Transport across Membranes

2.4

For a cell to survive and function, it must take in nutrients, expel waste, and communicate with its environment and neighbouring cells. This exchanging of substances is a complex process because the plasma membrane must be highly selective. It must be able to take in very large food molecules while preventing very small and valuable molecules from leaving the cell. It must also be able to recognize foreign substances that are harmful and block their passage while, at the same time, expelling the cell's toxic waste products. To further complicate matters, some molecules cannot be stopped by the plasma membrane—they enter and exit regardless of whether or not it is desirable for the cell. When this happens, the cell must be able to withstand the consequences.

The transmembrane exchange of materials is not limited to the outer surface of the cell. Countless substances must be able to cross the organelle membranes within a eukaryotic cell. In the mitochondria and chloroplasts, chemical reactions take place within the internal fluids, separated from the cytosol by two or three membrane layers. For these reactions to occur, reactants must be able to enter the organelle, while products must be permitted to leave. In this section, you will explore the free movement of certain molecules, such as O_2 and CO_2, across membranes, as well as the specialized cell transport mechanisms that are used to control the entry and exit of other molecules.

Passive Membrane Transport

Passive transport is the movement of a substance across a membrane without the need to expend chemical energy. Diffusion drives passive transport. Diffusion is the net movement of a substance from a region of higher concentration to a region of lower concentration. It occurs because molecules are in constant motion and, in an ideal closed environment, tend to become uniformly distributed in space. Diffusion is the primary mechanism of solute movement within a cell and between cellular compartments separated by a membrane. If molecules are more concentrated in one region of a solution or on one side of a membrane, the random motion of the molecules causes them to become evenly distributed (**Figure 1**). As diffusion proceeds, there is a net movement of molecules in one direction until the concentrations on both sides of the membrane become equal.

passive transport the movement of a substance across a membrane without expending energy

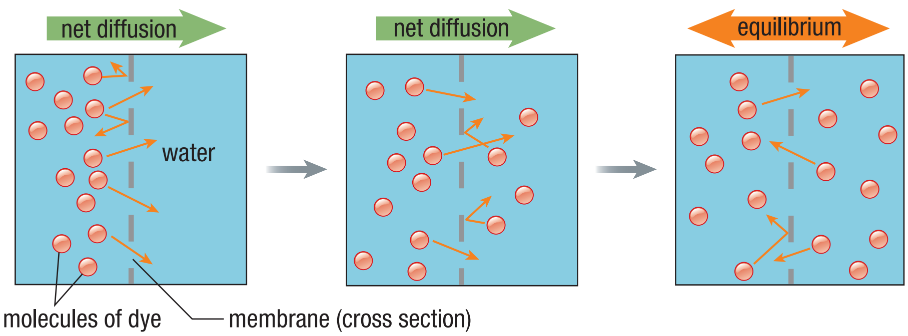


Figure 1 Diffusion is the process in which molecules move from a region of higher concentration to a region of lower concentration.

The rate of diffusion depends on the concentration difference, or concentration gradient, that exists between two areas or across a membrane. The larger the gradient, the faster the rate of diffusion is. Even after the concentration of molecules or ions is the same in both regions, the molecules or ions continue to move from one region to another. However, there is no net change in concentration. This is an example of a **dynamic equilibrium**.

dynamic equilibrium the state in which continuous action results in balanced conditions

Membranes have selective permeability, which means that some molecules can diffuse very rapidly across a membrane while other molecules are unable to transit the membrane without assistance. Two major factors, size and charge, determine the ease with which a molecule or ion can move across a membrane. There are two types of passive transport: simple diffusion and facilitated diffusion.

Simple Diffusion

simple diffusion the ability of small and non-polar substances to move across a membrane unassisted

Simple diffusion is the ability of substances to move across a membrane unassisted (**Figure 2**). Very small non-polar molecules, such as O_2 and CO_2, are readily soluble in the hydrophobic interior of a membrane and move rapidly from one side to the other. Non-polar steroid hormones and non-polar drugs can also cross a membrane easily. Small uncharged molecules, such as water and glycerol, even though they are polar, are still able to move quite rapidly across a membrane. In contrast, most membranes are practically impermeable to large molecules and ions. Compared with the rate of transport of water, the movement of small ions is about one-billionth the speed.

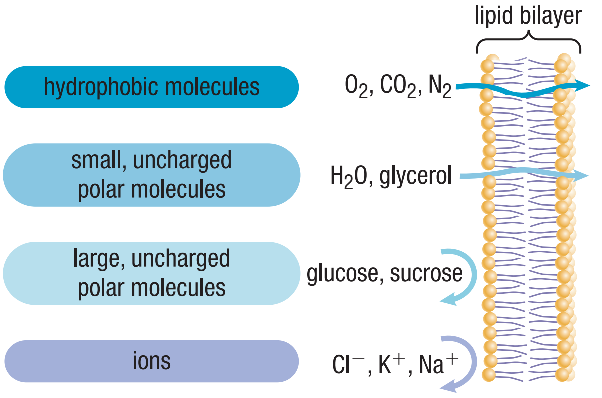


Figure 2 The size and charge of a molecule affect the rate of diffusion across a membrane.

