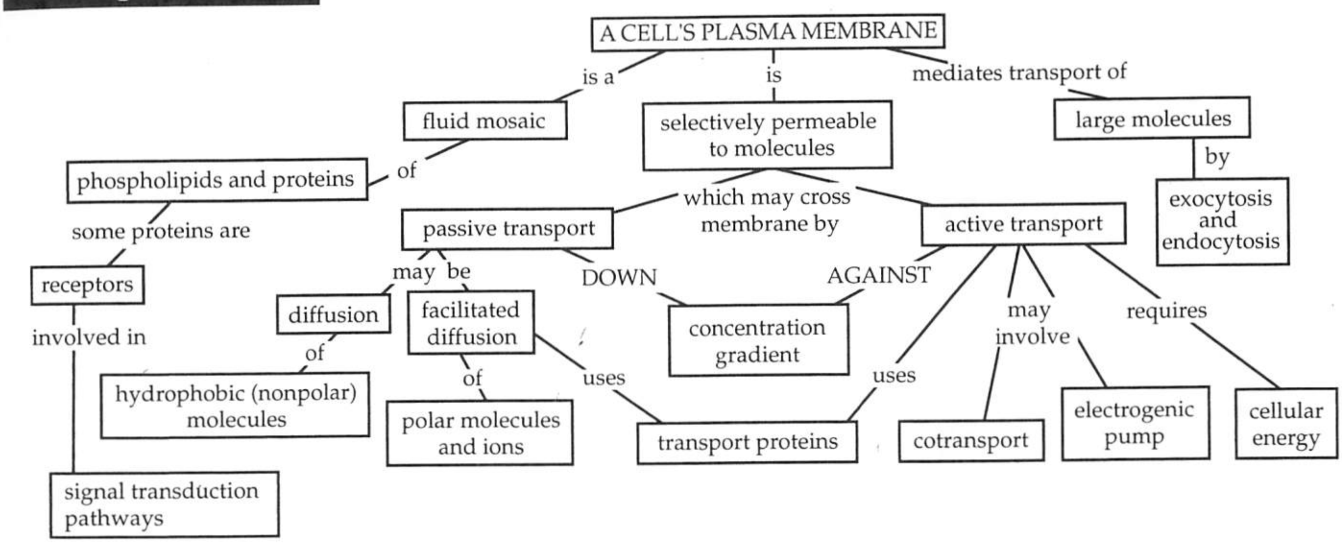
Chapter 5

Membrane Transport and Cell Signaling

Chapter Focus



Chapter Review

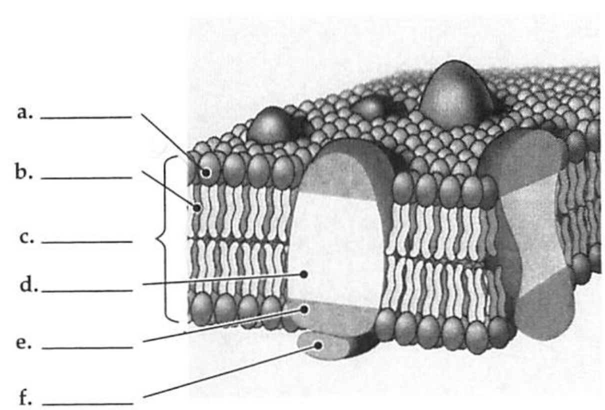
The plasma membrane is the boundary of life. Like all biological membranes, it has **selective permeability**, allowing some materials to cross it more easily than others.

5.1 Cellular membranes are fluid mosaics of lipids and proteins

According to the **fluid mosaic model**, biological membranes consist of various proteins that are embedded in a bilayer of **amphipathic** phospholipids (having both hydrophilic and hydrophobic regions). The membrane proteins are also amphipathic, with their hydrophilic regions extending into the aqueous surroundings.

FOCUS QUESTION 5.1

Label the components in the following diagram of the fluid mosaic model of membrane structure. Indicate whether regions are hydrophobic or hydrophilic.



