5 | STRUCTURE AND FUNCTION OF PLASMA MEMBRANES

Figure 5.1 Despite its seeming hustle and bustle, Grand Central Station functions with a high level of organization: People and objects move from one location to another, they cross or are contained within certain boundaries, and they provide a constant flow as part of larger activity. Analogously, a plasma membrane's functions involve movement within the cell and across boundaries in the process of intracellular and intercellular activities. (credit: modification of work by Randy Le'Moine)

Chapter Outline

Introduction

The plasma membrane, which is also called the cell membrane, has many functions; but, the most basic one is to define the borders and act as gatekeeper for the cell. The plasma membrane is selectively permeable, meaning some molecules can freely enter or leave the cell. Others require help from specialized structures, other molecules, or require energy in order to cross. One example of a molecule that assists other molecules across the plasma membrane is a protein called NPC1. This protein is involved in moving cholesterol and other types of fats across the plasma membrane. Some people have a genetic condition resulting in improperly functioning NPC1. As a result, excessive cholesterol accumulates within cells causing a condition called NPC Disease.

Scientists from the Albert Einstein College of Medicine, Harvard Medical School, and the Whitehead Institute for Biomedical Research discovered that the Ebola virus also uses NPC1 to hitch a ride into cells and replicate. The scientists used mice that lacked the NPC1 protein to test this hypothesis. When the scientists tried to infect these mice with Ebola, none of the mice got sick. Then they tried to infect mice with partially functioning NPC1 and found that they got sick, but did not die. In other words, without properly functioning NPC1, the Ebola virus cannot infect a mouse. If this pattern also exists in humans, it means that anyone with NPC Disease and its subsequent problem with high cholesterol may also be protected from Ebola.

The complete research report can be found **here (http://openstaxcollege.org/l/32ebolaentry)** .

5.1 | Components and Structure

In this section, you will explore the following questions:

- How does the fluid mosaic model describe the structure and components of the plasma cell membrane?
- How do the molecular components of the membrane provide fluidity?

Connection for AP® Courses

Like an art mosaic, the plasma membrane consists of several different components. Phospholipids (which we studied in previously) form a bilayer; the hydrophobic, fatty acid tails are in contact with each other and hydrophilic portions of the phospholipids are oriented toward the aqueous internal and external environments. Several types of proteins with different functions stud the membrane. Integral proteins often span the membrane and can transport materials into or out of the cells; these embedded proteins can be hydrophilic or hydrophobic, depending on their placement within the membrane. Peripheral proteins found on the exterior and interior surfaces of membranes can serve as enzymes, structural attachments for fibers of the cytoskeleton, and part of a cell's recognition sites. These "cell-specific" proteins play a vital role in immune function; enable cells of a certain type (e.g., liver cells) to identify each other when forming a tissue; and allow hormones and other molecules to recognize target cells. These proteins "float" throughout the membrane, constantly in flux.

Information presented and the examples highlighted in the section support concepts and learning objectives outlined in Big Idea 2 of the AP® Biology Curriculum Framework. The learning objectives provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.B	Growth, reproduction and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.
Essential Knowledge	**2.B.1** Cell membranes are selectively permeable due to their structure.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Science Practice	**3.1** The student can pose scientific questions.
Learning Objective	**2.10** The student is able to use representations and models to pose scientific questions about the properties of cell membranes and selective permeability based on molecular structure.
Essential Knowledge	**2.B.1** Cell membranes are selectively permeable due to their structure.
Science Practice	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain.
Science Practice	**7.1** The student can connect phenomena and models across spatial and temporal scales.
Science Practice	**7.2** The student can connect concepts in and across domain(s) to generalize and extrapolate in and/or across enduring understandings and/or big ideas.

Learning Objective	**2.11** The student is able to construct models that connect the movement of molecules across membrane with membrane structure and function.

A cell's plasma membrane defines the cell, outlines its borders, and determines the nature of its interaction with its environment (see **Figure 5.2** for a summary). Cells exclude some substances, take in others, and excrete still others, all in controlled quantities. The plasma membrane must be very flexible to allow certain cells, such as red blood cells and white blood cells, to change shape as they pass through narrow capillaries. These are the more obvious functions of a plasma membrane. In addition, the surface of the plasma membrane carries markers that allow cells to recognize one another, which is vital for tissue and organ formation during early development, and which later plays a role in the "self" versus "non-self" distinction of the immune response.

Among the most sophisticated functions of the plasma membrane is the ability to transmit signals by means of complex, integral proteins known as receptors. These proteins act both as receivers of extracellular inputs and as activators of intracellular processes. These membrane receptors provide extracellular attachment sites for effectors like hormones and growth factors, and they activate intracellular response cascades when their effectors are bound. Occasionally, receptors are hijacked by viruses that use them to gain entry into cells, and at times, the genes encoding receptors become mutated, causing the process of signal transduction to malfunction with disastrous consequences.

Fluid Mosaic Model

The existence of the plasma membrane was identified in the 1890s, and its chemical components were identified in 1915. The principal components identified at that time were lipids and proteins. The first widely accepted model of the plasma membrane's structure was proposed in 1935 by Hugh Davson and James Danielli; it was based on the "railroad track" appearance of the plasma membrane in early electron micrographs. They theorized that the structure of the plasma membrane resembles a sandwich, with protein being analogous to the bread, and lipids being analogous to the filling. In the 1950s, advances in microscopy, notably transmission electron microscopy (TEM), allowed researchers to see that the core of the plasma membrane consisted of a double, rather than a single, layer. A new model that better explains both the microscopic observations and the function of that plasma membrane was proposed by S.J. Singer and Garth L. Nicolson in 1972.

The explanation proposed by Singer and Nicolson is called the **fluid mosaic model**. The model has evolved somewhat over time, but it still best accounts for the structure and functions of the plasma membrane as we now understand them. The fluid mosaic model describes the structure of the plasma membrane as a mosaic of components—including phospholipids, cholesterol, proteins, and carbohydrates—that gives the membrane a fluid character. Plasma membranes range from 5 to 10 nm in thickness. For comparison, human red blood cells, visible via light microscopy, are approximately 8 µm wide, or approximately 1,000 times wider than a plasma membrane. The membrane does look a bit like a sandwich (**Figure 5.2**).

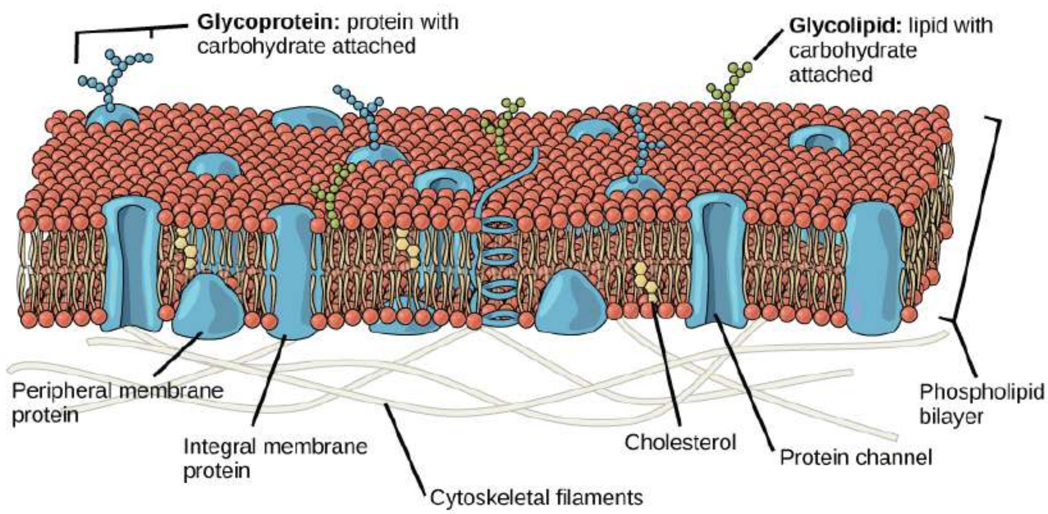

Figure 5.2 The fluid mosaic model of the plasma membrane describes the plasma membrane as a fluid combination of phospholipids, cholesterol, and proteins. Carbohydrates attached to lipids (glycolipids) and to proteins (glycoproteins) extend from the outward-facing surface of the membrane.

The principal components of a plasma membrane are lipids (phospholipids and cholesterol), proteins, and carbohydrates attached to some of the lipids and some of the proteins. A phospholipid is a molecule consisting of glycerol, two fatty acids, and a phosphate-linked head group. Cholesterol, another lipid composed of four fused carbon rings, is found alongside the phospholipids in the core of the membrane. The proportions of proteins, lipids, and carbohydrates in the plasma membrane vary with cell type, but for a typical human cell, protein accounts for about 50 percent of the composition by mass, lipids (of all types) account for about 40 percent of the composition by mass, with the remaining 10 percent of the composition by mass being carbohydrates. However, the concentration of proteins and lipids varies with different cell membranes. For example, myelin, an outgrowth of the membrane of specialized cells that insulates the axons of the peripheral nerves, contains only 18 percent protein and 76 percent lipid. The mitochondrial inner membrane contains 76 percent protein and only 24 percent lipid. The plasma membrane of human red blood cells is 30 percent lipid. Carbohydrates are present only on the exterior surface of the plasma membrane and are attached to proteins, forming **glycoproteins**, or attached to lipids, forming **glycolipids**.

Phospholipids

The main fabric of the membrane is composed of amphiphilic, phospholipid molecules. The **hydrophilic** or "water-loving" areas of these molecules (which look like a collection of balls in an artist's rendition of the model) (**Figure 5.2**) are in contact with the aqueous fluid both inside and outside the cell. **Hydrophobic**, or water-hating molecules, tend to be non-polar. They interact with other non-polar molecules in chemical reactions, but generally do not interact with polar molecules. When placed in water, hydrophobic molecules tend to form a ball or cluster. The hydrophilic regions of the phospholipids tend to form hydrogen bonds with water and other polar molecules on both the exterior and interior of the cell. Thus, the membrane surfaces that face the interior and exterior of the cell are hydrophilic. In contrast, the interior of the cell membrane is hydrophobic and will not interact with water. Therefore, phospholipids form an excellent two-layer cell membrane that separates fluid within the cell from the fluid outside of the cell.

A phospholipid molecule (**Figure 5.3**) consists of a three-carbon glycerol backbone with two fatty acid molecules attached to carbons 1 and 2, and a phosphate-containing group attached to the third carbon. This arrangement gives the overall molecule an area described as its head (the phosphate-containing group), which has a polar character or negative charge, and an area called the tail (the fatty acids), which has no charge. The head can form hydrogen bonds, but the tail cannot. A molecule with this arrangement of a positively or negatively charged area and an uncharged, or non-polar, area is referred to as **amphiphilic** or "dual-loving."

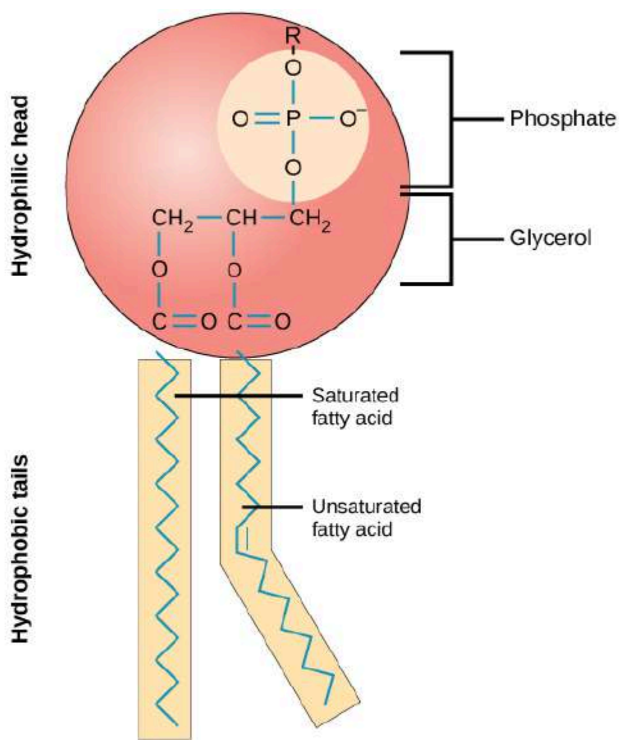

Figure 5.3 This phospholipid molecule is composed of a hydrophilic head and two hydrophobic tails. The hydrophilic head group consists of a phosphate-containing group attached to a glycerol molecule. The hydrophobic tails, each containing either a saturated or an unsaturated fatty acid, are long hydrocarbon chains.

This characteristic is vital to the structure of a plasma membrane because, in water, phospholipids tend to become arranged with their hydrophobic tails facing each other and their hydrophilic heads facing out. In this way, they form a lipid bilayer—a barrier composed of a double layer of phospholipids that separates the water and other materials on one side of the barrier from the water and other materials on the other side. In fact, phospholipids heated in an aqueous solution tend to spontaneously form small spheres or droplets (called micelles or liposomes), with their hydrophilic heads forming the exterior and their hydrophobic tails on the inside (**Figure 5.4**).

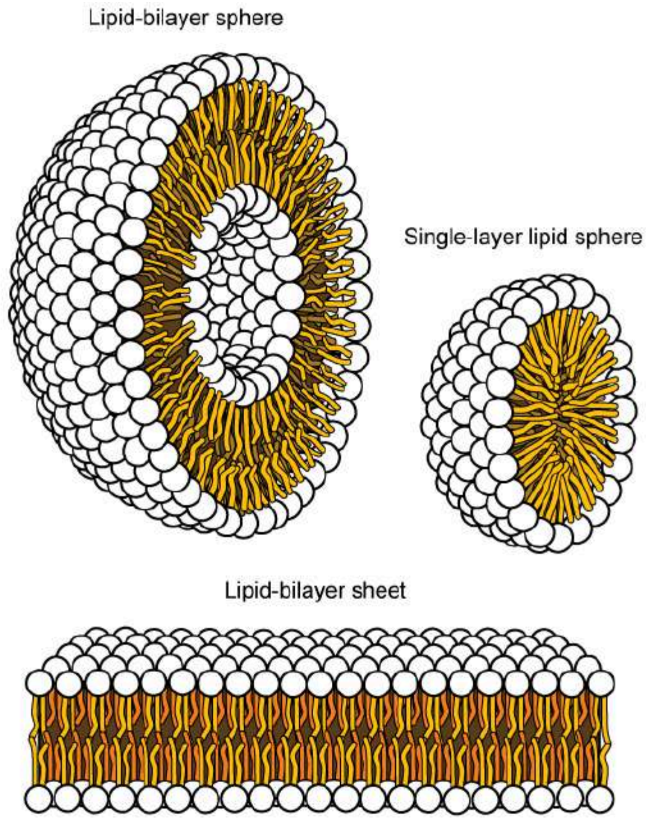

Figure 5.4 In an aqueous solution, phospholipids tend to arrange themselves with their polar heads facing outward and their hydrophobic tails facing inward. (credit: modification of work by Mariana Ruiz Villareal)

Proteins

Proteins make up the second major component of plasma membranes. **Integral proteins** (some specialized types are called integrins) are, as their name suggests, integrated completely into the membrane structure, and their hydrophobic membrane-spanning regions interact with the hydrophobic region of the the phospholipid bilayer (**Figure 5.2**). Single-pass integral membrane proteins usually have a hydrophobic transmembrane segment that consists of 20–25 amino acids. Some span only part of the membrane—associating with a single layer—while others stretch from one side of the membrane to the other, and are exposed on either side. Some complex proteins are composed of up to 12 segments of a single protein, which are extensively folded and embedded in the membrane (**Figure 5.5**). This type of protein has a hydrophilic region or regions, and one or several mildly hydrophobic regions. This arrangement of regions of the protein tends to orient the protein alongside the phospholipids, with the hydrophobic region of the protein adjacent to the tails of the phospholipids and the hydrophilic region or regions of the protein protruding from the membrane and in contact with the cytosol or extracellular fluid.