Facilitated Diffusion

facilitated diffusion the facilitated transport of ions and polar molecules through a membrane via protein complexes

transport protein an integral membrane protein that provides a pathway for molecules to cross a membrane

channel protein a hydrophilic pathway in a membrane that enables water and ions to pass through

A slow rate of diffusion may not keep up with the demand that metabolic processes often have for ions and many polar and charged molecules, such as water, amino acids, and sugars. Diffusion of these compounds across a membrane can be helped or facilitated by protein complexes that span the membrane. This is known as **facilitated diffusion**. Although facilitated diffusion involves specific transporters, the movement of the molecules and ions is still driven by diffusion based on a concentration gradient across the membrane. When equilibrium is reached and there is no longer a concentration gradient, facilitated diffusion stops.

Facilitated diffusion is carried out by integral membrane proteins called **transport proteins** that extend throughout the membrane. There are two types of transport proteins: channel proteins and carrier proteins. **Channel proteins** form hydrophilic pathways in the membrane through which water and certain ions can pass (**Figure 3**).

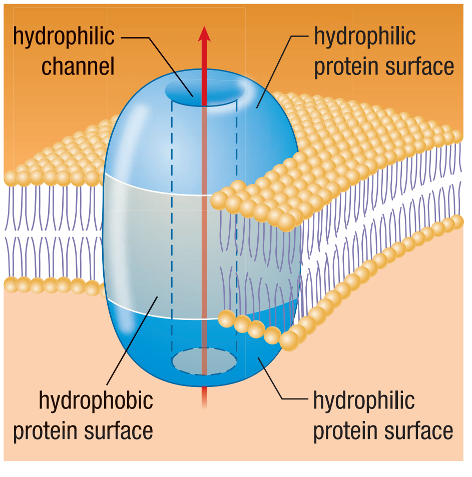


Figure 3 Channel proteins

Other channel proteins facilitate the transport of ions such as Na^+, K^+, Ca^{2+}, and Cl^-. Most of these ion channels, which occur in all eukaryotes, are voltage-gated channels. This means that they switch between open, closed, and intermediate states. The gates are opened or closed by changes in voltage across the membrane or by binding signal molecules. In animals, voltage-gated ion channels are used for nerve conduction and for the control of muscle contractions. In some people, however, the channel proteins do not function properly. People with a muscle ion channel disease often experience muscle stiffness or weakness as a result.

Carrier proteins also form passageways through the lipid bilayer (**Figure 4**). Each carrier protein binds to a specific solute, such as a glucose molecule or a particular amino acid, and transports it across the lipid bilayer. Diffusion is the driving mechanism for moving a solute down its concentration gradient, but it would not be able to move through the membrane without carrier proteins. When performing the transport step, the carrier protein changes shape, allowing the solute to move from one side of the membrane to the other. This change in shape distinguishes how carrier proteins and channel proteins function.

carrier protein a protein that binds to a molecule and transports it across the lipid bilayer

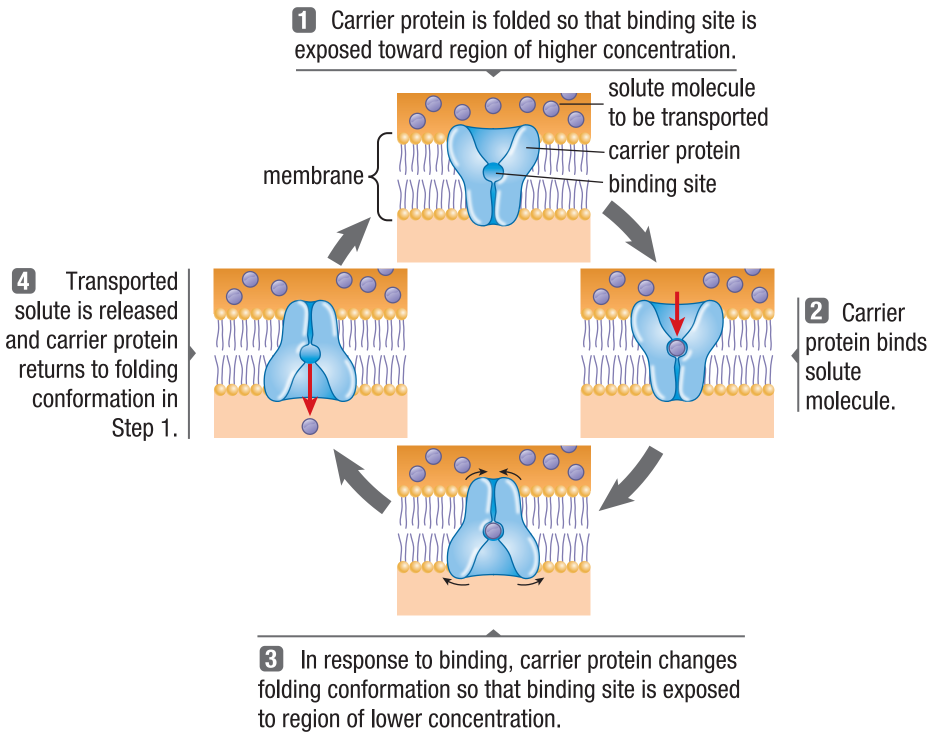


Figure 4 Carrier proteins transport solutes across membranes.