The Fluidity of Membranes Membranes are held together primarily by weak hydrophobic interactions that allow the lipids and some of the proteins to drift laterally. Some membrane proteins seem to be held by attachments to the cytoskeleton or ECM; others appear to be directed in their movements.

Phospholipids with unsaturated hydrocarbon tails maintain membrane fluidity at lower temperatures. The steroid cholesterol, common in plasma membranes of animals, restricts movement of phospholipids and thus reduces fluidity at warmer temperatures. Cholesterol also prevents the close packing of lipids and thus enhances fluidity at lower temperatures.

Evolution of Differences in Membrane Lipid Composition Variations in membrane lipid composition and the ability to change that composition in response to changing temperatures are evolutionary adaptations.

FOCUS QUESTION 5.2

a. Cite some experimental evidence that indicates that membrane proteins drift.

b. How might the composition of membrane lipids differ for two species of fish if one lives in cold, mountain lakes and the other lives in warm valley ponds?

Membrane Proteins and Their Functions Each membrane has its own unique set of proteins, which determine most of the specific functions of that membrane. **Integral proteins** often extend through the membrane (are *transmembrane* proteins), with two hydrophilic ends. The hydrophobic midsection usually consists of one or more α helical stretches of nonpolar amino acids. **Peripheral proteins** are attached to the surface of the membrane. Attachments of membrane proteins to the cytoskeleton and to fibers of the extracellular matrix provide support for the plasma membrane.

FOCUS QUESTION 5.3

Can you list the six major kinds of functions that membrane proteins may perform?

The Role of Membrane Carbohydrates in Cell–Cell Recognition The cell's ability to distinguish other cells is based on the recognition and binding of membrane proteins to carbohydrates on other cells. The **glycolipids** and **glycoproteins** extending to the outside of plasma membranes vary from species to species, from individual to individual, and even among cell types.

Synthesis and Sidedness of Membranes Membranes have distinct faces or sides, related to the composition of the lipid layers and the directional orientation of their proteins. Carbohydrates attached to membrane proteins as they are synthesized in the ER are modified in the Golgi apparatus. Carbohydrates may also be attached to lipids in the Golgi apparatus. When transport vesicles fuse with the plasma membrane, these interior glycoproteins and glycolipids become located on the extracellular face of the membrane.

5.2 Membrane structure results in selective permeability

The plasma membrane permits a regular exchange of nutrients, waste products, oxygen, and inorganic ions.

The Permeability of the Lipid Bilayer Hydrophobic, nonpolar molecules, such as hydrocarbons, CO_2, and O_2, can dissolve in and cross a membrane.

FOCUS QUESTION 5.4

What types of molecules have difficulty crossing the plasma membrane? Why?

Transport Proteins Ions and polar molecules may move across the plasma membrane with the aid of **transport proteins.** Hydrophilic passageways through a membrane are provided for specific molecules or ions by *channel proteins*, such as **aquaporins,** which facilitate water passage. *Carrier proteins* may physically bind and transport a specific molecule across a membrane.

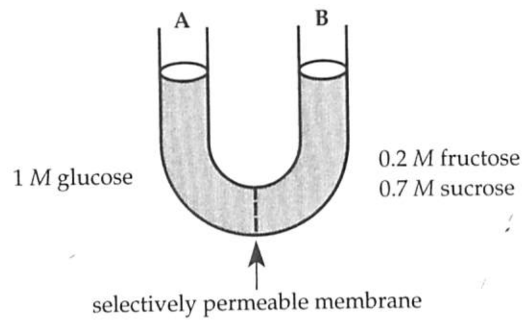
5.3 Passive transport is diffusion of a substance across a membrane with no energy investment

Diffusion is the movement of a substance down its **concentration gradient** due to random molecular motion (thermal energy). The diffusion of one solute is unaffected by the concentration gradients of other solutes; each solute will reach its own dynamic equilibrium. Remember that the cell does not expend energy when substances diffuse across membranes down their concentration gradients; therefore, the process is called **passive transport**.

