells have a higher concentration of Na^+ outside the cell than inside, and a higher concentration of K^+ inside the cell than outside. These concentration gradients of Na^+ and K^+ represent a form of energy storage, similar to a battery. An example of a concentration difference between the cytosol and an internal compartment is found in the lysosome, where the concentration of hydrogen ions (H^+) can be 100 to 1000 times greater than the concentration outside, in the cytosol.



Like pushing an object uphill, moving a molecule against a concentration gradient requires energy. Cells have evolved active transport proteins that can use energy to establish and maintain concentration gradients.

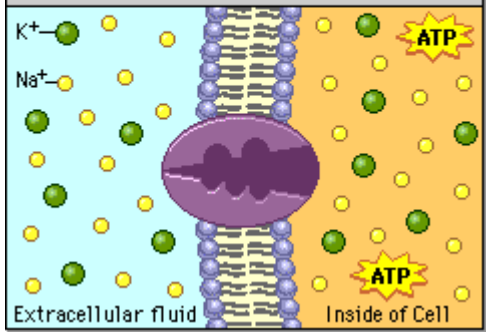
Concept 5 Review: ATP-powered Pumps

ATP-powered pumps (ATPases) couple the splitting, or hydrolysis, of ATP with the movement of ions across a membrane against a concentration gradient. ATP is hydrolyzed directly to ADP and inorganic phosphate, and the energy released is used to move one or more ions across the cell membrane. As much as 25% of a cell's ATP reserves may be spent in such ion transport. Examples include:

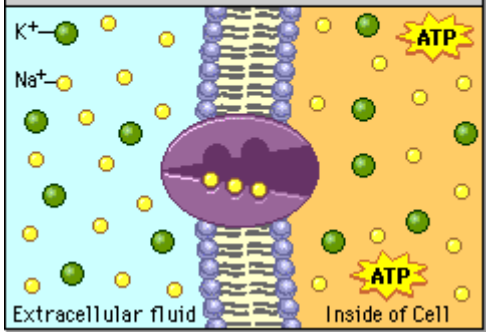
• The Na^+-K^+ ATPase pumps Na^+ out of the cell while it pumps K^+ in. Because the pump moves three Na^+ to the outside for every two K^+ that are moved to the inside, it creates an overall charge separation known as polarization. This electrical potential is required for nervous system activity, and supplies energy needed for other types of transport such as symport and antiport.

• Ca^{++} ATPases are responsible for keeping intracellular Ca^{++} at low levels, a necessary precondition for muscle contraction.

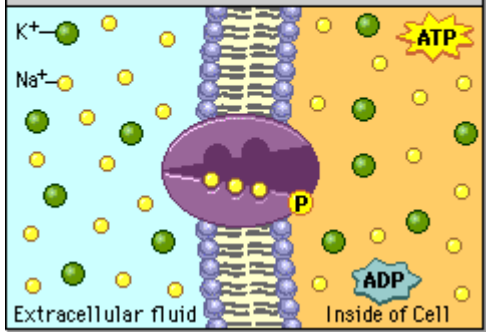
Step 1. Three Na+ ions bind to cytoplasmic high-affinity binding sites.



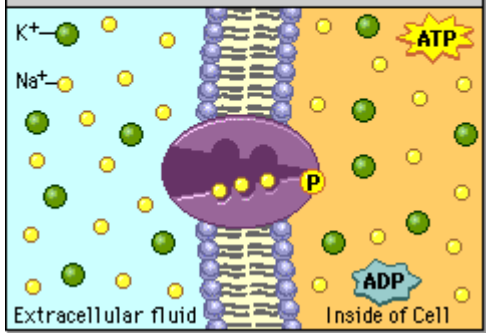
Step 2. ATP is hydrolyzed, transferring a phosphate group to the pump.



