Medical Devices

Lecture 3 - Cell Transport

Cell Transport

- Passive Transport:
  - Diffusion
  - Facilitated Diffusion
  - Osmosis
  - Filtration
  - Dialysis
- Active Transport:
  - Phagocytosis
  - Pinocytosis
- Import and Export of Material

Transport Through the Cell Membrane

- The cell needs to obtain nutrients from and dispose of waste to the outside of the cell.
- Without the process of obtaining nutrients, disposing of waste and communication a cell cannot survive.
- For substances to move across (through) the membrane, two processes exist:
  - Passive transport:
    - Substances move through the plasma membrane against little or no resistance.
    - The movement is caused by the kinetic energy of the individual molecules.
    - These substances move down the concentration gradient (from higher concentration to lower concentration; i.e. from an area of high pressure to one of low pressure).
  - Active transport:
    - This form of movement of substances through the membrane requires energy, which is contributed by the cell.
    - This movement is against the concentration gradient.

Passive Transport

http://www.northland.cc.mn.us/biology/biology1111/animations/transport1.swf

There are several methods which do not require external energy for molecules to move across the cell membrane.

These are called passive transport and they are:

- Diffusion
- Facilitated Diffusion
- Osmosis
- Filtration
- Dialysis

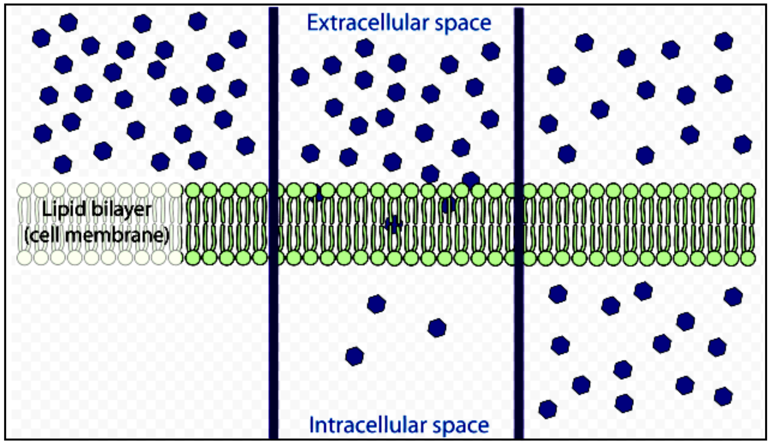
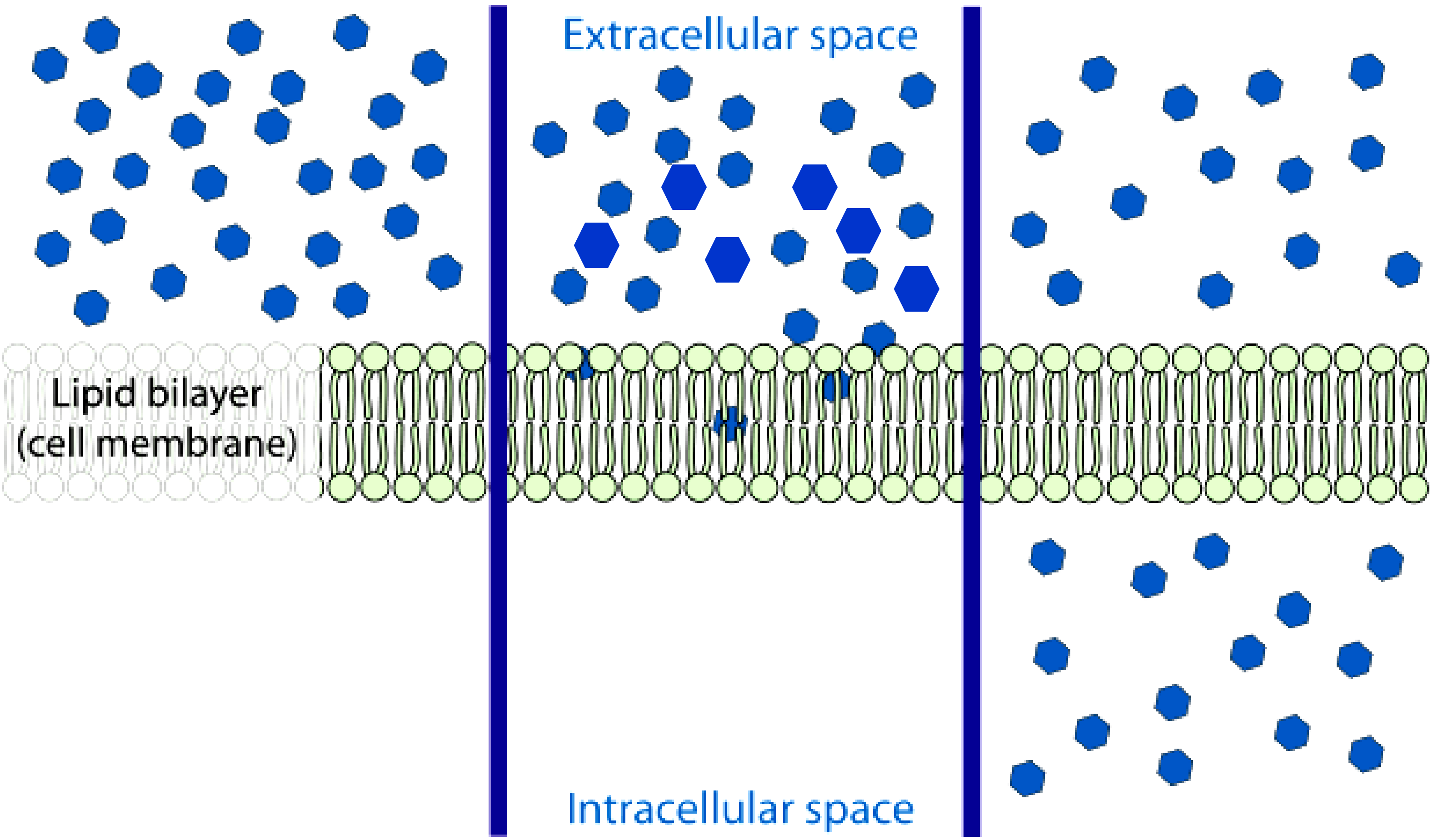