Many transport proteins are very selective about which solutes they will carry. For example, transporters that carry glucose are unable to transport fructose, which is structurally very similar. This specificity allows for tight control over what gets in and out of cells and cellular compartments. The types of transport proteins that are present in the plasma membrane and on the outer membrane of mitochondria depend ultimately on the type of cell and growth conditions.

In facilitated diffusion, the rate of diffusion across the membrane is influenced not only by the concentration gradient and the efficiency of the transport protein but also by the number of transport molecules. **Figure 5** illustrates the influence of solute concentration on the rate of diffusion in both facilitated and simple diffusion.

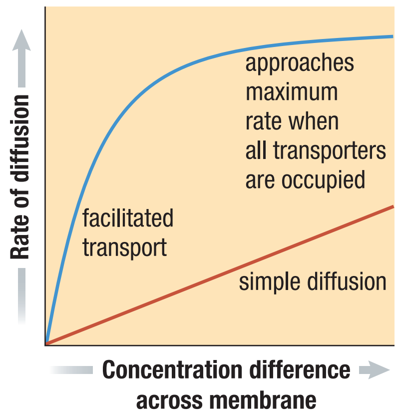


Figure 5 The rate of diffusion across a membrane increases as the difference in concentration increases. In facilitated transport, the maximum rate is reached quickly but is limited by the number of available transport proteins in the membrane.

Osmosis

Like solutes, water can diffuse passively across a membrane. The diffusion of water across a membrane is such a fundamental process in biology that it is given a special name: **osmosis**. In living cells, the inward or outward movement of water by osmosis

osmosis the passive diffusion of water across a membrane

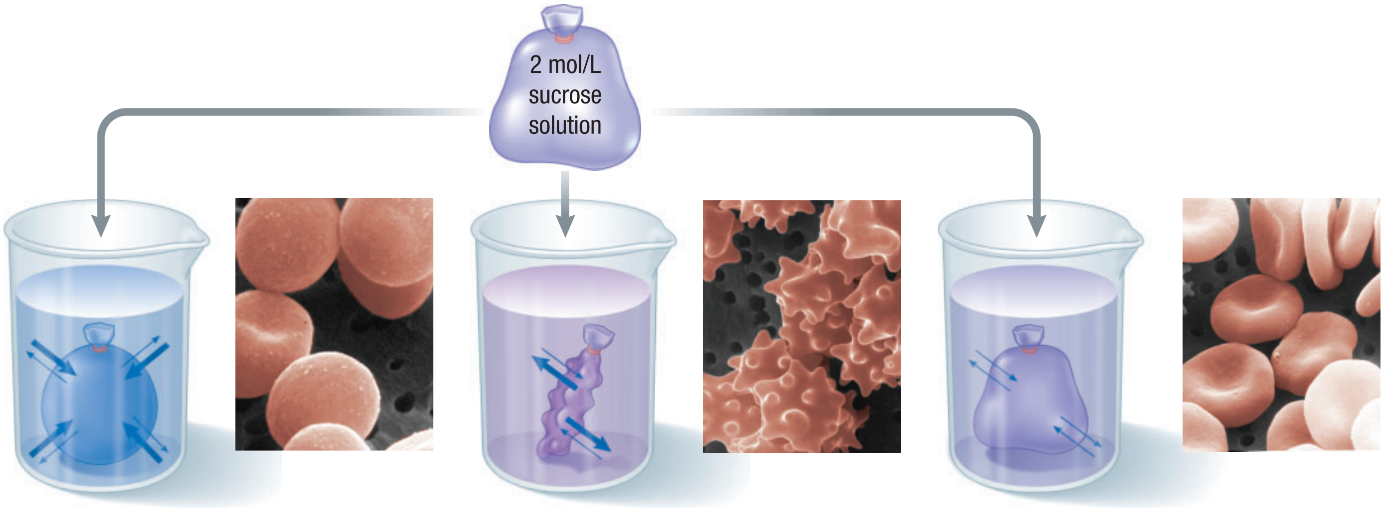
hypotonic the property of a solution that has a lower solute concentration than another solution

hypertonic the property of a solution that has a higher solute concentration than another solution

isotonic the property of a solution that has the same solute concentration as another solution

develops forces that can cause cells to swell or shrink. Water always diffuses from an area of lower solute concentration (high water concentration) to an area of greater solute concentration (low water concentration) and is therefore influenced by any difference or change in solute concentration on either side of a membrane.