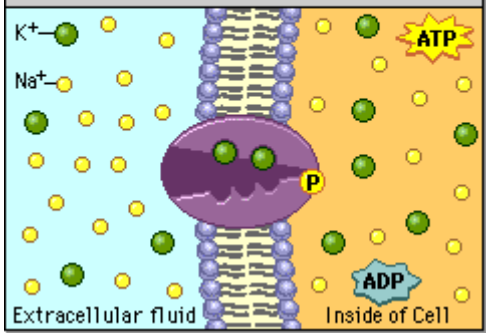
Step 3. The pump conformation changes, moving Na+ ions to the extracellular side of the membrane.



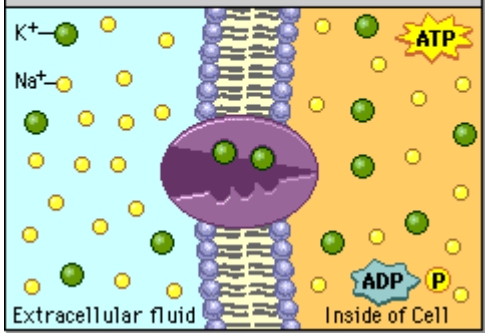
Step 4. Na+ ions dissociate, and two K+ ions bind to high-affinity extracellular sites.



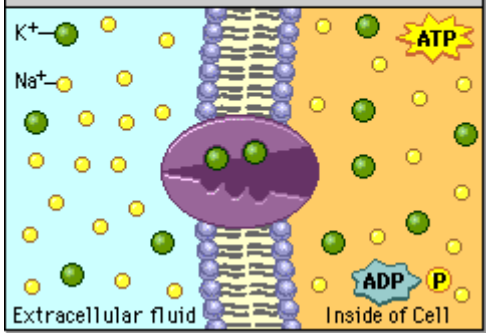
Step 5. The bond linking phosphate to the pump protein is hydrolyzed, releasing inorganic phosphate.



Step 6. The pump conformation changes, moving K+ ions to low-affinity cytoplasmic sites.

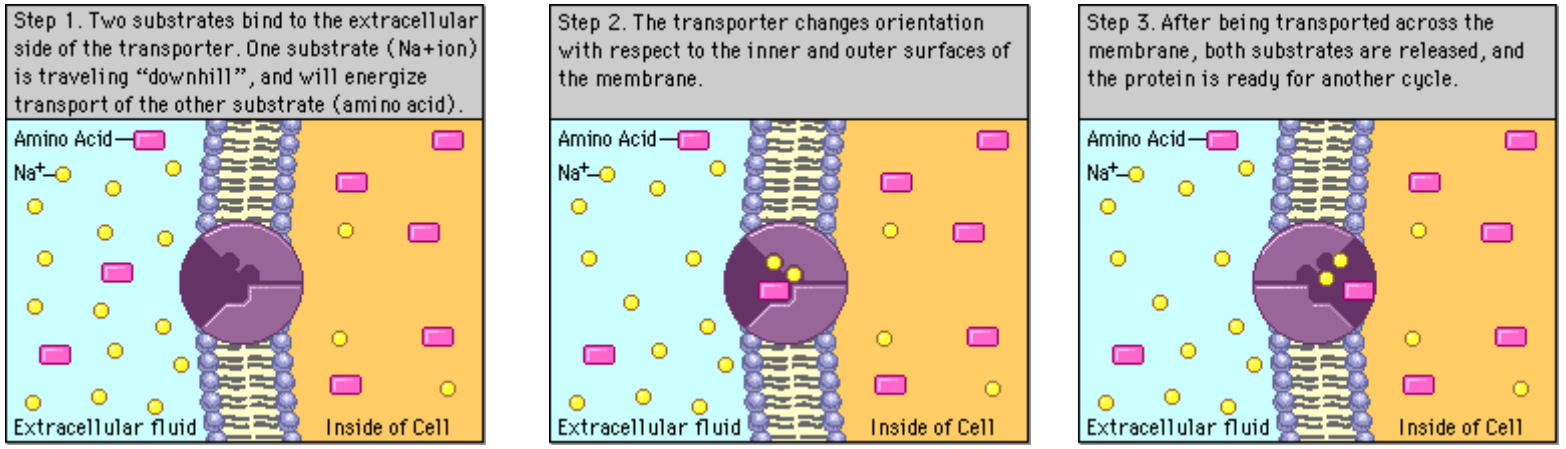


Step 7. K+ ions dissociate, and the pump is ready for another cycle.