Figure 14. Example of Passive Transport: Diffusion.

Passive Transport
Diffusion



Diffusion

- There is a net movement of molecules and/or ions from an area of higher concentration of that molecule/ion to one of lower concentration.
- This movement of molecules/ions continues until equilibrium is reached between the two regions.
- At equilibrium, the movement of molecules/ions between the region, in both directions, is at an equal rate.
- There is no need for energy as substances move with the concentration gradient.

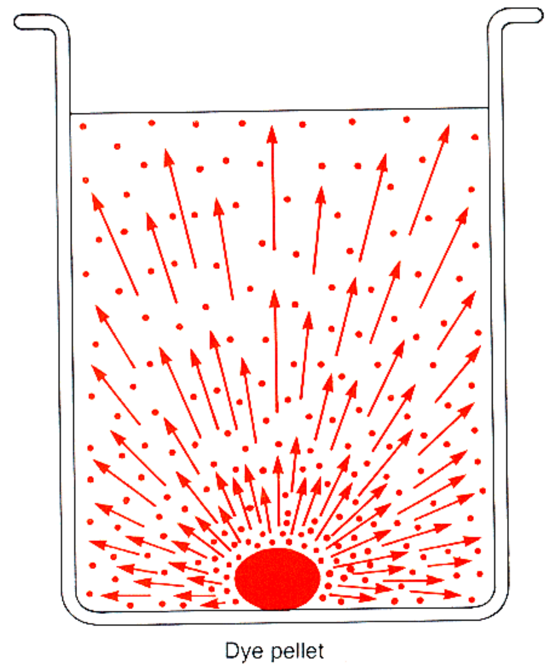


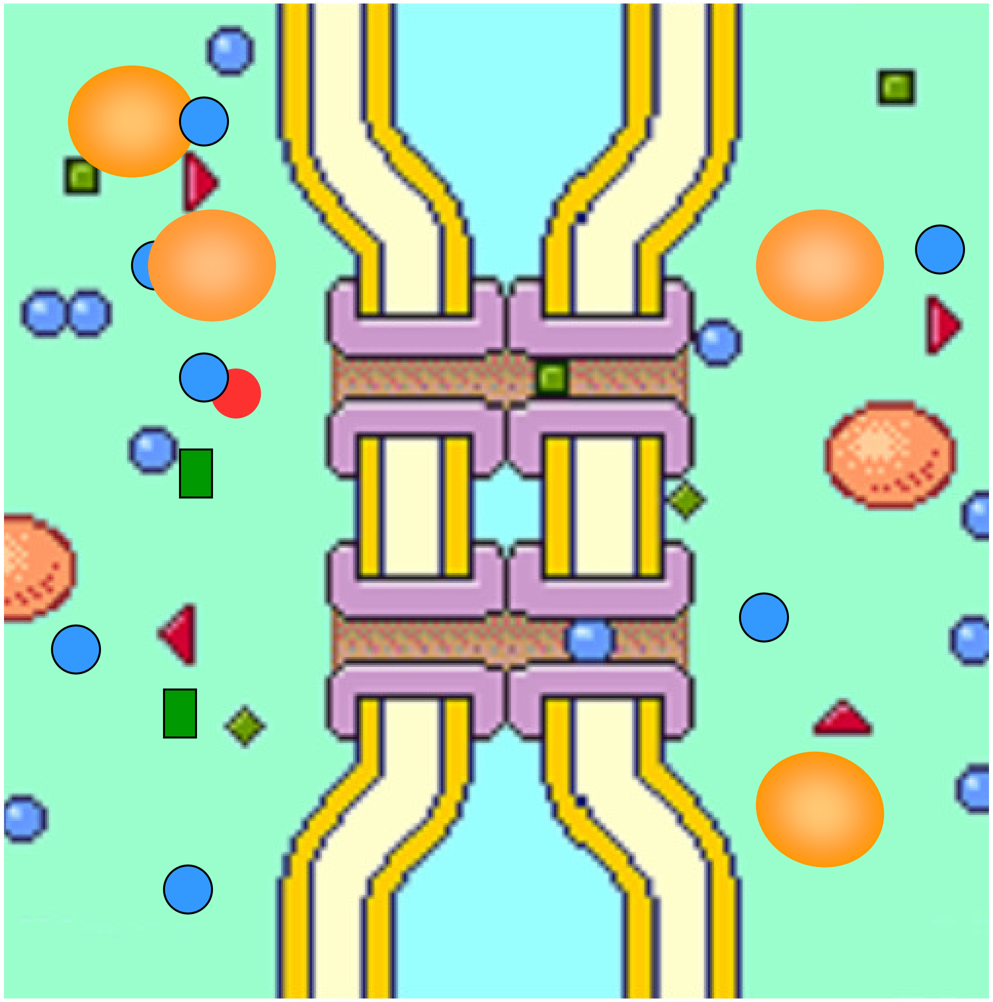
Figure 15. Principle of Diffusion. Molecules of dye (solute) in a beaker of water (solvent) move down the concentration gradient from a region of high concentration to a region of low concentration.