If the solution that is surrounding a cell contains dissolved substances at lower concentrations than they are in the cell, the solution is said to be **hypotonic** to the cell. When a cell is in a hypotonic solution, water enters by osmosis and the cell tends to swell (**Figure 6(a)**). Animal cells in a hypotonic solution may actually swell to the point of bursting. In contrast, an organism in a solution that contains salts or other molecules at higher concentrations than they are in its body must expend energy to replace the water that is lost by osmosis. In this situation, the outside solution is said to be **hypertonic** to the organism's cells (**Figure 6(b)**). The concentration of water inside and outside cells is often equal or **isotonic**, as shown in **Figure 6(c)**.



(a) hypotonic conditions:
The distilled water is hypotonic to the solution in the bag; net movement of water is into the bag; cells swell.

(b) hypertonic conditions:
The 10 mol/L solution is hypertonic to the solution in the bag; net movement of water is out of the bag; cells shrink.

(c) isotonic conditions:
The solutions inside and outside the bag are isotonic; there is no net movement of water into or out of the bag; no change in cell size or shape.

Figure 6 A cellophane bag filled with a 2 mol/L sucrose solution is placed in (a) a hypotonic solution, (b) a hypertonic solution, and (c) an isotonic solution. The cellophane is permeable to water but not to sucrose molecules. The width of the arrows shows the amount of water movement. The animal cell micrographs show the corresponding effects on red blood cells placed in hypotonic, hypertonic, and isotonic solutions.

Mini **Investigation**

Observing Diffusion and Osmosis

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK **A1, A2.1**

In this investigation, you will use dialysis tubing to test for the diffusion of substances across a semipermeable membrane. You will use Lugol's iodine to test for the presence of starch. Lugol's solution turns blue or black when starch is present.

Equipment and Materials: safety goggles; lab apron; 250 mL beaker; 25 mL pipette with pipette filler; scissors; electronic balance; 15 cm length of dialysis tubing (soaked in warm water); 2 pieces of cotton string; tap water; glucose test strip; 15 mL of 15 % glucose/1 % starch solution; paper towels; Lugol's iodine solution in a dropper bottle

Iodine in Lugol's solution is an irritant. If it touches your skin, wash your skin immediately with soap and water, and inform the teacher.

1. Put on your safety goggles and lab apron.
2. Gently take the dialysis tubing from the water. Use the string to tie off one end.
3. Fill your beaker with 150 mL of water. Test the water for glucose using the test strip. Record your results.

4. Fill the dialysis tubing with water to see if the tubing leaks. If not, empty the water and fill the tubing with 15 mL of glucose/starch solution using a pipette and pipette filler.
5. Use the glucose test strip to test the solution in the tubing. Record your results. Then tie off the open end of the tubing with the string (**Figure 7**).

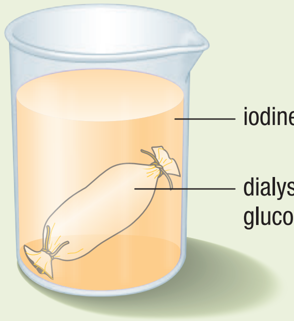


Figure 7

6. Rinse the tubing thoroughly, cut off any extra string, and gently dry the outside surface with a paper towel. Determine and record the mass of the tubing with the solution. Observe and record how full the tubing is.
7. Place the closed tubing in the beaker. Add water if necessary, so the tubing is completely submerged.
8. Add several drops of Lugol's iodine to the water in the beaker until the water turns pale orange.
9. Let the beaker stand for 30 min.
10. Test the water in the beaker for glucose. Record your results.
11. Remove the dialysis tubing, and observe its contents. Record your observations.
12. Gently dry the outside surface of the tubing. Determine and record the mass of the tubing with the solution.

A. Did the water in the beaker initially contain glucose? Did it contain glucose after 30 min with the tubing immersed? T/I

B. Did the solution in the tubing change colour? Is the colour different from the colour of the contents of the beaker? Explain. T/I

C. Was there a change in mass or an obvious change in volume of the solution in the tubing? Account for your observations. T/I

D. Draw a labelled diagram to explain the roles of diffusion and osmosis in this investigation. T/I C

Active Membrane Transport

You have learned how passive transport, driven by a concentration gradient, accounts for much of the movement of water, ions, and many types of molecules into and out of cells. Often, however, some substances must be moved against a concentration gradient, from a region of lower concentration to a region of higher concentration. Many of these substances are carried across a membrane against their concentration gradient by an energy-dependent process called **active transport**. Using "pumps," active transport is able to concentrate specific compounds inside cells and push others out. For example, in muscle cells, the calcium ion concentration in one compartment can be as much as 30 000 times as great as the calcium ion concentration in another compartment. Such a huge concentration difference, which is necessary for normal muscle function, is established and maintained through active transport.

active transport the movement of substances across membranes against their concentration gradient using pumps

Here, the term "active" refers to the fact that the cell has to expend energy, which is usually in the form of ATP, to pump molecules across a membrane. Scientists estimate that about 25 % of a cell's energy requirements are for active transport.