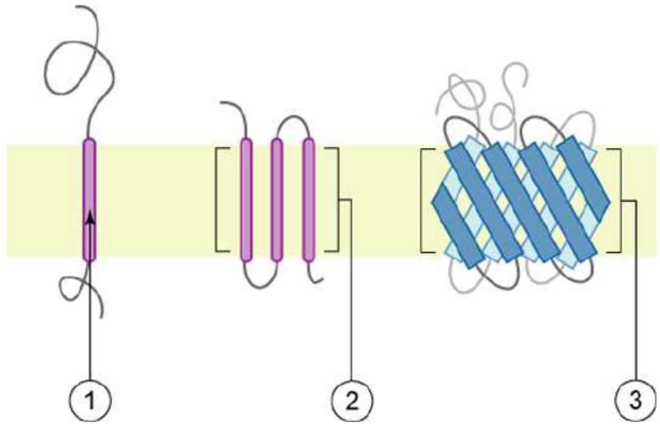

Figure 5.5 Integral membranes proteins may have one or more alpha-helices that span the membrane (examples 1 and 2), or they may have beta-sheets that span the membrane (example 3). (credit: "Foobar"/Wikimedia Commons)

Peripheral proteins are found on the exterior and interior surfaces of membranes, attached either to integral proteins or to phospholipids. Peripheral proteins, along with integral proteins, may serve as enzymes, as structural attachments for the fibers of the cytoskeleton, or as part of the cell's recognition sites. These are sometimes referred to as "cell-specific" proteins. The body recognizes its own proteins and attacks foreign proteins associated with invasive pathogens.

Carbohydrates

Carbohydrates are the third major component of plasma membranes. They are always found on the exterior surface of cells and are bound either to proteins (forming glycoproteins) or to lipids (forming glycolipids) (**Figure 5.2**). These carbohydrate chains may consist of 2–60 monosaccharide units and can be either straight or branched. Along with peripheral proteins, carbohydrates form specialized sites on the cell surface that allow cells to recognize each other. These sites have unique patterns that allow the cell to be recognized, much the way that the facial features unique to each person allow him or her to be recognized. This recognition function is very important to cells, as it allows the immune system to differentiate between body cells (called "self") and foreign cells or tissues (called "non-self"). Similar types of glycoproteins and glycolipids are found on the surfaces of viruses and may change frequently, preventing immune cells from recognizing and attacking them.

These carbohydrates on the exterior surface of the cell—the carbohydrate components of both glycoproteins and glycolipids—are collectively referred to as the glycocalyx (meaning "sugar coating"). The glycocalyx is highly hydrophilic and attracts large amounts of water to the surface of the cell. This aids in the interaction of the cell with its watery environment and in the cell's ability to obtain substances dissolved in the water. As discussed above, the glycocalyx is also important for cell identification, self/non-self determination, and embryonic development, and is used in cell-cell attachments to form tissues.

evolution CONNECTION

How Viruses Infect Specific Organs

Glycoprotein and glycolipid patterns on the surfaces of cells give many viruses an opportunity for infection. HIV and hepatitis viruses infect only specific organs or cells in the human body. HIV is able to penetrate the plasma membranes of a subtype of lymphocytes called T-helper cells, as well as some monocytes and central nervous system cells. The hepatitis virus attacks liver cells.

These viruses are able to invade these cells, because the cells have binding sites on their surfaces that are specific to and compatible with certain viruses (**Figure 5.6**). Other recognition sites on the virus's surface interact with the human immune system, prompting the body to produce antibodies. Antibodies are made in response to the antigens or proteins associated with invasive pathogens, or in response to foreign cells, such as might occur with an organ transplant. These same sites serve as places for antibodies to attach and either destroy or inhibit the activity of the virus. Unfortunately, these recognition sites on HIV change at a rapid rate because of mutations, making the production of an effective vaccine against the virus very difficult, as the virus evolves and adapts. A person infected with HIV will quickly develop different populations, or variants, of the virus that are distinguished by differences in these recognition sites. This rapid change of surface markers decreases the effectiveness of the person's immune system in attacking the virus, because the antibodies will not recognize the new variations of the surface patterns. In the case of HIV, the problem is compounded by the fact that the virus specifically infects and destroys cells involved in the immune response, further incapacitating the host.

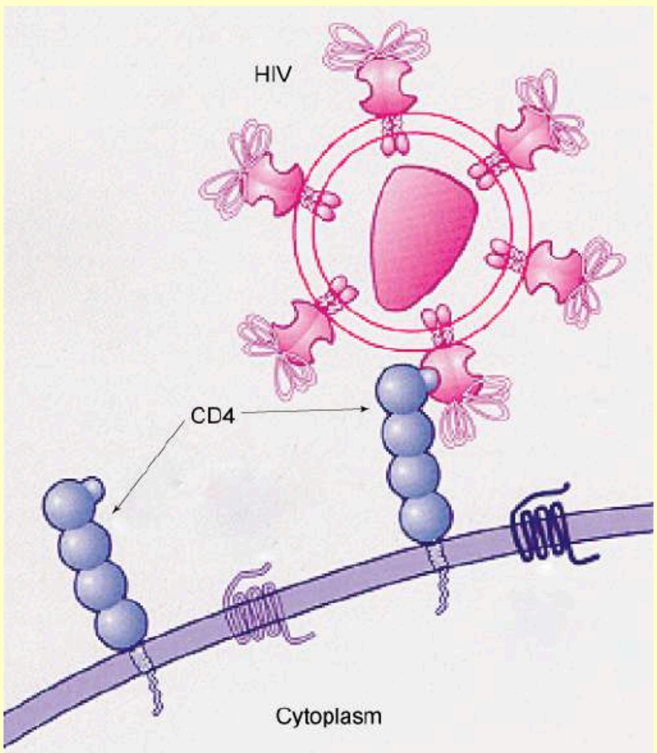

Figure 5.6 HIV binds to the CD4 receptor, a glycoprotein on the surfaces of T cells. (credit: modification of work by NIH, NIAID)

Why does the immune system attack a transplanted organ?

a. Glycoproteins and glycolipids on the surface of the organ are similar to those found on pathogens.
b. Glycoproteins and glycolipids on the surface of the organ are not recognized by the immune system.
c. Glycoproteins and glycolipids on the surface of the organ are toxic to the body.
d. Glycoproteins and glycolipids on the surface of the organ are similar to those found on immune cells.

Membrane Fluidity

The mosaic characteristic of the membrane, described in the fluid mosaic model, helps to illustrate its nature. The integral proteins and lipids exist in the membrane as separate but loosely attached molecules. These resemble the separate, multicolored tiles of a mosaic picture, and they float, moving somewhat with respect to one another. The membrane is not like a balloon, however, that can expand and contract; rather, it is fairly rigid and can burst if penetrated or if a cell takes in too much water. However, because of its mosaic nature, a very fine needle can easily penetrate a plasma membrane without causing it to burst, and the membrane will flow and self-seal when the needle is extracted.

The mosaic characteristics of the membrane explain some but not all of its fluidity. There are two other factors that help maintain this fluid characteristic. One factor is the nature of the phospholipids themselves. In their saturated form, the fatty acids in phospholipid tails are saturated with bound hydrogen atoms. There are no double bonds between adjacent carbon atoms. This results in tails that are relatively straight. In contrast, unsaturated fatty acids do not contain a maximal number of hydrogen atoms, but they do contain some double bonds between adjacent carbon atoms; a double bond results in a bend in the string of carbons of approximately 30 degrees (**Figure 5.3**).

Thus, if saturated fatty acids, with their straight tails, are compressed by decreasing temperatures, they press in on each other, making a dense and fairly rigid membrane. If unsaturated fatty acids are compressed, the “kinks” in their tails elbow adjacent phospholipid molecules away, maintaining some space between the phospholipid molecules. This “elbow room” helps to maintain fluidity in the membrane at temperatures at which membranes with saturated fatty acid tails in their phospholipids would “freeze” or solidify. The relative fluidity of the membrane is particularly important in a cold environment. A cold environment tends to compress membranes composed largely of saturated fatty acids, making them less fluid and more susceptible to rupturing. Many organisms (fish are one example) are capable of adapting to cold environments by changing the proportion of unsaturated fatty acids in their membranes in response to the lowering of the temperature.

LINK TO LEARNING

Visit this **site (http://openstaxcollege.org/l/biological_memb)** to see animations of the fluidity and mosaic quality of membranes.

Explain why glucose cannot pass directly through the cell membrane.

a. The plasma membrane is impermeable to polar molecules, so transport proteins are required.

b. The plasma membrane is selectively permeable to polar molecules, and a transport protein is required for larger molecules.

c. The plasma membrane is permeable to all polar molecules, but a transport protein is required.

d. The plasma membrane is selectively permeable to all polar molecules and a transport protein is never required for them.

Animals have an additional membrane constituent that assists in maintaining fluidity. Cholesterol, which lies alongside the phospholipids in the membrane, tends to dampen the effects of temperature on the membrane. Thus, this lipid functions as a buffer, preventing lower temperatures from inhibiting fluidity and preventing increased temperatures from increasing fluidity too much. Thus, cholesterol extends, in both directions, the range of temperature in which the membrane is appropriately fluid and consequently functional. Cholesterol also serves other functions, such as organizing clusters of transmembrane proteins into lipid rafts.

The Components and Functions of the Plasma Membrane

Component	Location
Phospholipid	Main fabric of the membrane
Cholesterol	Attached between phospholipids and between the two phospholipid layers
Integral proteins (for example, integrins)	Embedded within the phospholipid layer(s). May or may not penetrate through both layers
Peripheral proteins	On the inner or outer surface of the phospholipid bilayer; not embedded within the phospholipids
Carbohydrates (components of glycoproteins and glycolipids)	Generally attached to proteins on the outside membrane layer

Table 5.1

career CONNECTION

Immunologist

The variations in peripheral proteins and carbohydrates that affect a cell's recognition sites are of prime interest in immunology. These changes are taken into consideration in vaccine development. Many infectious diseases, such as smallpox, polio, diphtheria, and tetanus, were conquered by the use of vaccines.

Immunologists are the physicians and scientists who research and develop vaccines, as well as treat and study allergies or other immune problems. Some immunologists study and treat autoimmune problems (diseases in which a person's immune system attacks his or her own cells or tissues, such as lupus) and immunodeficiencies, whether acquired (by a virus, for example) or hereditary (such as severe combined immunodeficiency, or SCID). Immunologists are called in to help treat organ transplantation patients, who must have their immune systems suppressed so that their bodies will not reject a transplanted organ. Some immunologists work to understand natural immunity and the effects of a person's environment on it. Others work on questions about how the immune system affects the development of certain chronic diseases.

To work as an immunologist, a PhD or MD is required. In addition, immunologists undertake at least 2–3 years of training in an accredited program and must pass an examination given by the American Board of Allergy and Immunology. Immunologists must possess knowledge of the functions of the human body as they relate to issues beyond immunization, and knowledge of pharmacology and medical technology, such as medications, therapies, test materials, and surgical procedures.

science practices CONNECTION for AP® Courses

Activity

Using appropriate media, construct a model of the plasma membrane and its molecular components. In the next section, you will use the model to demonstrate the movement of different substances across the membrane.

Think About It

What research questions can be asked about plasma membranes? State three questions relating to plasma membranes along with possible solutions to the questions.

5.2 | Passive Transport

By the end of this section, you will be able to:

- Identify and describe the properties of life. Why and how does passive transport occur across membranes?
- What is tonicity, and how is it relevant to passive transport?

Connection for AP® Courses

Preventing dehydration is important for both plants and animals. Water moves across plasma membranes by a specific type of diffusion called osmosis. The concentration gradient of water across a membrane is inversely proportional to the concentration of solutes; that is, water moves through channel proteins called aquaporins from higher water concentration to lower water concentration. Solute concentration outside and inside the cell influences the rate of osmosis. Tonicity describes how the extracellular concentration of solutes can change the volume of a cell by affecting osmosis, often correlating with the osmolarity of the solution, i.e., the total solute concentration of the solution. In a hypotonic situation, because the extracellular fluid has a lower concentration of solutes (lower osmolarity) than the fluid inside the cell, water enters the cell, causing it to swell and possibly burst. The cell walls of plants prevent them from bursting, but animal cells, such as red blood cells, can lyse. When a cell is placed in a hypertonic solution, water leaves the cell because the cell has a higher water potential than the extracellular solution. When the concentrations of solute are equal on both sides of the membrane (isotonic), no net movement of water into or out of the cell occurs. Living organisms have evolved a variety of ways to maintain osmotic balance; for example, marine fish secrete excess salt through the gills to maintain dynamic homeostasis.

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Essential Knowledge	**2.B.2** Growth and dynamic homeostasis are maintained by the constant movement of molecules across membranes.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Science Practice	**3.1** The student can pose scientific questions.
Learning Objective	**2.11** The student is able to construct models that connect the movement of molecules across membranes with membrane structure and function.
Essential Knowledge	**2.B.2** Growth and dynamic homeostasis are maintained by the constant movement of molecules across membranes.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Science Practice	**3.1** The student can pose scientific questions.
Learning Objective	**2.12** The student is able to use representations and models to analyze situation or solve problems qualitatively and quantitatively to investigate whether dynamic homeostasis is maintained by the active movement of molecules across membranes.

The Science Practice Challenge Questions contain additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 2.25][APLO 2.27][APLO 4.3][APLO 4.17][APLO1.9] [APLO 2.16][APLO 2.17][APLO 2.18]

Plasma membranes must allow certain substances to enter and leave a cell, and prevent some harmful materials from entering and some essential materials from leaving. In other words, plasma membranes are **selectively permeable**—they allow some substances to pass through, but not others. If they were to lose this selectivity, the cell would no longer be able to sustain itself, and it would be destroyed. Some cells require larger amounts of specific substances than do other cells; they must have a way of obtaining these materials from extracellular fluids. This may happen passively, as certain materials move back and forth, or the cell may have special mechanisms that facilitate transport. Some materials are so important to a cell that it spends some of its energy, hydrolyzing adenosine triphosphate (ATP), to obtain these materials. Red blood cells use some of their energy doing just that. Most cells spend the majority of their energy to maintain an imbalance of sodium and potassium ions between the interior and exterior of the cell.