Effects of Osmosis on Water Balance **Osmosis** is the diffusion of free water across a selectively permeable membrane. Water diffuses down its own concentration gradient, which is affected by the solute concentration. Clustering of water molecules around solute particles lowers the proportion of free water that is available to cross the membrane.

FOCUS QUESTION 5.5

A solution of 1 *M* glucose is separated by a selectively permeable membrane from a solution of 0.2 *M* fructose and 0.7 *M* sucrose. The membrane is not permeable to the sugar molecules. Indicate which side initially has more free water molecules, and which side has fewer. Show the direction of osmosis.



Tonicity, the tendency of a surrounding solution to cause a cell to gain or lose water, is affected by the relative concentrations of those solutes in the solution and in the cell that cannot cross the membrane. An animal cell will neither gain nor lose water in an **isotonic** environment. An animal cell placed in a **hypertonic** solution (which has more nonpenetrating solutes) will lose water and shrivel. If placed in a **hypotonic** solution, the cell will gain water, swell, and possibly lyse (burst). Cells without rigid walls must either live in an isotonic environment, such as salt water or isotonic body fluids, or have adaptations for **osmoregulation**, the regulation of solute concentrations and water balance.

The cell walls of plants, fungi, prokaryotes, and some protists play a role in water balance in hypotonic environments. Water moving into the cell causes the cell to swell against its cell wall, creating *turgor pressure*. **Turgid** cells provide mechanical support for nonwoody plants. Plant cells in an isotonic surrounding are **flaccid**. In a hypertonic medium, a plant cell undergoes **plasmolysis**—that is, the plasma membrane pulls away from the cell wall as water exits and the cell shrivels.

FOCUS QUESTION 5.6

a. What osmotic problems does the freshwater protist *Paramecium* face, and what adaptation enables it to osmoregulate?

b. Compare the ideal osmotic environment for animal cells and plant cells.

Facilitated Diffusion: Passive Transport Aided by Proteins **Facilitated diffusion** involves the diffusion of polar molecules and ions across a membrane with the aid of transport proteins, either channel proteins or carrier proteins. Many **ion channels** are **gated channels**, which open or close in response to electrical or chemical stimuli. The binding of a solute to a carrier protein may cause a change in the protein's shape that translocates the solute across the membrane.

FOCUS QUESTION 5.7

Why is facilitated diffusion considered a form of passive transport?

5.4 Active transport uses energy to move solutes against their gradients

The Need for Energy in Active Transport **Active transport**, which requires the expenditure of energy to transport a solute against its concentration gradient, is essential if a cell is to maintain internal concentrations of small molecules that differ from their concentrations outside the cell. The terminal phosphate group of ATP may be transferred to a carrier protein, inducing it to change its shape and translocate the bound solute across the membrane. The **sodium-potassium pump** works this way to exchange N^+ and K^+ across animal cell membranes, creating a higher concentration of potassium ions and a lower concentration of sodium ions within the cell.

How Ion Pumps Maintain Membrane Potential Cells have a **membrane potential**, a voltage across the plasma membrane due to the unequal distribution of ions on either side. This electrical potential energy results from the separation of opposite charges: The cytoplasm of a cell is negatively charged relative to the extracellular fluid. The membrane potential favors the diffusion of cations into the cell and anions out of the cell. Both the membrane potential and the concentration gradient affect the diffusion of an ion; thus, an ion diffuses down its **electrochemical gradient**.

Electrogenic pumps are membrane proteins that generate voltage across a membrane by the active transport of ions. A **proton pump** that transports H^+ out of the cell generates voltage across membranes in plants, fungi, and bacteria.

FOCUS QUESTION 5.8

The sodium-potassium pump, the major electrogenic pump in animal cells, exchanges sodium ions for potassium ions, both of which are cations. How does this exchange generate a membrane potential?

Cotransport: Coupled Transport by a Membrane Protein **Cotransport** is a mechanism through which the active transport of a solute is indirectly driven by an ATP-powered pump that transports another substance against its gradient. As that actively transported substance diffuses back down its concentration gradient through a cotransporter, the solute is carried against its concentration gradient across the membrane.