Primary Active Transport

All primary active transport pumps move positively charged ions, such as H^+, Ca^{2+}, Na^+, and K^+, across membranes. The concentration gradients that are established by these active transport pumps underlie functions that are absolutely essential for cellular life. For example, an H^+ pump (also called a proton pump) in the plasma membrane pushes hydrogen ions from the cytosol to the cell exterior. This pump temporarily binds to a phosphate group removed from ATP during the pumping cycle (**Figure 8**, next page). A Ca^{2+} pump (or calcium pump) pumps Ca^{2+} from the cytosol to the cell exterior and into the vesicles of the endoplasmic reticulum (ER). A Na^+/K^+ pump (or sodium–potassium pump) located in the plasma membrane simultaneously pushes three Na^+ ions out of the cell and two K^+ ions into the cell.

Voltage (an electrical potential difference) across the plasma or internal membrane is a difference in electrical charge on either side of the membrane. This difference results from an unequal net distribution of the many positive cations and negative anions. Differences in the various ion concentrations are the result of both

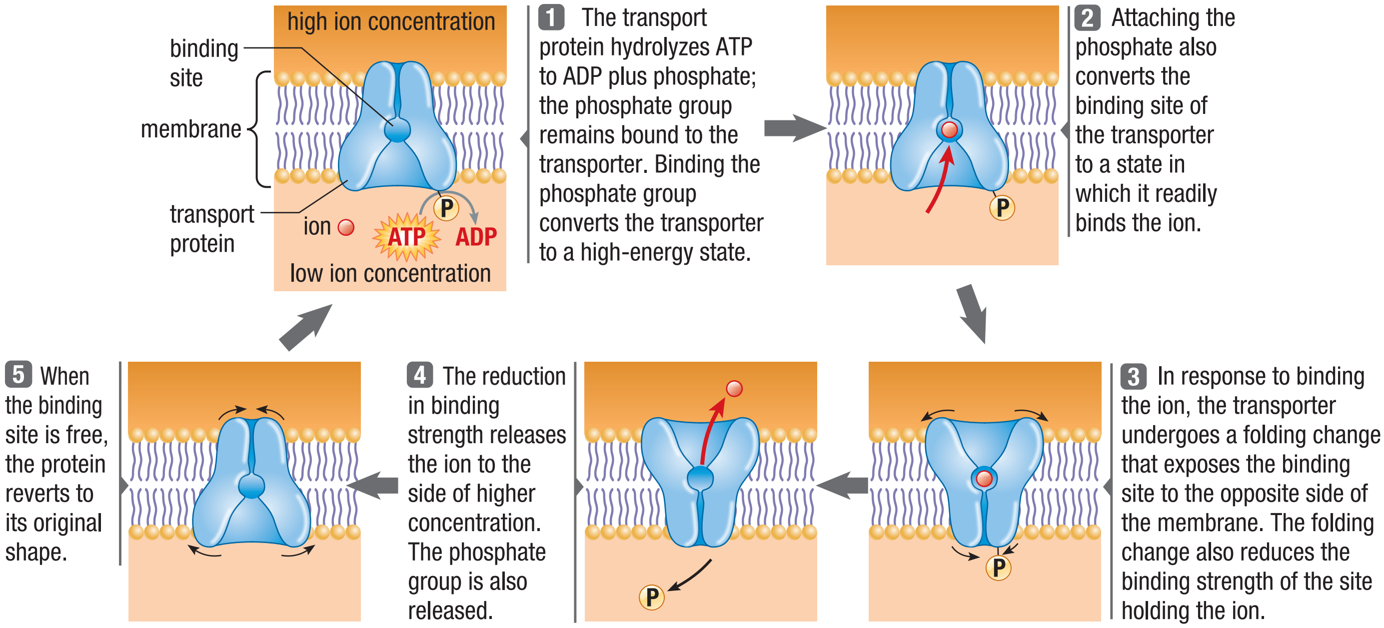


Figure 8 This model shows how an active transport pump operates.

passive and active transport, as well as chemical reactions that take place on both sides of the membrane. The combined effects of the voltage and the differences in ion concentrations create an **electrochemical gradient**. An electrochemical gradient is a form of stored potential energy that can be used for other transport mechanisms. For example, the electrochemical gradient across the plasma membrane is involved in the movement of ions associated with nerve impulse transmission.