The most direct forms of membrane transport are passive. **Passive transport** is a naturally occurring phenomenon and does not require the cell to exert any of its energy to accomplish the movement. In passive transport, substances move from an area of higher concentration to an area of lower concentration. A physical space in which there is a range of concentrations of a single substance is said to have a **concentration gradient**.

Selective Permeability

Plasma membranes are asymmetric: the interior of the membrane is not identical to the exterior of the membrane. In fact, there is a considerable difference between the array of phospholipids and proteins between the two leaflets that form a membrane. On the interior of the membrane, some proteins serve to anchor the membrane to fibers of the cytoskeleton. There are peripheral proteins on the exterior of the membrane that bind elements of the extracellular matrix. Carbohydrates, attached to lipids or proteins, are also found on the exterior surface of the plasma membrane. These carbohydrate complexes help the cell bind substances that the cell needs in the extracellular fluid. This adds considerably to the selective nature of plasma membranes (**Figure 5.7**).

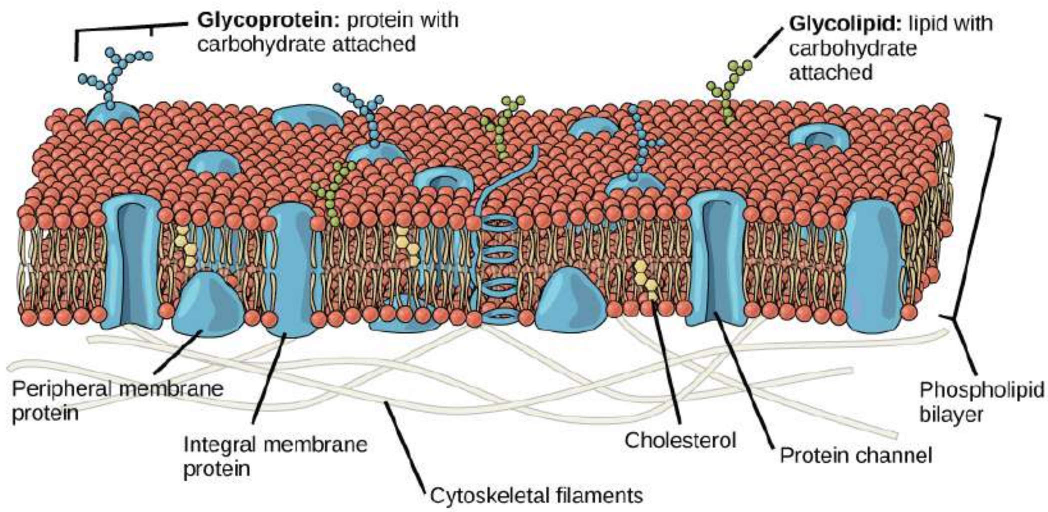

Figure 5.7 The exterior surface of the plasma membrane is not identical to the interior surface of the same membrane.

Recall that plasma membranes are amphiphilic: They have hydrophilic and hydrophobic regions. This characteristic helps the movement of some materials through the membrane and hinders the movement of others. Lipid-soluble material with a low molecular weight can easily slip through the hydrophobic lipid core of the membrane. Substances such as the fat-soluble vitamins A, D, E, and K readily pass through the plasma membranes in the digestive tract and other tissues. Fat-soluble drugs and hormones also gain easy entry into cells and are readily transported into the body's tissues and organs. Similarly, molecules of oxygen and carbon dioxide have no charge and so pass through membranes by simple diffusion.

Polar substances present problems for the membrane. While some polar molecules connect easily with the outside of a cell, they cannot readily pass through the lipid core of the plasma membrane. Additionally, while small ions could easily slip through the spaces in the mosaic of the membrane, their charge prevents them from doing so. Ions such as sodium, potassium, calcium, and chloride must have special means of penetrating plasma membranes. Simple sugars and amino acids also need help with transport across plasma membranes, achieved by various transmembrane proteins (channels).

Diffusion

Diffusion is a passive process of transport. A single substance tends to move from an area of high concentration to an area of low concentration until the concentration is equal across a space. You are familiar with diffusion of substances through the air. For example, think about someone opening a bottle of ammonia in a room filled with people. The ammonia gas is at its highest concentration in the bottle; its lowest concentration is at the edges of the room. The ammonia vapor will diffuse, or spread away, from the bottle, and gradually, more and more people will smell the ammonia as it spreads. Materials move within the cell's cytosol by diffusion, and certain materials move through the plasma membrane by diffusion (**Figure 5.8**). Diffusion expends no energy. On the contrary, concentration gradients are a form of potential energy, dissipated as the gradient is eliminated.

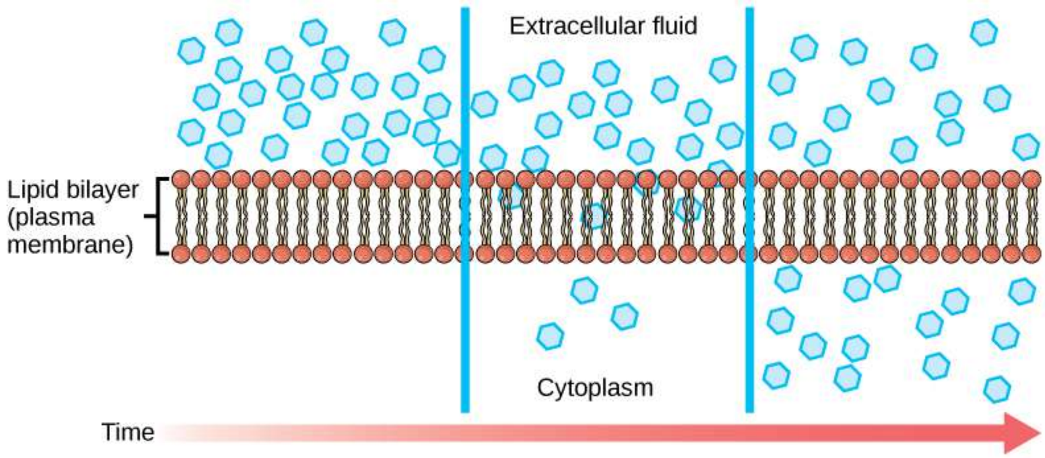

Figure 5.8 Diffusion through a permeable membrane moves a substance from an area of high concentration (extracellular fluid, in this case) down its concentration gradient (into the cytoplasm). (credit: modification of work by Mariana Ruiz Villareal)

Each separate substance in a medium, such as the extracellular fluid, has its own concentration gradient, independent of the concentration gradients of other materials. In addition, each substance will diffuse according to that gradient. Within a system, there will be different rates of diffusion of the different substances in the medium.

Factors That Affect Diffusion

Molecules move constantly in a random manner, at a rate that depends on their mass, their environment, and the amount of thermal energy they possess, which in turn is a function of temperature. This movement accounts for the diffusion of molecules through whatever medium in which they are localized. A substance will tend to move into any space available to it until it is evenly distributed throughout it. After a substance has diffused completely through a space, removing its concentration gradient, molecules will still move around in the space, but there will be no *net* movement of the number of molecules from one area to another. This lack of a concentration gradient in which there is no net movement of a substance is known as dynamic equilibrium. While diffusion will go forward in the presence of a concentration gradient of a substance, several factors affect the rate of diffusion.

- Extent of the concentration gradient: The greater the difference in concentration, the more rapid the diffusion. The closer the distribution of the material gets to equilibrium, the slower the rate of diffusion becomes.
- Mass of the molecules diffusing: Heavier molecules move more slowly; therefore, they diffuse more slowly. The reverse is true for lighter molecules.
- Temperature: Higher temperatures increase the energy and therefore the movement of the molecules, increasing the rate of diffusion. Lower temperatures decrease the energy of the molecules, thus decreasing the rate of diffusion.
- Solvent density: As the density of a solvent increases, the rate of diffusion decreases. The molecules slow down because they have a more difficult time getting through the denser medium. If the medium is less dense, diffusion increases. Because cells primarily use diffusion to move materials within the cytoplasm, any increase in the cytoplasm's density will inhibit the movement of the materials. An example of this is a person experiencing dehydration. As the body's cells lose water, the rate of diffusion decreases in the cytoplasm, and the cells' functions deteriorate. Neurons tend to be very sensitive to this effect. Dehydration frequently leads to unconsciousness and possibly coma because of the decrease in diffusion rate within the cells.
- Solubility: As discussed earlier, nonpolar or lipid-soluble materials pass through plasma membranes more easily than polar materials, allowing a faster rate of diffusion.
- Surface area and thickness of the plasma membrane: Increased surface area increases the rate of diffusion, whereas a thicker membrane reduces it.
- Distance travelled: The greater the distance that a substance must travel, the slower the rate of diffusion. This places an upper limitation on cell size. A large, spherical cell will die because nutrients or waste cannot reach or leave the

center of the cell, respectively. Therefore, cells must either be small in size, as in the case of many prokaryotes, or be flattened, as with many single-celled eukaryotes.

A variation of diffusion is the process of filtration. In filtration, material moves according to its concentration gradient through a membrane; sometimes the rate of diffusion is enhanced by pressure, causing the substances to filter more rapidly. This occurs in the kidney, where blood pressure forces large amounts of water and accompanying dissolved substances, or **solutes**, out of the blood and into the renal tubules. The rate of diffusion in this instance is almost totally dependent on pressure. One of the effects of high blood pressure is the appearance of protein in the urine, which is "squeezed through" by the abnormally high pressure.

Facilitated transport

In **facilitated transport**, also called facilitated diffusion, materials diffuse across the plasma membrane with the help of membrane proteins. A concentration gradient exists that would allow these materials to diffuse into the cell without expending cellular energy. However, these materials are polar molecules that are repelled by the hydrophobic parts of the cell membrane. Facilitated transport proteins shield these materials from the repulsive force of the membrane, allowing them to diffuse into the cell.

The material being transported is first attached to protein or glycoprotein receptors on the exterior surface of the plasma membrane. This allows the material that is needed by the cell to be removed from the extracellular fluid. The substances are then passed to specific integral proteins that facilitate their passage. Some of these integral proteins are collections of beta pleated sheets that form a pore or channel through the phospholipid bilayer. Others are carrier proteins which bind with the substance and aid its diffusion through the membrane.

Channels

The integral proteins involved in facilitated transport are collectively referred to as **transport proteins**, and they function as either channels for the material or carriers. In both cases, they are transmembrane proteins. Channels are specific for the substance that is being transported. **Channel proteins** have hydrophilic domains exposed to the intracellular and extracellular fluids; they additionally have a hydrophilic channel through their core that provides a hydrated opening through the membrane layers (**Figure 5.9**). Passage through the channel allows polar compounds to avoid the nonpolar central layer of the plasma membrane that would otherwise slow or prevent their entry into the cell. **Aquaporins** are channel proteins that allow water to pass through the membrane at a very high rate.

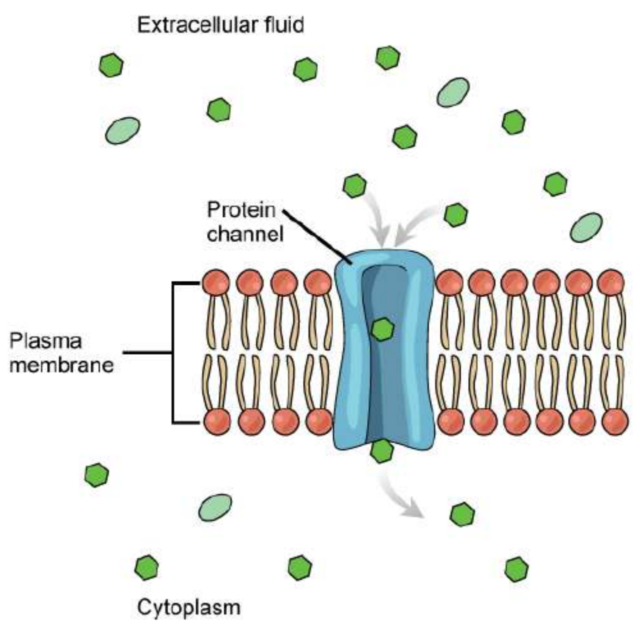

Figure 5.9 Facilitated transport moves substances down their concentration gradients. They may cross the plasma membrane with the aid of channel proteins. (credit: modification of work by Mariana Ruiz Villareal)

Channel proteins are either open at all times or they are "gated," which controls the opening of the channel. The attachment of a particular ion to the channel protein may control the opening, or other mechanisms or substances may be involved. In some tissues, sodium and chloride ions pass freely through open channels, whereas in other tissues a gate must be opened to allow passage. An example of this occurs in the kidney, where both forms of channels are found in different parts of the renal tubules. Cells involved in the transmission of electrical impulses, such as nerve and muscle cells, have gated channels for sodium, potassium, and calcium in their membranes. Opening and closing of these channels changes the relative concentrations on opposing sides of the membrane of these ions, resulting in the facilitation of electrical transmission along membranes (in the case of nerve cells) or in muscle contraction (in the case of muscle cells).

Carrier Proteins

Another type of protein embedded in the plasma membrane is a **carrier protein**. This aptly named protein binds a substance and, in doing so, triggers a change of its own shape, moving the bound molecule from the outside of the cell to its interior (**Figure 5.10**); depending on the gradient, the material may move in the opposite direction. Carrier proteins are typically specific for a single substance. This selectivity adds to the overall selectivity of the plasma membrane. The exact mechanism for the change of shape is poorly understood. Proteins can change shape when their hydrogen bonds are affected, but this may not fully explain this mechanism. Each carrier protein is specific to one substance, and there are a finite number of these proteins in any membrane. This can cause problems in transporting enough of the material for the cell to function properly. When all of the proteins are bound to their ligands, they are saturated and the rate of transport is at its maximum. Increasing the concentration gradient at this point will not result in an increased rate of transport.