Diffusion

http://www.northland.cc.mn.us/biology/biology1111/animations/transport1.swf

- The experimental observation of diffusion can be performed by dropping a dye or coloured tablet into a glass of water and observing the movement of molecules of dye down the gradient (from an area of higher concentration to lower concentration).
- There are two elements in this experiment:
  - The water, which is called the solvent.
  - The dye/coloured tablet, which is called the solute (the substance which is to be dissolved in the solvent).
- In the above experiment, the solvent and solute molecules (the water and colour molecules) move from higher concentration to lower concentration and when an equilibrium for the dye (colour) concentration is reached there is no more diffusion. This is also true for movement of the water molecules.
  - At equilibrium, molecules may move, but there is no diffusion of the coloured molecules.
  - This is the method of diffusion of aftershave, perfume or obnoxious smells through the air.
  - The diffusion can occur through the membrane selectively.
  - Lipid soluble molecules pass through the phospholipid bilayer through this process. An example of such diffusion across the cell membrane is the exchange of oxygen and carbon dioxide across the cell membrane. Without this exchange cells die.
  - Molecules which are not lipid soluble (do not dissolve in fat), such as sodium, chloride, potassium and others, go through the membrane by diffusion through channels, which are structured from the proteins within the cell membrane.

Passive Transport
Facilitated Diffusion



Legend:

Large hydrophilic molecule

Small hydrophilic molecules requiring transport channels

Facilitated Diffusion

- This type of transport is done with a system of integral proteins (those proteins embedded in phospholipid bilayer among the fatty acid tails).
- The integral proteins serve as a carrier for transportation.
- Through this process even large molecules or lipid-insoluble molecules can pass through the membrane.
- Diffusion of glucose is a good example of facilitated diffusion. Glucose is combined with the glucose carrier molecules, which are soluble within the cell membrane. In this manner, glucose is carried to the inside of the cell. See Figure 16.
- The purpose of the carrier is to make the glucose or other substance soluble within the phospholipid bilayer of the membrane.
- Glucose could not pass through the membrane if it was not for this type of diffusion, and glucose is necessary for the energy production machinery of the cell.

Facilitated Diffusion

- Generally, facilitated diffusion is faster than simple diffusion and the rate is related to:
  - Concentration difference of the substance (concentration gradient). The higher the concentration gradient, the faster the rate of diffusion.
  - The amount of carrier available for transport. The greater the number of carriers available, the faster the transport.
  - The rate of combination of the carrier and substance to be moved.
  - Insulin speeds up the facilitated diffusion of glucose, among its other functions.

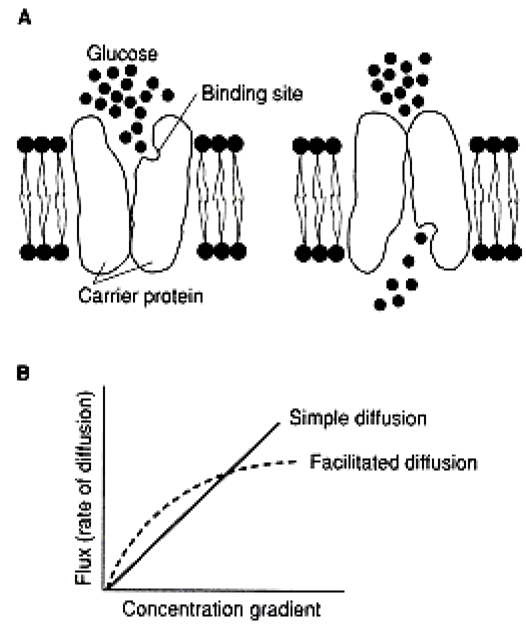
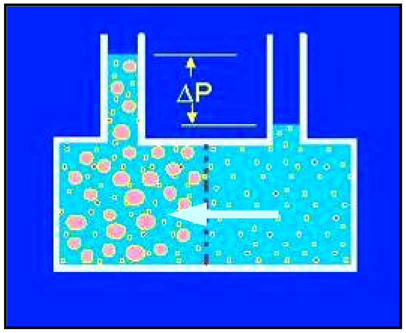