Concept 5 Review: Symport

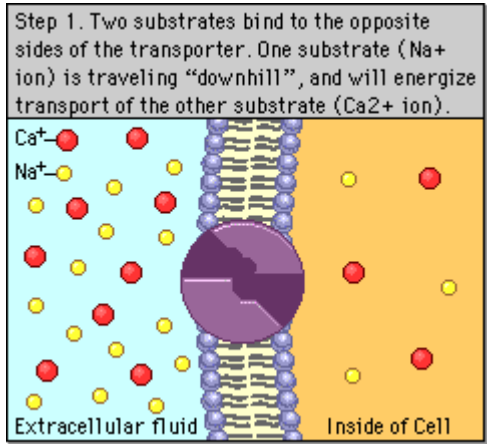
To transport some substances against a concentration gradient, cells use energy already stored in ion gradients, such as proton (H^+) or sodium (Na^+) gradients, to power membrane proteins called transporters. When the transported molecule and the co-transported ion move in the same direction, the process is known as symport.



An example of a symport process is the transport of amino acids across the intestinal lining in the human gut.

Concept 5 Review: Antiport

In antiport, a cell uses movement of an ion across a membrane and down its concentration gradient to power the transport of a second substance "uphill" against its gradient. In this process, the two substances move across the membrane in opposite directions.