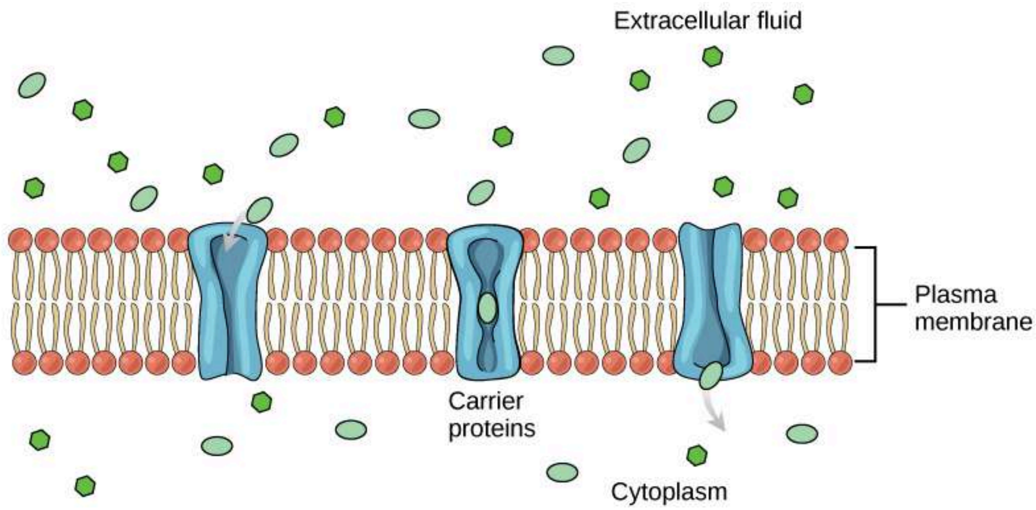

Figure 5.10 Some substances are able to move down their concentration gradient across the plasma membrane with the aid of carrier proteins. Carrier proteins change shape as they move molecules across the membrane. (credit: modification of work by Mariana Ruiz Villareal)

An example of this process occurs in the kidney. Glucose, water, salts, ions, and amino acids needed by the body are filtered in one part of the kidney. This filtrate, which includes glucose, is then reabsorbed in another part of the kidney. Because there are only a finite number of carrier proteins for glucose, if more glucose is present than the proteins can handle, the excess is not transported and it is excreted from the body in the urine. In a diabetic individual, this is described as "spilling glucose into the urine." A different group of carrier proteins called glucose transport proteins, or GLUTs, are involved in transporting glucose and other hexose sugars through plasma membranes within the body.

Channel and carrier proteins transport material at different rates. Channel proteins transport much more quickly than do carrier proteins. Channel proteins facilitate diffusion at a rate of tens of millions of molecules per second, whereas carrier proteins work at a rate of a thousand to a million molecules per second.

Osmosis

Osmosis is the movement of water through a semipermeable membrane according to the concentration gradient of water across the membrane, which is inversely proportional to the concentration of solutes. While diffusion transports material across membranes and within cells, osmosis transports *only water* across a membrane and the membrane limits the diffusion of solutes in the water. Not surprisingly, the aquaporins that facilitate water movement play a large role in osmosis, most prominently in red blood cells and the membranes of kidney tubules.

Mechanism

Osmosis is a special case of diffusion. Water, like other substances, moves from an area of high concentration to one of low concentration. An obvious question is what makes water move at all? Imagine a beaker with a semipermeable membrane separating the two sides or halves (**Figure 5.11**). On both sides of the membrane the water level is the same, but there are different concentrations of a dissolved substance, or **solute**, that cannot cross the membrane (otherwise the concentrations on each side would be balanced by the solute crossing the membrane). If the volume of the solution on both sides of the membrane is the same, but the concentrations of solute are different, then there are different amounts of water, the solvent, on either side of the membrane.

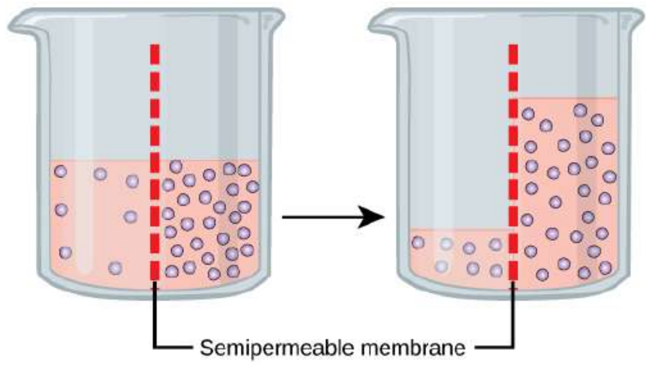

Figure 5.11 In osmosis, water always moves from an area of higher water concentration to one of lower concentration. In the diagram shown, the solute cannot pass through the selectively permeable membrane, but the water can.

To illustrate this, imagine two full glasses of water. One has a single teaspoon of sugar in it, whereas the second one contains one-quarter cup of sugar. If the total volume of the solutions in both cups is the same, which cup contains more water? Because the large amount of sugar in the second cup takes up much more space than the teaspoon of sugar in the first cup, the first cup has more water in it.

Returning to the beaker example, recall that it has a mixture of solutes on either side of the membrane. A principle of diffusion is that the molecules move around and will spread evenly throughout the medium if they can. However, only the material capable of getting through the membrane will diffuse through it. In this example, the solute cannot diffuse through the membrane, but the water can. Water has a concentration gradient in this system. Thus, water will diffuse down its concentration gradient, crossing the membrane to the side where it is less concentrated. This diffusion of water through the membrane—osmosis—will continue until the concentration gradient of water goes to zero or until the hydrostatic pressure of the water balances the osmotic pressure. Osmosis proceeds constantly in living systems.

The beaker example here occurs in an open system where the volume of fluid can increase and decrease freely. Cells, on the other hand, are composed of proteins and other substances embedded in the aqueous cytoplasm. These substances could be considered solutes for the purposes of predicting osmosis. The cell membrane keeps most of the proteins and other substances within the cell, causing the cell to have a higher osmolarity than pure water.

Suppose you perform an experiment where you placed red blood cells in an environment of pure water. What do you suppose would happen to the cells? Because the concentration of solute is higher in the red blood cell than it is in the beaker, water would rush into the red blood cell. What do you think would happen to the red blood cell, given that its cell membrane is made up of a fixed surface area? It is likely that the red blood cell will undergo hemolysis, where they swell up with water and burst. It should be noted, however, that most cells have mechanisms to prevent them from taking on too much water. However, red blood cells lack these controls, making them ideal for osmolarity studies.

This is an important consideration for clinicians delivering drugs intravenously. How would the drug have to be formulated, in terms of osmolarity, to prevent red blood cells from undergoing hemolysis? In order to prevent hemolysis of red blood cells in the blood, drugs are typically formulated in an isotonic solution with the blood to maintain osmolarity.

Tonicity

Tonicity describes how an extracellular solution can change the volume of a cell by affecting osmosis. A solution's tonicity often directly correlates with the osmolarity of the solution. **Osmolarity** describes the total solute concentration of the solution. A solution with low osmolarity has a greater number of water molecules relative to the number of solute particles; a solution with high osmolarity has fewer water molecules with respect to solute particles. In a situation in which solutions of two different osmolarities are separated by a membrane permeable to water, though not to the solute, water will move from the side of the membrane with lower osmolarity (and more water) to the side with higher osmolarity (and less water). This effect makes sense if you remember that the solute cannot move across the membrane, and thus the only component in the system that can move—the water—moves along its own concentration gradient. An important distinction that concerns living systems is that osmolarity measures the number of particles (which may be molecules) in a solution. Therefore, a solution that is cloudy with cells may have a lower osmolarity than a solution that is clear, if the second solution contains more dissolved molecules than there are cells.

Hypotonic Solutions

Three terms—hypotonic, isotonic, and hypertonic—are used to relate the osmolarity of a cell to the osmolarity of the extracellular fluid that contains the cells. In a **hypotonic** situation, the extracellular fluid has lower osmolarity than the fluid inside the cell, and water enters the cell. (In living systems, the point of reference is always the cytoplasm, so the prefix *hypo-* means that the extracellular fluid has a lower concentration of solutes, or a lower osmolarity, than the cell cytoplasm.) It also means that the extracellular fluid has a higher concentration of water in the solution than does the cell. In this situation, water will follow its concentration gradient and enter the cell.

Hypertonic Solutions

As for a **hypertonic** solution, the prefix *hyper-* refers to the extracellular fluid having a higher osmolarity than the cell's cytoplasm; therefore, the fluid contains less water than the cell does. Because the cell has a relatively higher concentration of water, water will leave the cell.

Isotonic Solutions

In an **isotonic** solution, the extracellular fluid has the same osmolarity as the cell. If the osmolarity of the cell matches that of the extracellular fluid, there will be no net movement of water into or out of the cell, although water will still move in and out. Blood cells and plant cells in hypertonic, isotonic, and hypotonic solutions take on characteristic appearances (**Figure 5.12**).

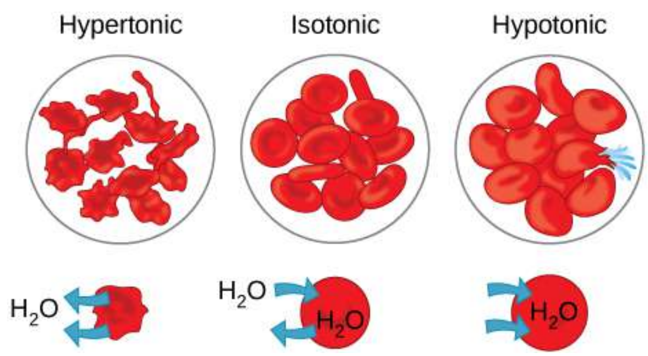

Figure 5.12 Osmotic pressure changes the shape of red blood cells in hypertonic, isotonic, and hypotonic solutions (credit: Mariana Ruiz Villareal)

LINK TO LEARNING

For a video illustrating the process of diffusion in solutions, visit this **site (http://openstaxcollege.org/l/dispersion)** .

Explain the difference between the **two beakers (http://openstaxcollege.org/l/dispersion)** .

a. The lower temperature of left beaker causes yellow dye to diffuse faster than the right beaker.

b. The lower temperature in left beaker causes yellow dye to diffuse slower in it than in the right beaker.

c. The higher temperature of left beaker causes faster diffusion of yellow dye in the left beaker.

d. The higher temperature of right beaker causes slower diffusion of yellow dye in the right beaker.

Tonicity in Living Systems

In a hypotonic environment, water enters a cell, and the cell swells. In an isotonic condition, the relative concentrations of solute and solvent are equal on both sides of the membrane. There is no net water movement; therefore, there is no change in the size of the cell. In a hypertonic solution, water leaves a cell and the cell shrinks. If either the hypo- or hyper- condition goes to excess, the cell's functions become compromised, and the cell may be destroyed.

A red blood cell will burst, or lyse, when it swells beyond the plasma membrane's capability to expand. Remember, the membrane resembles a mosaic, with discrete spaces between the molecules composing it. If the cell swells, and the spaces between the lipids and proteins become too large, the cell will break apart.

In contrast, when excessive amounts of water leave a red blood cell, the cell shrinks, or crenates. This has the effect of concentrating the solutes left in the cell, making the cytosol denser and interfering with diffusion within the cell. The cell's ability to function will be compromised and may also result in the death of the cell.

Various living things have ways of controlling the effects of osmosis—a mechanism called osmoregulation. Some organisms, such as plants, fungi, bacteria, and some protists, have cell walls that surround the plasma membrane and prevent cell lysis in a hypotonic solution. The plasma membrane can only expand to the limit of the cell wall, so the cell will not lyse. In fact, the cytoplasm in plants is always slightly hypertonic to the cellular environment, and water will always enter a cell if water is available. This inflow of water produces turgor pressure, which stiffens the cell walls of the plant (**Figure 5.13**). In nonwoody plants, turgor pressure supports the plant. Conversly, if the plant is not watered, the extracellular fluid will become hypertonic, causing water to leave the cell. In this condition, the cell does not shrink because the cell wall is not flexible. However, the cell membrane detaches from the wall and constricts the cytoplasm. This is called **plasmolysis**. Plants lose turgor pressure in this condition and wilt (**Figure 5.14**).

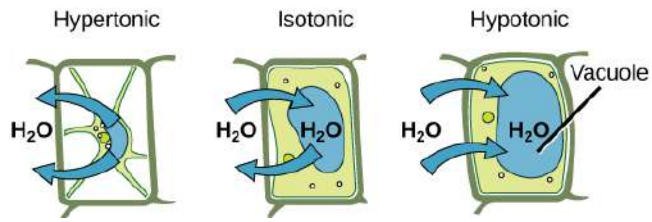

Figure 5.13 The turgor pressure within a plant cell depends on the tonicity of the solution that it is bathed in. (credit: modification of work by Mariana Ruiz Villareal)

Figure 5.14 Without adequate water, the plant on the left has lost turgor pressure, visible in its wilting; the turgor pressure is restored by watering it (right). (credit: Victor M. Vicente Selvas)

Tonicity is a concern for all living things. For example, paramecia and amoebas, which are protists that lack cell walls, have contractile vacuoles. This vesicle collects excess water from the cell and pumps it out, keeping the cell from lysing as it takes on water from its environment (**Figure 5.15**).

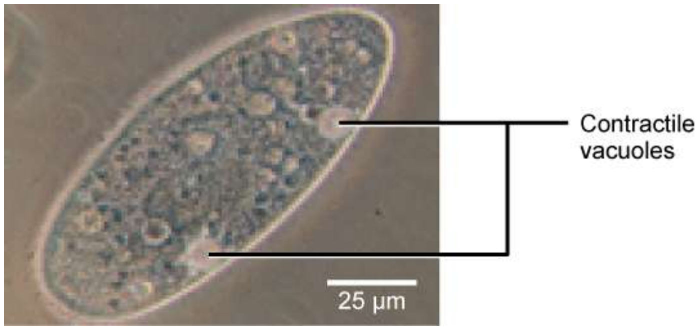

Figure 5.15 A paramecium's contractile vacuole, here visualized using bright field light microscopy at 480x magnification, continuously pumps water out of the organism's body to keep it from bursting in a hypotonic medium. (credit: modification of work by NIH; scale-bar data from Matt Russell)

Many marine invertebrates have internal salt levels matched to their environments, making them isotonic with the water in which they live. Fish, however, must spend approximately five percent of their metabolic energy maintaining osmotic homeostasis. Freshwater fish live in an environment that is hypotonic to their cells. These fish actively take in salt through their gills and excrete diluted urine to rid themselves of excess water. Saltwater fish live in the reverse environment, which is hypertonic to their cells, and they secrete salt through their gills and excrete highly concentrated urine.

In vertebrates, the kidneys regulate the amount of water in the body. Osmoreceptors are specialized cells in the brain that monitor the concentration of solutes in the blood. If the levels of solutes increase beyond a certain range, a hormone is released that retards water loss through the kidney and dilutes the blood to safer levels. Animals also have high concentrations of albumin, which is produced by the liver, in their blood. This protein is too large to pass easily through plasma membranes and is a major factor in controlling the osmotic pressures applied to tissues.

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Activity

Use the model of the plasma cell membrane you constructed to demonstrate how O_2 and CO_2, H_2O, Na^+ and K^+, and glucose are transported across the membrane.

Think About It

Why should farmers consider the salinity of the soil in which they grow crops?

Answer: Farmers need to consider the salinity of soil, because the movement of water into and out of plant cells depends on the solute concentration of their environment. In soil high in saline, water will be drawn out of root cells causing the cells to shrivel, and the plant to die.