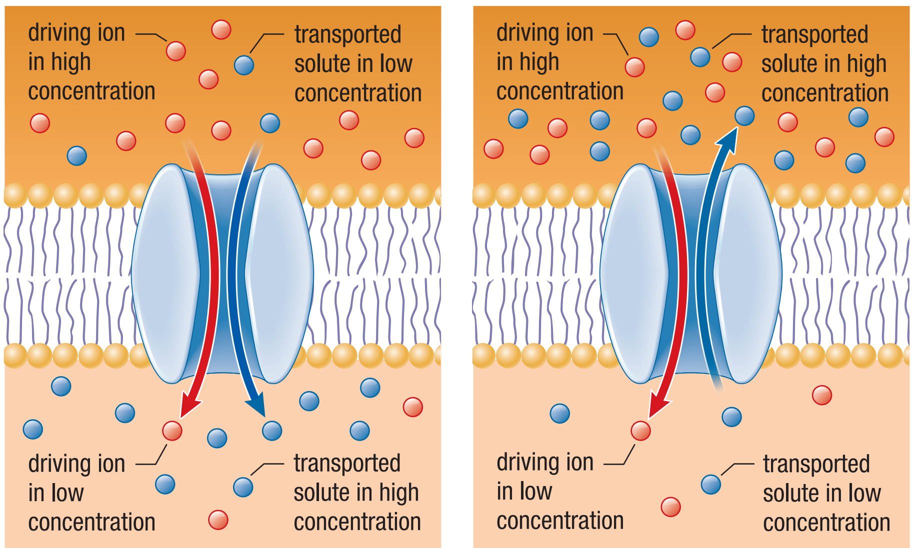
electrochemical gradient the combined effects of a difference in electrical potential energy and a difference in the concentration gradients of ions

Investigation 2.4.1

Plasma Membrane Permeability (p. 98)
You have learned about diffusion and osmosis. You have also learned about the importance of plasma membranes to proper cell and organelle function. This investigation will give you an opportunity to examine outside factors that can affect cells.

Secondary Active Transport

A secondary active transport pump uses the concentration gradient of an ion, established by a primary pump, as its energy source. For example, the driving force for most secondary active transport in animal cells is the high outside/low inside Na^+ gradient set up by the sodium–potassium pump. Secondary active transport is facilitated by two mechanisms, known as symport and antiport (**Figure 9**).



(a) symport **(b)** antiport

Figure 9 (a) In symport, the transported solute moves in the same direction as the gradient of the driving ion. (b) In antiport, the transported solute moves in the direction that is opposite to the gradient of the driving ion.

In symport, a solute moves through the membrane channel in the same direction as the driving ion. In antiport, the driving ion moves through the membrane channel in one direction, providing the energy for the active transport of another molecule in the opposite direction. In many cases, ions such as Na^+ are exchanged by antiport.

Comparison of Passive and Active Transport

Both passive transport and active transport move ions and small molecules across cellular membranes. **Table 1** summarizes the characteristics of these two transport mechanisms.

Table 1 Characteristics of Transport Mechanisms

	Passive transport		
Characteristic	**Simple diffusion**	**Facilitated diffusion**	**Active transport**
Membrane component that is responsible for influencing transport	lipids	proteins	proteins
Binding to transported substance	no	yes	yes
Energy source	concentration gradients	concentration gradients	ATP hydrolysis or concentration gradients
Direction of transport	with gradient of transported substance	with gradient of transported substance	against gradient of transported substance
Specificity for molecules or molecular classes	non-specific	specific	specific
Saturation at high concentrations of transported molecules	no	yes	yes

Exocytosis and Endocytosis

The largest molecules that can be transported across a cellular membrane by passive or active transport are about the size of amino acids or monosaccharides such as glucose. However, eukaryotic cells can export and import larger molecules by two other mechanisms, called exocytosis and endocytosis. The export of materials by exocytosis primarily carries secretory proteins and some waste materials from the cytosol to the exterior of a cell. Import by endocytosis may carry proteins, larger aggregates of molecules, or even whole cells from the exterior of a cell into the cytosol. Exocytosis and endocytosis also contribute to the back-and-forth flow of portions of actual membranes between the endomembrane system and the plasma membrane. Both exocytosis and endocytosis require energy. Thus, both processes stop if the ability of a cell to make ATP is inhibited.

In exocytosis, secretory vesicles move through the cytosol and contact the plasma membrane (**Figure 10**). The vesicle membrane fuses with the plasma membrane, releasing the contents of the vesicle to the exterior of the cell. All eukaryotic cells