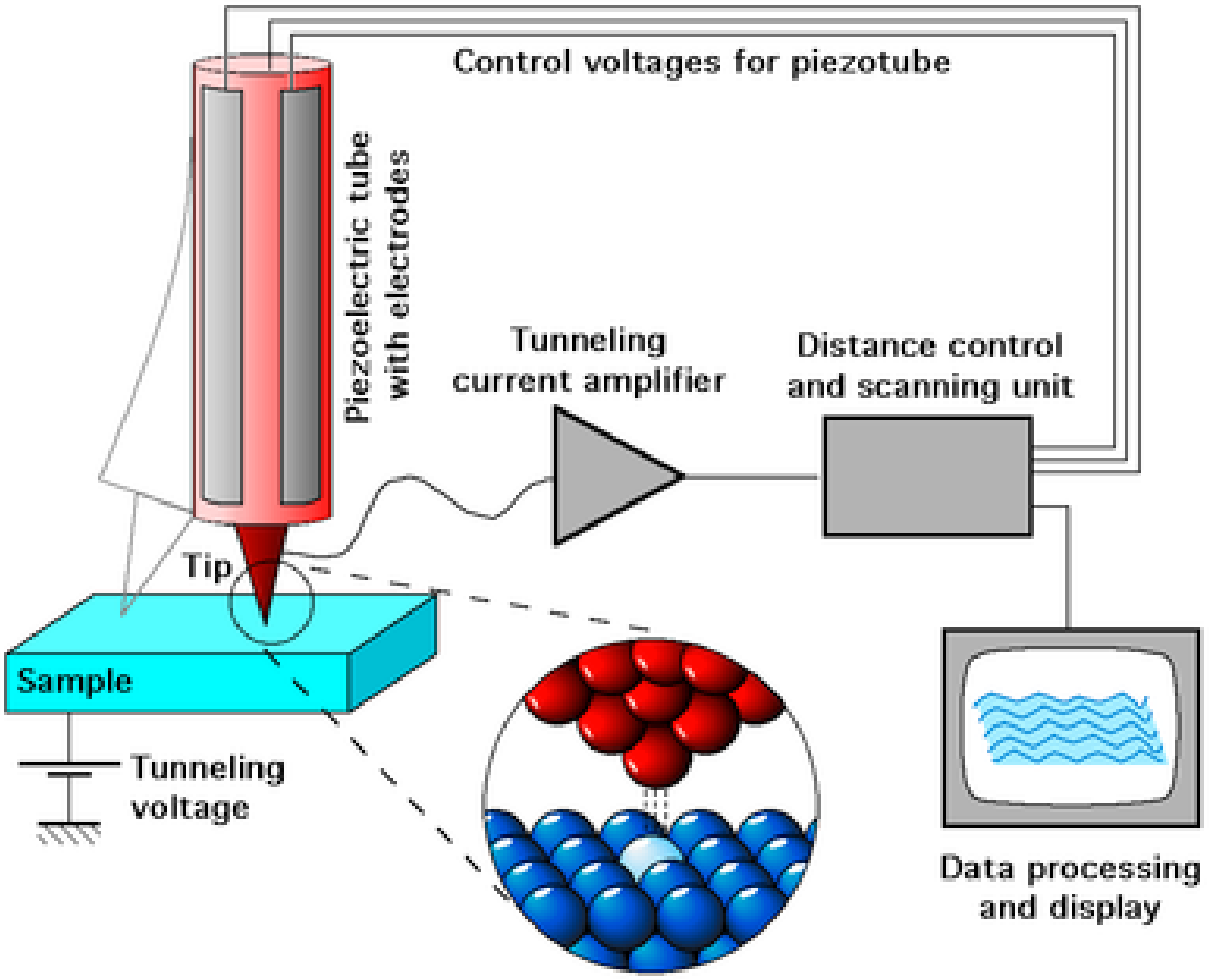


An example of an antiport process is the transport of Ca^{2+} ions out of cardiac muscle cells. Muscle cells are triggered to contract by a rise in intracellular Ca^{2+} concentration, so it is imperative that Ca^{2+} be removed from the cytoplasm so that the muscle can relax before contracting again. This antiport system is so effective that it can maintain the cellular concentration of Ca^{2+} at levels 10,000 times lower than the external concentration. To view animations summarizing operation of an antiporter, click on the buttons, starting with "Step 1."

Methods for Making Small Objects

Scanning Tunneling Microscope (STM)

The tip of STM is used to nudge the atoms gently from one side to neighboring one, thus assembling nano-structure.



Review on STM

A scanning tunneling microscope (STM) is an instrument for imaging surfaces at the atomic level. Its development in 1981 earned its inventors, Gerd Binnig and Heinrich Rohrer (at IBM Zürich), the Nobel Prize in Physics in 1986.

For an STM, good resolution is considered to be 0.1 nm lateral resolution and 0.01 nm depth resolution. With this resolution, individual atoms within materials are routinely imaged and manipulated. The STM can be used not only in ultra high vacuum but also in air, water, and various other liquid or gas ambients, and at temperatures ranging from near zero kelvin to a few hundred degrees Celsius.

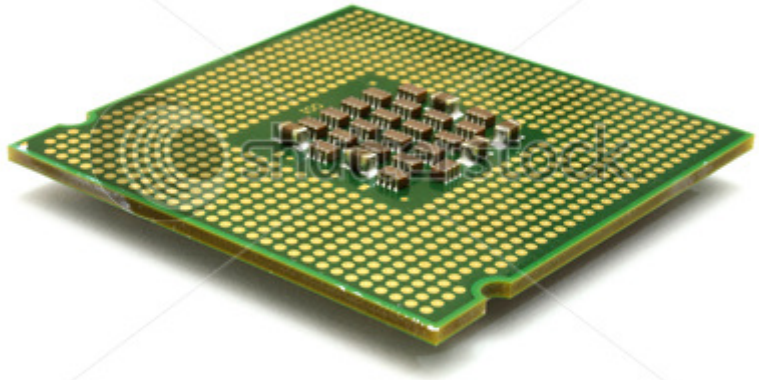
The STM is based on the concept of quantum tunnelling. When a conducting tip is brought very near to the surface to be examined, a bias (voltage difference) applied between the two can allow electrons to tunnel through the vacuum between them. The resulting *tunneling current* is a function of tip position, applied voltage, and the local density of states (LDOS) of the sample. Information is acquired by monitoring the current as the tip's position scans across the surface, and is usually displayed in image form. STM can be a challenging technique, as it requires extremely clean and stable surfaces, sharp tips, excellent vibration control, and sophisticated electronics.