Figure 16. (A) Transmembrane carrier protein responsible for the facilitated diffusion of glucose undergoes a conformation change when glucose binds to it. The conformational change allows glucose to diffuse across the membrane down its concentration gradient. (B) In facilitated diffusion, the diffusion rate reaches a maximum when all the binding sites on the carrier protein are filled.

Osmosis



- This is another passive method of transport.
- Osmosis is the transport of water (movement of water molecules) through the selectively permeable membrane.
- The movement is from high concentration to lower concentration of water molecules.

- The integral proteins have channels within them and these channels allow water to move through them.
- Osmotic Pressure is the force under which solvent, such as water, moves from a solution of higher concentration of water to one of lower concentration of water.
- Osmotic Pressure is a very important force in the movement of water between various parts of the body.
- Osmotic Pressure is related to the number of particles dissolved in the solution. This is called "Colligative Property".
- The osmotic concentration difference (ΔC) relates the difference in the particle concentrations. It is not related to the size or molecular weight of the substance.
- See also figures 17 and 18.

Osmosis

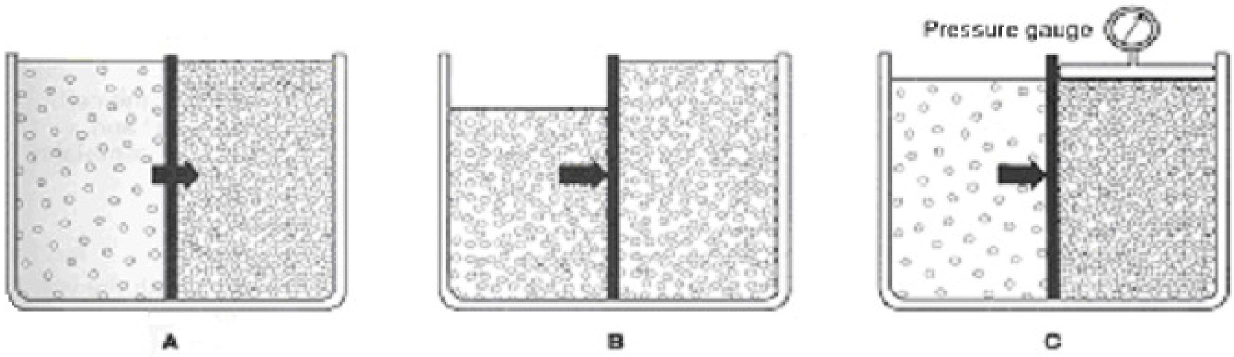


Figure 17. When a selectively permeable membrane separates two solutions of different osmolalities (A), the water flows from the solution with the lower osmotic pressure (concentration) to the solution with the higher osmotic pressure (concentration). (B) Water will flow into the chamber until the pressure (i.e., hydrostatic and osmotic) difference between the two chambers is zero. Because the flow of water increases the height of water in the chamber on the right side, the hydrostatic pressure in this chamber is higher than it is in the chamber on the left. Consequently, at equilibrium, the osmotic pressure is somewhat less in the chamber on the right than in the chamber on the left. (C) The flow of water can also be prevented by applying pressure to the chamber that contains the higher solute concentration. The amount of pressure that must be applied to prevent the flow of water is a measure of the osmotic pressure difference between the two chambers.