5.5 Bulk transport across the plasma membrane occurs by exocytosis and endocytosis

Bulk transport, like active transport, requires energy to transport larger biological molecules packaged in vesicles across the membrane.

Exocytosis In **exocytosis**, the cell secretes large molecules by the fusion of vesicles with the plasma membrane.

Endocytosis In **endocytosis**, a region of the plasma membrane sinks inward and pinches off to form a vesicle containing material that had been outside the cell. **Phagocytosis** is a form of endocytosis in which pseudopodia wrap around a food particle or another large particle, creating a vacuole that then fuses with a lysosome containing hydrolytic enzymes. In **pinocytosis**, droplets of extracellular fluid are taken into the cell in small vesicles. **Receptor-mediated endocytosis** enables a cell to acquire specific substances from extracellular fluid. Molecules bind to receptor proteins that are usually clustered in coated pits on the cell surface and are carried into the cell when a vesicle forms.

FOCUS QUESTION 5.9

a. How is cholesterol transported into human cells?

b. Explain why cholesterol accumulates in the blood of individuals with the disease familial hypercholesterolemia.

5.6 The plasma membrane plays a key role in most cell signaling

Local and Long-Distance Signaling Chemical signals may be communicated between cells through direct cytoplasmic connections (gap junctions or plasmodesmata) or through contact of membrane-bound surface molecules (cell–cell recognition in animal cells).

In *paracrine signaling* in animals, a signaling cell releases messenger molecules into the extracellular fluid, and these **local regulators** influence nearby cells. *Growth factors* are one class of local regulators. In another type of local signaling called *synaptic signaling*, a nerve cell releases neurotransmitter molecules, which diffuse across the narrow synapse to its target cell.

Hormones are chemical signals that travel to more distant cells. In hormonal or *endocrine signaling* in animals, the circulatory system transports hormones throughout the body to reach and bind to target cells that have appropriate receptors. Plant hormones may reach their target cells by traveling through plant vascular tissues or even through the air as a gas.

Transmission of electrical and chemical signals within the nervous system is also a type of long-distance signaling.

The Three Stages of Cell Signaling: A Preview E. W. Sutherland's studies of epinephrine's effect on the hydrolysis of glycogen in liver cells established that cell signaling involves three stages: **reception** of a chemical signal by binding to a receptor protein either inside a target cell or on its surface; **transduction** of the signal, often by a **signal transduction pathway**—a sequence of changes in relay molecules; and the specific **response** of the cell.

5.7 Reception, the binding of a signaling molecule to a receptor protein

A signaling molecule acts as a **ligand**, which specifically binds to a receptor protein and usually induces a change in the receptor protein's shape, activating the receptor. Most ligands are large and water-soluble, and they bind to receptors in the plasma membrane.

A cell-surface transmembrane receptor that works with the aid of a G protein is called a **G protein-coupled receptor (GPCR)**. Binding of the appropriate signaling molecule to a G protein-coupled receptor activates the receptor, which then binds to and activates a specific **G protein** located on the cytoplasmic side of the membrane. The activated G protein, which carries a GTP molecule, activates a membrane-bound enzyme, which then triggers the next step in the pathway to the cell's response.

G protein-coupled receptor systems are involved in the function of many hormones and neurotransmitters and in embryological development and sensory reception. Many bacteria produce toxins that interfere with G-protein function; up to 60% of all medicines influence G-protein pathways.

The binding of a signaling molecule to a **ligand-gated ion channel** opens or closes a "gate," thereby allowing or blocking the flow of specific ions through the receptor channel. The resulting change in ion concentration inside the cell triggers a cellular response. Neurotransmitters often bind to ligand-gated ion channels in the transmission of neural signals.

Hydrophobic chemical messengers and small signaling molecules such as the gas nitric oxide may cross a cell's plasma membrane and bind to receptors in the cytoplasm or nucleus of target cells. Steroid hormones activate receptors in target cells that function as *transcription factors* that regulate gene expression.

FOCUS QUESTION 5.10

Describe the difference between signaling molecules that bind to cell membrane receptors and those that bind to intracellular receptors.