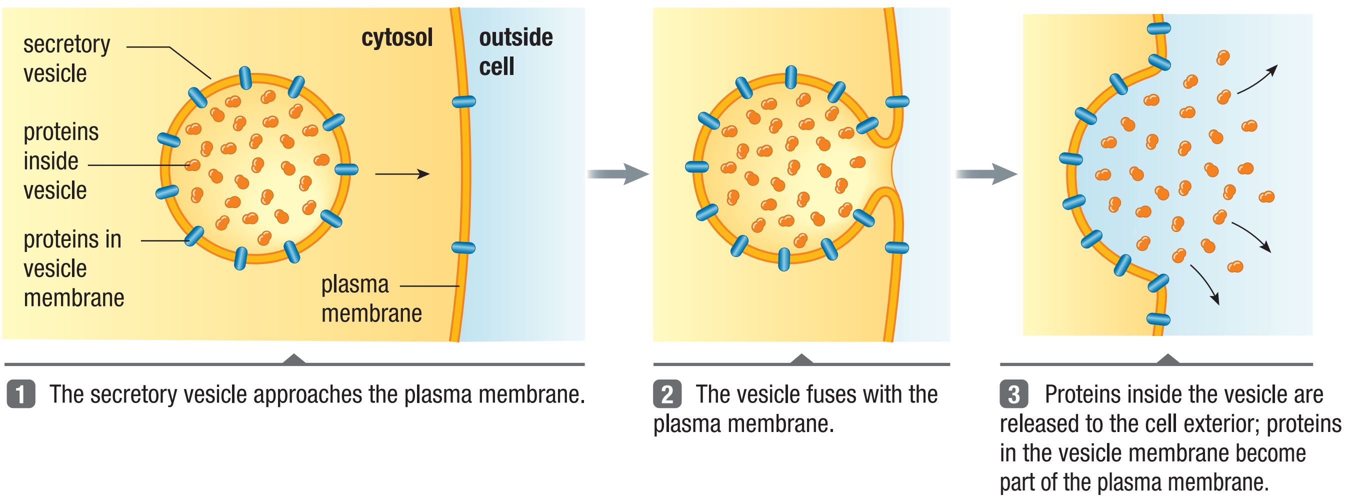


Figure 10 Exocytosis

secrete materials outside the cell through exocytosis. For example, glandular cells in animals secrete peptide hormones or milk proteins, and cells lining the digestive tract secrete mucus and digestive enzymes. Plant cells secrete carbohydrates by exocytosis to build a strong cell wall.

In endocytosis, proteins and other substances are trapped in a pit-like depression that bulges inward from the plasma membrane. The depression then pinches off as an endocytic vesicle. Endocytosis takes place in most eukaryotic cells by one of three distinct but related pathways. In the simplest of these pathways, bulk-phase endocytosis (sometimes called pinocytosis, meaning "cell drinking"), extracellular water is taken in, along with any molecules that happen to be in solution in the water (**Figure 11**). No binding by surface receptors takes place.

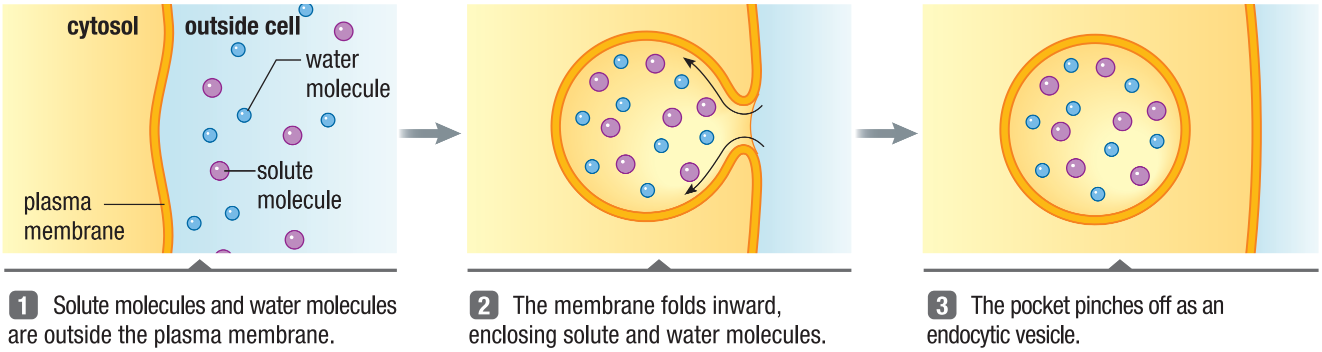


Figure 11 Bulk-phase endocytosis, or pinocytosis

In the second endocytic pathway, receptor-mediated endocytosis, the molecules to be taken in are bound to the outer cell surface by receptor proteins (**Figure 12**). The receptors bind to only certain molecules—primarily proteins or molecules carried by proteins. After binding, the receptors collect into a pit coated with a network of proteins, called clathrin, that reinforce the cytosol side. The coated pit then breaks free of the membrane to form a vesicle. In the cytosol, the vesicle loses its clathrin coating and may fuse with a lysosome. Enzymes within the lysosome then digest the cargo, breaking it down into smaller molecules that are useful to the cell.