Osmosis

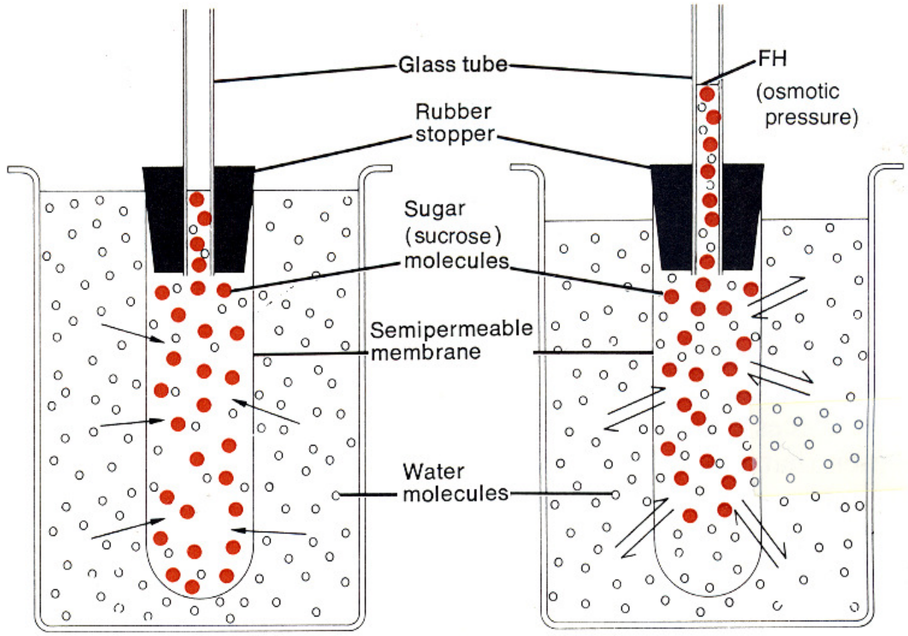


Figure 18. Principle of Osmosis. (a) Apparatus at the start of the experiment. (b) Apparatus at equilibrium. In (a), the cellophane tube contains a 20% sugar solution and is immersed in a beaker of distilled water. The 20% sugar solution contains 20 parts of sugar and 80 parts of water, while the distilled water contains 0 parts sugar and 100 parts water The arrows indicate that water molecules can pass freely into the tube, but that sugar molecules are held back by the selectively permeable membrane. As water moves into the tube by osmosis, the sugar solution is diluted and the volume of the solution in the cellophane tube increases. This increased volume is shown in (b), with the sugar solution moving up the glass tubing. The final height reached (FH) occurs at equilibrium and represents the osmotic pressure. At this point, the number of water molecules leaving the cellophane tube is equal to the number of water molecules entering the tube.

Calculation of Osmotic Pressure

The osmotic pressure across the membrane can be calculated using the formula called the van't Hoff Equation. This equation relates the osmotic pressure to the concentration difference of particles between two solutions, the natural gas constant and absolute temperature.

That is:

$$\pi = \Delta C \cdot R \cdot T$$

Where

π = osmotic pressure (mmHg)
ΔC = difference in the concentration of particles between the two solutions (mOsm/L)
R = natural gas constant (62 mm Hg·L/mmol·˚K)
T = absolute temperature (˚K)

Calculation of Flow of Water Through the Membrane

The amount of water moved due to osmotic differences can be calculated by the Osmotic Flow Equation:

$$Q = L \cdot A \cdot \Delta\pi$$

Where

Q = Flow

L = hydraulic conductivity of the membrane (L/sec/cm^2/mmHg)

A = area of the cell membrane (cm^2)

$\Delta\pi$ = the difference in osmotic pressures on either side of the membrane or $\pi_1 - \pi_2$ (mmHg)

Osmotic Flow Equation for Permeable Particles

When particles in the solution are permeable to the membrane, an additional factor will be include in the above formula called the reflection coefficient (σ). The reflection coefficient can be calculated through the following formula:

$$\sigma = \frac{1 - P_{st}}{P_{sl}}$$

Where

σ = Reflection coefficient

P_{st} = Membrane permeability of the solute

P_{sl} = Membrane permeability of the solvent

The osmotic flow equation for conditions where the particles in solution (solute) are permeable, results in the flow equation being:

$$Q = L \cdot A \cdot \Delta\pi$$

Where

Q = Flow

σ = Reflection coefficient

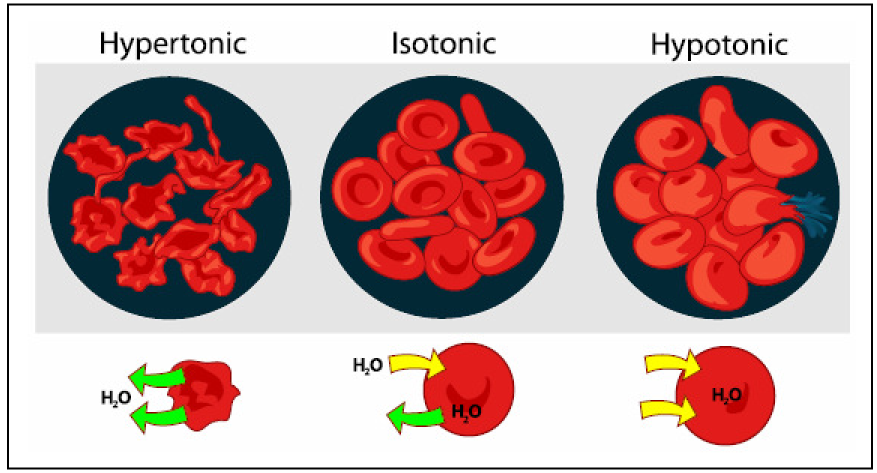
L = Hydraulic conductivity of the membrane (L/sec/cm^2/mm Hg)

A = Area of the cell membrane (cm^2)

$\Delta\pi$ = The difference in osmotic pressures on either side of the membrane or π_1 - π_2 (mm Hg)

Impact of Osmotic Pressure on the Cells

- **Isotonic Solution:** In this solution, the total concentration of water molecules and solute molecules are the same on both sides of the membrane. For red blood cells, an 0.9% NaCl solution is isotonic, that is water molecules enter and exit the cell at the same rate, allowing the cell to maintain its normal shape.