Transduction by Cascades of Molecular Interactions Multistep pathways enable a small number of extracellular signals to be amplified to produce a large cellular response. Such pathways also provide opportunities for regulation and coordination.

The relay molecules in a signal transduction pathway are usually proteins, which interact as they pass the message from the extracellular signaling molecule to the protein that produces the cellular response.

Protein kinases are enzymes that transfer phosphate groups from ATP to proteins. Relay molecules in signal transduction pathways are often protein kinases, which are sequentially phosphorylated. Phosphorylation produces a shape change that usually activates each enzyme. Hundreds of different kinds of protein kinases regulate the activity of a cell's proteins.

FOCUS QUESTION 5.11

a. What does a protein kinase do?

b. What does a **protein phosphatase** do?

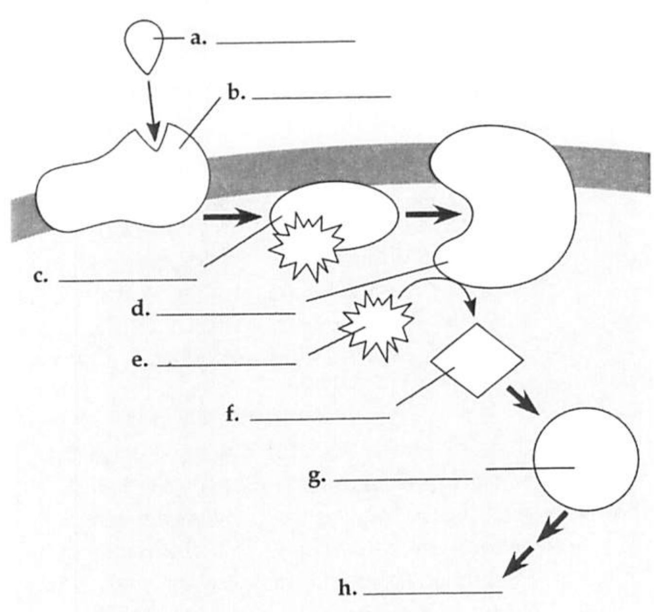
c. What is a "phosphorylation cascade"?

Small, water-soluble molecules or ions often function as **second messengers**, which rapidly relay the signal from the membrane-receptor-bound "first messenger" into a cell's interior.

Binding of an extracellular signal to a G protein-coupled receptor activates a G protein that may activate adenylyl cyclase, a membrane protein that converts ATP to **cyclic AMP (cAMP)**. The cAMP often activates *protein kinase A*, which phosphorylates other proteins. A cytoplasmic enzyme converts cAMP to inactive AMP, thereby removing the second messenger in the absence of a signaling molecule.

FOCUS QUESTION 5.12

Label the components in the following diagram depicting the steps in a signal transduction pathway that uses cAMP as a second messenger.



5.8 Response: Regulation of transcription or cytoplasmic activities

Signal transduction pathways may lead to the activation of transcription factors, which regulate the expression of specific genes. Signaling pathways may also activate existing cytoplasmic enzymes.

The Evolution of Cell Signaling Similarities among cell-signaling pathways in diverse species suggest an early evolution of such mechanisms.

Word Roots

amphi- = dual (*amphipathic molecule:* a molecule that has both hydrophobic and hydrophilic regions)

aqua- = water; **-pori** = a small opening (*aquaporin:* a channel protein in the plasma membrane that specifically facilitates osmosis, the diffusion of free water across the membrane)

co- = together; **trans-** = across (*cotransport:* the coupling of the "downhill" diffusion of one substance to the "uphill" transport of another against its concentration gradient)

electro- = electricity; **-genic** = producing (*electrogenic pump:* an active transport protein that generates voltage across a membrane while pumping ions)

endo- = inner; **cyto-** = cell (*endocytosis:* cellular uptake of matter via formation of vesicles from the plasma membrane)

exo- = outer (*exocytosis:* cellular secretion by the fusion of vesicles with the plasma membrane)