5.3 | Active Transport

By the end of this section, you will be able to:

- How do electrochemical gradients affect the active transport of ions and molecules across membranes?

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If a substance must move into the cell against its concentration gradient, the cell must use free energy, often provided by ATP, and carrier proteins acting as pumps to move the substance. Substances that move across membranes by this mechanism, a process called active transport, include ions, such as Na^+ and K^+. The combined gradients that affect movement of an ion are its concentration gradient and its electrical gradient (the difference in charge across the membrane); together these gradients are called the electrochemical gradient. To move substances against an electrochemical gradient requires free energy. The sodium-potassium pump, which maintains electrochemical gradients across the membranes of nerve cells in animals, is an example of primary active transport. The formation of H^+ gradients by secondary active transport (co-transport) is important in cellular respiration and photosynthesis and moving glucose into cells.

Information presented and the examples highlighted in the section support concepts and learning objectives outlined in Big Idea 2 of the AP® Biology Curriculum Framework. The learning objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices (SP).

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.B	Growth, reproduction and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.
Essential Knowledge	**2.B.2** Growth and dynamic homeostasis are maintained by the constant movement of molecules across membranes.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	**2.12** The student is able to use representations and models to analyze situations or solve problems qualitatively and quantitatively to investigate whether dynamic homeostasis is maintained by the active movement of molecules across membranes.

The Science Practice Challenge Questions contain additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 2.10][APLO 2.17][APLO 1.2][APLO 3.24]

Active transport mechanisms require the use of the cell’s energy, usually in the form of adenosine triphosphate (ATP). If a substance must move into the cell against its concentration gradient—that is, if the concentration of the substance inside the cell is greater than its concentration in the extracellular fluid (and vice versa)—the cell must use energy to move the substance. Some active transport mechanisms move small-molecular weight materials, such as ions, through the membrane. Other mechanisms transport much larger molecules.

Electrochemical Gradient

We have discussed simple concentration gradients—differential concentrations of a substance across a space or a membrane—but in living systems, gradients are more complex. Because ions move into and out of cells and because cells contain proteins that do not move across the membrane and are mostly negatively charged, there is also an electrical gradient, a difference of charge, across the plasma membrane. The interior of living cells is electrically negative with respect to the extracellular fluid in which they are bathed, and at the same time, cells have higher concentrations of potassium (K^+) and lower concentrations of sodium (Na^+) than does the extracellular fluid. So in a living cell, the concentration gradient of Na^+ tends to drive it into the cell, and the electrical gradient of Na^+ (a positive ion) also tends to drive it inward to the negatively charged interior. The situation is more complex, however, for other elements such as potassium. The electrical gradient of K^+, a positive ion, also tends to drive it into the cell, but the concentration gradient of K^+ tends to drive K^+ *out* of the cell (**Figure 5.16**). The combined gradient of concentration and electrical charge that affects an ion is called its **electrochemical gradient**.

visual CONNECTION

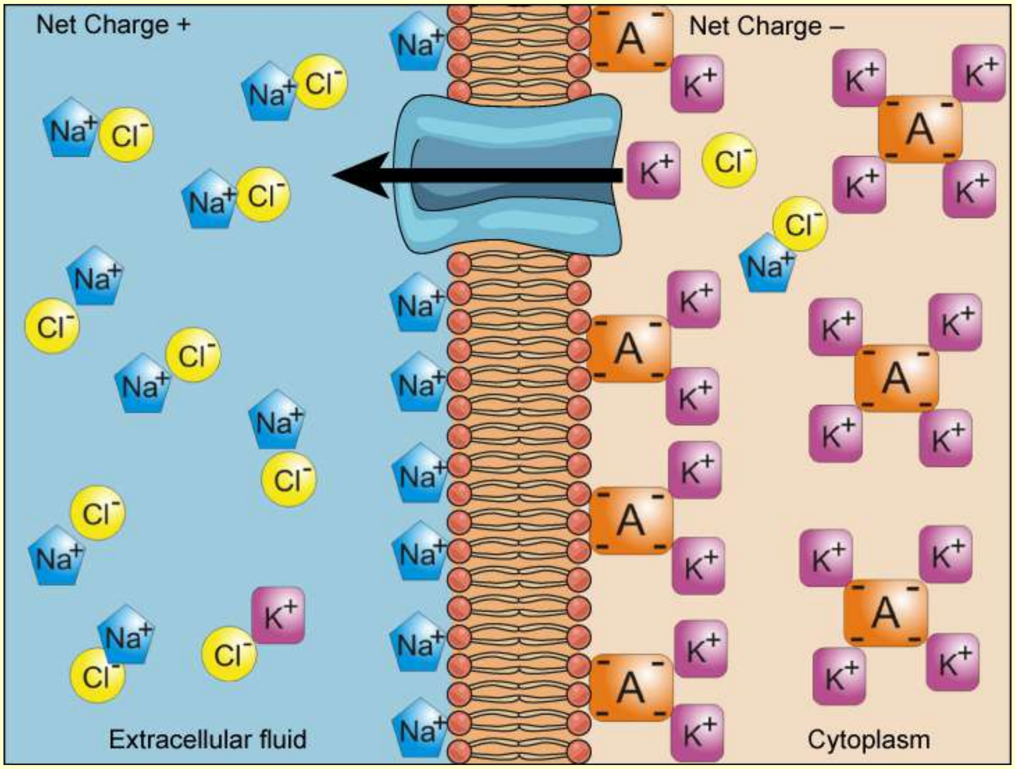

Figure 5.16 Electrochemical gradients arise from the combined effects of concentration gradients and electrical gradients. Structures labeled A represent proteins. (credit: "Synaptitude"/Wikimedia Commons)

If the pH outside the cell decreases, would you expect the amount of amino acids transported into the cell to increase or decrease?

a. Transport of amino acids into the cell increases
b. Transport of amino acids into the cell stops.
c. Transport of amino acids into the cell is not affected by pH.
d. Transport of amino acid into the cell decreases.

Moving Against a Gradient

To move substances against a concentration or electrochemical gradient, the cell must use energy. This energy is harvested from ATP generated through the cell's metabolism. Active transport mechanisms, collectively called **pumps**, work against electrochemical gradients. Small substances constantly pass through plasma membranes. Active transport maintains concentrations of ions and other substances needed by living cells in the face of these passive movements. Much of a cell's supply of metabolic energy may be spent maintaining these processes. (Most of a red blood cell's metabolic energy is used to maintain the imbalance between exterior and interior sodium and potassium levels required by the cell.) Because active transport mechanisms depend on a cell's metabolism for energy, they are sensitive to many metabolic poisons that interfere with the supply of ATP.

Two mechanisms exist for the transport of small-molecular weight material and small molecules. **Primary active transport** moves ions across a membrane and creates a difference in charge across that membrane, which is directly dependent on ATP. **Secondary active transport** describes the movement of material that is due to the electrochemical gradient established by primary active transport that does not directly require ATP.

Carrier Proteins for Active Transport

An important membrane adaption for active transport is the presence of specific carrier proteins or pumps to facilitate movement: there are three types of these proteins or **transporters** (Figure 5.17). A **uniporter** carries one specific ion or molecule. A **symporter** carries two different ions or molecules, both in the same direction. An **antiporter** also carries two different ions or molecules, but in different directions. All of these transporters can also transport small, uncharged organic molecules like glucose. These three types of carrier proteins are also found in facilitated diffusion, but they do not require ATP to work in that process. Some examples of pumps for active transport are Na^+-K^+ ATPase, which carries sodium and potassium ions, and H^+-K^+ ATPase, which carries hydrogen and potassium ions. Both of these are antiporter carrier proteins. Two other carrier proteins are Ca^{2+} ATPase and H^+ ATPase, which carry only calcium and only hydrogen ions, respectively. Both are pumps.

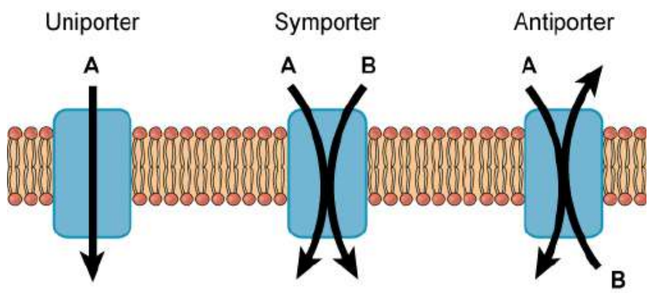

Figure 5.17 A uniporter carries one molecule or ion. A symporter carries two different molecules or ions, both in the same direction. An antiporter also carries two different molecules or ions, but in different directions. (credit: modification of work by “Lupask”/Wikimedia Commons)

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The primary active transport that functions with the active transport of sodium and potassium allows secondary active transport to occur. The second transport method is still considered active because it depends on the use of energy as does primary transport (illustrative example).

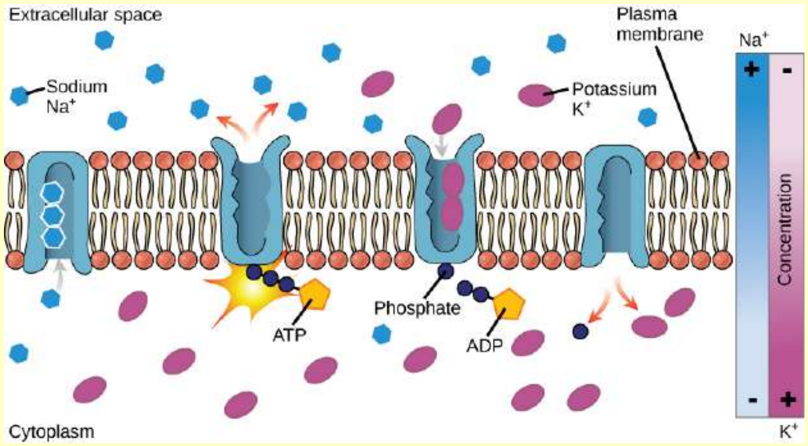

Figure 5.18 Primary active transport moves ions across a membrane, creating an electrochemical gradient (electrogenic transport). (credit: modification of work by Mariana Ruiz Villareal)

One of the most important pumps in animal cells is the sodium-potassium pump (Na^+-K^+ ATPase), which maintains the electrochemical gradient (and the correct concentrations of Na^+ and K^+) in living cells. The sodium-potassium pump moves K^+ into the cell while moving Na^+ out at the same time, at a ratio of three Na^+ for every two K^+ ions moved in. The Na^+-K^+ ATPase exists in two forms, depending on its orientation to the interior or exterior of the cell and its affinity for either sodium or potassium ions. The process consists of the following six steps:

1. With the enzyme oriented towards the interior of the cell, the carrier has a high affinity for sodium ions. Three ions bind to the protein.
2. The protein carrier hydrolyzes ATP and a low-energy phosphate group attaches to it.
3. As a result, the carrier changes shape and re-orients itself towards the exterior of the membrane. The protein's affinity for sodium decreases and the three sodium ions leave the carrier.
4. The shape change increases the carrier's affinity for potassium ions, and two such ions attach to the protein. Subsequently, the low-energy phosphate group detaches from the carrier.
5. With the phosphate group removed and potassium ions attached, the carrier protein repositions itself towards the interior of the cell.
6. The carrier protein, in its new configuration, has a decreased affinity for potassium, and the two ions are released into the cytoplasm. The protein now has a higher affinity for sodium ions, and the process starts again.

Several things have happened as a result of this process. At this point, there are more sodium ions outside of the cell than inside and more potassium ions inside than out. For every three ions of sodium that move out, two ions of potassium move in. This results in the interior being slightly more negative relative to the exterior. This difference in charge is important to creating the conditions necessary for the secondary process. Therefore, the sodium-potassium pump is an **electrogenic pump** (a pump that creates a charge imbalance) contributing to the membrane potential.

What will happen to the opening of the sodium-potassium pump if no ATP is present in a cell?

a. It will remain facing the extracellular space, with sodium ions bound.

b. It will remain facing the extracellular space, with potassium ions bound.

c. It will remain facing the cytoplasm, but no sodium ions would bind.

d. It will remain facing the cytoplasm, with sodium ions bound.

LINK TO LEARNING

Visit the site (http://openstaxcollege.org/l/Na_K_ATPase) to see a simulation of active transport in a sodium-potassium ATPase.

Sodium and potassium are necessary electrolytes. As a result, the human body uses a great deal of energy keeping these electrolytes in balance. Explain why the body needs to use energy for this process.

a. ATP is required to move sodium ions against their concentration gradient outside the cell.

b. ATP is required to allow entry of potassium ions inside the cell.

c. ATP is required to allow entry of sodium ions inside the cell.

d. ATP is required to release potassium ions outside the cell.

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Activity

Create a representation/diagram (or use the model you constructed of the plasma cell membrane) to explain how the sodium-potassium pump contributes to the net negative change of the interior of an animal nerve cell.

Think About It

If the pH outside the cell decreases, would you expect the amount of amino acids and glucose transported into the cell to increase or decrease? Justify your reasoning.

Secondary Active Transport (Co-transport)

Secondary active transport brings sodium ions, and possibly other compounds, into the cell. As sodium ion concentrations build outside of the plasma membrane because of the action of the primary active transport process, an electrochemical gradient is created. If a channel protein exists and is open, the sodium ions will be pulled through the membrane. This movement is used to transport other substances that can attach themselves to the transport protein through the membrane (**Figure 5.19**). Many amino acids, as well as glucose, enter a cell this way. This secondary process is also used to store high-energy hydrogen ions in the mitochondria of plant and animal cells for the production of ATP. The potential energy that accumulates in the stored hydrogen ions is translated into kinetic energy as the ions surge through the channel protein ATP synthase, and that energy is used to convert ADP into ATP.

visual CONNECTION

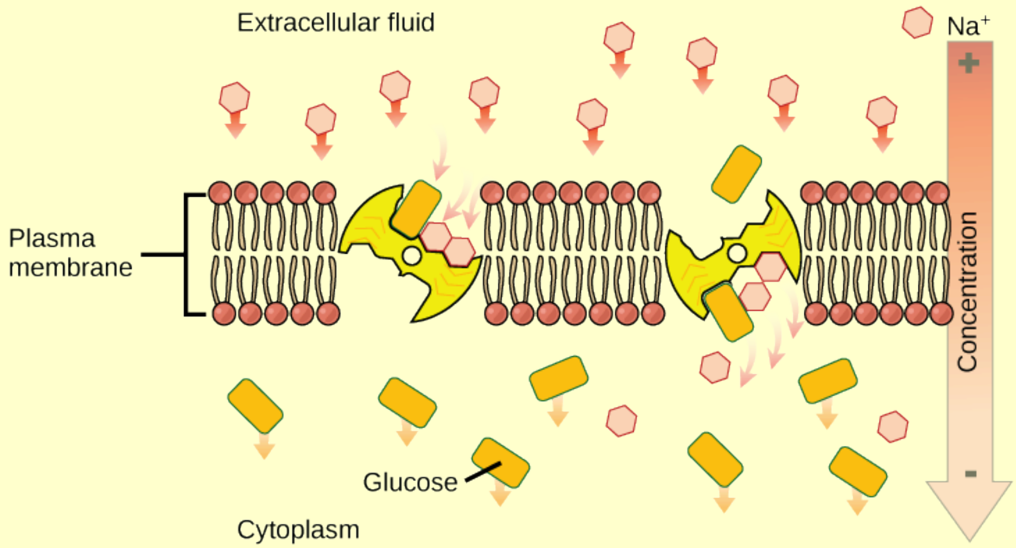


Figure 5.19 An electrochemical gradient, created by primary active transport, can move other substances against their concentration gradients, a process called co-transport or secondary active transport. (credit: modification of work by Mariana Ruiz Villareal)

Injection of a potassium solution into a person's blood is lethal. Potassium is used in capital punishment and euthanasia. Why do you think a potassium solution injection is lethal?

a. Excess potassium disrupts the membrane components
b. Excess potassium increases action potential generation, leading to uncoordinated organ activity.
c. Potassium dissipates the electrochemical gradient in cardiac muscle cells, preventing them from contracting.
d. Potassium creates a new concentration gradient across the cell membrane, preventing sodium from leaving the cell.