- **Hypotonic Solution:** In this solution, the water molecules enter the cell faster than they leave the cell. This causes the Red Blood Cells to swell and finally burst. This rupture of the red blood cells in this way is called hemolysis. Distilled water is a strongly hypotonic solution.
- **Hypertonic Solution:** This is where there is a higher concentration of solutes and a lower concentration of water than in the Red Blood Cell . An example of a hypertonic solution is a 5% NaCl solution. In this solution, the water molecules leave the cell faster than they enter the cell. This causes the cell to shrink.

Filtration, Dialysis

- **Filtration** is another method of passive transport.
  - The movement is caused by pressure, from higher to lower pressure, either gravitational or hydrostatic (water).
  - An example of filtration is in the kidneys where blood pressure supplied by the heart is higher forcing water and small molecules, such as urea, through the membrane.
- **Dialysis** is diffusion by passive transport in which small solute particles are separated from larger molecules.
  - This is method used in dialysis or the artificial kidney machine.

Active Transport

http://www.northland.cc.mn.us/biology/biology1111/animations/transport1.swf

- This type of transport requires energy in order to move a substance against a concentration gradient. Typically, these transported substances are ions.
- This energy is supplied by ATP (adenosine triphosphate), produced in the mitochondria of the cell. Indeed, about 40% of a cell's ATP is used for the purpose of active transport.
- Active transport is responsible for maintaining the concentration of ions both inside and outside the cell. This is important for conduction of the action potential.
- A good example of maintaining the required concentration of ions inside and outside of the cell is the concentration of potassium (K^+ ion), which must be higher concentration inside the cell than outside or the concentration of sodium (Na^+ ion) needs to be higher outside the cell than outside the cell.
- This maintenance of concentration of ions against the concentration gradient is accomplished by the sodium-potassium pump. sodium-potassium pump is powered by ATP and involves an integral protein serving as a pump using ATP.
- See Figures 19, 20 and 21. Other forms of active transport include phagocytosis and pinocytosis.

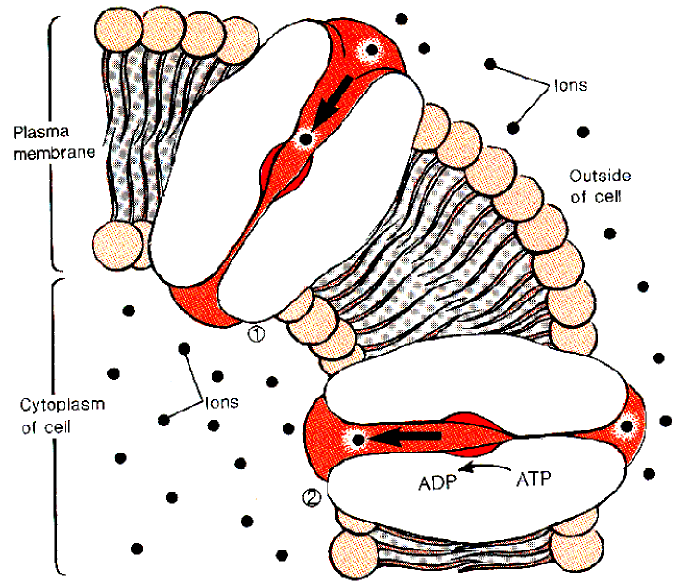


Figure 19. Mechanism of active transport.

Active Transport

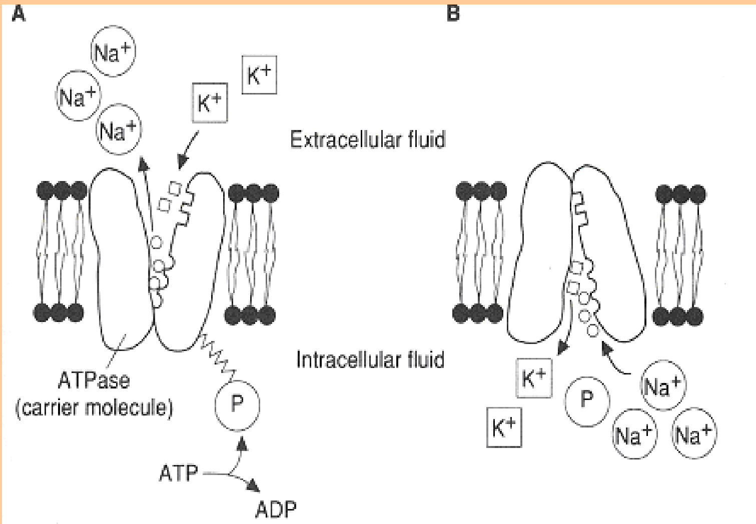


Figure 20. (A) The energy contained in the high-energy phosphate bond produces a conformational change in the carrier, during which three ions of Na^+ are transported out of the cell. A second conformational change occurs after two K^+ ions bind to the carrier on the outside of the cell, (B) transporting K^+ into the cell and causing the phosphate (P) to dissociate from the carrier.