hyper- = exceeding; **-tonus** = tension (*hypertonic:* referring to a surrounding solution that will cause a cell to lose water)

hypo- = lower (*hypotonic:* referring to a surrounding solution that will cause a cell to take up water)

iso- = same (*isotonic*: referring to a surrounding solution that causes no net movement of water into or out of a cell)

liga- = bound or tied (*ligand:* a molecule that binds specifically to another, usually larger molecule)

phago- = eat (*phagocytosis*: "cell eating"; endocytosis in which large particulate substances are taken up by a cell)

pino- = drink (*pinocytosis*: "cell drinking"; endocytosis in which the cell ingests extracellular fluid and its dissolved solutes)

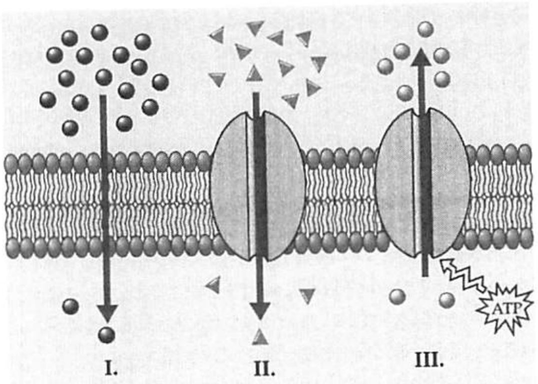
plasm- = molded; **-lyso** = loosen (*plasmolysis:* a phenomenon in walled cells in which the cytoplasm shrivels and the plasma membrane pulls away from the cell wall when the cell loses water to a hypertonic environment)

trans- = across (*signal transduction pathway:* a series of steps linking a mechanical, chemical, or electrical stimulus to a specific cellular response)

Structure Your Knowledge

1. Create a concept map to illustrate your understanding of osmosis. This exercise will help you to practice using the words *hypotonic*, *isotonic*, and *hypertonic*, and to focus on the effect of these osmotic environments on plant and animal cells. Explain your map to a friend.

2. The following diagram illustrates passive and active transport across a plasma membrane. Use it to answer questions **a** through **d**.
   a. Which section represents facilitated diffusion? How can you tell? Does the cell expend energy in this transport? Why or why not? What types of solute molecules may be moved by this type of transport?
   b. Which section shows active transport? List two ways that you can tell.
   c. What types of solute molecules can diffuse through the membrane shown in section I?
   d. Which of these sections are considered passive transport?



3. Briefly describe the three stages of cell signaling.

4. Some signaling pathways alter a protein's activity; others result in the production of new proteins. Explain the mechanisms for these two different responses.

Test Your Knowledge

MULTIPLE CHOICE: *Choose the one best answer.*

1. If a single layer of phospholipids coats the water in a beaker, which parts of the molecules face the air?
   a. the phosphate groups
   b. the hydrocarbon tails
   c. both heads and tails because the molecules are amphipathic and lie sideways
   d. the glycolipid regions
   e. No parts of the molecules face the air, because the phospholipids dissolve in the water and do not form a layer.

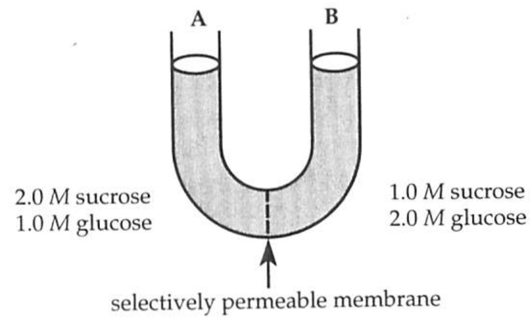
2. Glycoproteins and glycolipids are important for
   a. facilitated diffusion.
   b. active transport.
   c. cell–cell recognition.
   d. intercellular joining.
   e. signal transduction pathways.