5.4 | Bulk Transport

By the end of this section, you will be able to:

- What are the differences among the different types of endocytosis: (phagocytosis, pinocytosis, and receptor-mediated endocytosis) and exocytosis?

Connection for AP® Courses

Diffusion, osmosis, and active transport are used to transport fairly small molecules across plasma cell membranes. However, sometimes large particles, such as macromolecules, parts of cells, or even unicellular microorganisms, can be engulfed by other cells in a process called phagocytosis or "cell eating." In this form of endocytosis, the cell membrane surrounds the particle, pinches off, and brings the particle into the cell. For example, when bacteria invade the human body, a type of white blood cell called a neutrophil will remove the invaders by this process. Similarly, in pinocytosis or "cell drinking," the cell takes in droplets of liquid. In receptor-mediated endocytosis, uptake of substances by the cell is targeted to a single type of substance that binds to a specific receptor protein on the external surface of the cell membrane (e.g., hormones and their target cells) before under going endocytosis. Some human diseases, such as familial hypercholesterolemia, are caused by the failure of receptor-mediated endocytosis. Exocytosis is the process of exporting material out of the cell; vesicles containing substances fuse with the plasma membrane and the contents are released to the exterior of the cell. The secretion of neurotransmitters at synapses between neurons is an example of exocytosis.

Information presented and the examples highlighted in the section support concepts and learning objectives outlined in Big Idea 2 of the AP® Biology Curriculum Framework. The learning objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.B	Growth, reproduction and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.
Essential Knowledge	**2.B.2** Growth and dynamic homeostasis are maintained by the constant movement of molecules across membranes.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	**2.12** The student is able to use representations and models to analyze situations or solve problems qualitatively and quantitatively to investigate whether dynamic homeostasis is maintained by the active movement of molecules across membranes.
Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.D	Growth and dynamic homeostasis of a biological system are influenced by changes in the system's environment.
Essential Knowledge	**2.D.4** Plants and animals have a variety of chemical defenses against infections that affect dynamic homeostasis.
Science Practice	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain.
Science Practice	**1.2** The student can describe representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	**2.30** The student can create representations or models to describe nonspecific immune defenses in plants and animals.

In addition to moving small ions and molecules through the membrane, cells also need to remove and take in larger molecules and particles (see **Table 5.2** for examples). Some cells are even capable of engulfing entire unicellular microorganisms. You might have correctly hypothesized that the uptake and release of large particles by the cell requires energy. A large particle, however, cannot pass through the membrane, even with energy supplied by the cell.

Endocytosis

Endocytosis is a type of active transport that moves particles, such as large molecules, parts of cells, and even whole cells, into a cell. There are different variations of endocytosis, but all share a common characteristic: The plasma membrane of the cell invaginates, forming a pocket around the target particle. The pocket pinches off, resulting in the particle being contained in a newly created intracellular vesicle formed from the plasma membrane.

Phagocytosis

Phagocytosis (the condition of "cell eating") is the process by which large particles, such as cells or relatively large particles, are taken in by a cell. For example, when microorganisms invade the human body, a type of white blood cell called a neutrophil will remove the invaders through this process, surrounding and engulfing the microorganism, which is then destroyed by the neutrophil (**Figure 5.20**).

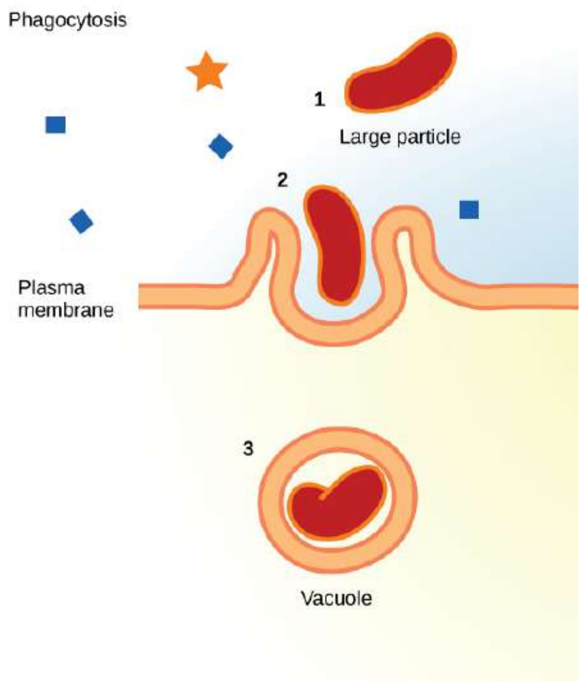


Figure 5.20 In phagocytosis, the cell membrane surrounds the particle and engulfs it. (credit: Mariana Ruiz Villareal)

In preparation for phagocytosis, a portion of the inward-facing surface of the plasma membrane becomes coated with a protein called **clathrin**, which stabilizes this section of the membrane. The coated portion of the membrane then extends from the body of the cell and surrounds the particle, eventually enclosing it. Once the vesicle containing the particle is enclosed within the cell, the clathrin disengages from the membrane and the vesicle merges with a lysosome for the breakdown of the material in the newly formed compartment (endosome). When accessible nutrients from the degradation of the vesicular contents have been extracted, the newly formed endosome merges with the plasma membrane and releases its contents into the extracellular fluid. The endosomal membrane again becomes part of the plasma membrane.

science practices CONNECTION for AP® Courses

Activity

Create a representation/diagram to describe how a neutrophil, a type of human white blood cell, attacks and destroys an invading bacterium. What cellular organelles are involved in this process?

Pinocytosis

A variation of endocytosis is called **pinocytosis**. This literally means “cell drinking” and was named at a time when the assumption was that the cell was purposefully taking in extracellular fluid. In reality, this is a process that takes in molecules, including water, which the cell needs from the extracellular fluid. Pinocytosis results in a much smaller vesicle than does phagocytosis, and the vesicle does not need to merge with a lysosome (**Figure 5.21**).

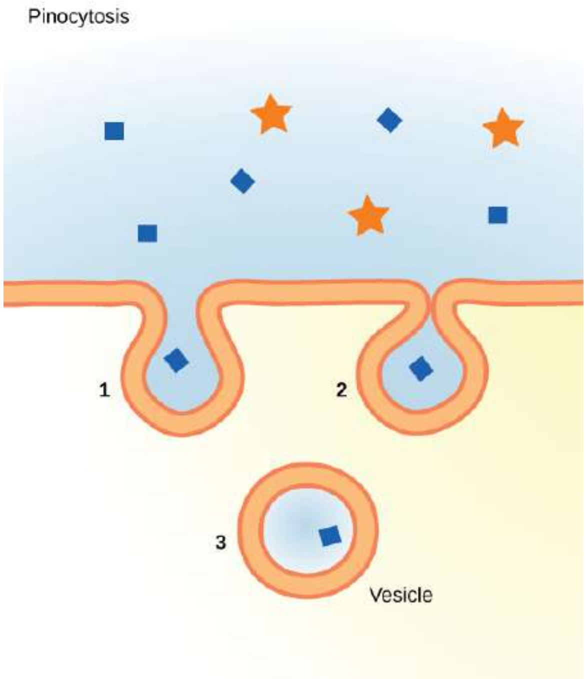


Figure 5.21 In pinocytosis, the cell membrane invaginates, surrounds a small volume of fluid, and pinches off. (credit: Mariana Ruiz Villareal)

A variation of pinocytosis is called **potocytosis**. This process uses a coating protein, called **caveolin**, on the cytoplasmic side of the plasma membrane, which performs a similar function to clathrin. The cavities in the plasma membrane that form the vacuoles have membrane receptors and lipid rafts in addition to caveolin. The vacuoles or vesicles formed in caveolae (singular caveola) are smaller than those in pinocytosis. Potocytosis is used to bring small molecules into the cell and to transport these molecules through the cell for their release on the other side of the cell, a process called transcytosis.

Receptor-mediated Endocytosis

A targeted variation of endocytosis employs receptor proteins in the plasma membrane that have a specific binding affinity for certain substances (**Figure 5.22**).

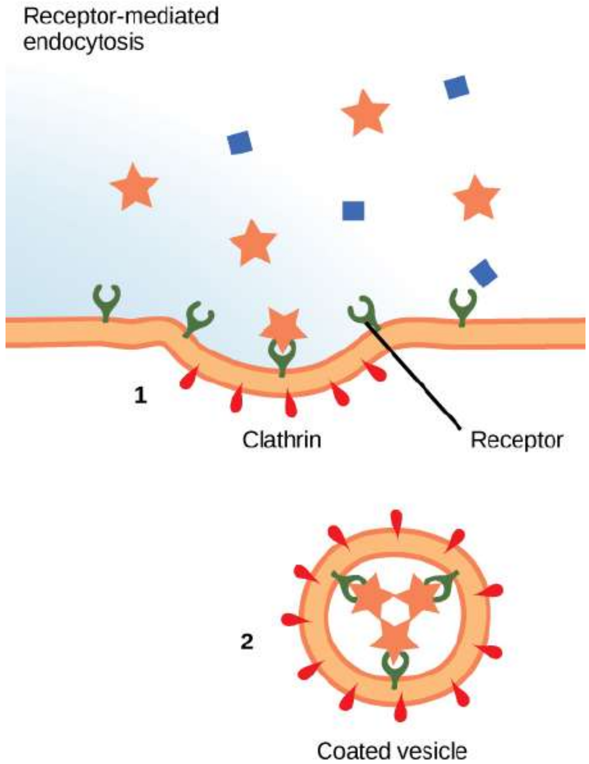


Figure 5.22 In receptor-mediated endocytosis, uptake of substances by the cell is targeted to a single type of substance that binds to the receptor on the external surface of the cell membrane. (credit: modification of work by Mariana Ruiz Villareal)

In **receptor-mediated endocytosis**, as in phagocytosis, clathrin is attached to the cytoplasmic side of the plasma membrane. If uptake of a compound is dependent on receptor-mediated endocytosis and the process is ineffective, the material will not be removed from the tissue fluids or blood. Instead, it will stay in those fluids and increase in concentration. Some human diseases are caused by the failure of receptor-mediated endocytosis. For example, the form of cholesterol termed low-density lipoprotein or LDL (also referred to as “bad” cholesterol) is removed from the blood by receptor-mediated endocytosis. In the human genetic disease familial hypercholesterolemia, the LDL receptors are defective or missing entirely. People with this condition have life-threatening levels of cholesterol in their blood, because their cells cannot clear LDL particles from their blood.

Although receptor-mediated endocytosis is designed to bring specific substances that are normally found in the extracellular fluid into the cell, other substances may gain entry into the cell at the same site. Flu viruses, diphtheria, and cholera toxin all have sites that cross-react with normal receptor-binding sites and gain entry into cells.

LINK TO LEARNING

See receptor-mediated endocytosis in action, and click on different **parts (http://openstaxcollege.org/l/endocytosis)** for a focused animation.

Salmonella is one of the most common food borne illnesses. When salmonella bacteria are engulfed by a white blood cell during phagocytosis, it secretes a protein that prevents the fusion of the encased bacteria with the lysosome of the cell. What effect would this have?

a. The bacteria will be destroyed and will not cause any illness.

b. The bacteria will survive and will definitely result in illness.

c. The bacteria will be destroyed, but will still cause illness.

d. The bacteria will survive and possibly will cause illness.

Exocytosis

The reverse process of moving material into a cell is the process of exocytosis. **Exocytosis** is the opposite of the processes discussed above in that its purpose is to expel material from the cell into the extracellular fluid. Waste material is enveloped in a membrane and fuses with the interior of the plasma membrane. This fusion opens the membranous envelope on the exterior of the cell, and the waste material is expelled into the extracellular space (**Figure 5.23**). Other examples of cells releasing molecules via exocytosis include the secretion of proteins of the extracellular matrix and secretion of neurotransmitters into the synaptic cleft by synaptic vesicles.