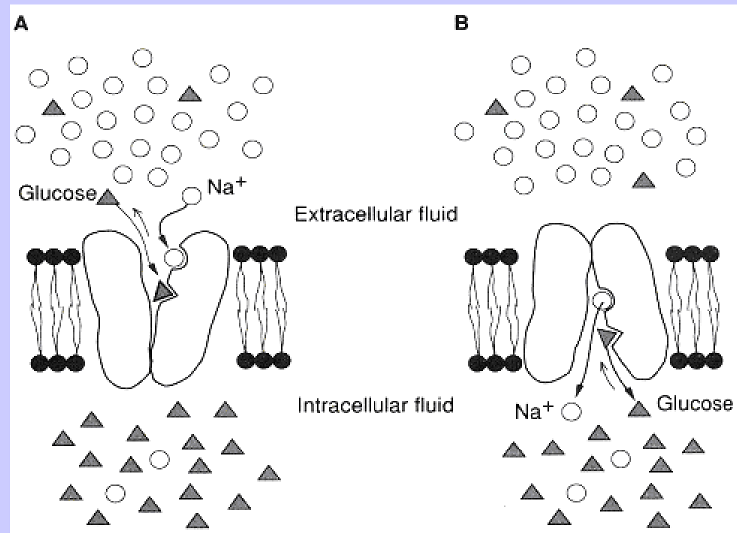
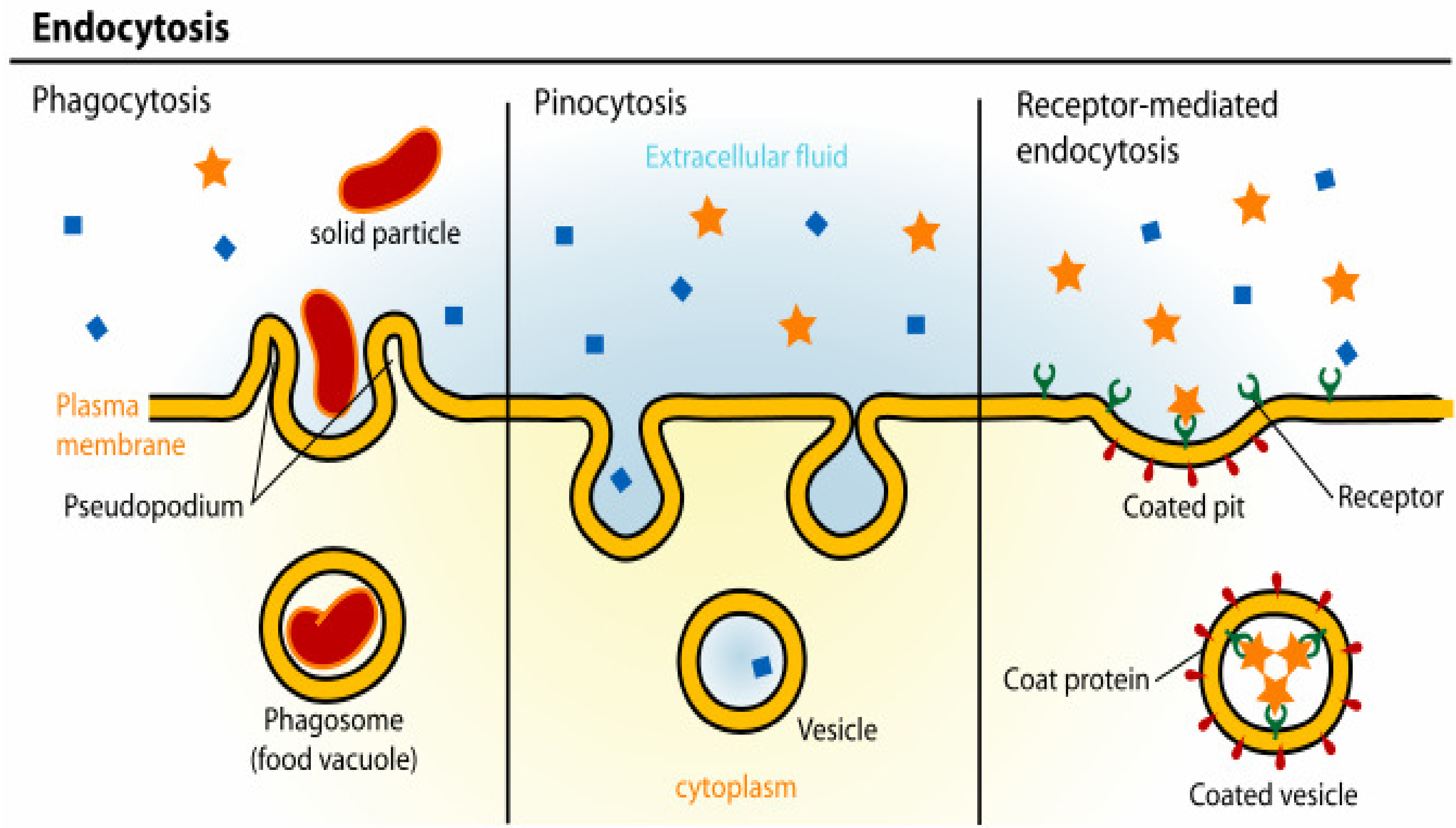