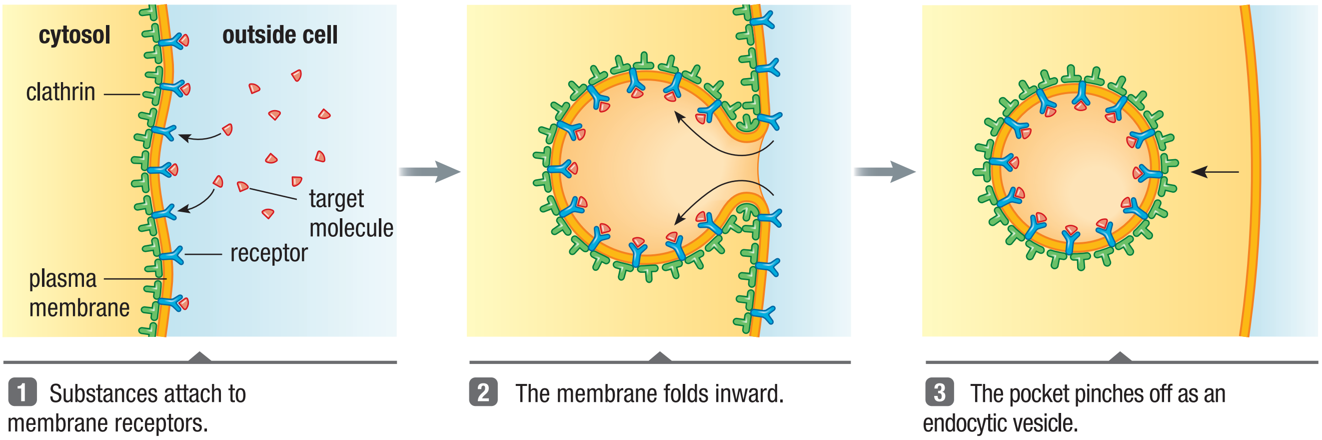


Figure 12 Receptor-mediated endocytosis

A third type of endocytosis is phagocytosis. It is the pathway in which cells engulf bacteria, parts of dead cells, viruses, or other foreign particles. This pathway is most commonly performed by a macrophage, a type of white blood cell that helps to fight infection by engulfing invading organisms or particles.

Through the combined mechanisms of passive transport, active transport, exocytosis, and endocytosis, cells maintain their internal concentrations of ions and molecules and exchange larger molecules, such as proteins, with their surroundings.

2.4 Review

Summary

- Cells and cell organelles must interact with their environment by allowing and controlling the inward and outward movement of molecules and ions through their membrane.
- Some molecules can pass through a membrane using passive transport (simple or facilitated diffusion), which depends on a concentration gradient.
- Osmosis is the passive diffusion of water across a membrane.
- Active transport moves a substance against a concentration gradient across a membrane, using a pump. Primary active transport pumps include H^+, Ca^+, Na^+, and K^+ pumps. Secondary transport pumps occur via symport or antiport.
- Endocytosis moves aggregate molecules into the cell. Exocytosis moves proteins and wastes out of the cell.

Questions

1. Your biology study partner asks you a question about the concentration gradient of water. K/U
   (a) What is meant by the term "concentration gradient"?
   (b) Is your study partner using the term correctly in reference to water? Explain why or why not.
2. Facilitated diffusion is specific. What does this mean? K/U
3. A red blood cell was placed in a beaker of solution. The cell immediately began to swell and finally burst. Explain what happened, referring to the cytosol of the cell and the solution in the beaker. K/U
4. Distilled water is considered hypotonic to body cells. Explain. T/I
5. Compare the energy requirements of passive transport, primary active transport, and secondary active transport. K/U
6. (a) How do size, polarity, and charge influence the ability of a substance to diffuse across a membrane?
   (b) Which combinations of these factors require cells to use active transport to move a substance across a membrane? K/U
7. (a) How does the concentration of a solute on the two sides of a membrane affect passive transport?
   (b) How does this concentration affect primary and secondary active transport? T/I
8. (a) What process is shown in the micrographs in **Figure 13**?
   (b) Draw a labelled scientific drawing of the micrographs. T/I C

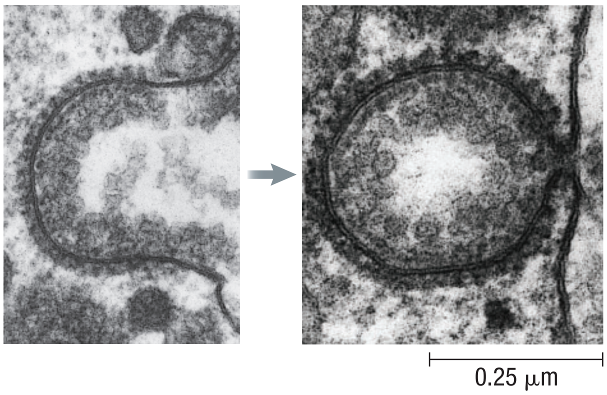


Figure 13

9. The transport of molecules across cellular membranes is important for the proper functioning of cells. Explain the role of transport across cell membranes in the proper functioning of the following:
   (a) red blood cells
   (b) cells in the gut
   (c) the release of hormones K/U T/I
10. Cystic fibrosis can be caused by the Cl^- transport channel malfunctioning. Conduct research to identify a disease that can be caused by a K^+ or Na^+ transport channel malfunctioning. What are the physical effects of this disease? CAREER LINK T/I A

WEB LINK