3. Which of the following is the most probable description of an integral, transmembrane protein?
   a. amphipathic with a hydrophilic head and a hydrophobic tail region
   b. a globular protein with hydrophobic amino acids in the interior and hydrophilic amino acids arranged around the outside
   c. a fibrous protein coated with hydrophobic fatty acids
   d. a glycolipid attached to the portion of the protein facing the exterior of the cell and cytoskeletal elements attached to the interior portion
   e. a middle region composed of α helical stretches of hydrophobic amino acids, with hydrophilic regions at both ends of the protein

4. A cell is manufacturing receptor proteins for cholesterol. How would those proteins be oriented before they reach the plasma membrane?
   a. facing inside the ER lumen but outside the transport vesicle membrane
   b. facing inside the ER lumen and inside the transport vesicle
   c. attached outside the ER and outside the transport vesicle
   d. attached outside the ER but facing inside the transport vesicle
   e. embedded in the hydrophobic center of both the ER and transport vesicle membranes

5. The fluidity of membranes in a plant in cold weather may be maintained by increasing the
   a. proportion of peripheral proteins.
   b. action of an H^+ pump.
   c. concentration of cholesterol in the membrane.
   d. number of phospholipids with unsaturated hydrocarbon tails.
   e. number of phospholipids with saturated hydrocarbon tails.

Use the following U-tube setup to answer questions 6 through 8.



The solutions in the two arms of this U-tube are separated by a membrane that is permeable to water and glucose but not to sucrose. Side A is filled with a solution of 2.0 *M* sucrose and 1.0 *M* glucose. Side B is filled with 1.0 *M* sucrose and 2.0 *M* glucose.

6. *Initially*, the solution in side A, with respect to that in side B,
   a. has a lower solute concentration.
   b. has a higher solute concentration.
   c. has an equal solute concentration.
   d. is lower in the tube.
   e. is higher in the tube.

7. During the period *before* equilibrium is reached, which molecule(s) will show net movement through the membrane?
   a. water
   b. glucose
   c. sucrose
   d. water and sucrose
   e. water and glucose

8. *After* the system reaches equilibrium, what changes can be observed?
   a. The water level is higher in side A than in side B.
   b. The water level is higher in side B than in side A.
   c. The molarity of glucose is higher in side A than in side B.
   d. The molarity of sucrose has increased in side A.
   e. Both **a** and **c** have occurred.

9. An animal cell placed in a hypotonic environment will
   a. become flaccid.
   b. become turgid.
   c. burst (lyse).
   d. plasmolyze.
   e. shrivel.

10. You observe plant cells under a microscope as they are placed in an unknown solution. First the cells plasmolyze; after a minute, the plasmolysis reverses and the cells appear normal. What would you conclude about the unknown solution?
    a. It is hypertonic to the plant cells, and its solute cannot cross the plant cell membranes.
    b. It is hypotonic to the plant cells, and its solute cannot cross the plant cell membranes.
    c. It is isotonic to the plant cells, but its solute can cross the plant cell membranes.
    d. It is hypertonic to the plant cells, but its solute can cross the plant cell membranes.
    e. It is hypotonic to the plant cells, but its solute can cross the plant cell membranes.

11. Which of the following is *not* true about osmosis?
    a. It is a passive process in cells without walls, but an active one in cells with walls.
    b. Water moves into a cell from a hypotonic environment.
    c. Solute molecules bind to water and decrease the free water available to move.
    d. It can occur more rapidly through channel proteins known as aquaporins.
    e. There is no net osmosis when cells are in isotonic solutions.

12. Which of the following is *not* true of carrier molecules involved in facilitated diffusion?
    a. They increase the speed of transport across a membrane.
    b. They can concentrate solute molecules on one side of the membrane.
    c. They may have specific binding sites for the molecules they transport.
    d. They may undergo a change in shape upon binding of solute.
    e. They do not require an energy investment from the cell to function.

13. Facilitated diffusion of ions across a cellular membrane requires _____; and the ions move _____.
    a. energy and channel proteins; against their electrochemical gradient
    b. energy and channel proteins; against their concentration gradient
    c. cotransport proteins; against their electrochemical gradient
    d. channel proteins; down their electrochemical gradient
    e. channel proteins; down their concentration gradient

14. The membrane potential of a cell favors
    a. the movement of cations into the cell.
    b. the movement of anions into the cell.
    c. the action of an electrogenic pump.
    d. the movement of sodium out of the cell.
    e. both b and d.