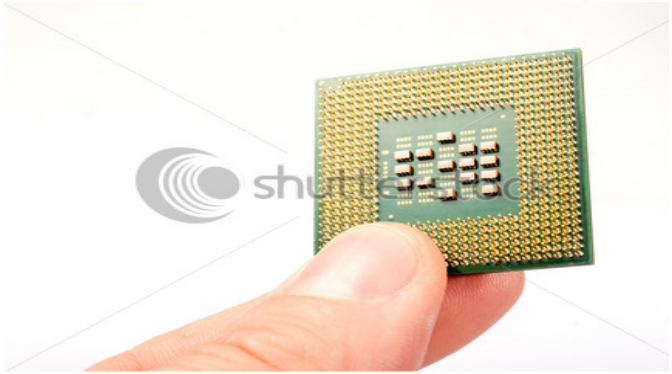
The tip of STM is used to nudge
the atoms gently from
one side to neighboring one, thus
assembling nano-structure.

Assembling small Three-Dimensional (3D)

Fabrication of small device

Welcome to the country of microchip, Welcome to TAIWAN





Fabrication of small device

Soft-Photo Lithography Technology for microfabrication

Nanotechnology Core Facility
10,000 ppm particles
EU standard Clean Room

Master templat

2. Fabrication of device

Soft-Photo Lithography Technology for microfabrication

2. Fabrication of device

Soft Photo Lithography Technology for microfabrication

Mask

2. Fabrication of device

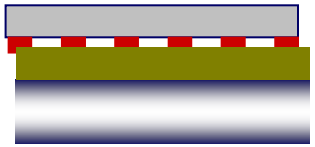
Soft Photo Lithography Technology for microfabrication