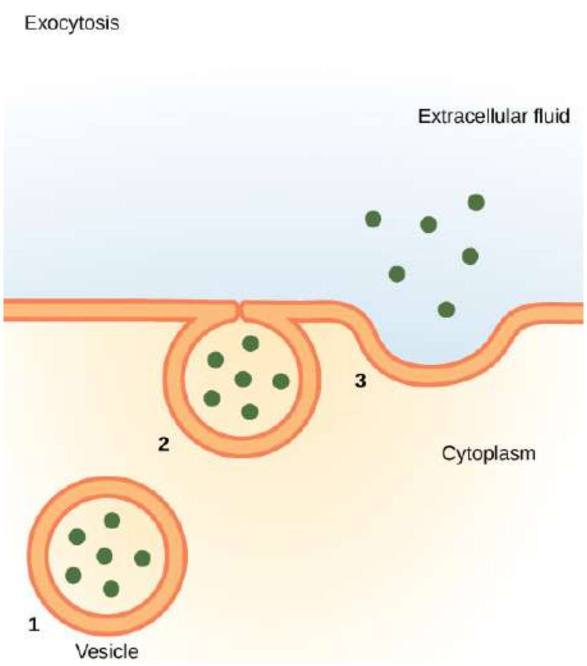


Figure 5.23 In exocytosis, vesicles containing substances fuse with the plasma membrane. The contents are then released to the exterior of the cell. (credit: modification of work by Mariana Ruiz Villareal)

Methods of Transport, Energy Requirements, and Types of Material Transported

Transport Method	Active/ Passive	Material Transported
Diffusion	Passive	Small-molecular weight material
Osmosis	Passive	Water
Facilitated transport/diffusion	Passive	Sodium, potassium, calcium, glucose
Primary active transport	Active	Sodium, potassium, calcium
Secondary active transport	Active	Amino acids, lactose
Phagocytosis	Active	Large macromolecules, whole cells, or cellular structures
Pinocytosis and potocytosis	Active	Small molecules (liquids/water)
Receptor-mediated endocytosis	Active	Large quantities of macromolecules

Table 5.2

KEY TERMS

active transport method of transporting material that requires energy

amphiphilic molecule possessing a polar or charged area and a nonpolar or uncharged area capable of interacting with both hydrophilic and hydrophobic environments

antiporter transporter that carries two ions or small molecules in different directions

aquaporin channel protein that allows water through the membrane at a very high rate

carrier protein membrane protein that moves a substance across the plasma membrane by changing its own shape

caveolin protein that coats the cytoplasmic side of the plasma membrane and participates in the process of liquid uptake by potocytosis

channel protein membrane protein that allows a substance to pass through its hollow core across the plasma membrane

clathrin protein that coats the inward-facing surface of the plasma membrane and assists in the formation of specialized structures, like coated pits, for phagocytosis

concentration gradient area of high concentration adjacent to an area of low concentration

diffusion passive process of transport of low-molecular weight material according to its concentration gradient

electrochemical gradient gradient produced by the combined forces of an electrical gradient and a chemical gradient

electrogenic pump pump that creates a charge imbalance

endocytosis type of active transport that moves substances, including fluids and particles, into a cell

exocytosis process of passing bulk material out of a cell

facilitated transport process by which material moves down a concentration gradient (from high to low concentration) using integral membrane proteins

fluid mosaic model describes the structure of the plasma membrane as a mosaic of components including phospholipids, cholesterol, proteins, glycoproteins, and glycolipids (sugar chains attached to proteins or lipids, respectively), resulting in a fluid character (fluidity)

glycolipid combination of carbohydrates and lipids

glycoprotein combination of carbohydrates and proteins

hydrophilic molecule with the ability to bond with water; “water-loving”

hydrophobic molecule that does not have the ability to bond with water; “water-hating”

hypertonic situation in which extracellular fluid has a higher osmolarity than the fluid inside the cell, resulting in water moving out of the cell

hypotonic situation in which extracellular fluid has a lower osmolarity than the fluid inside the cell, resulting in water moving into the cell

integral protein protein integrated into the membrane structure that interacts extensively with the hydrocarbon chains of membrane lipids and often spans the membrane; these proteins can be removed only by the disruption of the membrane by detergents

isotonic situation in which the extracellular fluid has the same osmolarity as the fluid inside the cell, resulting in no net movement of water into or out of the cell

osmolarity total amount of substances dissolved in a specific amount of solution

osmosis transport of water through a semipermeable membrane according to the concentration gradient of water across the membrane that results from the presence of solute that cannot pass through the membrane

passive transport method of transporting material through a membrane that does not require energy

peripheral protein protein found at the surface of a plasma membrane either on its exterior or interior side

pinocytosis a variation of endocytosis that imports macromolecules that the cell needs from the extracellular fluid

plasmolysis detaching of the cell membrane from the cell wall and constriction of the cell membrane when a plant cell is in a hypertonic solution

potocytosis variation of pinocytosis that uses a different coating protein (caveolin) on the cytoplasmic side of the plasma membrane

primary active transport active transport that moves ions or small molecules across a membrane and may create a difference in charge across that membrane

pump active transport mechanism that works against electrochemical gradients

receptor-mediated endocytosis variation of endocytosis that involves the use of specific binding proteins in the plasma membrane for specific molecules or particles, and clathrin-coated pits that become clathrin-coated vesicles

secondary active transport movement of material that is due to the electrochemical gradient established by primary active transport

selectively permeable characteristic of a membrane that allows some substances through but not others

solute substance dissolved in a liquid to form a solution

symporter transporter that carries two different ions or small molecules, both in the same direction

tonicity amount of solute in a solution

transport protein membrane protein that facilitates passage of a substance across a membrane by binding it

transporter specific carrier proteins or pumps that facilitate movement

uniporter transporter that carries one specific ion or molecule

CHAPTER SUMMARY

5.1 Components and Structure

The modern understanding of the plasma membrane is referred to as the fluid mosaic model. The plasma membrane is composed of a bilayer of phospholipids, with their hydrophobic, fatty acid tails in contact with each other. The landscape of the membrane is studded with proteins, some of which span the membrane. Some of these proteins serve to transport materials into or out of the cell. Carbohydrates are attached to some of the proteins and lipids on the outward-facing surface of the membrane, forming complexes that function to identify the cell to other cells. The fluid nature of the membrane is due to temperature, the configuration of the fatty acid tails (some kinked by double bonds), the presence of cholesterol embedded in the membrane, and the mosaic nature of the proteins and protein-carbohydrate combinations, which are not firmly fixed in place. Plasma membranes enclose and define the borders of cells, but rather than being a static bag, they are dynamic and constantly in flux.

5.2 Passive Transport

The passive forms of transport, diffusion and osmosis, move materials of small molecular weight across membranes. Substances diffuse from areas of high concentration to areas of lower concentration, and this process continues until the substance is evenly distributed in a system. In solutions containing more than one substance, each type of molecule diffuses according to its own concentration gradient, independent of the diffusion of other substances. Many factors can affect the rate of diffusion, including concentration gradient, size of the particles that are diffusing, temperature of the system, and so on.

In living systems, diffusion of substances into and out of cells is mediated by the plasma membrane. Some materials diffuse readily through the membrane, but others are hindered, and their passage is made possible by specialized proteins, such as channels and transporters. The chemistry of living things occurs in aqueous solutions, and balancing the concentrations of those solutions is an ongoing problem. In living systems, diffusion of some substances would be slow or difficult without membrane proteins that facilitate transport.

5.3 Active Transport

The combined gradient that affects an ion includes its concentration gradient and its electrical gradient. A positive ion, for example, might tend to diffuse into a new area, down its concentration gradient, but if it is diffusing into an area of net positive charge, its diffusion will be hampered by its electrical gradient. When dealing with ions in aqueous solutions, a combination of the electrochemical and concentration gradients, rather than just the concentration gradient alone, must be considered. Living cells need certain substances that exist inside the cell in concentrations greater than they exist in the extracellular space. Moving substances up their electrochemical gradients requires energy from the cell. Active transport uses energy stored in ATP to fuel this transport. Active transport of small molecular-sized materials uses integral proteins in the cell membrane to move the materials: These proteins are analogous to pumps. Some pumps, which carry out primary active transport, couple directly with ATP to drive their action. In co-transport (or secondary active transport), energy from primary transport can be used to move another substance into the cell and up its concentration gradient.

5.4 Bulk Transport

Active transport methods require the direct use of ATP to fuel the transport. Large particles, such as macromolecules, parts of cells, or whole cells, can be engulfed by other cells in a process called phagocytosis. In phagocytosis, a portion of the membrane invaginates and flows around the particle, eventually pinching off and leaving the particle entirely enclosed by an envelope of plasma membrane. Vesicle contents are broken down by the cell, with the particles either used as food or dispatched. Pinocytosis is a similar process on a smaller scale. The plasma membrane invaginates and pinches off, producing a small envelope of fluid from outside the cell. Pinocytosis imports substances that the cell needs from the extracellular fluid. The cell expels waste in a similar but reverse manner: it pushes a membranous vacuole to the plasma membrane, allowing the vacuole to fuse with the membrane and incorporate itself into the membrane structure, releasing its contents to the exterior.

REVIEW QUESTIONS

1. Which plasma membrane component can be either found on its surface or embedded in the membrane structure?

a. carbohydrates
b. cholesterol
c. glycolipid
d. protein

2. In addition to a plasma membrane, eukaryotic cell organelles, such as mitochondria, also have membranes. In which way would these membranes differ?

a. The proportion of phosphate within the phospholipids will vary.
b. Only certain membranes contain phospholipids.
c. Only certain membranes are selectively permeable.
d. The proportions of proteins, lipids, and carbohydrates will vary.

3. Which characteristic of a phospholipid increases the fluidity of the membrane?

a. cholesterol
b. its head
c. saturated fatty acid tail
d. unsaturated fatty acid tail

4. How would an organism maintain membrane fluidity in an environment where temperatures fluctuated from very high to very low?

a. Greater proportion of unsaturated phospholipids in membranes.
b. Greater proportion of saturated phospholipids in membranes.
c. Greater proportion of carbohydrates in membranes.
d. Greater proportion of proteins in membranes.

5. According to the fluid mosaic model of the plasma cell membrane, what is the primary function of carbohydrates attached to the exterior of cell membranes?

a. Carbohydrates are in contact with the aqueous fluid both inside and outside the cell.
b. Carbohydrates are present only on the interior surface of a membrane.
c. Carbohydrates are present only on the exterior surface of a membrane.
d. Carbohydates span only the interior of a membrane.

6. What do double bonds in phospholipid fatty acid tails contribute to?

a. the fluidity of membranes
b. the hydrophobic nature of membranes
c. the hydrophilic nature of membranes
d. preventing high temperatures from increasing fluidity of membranes

7. Identify the principal force driving movement in diffusion.

a. concentration gradient
b. membrane surface area
c. particle size
d. temperature

8. Which of the following is an example of passive transport across a membrane?

a. the movement of H^+ into a thylakoid disc during photosynthesis
b. the uptake of glucose in the intestine
c. the uptake of mineral ions into root hair cells of plants
d. the movement of water from a nephron into the collecting duct of the kidney

9. Water moves via osmosis across plasma cell membranes in which direction?

a. from an area with a high concentration of other solutes to a lower one
b. from an area with a high concentration of water to one of lower concentration
c. from an area with a low concentration of water to one of higher concentration.
d. throughout the cytoplasm

10. What problem is faced by organisms that live in fresh water?

a. They will have higher concentrations of body solutes.
b. Without compensating mechanisms, their bodies tend to take in too much water.
c. They have no way of controlling their tonicity.
d. Their bodies tend to lose too much water to their environment.

11. Which of the following questions can be asked about organisms that live in fresh water?

a. Will their bodies take in too much water?
b. Can they control their tonicity?
c. Can they survive in salt water?
d. Will their bodies lose too much water to their environment?

12. Which of the following explains why active movement of molecules across membranes must function continuously?

13. Why must active transport of molecules across plasma membranes function continuously?

a. Diffusion cannot occur in certain cells.
b. Diffusion is constantly moving solutes in opposite directions.
c. Facilitated diffusion works in the same direction as active transport.
d. Not all membranes are amphiphilic.

14. How does the sodium-potassium pump make the interior of the cell negatively charged?

a. by expelling anions
b. by pulling in anions
c. by expelling more cations than it takes in
d. By taking in and expelling an equal number of cations.

15. What is the difference between primary and secondary active transport?

a. Primary active transport is indirectly dependent on ATP, while secondary active transport is directly dependent on ATP.
b. Primary active transport is directly dependent on ATP, while secondary active transport is indirectly dependent on ATP.
c. Primary active transport does not require ATP, while secondary active transport is indirectly dependent on ATP.
d. Primary active transport is indirectly dependent on ATP, while secondary active transport does not require ATP

16. What happens to the membrane of a vesicle after exocytosis?

a. It leaves the cell.
b. It is disassembled by the cell.
c. It fuses with and becomes part of the plasma membrane.
d. It is used again in another exocytosis event.

17. In what important way does receptor-mediated endocytosis differ from phagocytosis?

a. It transports only small amounts of fluid.
b. It does not involve the pinching off of membrane.
c. It brings in only a specifically targeted substance.
d. It brings substances into the cell, while phagocytosis removes substances.

CRITICAL THINKING QUESTIONS

18. Why do phospholipids tend to spontaneously orient themselves into something resembling a membrane?

a. Phospholipids are amphipathic molecules. The polar head faces towards water and the nonpolar fatty acid tails face towards other fatty acid tails.
b. Phospholipids are lipophilic molecules. The polar head faces towards water and the nonpolar fatty acid tails face towards other fatty acid tails
c. Phospholipids are amphipathic molecules. The nonpolar head faces towards other fatty acid tails and the polar fatty acid tails face towards water.
d. Phospholipids are hydrophilic molecules. The polar head faces towards water and the nonpolar fatty acid tails face towards other fatty acid tails.

19. Why is it advantageous for the plasma membrane to be fluid in nature?

a. Fluidity allows greater flexibility to the cell and motion of membrane components required for transport.
b. Fluidity helps only in transport of some materials, and does not contribute to the flexibility.
c. Fluidity helps in maintaining the pH of intracellular fluid, and helps in maintaining the physiological pH of the cell.
d. Fluidity helps in providing mechanical strength to the plasma membrane.

20. List four components of a plasma membrane and explain their function.

a. Phospholipids: form the bilayer; Carbohydrates: help in adhesion; Cholesterol: provide flexibility; Integral proteins: form transporters; Peripheral proteins: part of the cell's recognition sites.
b. Phospholipids: form the bilayer; Carbohydrates: help in adhesion; Cholesterol: form transporters; Integral proteins: provide flexibility; Peripheral proteins: part of the cell's recognition sites.
c. Phospholipids: form the bilayer; Carbohydrates: part of the cell's recognition sites; Cholesterol: provide flexibility to the membrane; Integral proteins: form transporters; Intermediate filaments: help in adhesion.
d. Phospholipids: form the bilayer; Carbohydrates: function as adhesion; Cholesterol: provide flexibility to the membrane, Integral proteins: form transporters; Intermediate filaments: part of the cell's recognition sites.

21. Discuss why the following affect the rate of diffusion: molecular size, temperature, solution density, and the distance that must be traveled.

a. Larger molecules move faster than lighter molecules. Temperature affects the molecular movement. Density is directly proportional to the molecular movement. Greater distance slows the diffusion.

b. Larger molecules move slower than lighter molecules. Increasing or decreasing temperature increases or decreases the energy in the medium, affecting molecular movement. Density is inversely proportional to molecular movement. Greater distance slows the diffusion.

c. Larger molecules move slower than lighter molecules. Temperature does not affect the rate of diffusion. Density is inversely proportional to molecular movement. Greater distance speeds up the diffusion.

d. Larger molecules move slower than lighter molecules. Increasing or decreasing temperature increases or decreases the energy in the medium, affecting molecular movement. Density is inversely proportional to the molecular movement. Greater distance speeds up the diffusion.

22. Both of the regular intravenous solutions administered in medicine, normal saline and lactated Ringer's solution, are isotonic. Why is this important?

a. Isotonic solutions maintain equilibrium and avoid the exchange of materials to or from the blood.

b. Isotonic solutions disrupt equilibrium and allow better exchange of materials in the blood.

c. Isotonic solutions increase the pH of blood and allow better absorption of saline in blood.

d. Isotonic solutions decrease the pH of the blood and avoid the exchange of materials to or from the blood.

23. If a doctor injected a patient with what was labeled as an isotonic saline solution, but then the patient died, and an autopsy revealed that several of the patient's red blood cells had burst, would it be true that the injected solution was really isotonic? Why or why not?

a. False, the solution was hypertonic.

b. False, the solution was osmotic.

c. False, the solution was hypotonic.

d. True, the solution was isotonic.