15. Which of the following describes cotransport?
    a. active transport of two solutes through a cotransport protein
    b. passive transport of two solutes through a cotransport protein
    c. ion diffusion against the electrochemical gradient created by an electrogenic pump
    d. a pump such as the sodium-potassium pump that moves ions in two different directions
    e. transport of one solute against its concentration gradient in tandem with another that is diffusing down its concentration gradient

16. The proton pump in plant cells is the functional equivalent of an animal cell's
    a. cotransport mechanism.
    b. sodium-potassium pump.
    c. contractile vacuole for osmoregulation.
    d. receptor-mediated endocytosis of cholesterol.
    e. ATP pump.

17. Which of the following is an example of active transport?
    a. the transport of a solute in which a carrier protein binds the solute, changes shape, and moves the solute across a membrane
    b. the flow of K^+ through an open ion channel out of a cell
    c. the movement of water into a plant cell
    d. the movement of LDL particles into a cell
    e. the movement of O_2 into a cell

18. Exocytosis may involve all of the following *except*
    a. ligands and coated pits.
    b. the fusion of a vesicle with the plasma membrane.
    c. a mechanism to export some carbohydrates during the formation of plant cell walls.
    d. a mechanism to rejuvenate the plasma membrane.
    e. a means of exporting large molecules.

19. What is a key difference between a local regulator and a hormone?
    a. Local regulators are small, hydrophobic molecules; hormones are either larger polypeptides or steroids.
    b. Local regulators diffuse to neighboring cells; hormones usually travel throughout the plant or animal body to distant target cells.
    c. Local regulators initiate short-term responses; hormones trigger longer-lasting responses to environmental stimuli.
    d. The signal transduction pathways of local regulators do not involve second messengers; pathways triggered by hormones do involve second messengers.
    e. Local regulators often open ligand-gated channels and affect ion concentrations in a cell; hormones bind with intracellular receptors and affect gene expression.

20. A signaling molecule that binds to a plasma-membrane protein receptor functions as a
    a. ligand.
    b. second messenger.
    c. protein phosphatase.
    d. protein kinase.
    e. receptor protein.

21. A G protein is
    a. a specific type of membrane-receptor protein.
    b. a protein on the cytoplasmic side of a membrane that becomes activated by a transmembrane receptor protein.
    c. a membrane-bound enzyme that converts ATP to cAMP.
    d. an intracellular receptor protein that, once activated, functions as a transcription factor.
    e. a guanine nucleotide that converts between GDP and GTP to activate and inactivate relay proteins.

22. Which of the following compounds can activate a protein by transferring a phosphate group to it?
    a. G protein
    b. adenyl cyclase
    c. protein phosphatase
    d. protein kinase
    e. both **a** and **c**

23. Many signal transduction pathways use second messengers to
    a. transport a signaling molecule through the hydrophobic center of the plasma membrane.
    b. relay a signal from the outside to the inside of the cell.
    c. relay the message from the inside of the membrane throughout the cytoplasm.
    d. amplify the message by phosphorylating cascades of proteins.
    e. dampen the message once the signaling molecule has left the receptor.

24. When epinephrine binds to cardiac (heart) muscle cells, it speeds their contraction. When it binds to muscle cells of the small intestine, it inhibits their contraction. How can the same hormone have different effects on muscle cells?
    a. Cardiac cells have more receptors for epinephrine than do intestinal muscle cells.
    b. Epinephrine circulates to the heart first and is in higher concentration around cardiac cells.
    c. The two types of muscle cells have different signal transduction pathways for epinephrine and thus have different cellular responses.
    d. Cardiac muscle is stronger than intestinal muscle and thus has a stronger response to epinephrine.
    e. Epinephrine binds to G protein-coupled receptors in cardiac cells, and these receptors always increase a response to the signal. Epinephrine binds to intracellular receptors in intestinal muscle cells, and these receptors inhibit a response to the signal.