Mask

UV Crosslinkable Hydrogel

2. Fabrication of device

Soft Photo Lithography Technology for microfabrication

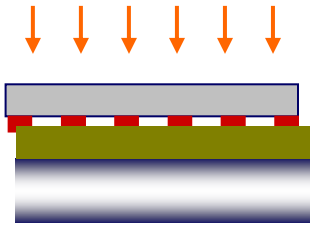


Mask

UV Crosslinkable Hydrogel

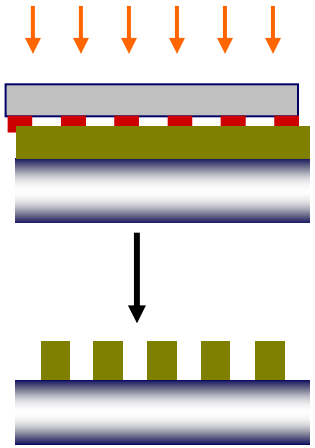
2. Fabrication of device

Soft Photo Lithography Technology for microfabrication

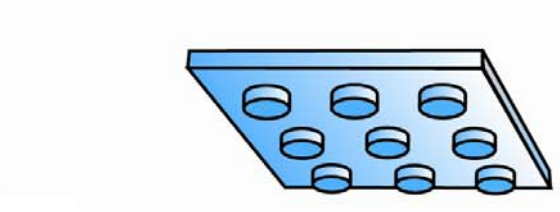


2. Fabrication of device

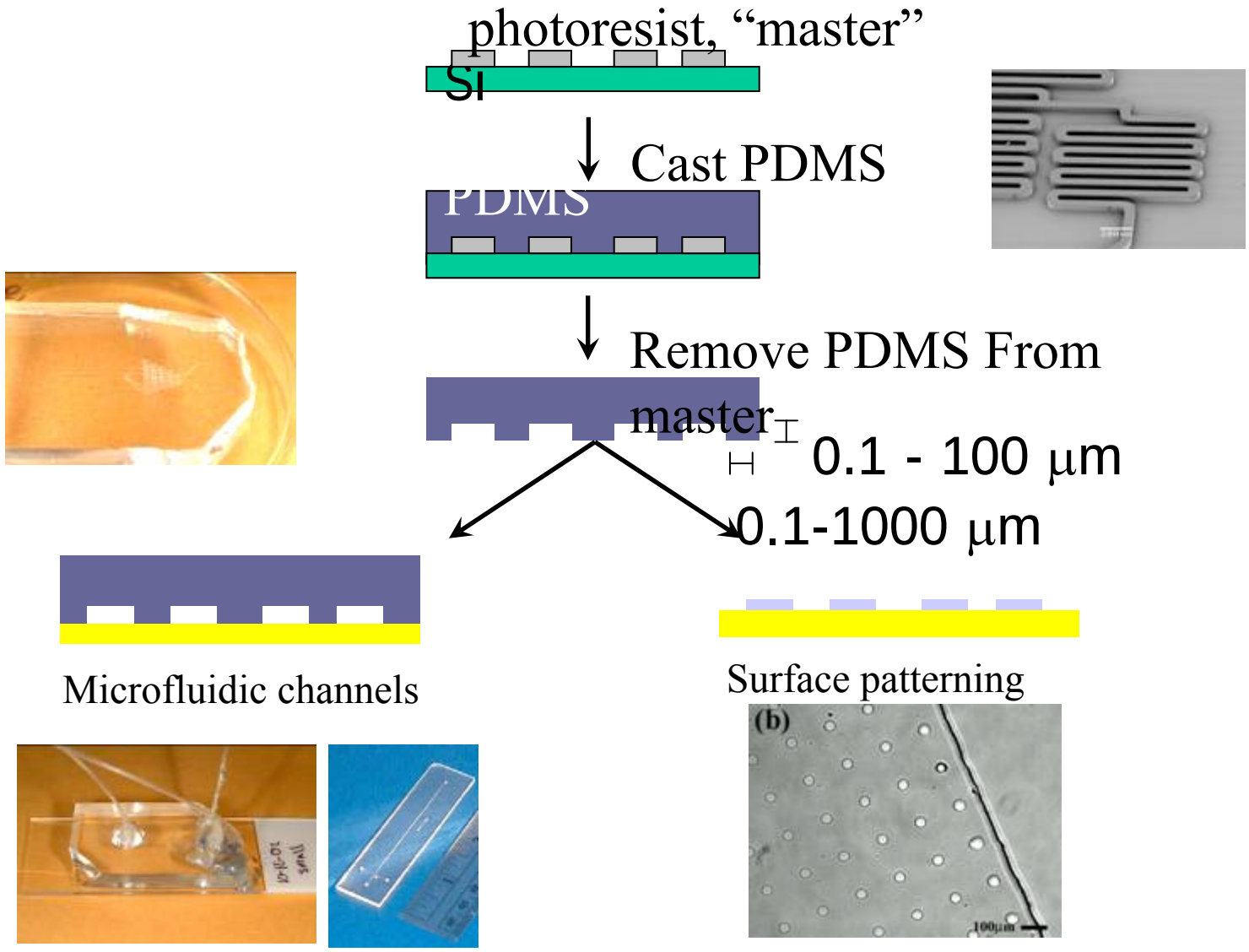
Soft Photo Lithography Technology for microfabrication