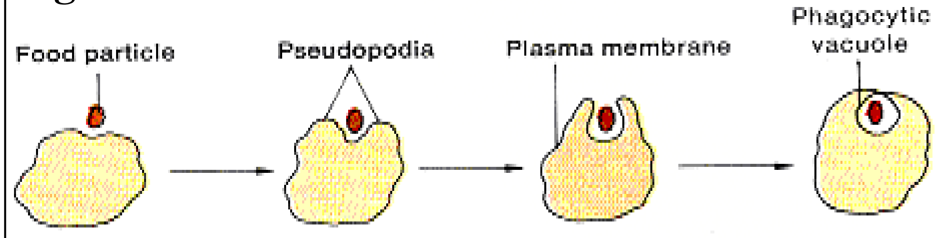
Figure 21. Glucose is transported through the membrane by secondary active transport (i.e., active transport that uses an indirect energy source). (A) As indicated by the length of the arrows, the affinity of the carrier for glucose is increased in the presence of Na^+. The glucose and Na^+ pass through the membrane together. (B) Once inside the cell, the Na^+ dissociates from the carrier, reducing the carrier's affinity for glucose and causing the glucose to dissociate from the carrier.

Active Transport
Endocytosis



Phagocytosis

Figure 22.



- An active method of transporting substances across the cell membrane.
- Phagocytosis means "cell eating" by which projections of the cytoplasm (pseudopodia) engulf (hug) solid particles outside of the cell. The membrane folds around the particle forming a sack (bag) and the foreign substance enters the cell.
- If the foreign substance is digestible, it is digested by the cell. If it is not digestible, it is removed from the cell by the reverse process.
- White blood cells, which play an important immune defence role, perform phagocytosis by eating foreign substances, destroying bacteria and other substances.

Pinocytosis

- This is an active transport process for liquids. Pinocytosis means “cell drinking”. Similar to phagocytosis, the liquids are engulfed without cytoplasmic projection.
- The liquid is attached to the surface of the membrane, possibly by surface tension. The membrane folds inwardly and surrounds (engulfs) the liquid particle.
- Pinocytosis is done by more cells than phagocytosis.
- An example of this type of transport is in:
  - Urinary bladder
  - Kidneys

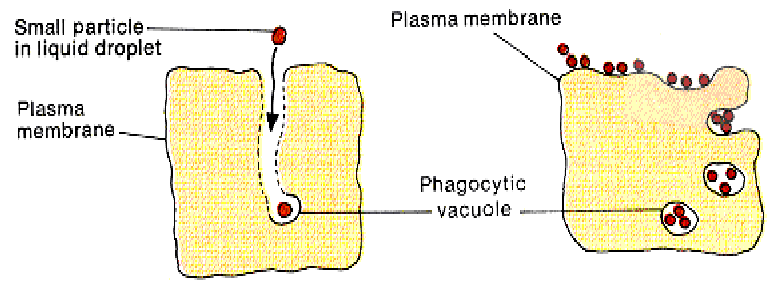


Figure 23. Two variations of Pinocytosis. In the variation on the left, the ingested substance enters a channel formed by the plasma membrane and becomes enclosed in a vacuole at the base of the channel. In the variation on the right, the ingested substance becomes enclosed in a vacuole that forms and detaches at the surface of the cell.

Import and Export of Material

- **Endocytosis:** This refers to import of material into the cell.
- **Exocytosis:** This refers to the export of material from the cell.
- **Microvilli:** These are membrane modifications of cells lining the small intestine which have small cylindrical projections (finger-like) for increasing the surface area of the cell for absorption. Some cells may have up to 3000 microvilli.
- **Photoreceptors:** This another form of modification found in the membrane in the rods and cones of the cells of the eye. They receive light and are involved in vision.
- **Stereocilia:** These are found in the cell lining of the male reproductive system.
- **Myelin sheath:** This is a modification of the cell membrane surrounding certain nerve cells. It is used in speeding the conduction of the action potential and protects the portion that is covered.

Summary

- Proper ionic concentrations in the cell are required for numerous reasons, such as to support action potential propagation (through membrane charge), and to regulate water content (tonicity).
- The cell membrane allows movement of substances through a number of active and passive transport processes.
- Active transport requires energy in the form of ATP, whereas passive transport requires no energy.