Mask

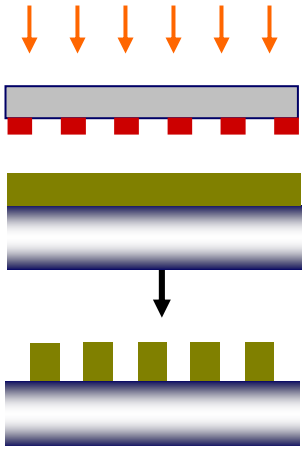


Soft lithography for microfabrication

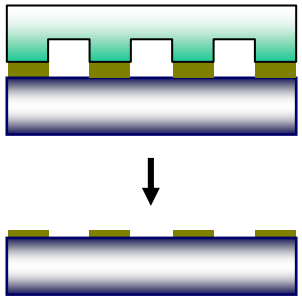


Microcontact Printing and Photolithography vs. Capillary force lithography (CFL)

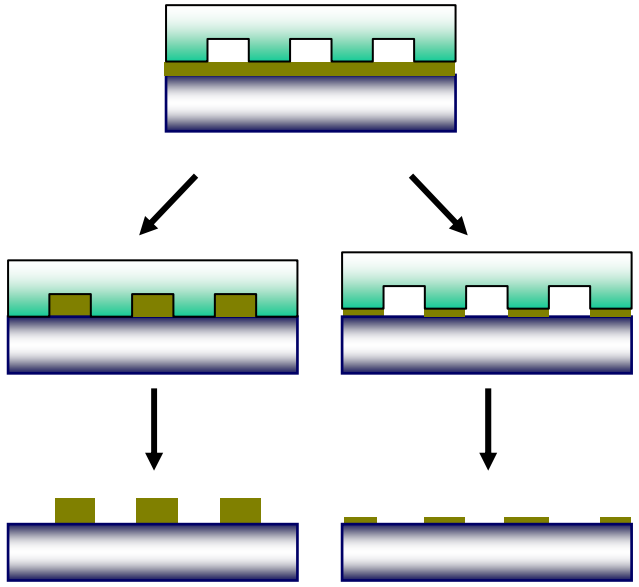
Photolithography



Microcontact printing



Capillary force lithography

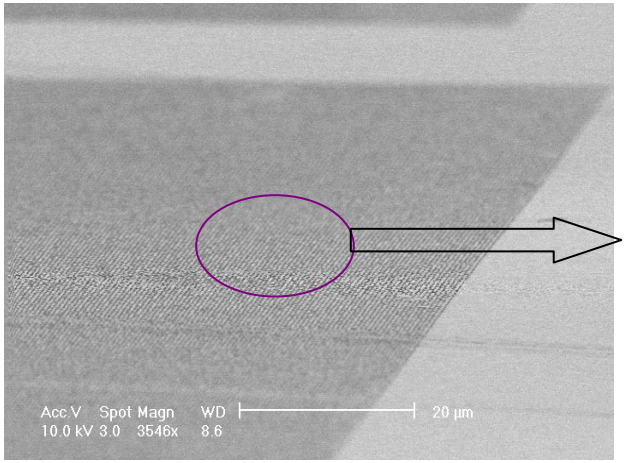


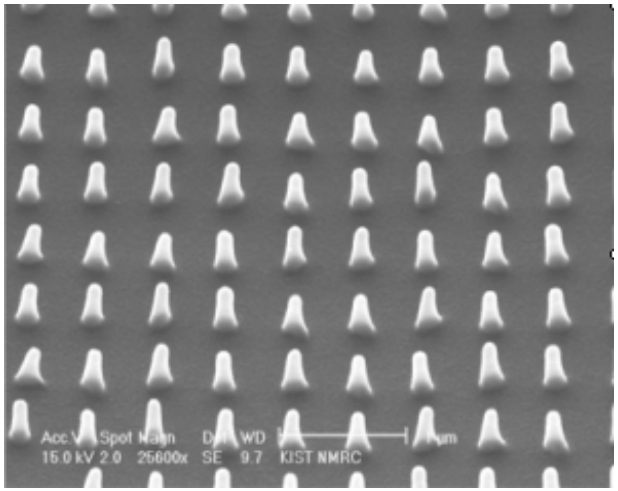
Capillary rise ($\theta < 90°$)

Capillary depression ($\theta > 90°$)

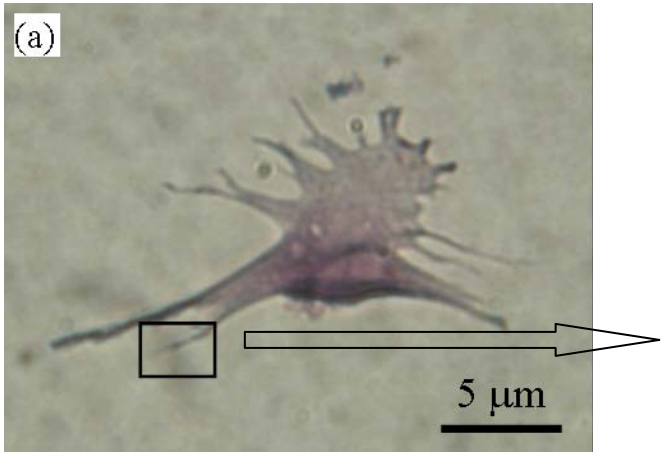
Nano-patterning of collagen

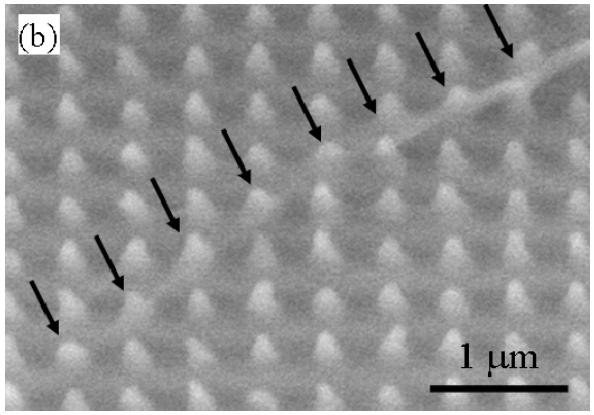
Polyurethane molds used to fabricate collagen nanostructures



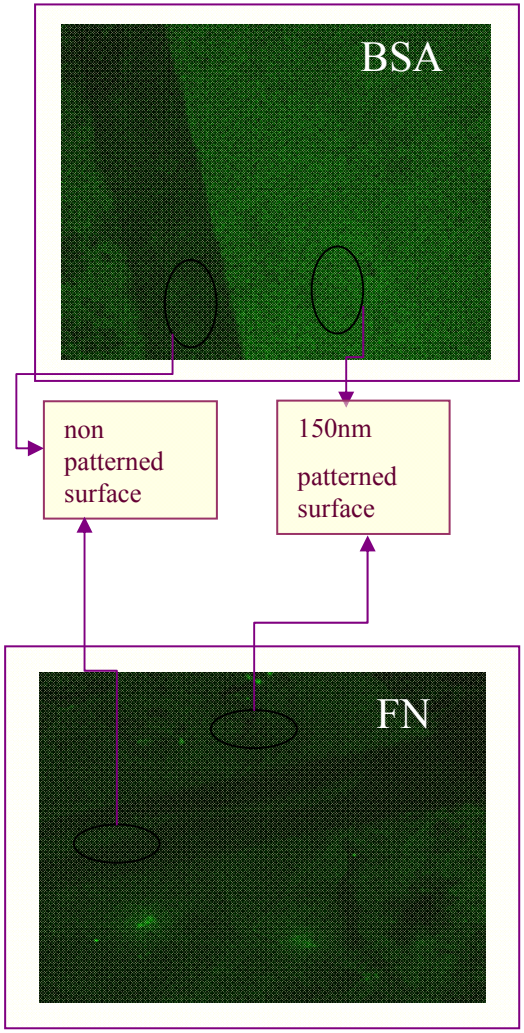


150nm pillar pattern





Filopodia extension



Patterned surface