24. How does the sodium-potassium pump contribute to the net negative charge of the interior of the cell?

a. The sodium-potassium pump forces out three (positive) Na^+ ions for every two (positive) K^+ ions it pumps in, thus the cell loses a net positive charge of one at every cycle of the pump.

b. The sodium-potassium pump expels three ions K^+ for every two Na^+ inside the cells, creating a net positive charge outside the cell and a net negative charge inside the cell.

c. The sodium-potassium pump helps the development of negative charge inside the cell by making the membrane more permeable to negatively charged proteins.

d. The sodium-potassium pump helps in the development of negative charge inside the cell by making the membrane impermeable to positively charged ions.

25. Potassium is a necessary nutrient in order to maintain the function of our cells. What would occur to a person that is deficient in potassium?

a. The excess sodium disrupts the membrane components.

b. The excess sodium increases action potential generation.

c. The cell would not be able to get rid of extra sodium.

d. The cell would not be able to bring sodium into the cell.

26. Choose the statement that describes processes of receptor-mediated endocytosis, exocytosis, and the changes in the membrane organization.

a. Endocytosis involves the opsonization of a receptor and its ligand in clathrin-coated vesicles, along with the inward budding of the plasma membrane. In exocytosis, waste material is enveloped in a membrane that fuses with the interior of the plasma membrane via attachment proteins.
b. In endocytosis, waste material is enveloped in a membrane that fuses with the interior of the plasma membrane via attachment proteins. Exocytosis involves the opsonization of the receptor and its ligand in a clathrin-coated vesicles.
c. In endocytosis, waste material is enveloped in a membrane that fuses with the interior of the plasma membrane via attachment proteins. Exocytosis involves the opsonization of the receptor and its ligand in caveolae-coated vesicles.
d. Endocytosis involves the opsonization of the receptor and its ligand in clathrin-coated vesicles. In exocytosis, waste material is enveloped in a membrane that fuses with the exterior of the plasma membrane via attachment proteins.

27. Describe the process of potocytosis and explain how it differs from pinocytosis.

a. Potocytosis is a form of receptor-mediated endocytosis where molecules are transported via caveolae-coated vesicles. Pinocytosis is a form of exocytosis used for excreting excess water.
b. Potocytosis is a form of exocytosis where molecules are transported via clathrin-coated vesicles. Pinocytosis is a form of receptor-mediated endocytosis used for excreting excess water.
c. Potocytosis is a form of receptor-mediated endocytosis where molecules are transported via caveolae-coated vesicles. Pinocytosis is a mode of endocytosis used for absorption of extracellular water.
d. Potocytosis is a form of receptor-mediated endocytosis used for absorption of water. Pinocytosis is a mode of endocytosis used for excretion of extracellular water.

TEST PREP FOR AP® COURSES

28. One type of mutation in the CFTR protein prevents the transport of chloride ions through the channel. Which of the following is most likely to be observed in the lungs of patients with this mutation?

a. dehydrated epithelial cells
b. dehydrated mucus
c. mucus with excess water
d. mucus with high electrolyte concentration

29. Arsenic poisoning disrupts ATP production by inhibiting several of the enzymes in the oxidative phosphorylation pathway. Some of the symptoms of arsenic poisoning are similar to cystic fibrosis (difficulty breathing and frequent lung infections). Explain what impact arsenic poisoning may have on components of the plasma membrane and transport that result in CF like symptoms.

a. Arsenic poisoning disrupts ATP production, leading to decreased transport of Cl^- ions by epithelial cells. This leads to decreased electrolyte concentration in the mucus and retention of water into the cells. The mucus becomes dehydrated, as in CF.
b. Arsenic poisoning disrupts the Na^+ / Cl^- pump, leading to decreased transport of Cl^- ions outside the epithelial cells. This increases the electrolyte concentration in the mucus and movement of water out of the cells. The mucus becomes hydrated as in CF.
c. Arsenic poisoning affects the oxidative phosphorylation pathway, leading to decreased transport of Na^+ ions outside the epithelial cells. This leads to increased electrolyte concentration in the mucus and movement of water into the cells. The mucus becomes dehydrated as in CF.
d. Arsenic poisoning disrupts the binding sites for Cl^- ions, leading to decreased transport of Cl^- ions outside the epithelial cells. This leads to decreased electrolyte concentration in the mucus and movement of water outside the cells. The mucus becomes hydrated as in CF.

30. In individuals with normally functioning CFTR protein, which substances are transported via active transport?

a. Cl^-

b. mucus

c. Na^+

d. water

31.

Experiment	ATP present inside cells?	ATP present outside cells?	Ouabain present inside cells?	Ouabain present outside cells?	Was Na+ transported?	Was K+ transported?
1	Yes	Yes	No	No	Yes	Yes
2	Yes	No	No	No	Yes	Yes
3	No	Yes	No	No	No	No
4	No	No	No	No	No	No
5	Yes	No	Yes	Yes	No	No
6	Yes	No	Yes	No	No	Yes
7	Yes	No	No	Yes	Yes	No

The sodium-potassium (Na^+ / K^+) pump functions like an anti-porter transporting Na^+ and K^+ across membranes using ATP. This protein spans the membrane with intracellular and extracellular domains. It has a binding site for Na^+, K^+, and ATP. An experiment was conducted to determine the locations of these binding sites. Artificial cells were created and incubated in buffers containing ATP, ouabain (or oubain), Na^+, and K^+ in varying combinations inside and outside of the cell as indicated in the chart. The transport of Na^+ and K^+ was measured to determine activity of the Na^+ / K^+ pump. Which of the following conclusions is supported by the data?

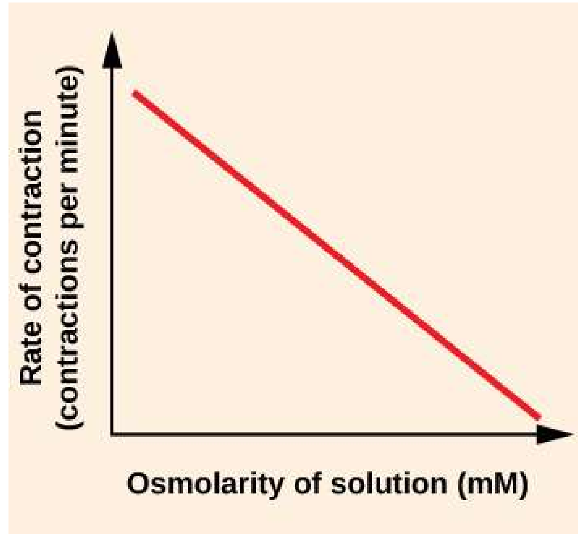
a. Ouabain can disrupt ATP binding to the Na^+ / K^+ pump.

b. ATP is required for transport of Na^+ and not for transport of K^+.

c. The ATP binding site of the Na^+ / K^+ pump is located on the intracellular domain of the pump.

d. The ATP binding site of the Na^+ / K^+ pump is located on the extracellular domain of the pump.

32.



Paramecia are unicellular protists that have contractile vacuoles to remove excess intracellular water. In an experimental investigation, *Paramecia* were placed in salt solutions of increasing osmolarity. The rate at which a *Paramecium*'s contractile vacuole contracted to pump out excess water was determined and plotted against osmolarity of the solutions, as shown in the graph. Which of the following is the correct explanation for the data?

a. At higher osmolarity, lower rates of contraction are required because more salt diffuses into the *Paramecium*.

b. In an isosmotic salt solution, there is no diffusion of water into or out of the *Paramecium*, so the contraction rate is zero.

c. The contraction rate increases as the osmolarity decreases because the amount of water entering the *Paramecium* by osmosis increases.

d. The contractile vacuole is less efficient in solutions of high osmolarity because of the reduced amount of ATP produced from cellular respiration.

33. What is most likely to happen if *Paramecia* are moved from a hypertonic solution to solutions of decreasing osmolarity?

a. The rate of contraction would increase with decreasing osmolarity because more water diffuses into the *Paramecium*.

b. The rate of contraction would decrease with decreasing osmolarity because more water diffuses into the *Paramecium*.

c. The rate of contraction would increase with decreasing osmolarity because more salt diffuses into the *Paramecium*.

d. The rate of contraction would decrease with decreasing osmolarity because more salt diffuses into the *Paramecium*.

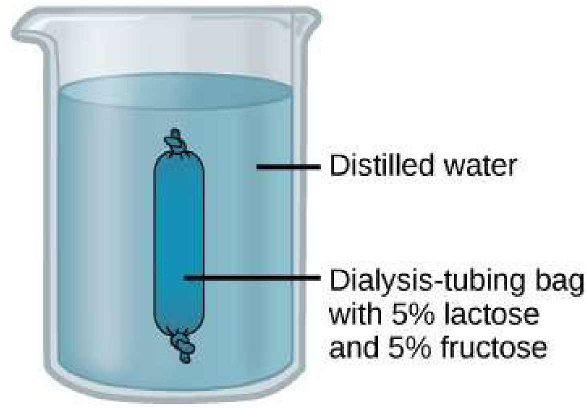
34.

Experiment	ATP present inside cells?	ATP present outside cells?	Ouabain present inside cells?	Ouabain present outside cells?	Was Na^+ trans-ported?	Was K^+ trans-ported?
1	Yes	Yes	No	No	Yes	Yes
2	Yes	No	No	No	Yes	Yes
3	No	Yes	No	No	No	No
4	No	No	No	No	No	No
5	Yes	No	Yes	Yes	No	No
6	Yes	No	Yes	No	No	Yes
7	Yes	No	No	Yes	Yes	No

Describe the Na^+ / K^+ pump, labeling the binding sites for Na^+, K^+, and ATP. Explain how the data indicates the location of the binding sites for Na^+ and K^+ on the pump. Based on the data, choose the correct statement describing the location of the binding sites for Na^+ and K^+ on the pump.

a. The binding of Na^+ occurs on the outer surface of the cell, as its transportation remains unaffected by the presence of ouabain. The binding of K^+ occurs on the inner surface of the cell, as its transportation is blocked when ouabain is present inside the cell
b. The binding of K^+ occurs on the outer surface of the cell, as its transportation is blocked when ouabain is present outside the cell. The binding of Na^+ occurs on the inner surface of the cell as its transportation remains unaffected by the presence of ouabain.
c. The binding of K^+ occurs on the outer surface of the cell and the binding of Na^+ occurs on the inner surface of the cell, as they are not transported when ATP is absent.
d. The binding of Na^+ occurs on the outer surface of the cell and the binding of K^+ occurs on the inner surface of the cell, as they are not transported when ATP is absent.

35.



An experiment was set up to determine the movement of molecules through a dialysis-tubing bag into water. A dialysis-tubing bag containing 5% lactose and 5% fructose was placed in a beaker of distilled water, as illustrated. After four hours, fructose is detected in the distilled water outside of the dialysis-tubing bag, but lactose is not. What conclusions can be made about the movement of molecules in this experiment?

a. Fructose, being a monosaccharide, diffused through the dialysis bag into the distilled water. However, lactose, being a disaccharide, could not diffuse through the dialysis bag.
b. Fructose was homogenized by lactose, allowing the fructose to diffuse through the dialysis bag and into the distilled water. Lactose is not homogenized, so it could not pass through the dialysis bag.
c. Fructose and lactose are oppositely charged and separated out due to the force of repulsion.
d. Fructose diffused because of the pore specificity of the semipermeable membrane, not because of its concentration gradient.

36. Based on the information provided, which cell types are most likely to contain clathrin?

a. monocytes and mast cells
b. neutrophils, monocytes, and mast cells
c. neutrophils and mast cells
d. neutrophils and monocytes

37. Which of the following statements appropriately describe the role of opsonin and clathrin proteins in neutrophils based on your understanding of phagocytosis?

a. A clathrin coating enhances phagocytosis, whereas opsonin reverses the process of phagocytosis.
b. Opsonins are proteins that enhance phagocytosis, whereas clathrin opposes phagocytosis.
c. Opsonin stabilizes the inward facing surface of the plasma membrane, which engulfs the antigen, whereas clathrin marks the antigen for phagocytosis by neutrophils.
d. Opsonin marks the antigen for phagocytosis by neutrophils, whereas clathrin stabilizes the inward facing surface of the plasma membrane, which engulfs the antigen.

38. Based on the information provided, which cell types produce endosomes?

a. monocytes and mast cells
b. neutrophils, monocytes, and mast cells
c. neutrophils and mast cells
d. neutrophils and monocytes

SCIENCE PRACTICE CHALLENGE QUESTIONS

39. Membrane fluidity is influenced by the number of C-C double bonds (unsaturation) in the hydrocarbon tails of the lipids composing cell membranes. Fluidity is also dependent on temperature. The transit of materials through the cell membrane is controlled by fluidity. To maintain homeostasis, all organisms, including the simple bacterium *E. coli*, must sense the temperature of the environment and adapt to changes.

Samples of *E. coli* were grown at four different temperatures, and then researchers determined the fatty acid composition of their plasma membranes. The data are shown in the following table.

	Growth Temperature (°C)			
Fatty acid	10	20	30	40
Myristic	17%	14%	14%	16%
Palmitic	18%	25%	29%	48%
Palmitoleic	26%	24%	23%	9%
Oleic	38%	34%	30%	12%
Ratio (U/S)				

Table 5.3

Fatty acid compositions of the plasma membrane of *E. coli* were incubated at the temperatures shown. Myristic and palmitic acid are saturated, while palmitoleic and oleic acids each have one C-C double bond.

A. **Analyze** the data to calculate the ratio of the fraction of unsaturated (U) to the fraction of saturated (S) fatty acids in the plasma membrane, and complete the table.
B. **Graph** the ratio U/S versus growth temperature.
C. **Explain** the response of *E. coli* to the temperature of the environment.
D. We know that the temperature of the environment is sensed by *E. coli* through the temperature-dependent confirmation of enzymes that convert a single bond in the lipid tail to a double bond, and vice versa. **Explain** how the discovery of a mutant strain of *E. coli* could lead to this insight.

TeachingTip: This question connects concepts drawn from Big Ideas 2, 4, and 1.

40. Aquaporins that allow for the movement of water across a cell membrane are gated. Both low and high pH within a plant cell can cause alterations of the membrane-spanning protein. **Describe** the advantage of this feedback mechanism. **Predict** how conditions of flooding or drought could activate this mechanism.

41. Rice plants grown in high-salt environments can actively transport sodium ions into the vacuole by the antiporter movement of protons out of the vacuole. In a study aimed at the development of salt-tolerant rye, researchers produced several varieties of transgenic rye. Measurements of height and stem diameter for the transgenic varieties (TG1 – TG4) are compared with the wild type varieties WT1 and WT2. Shown in the table below are the mean and standard deviation from measurements of a very large sample size.

This OpenStax book is available for free at http://cnx.org/content/col12078/1.6

Variety	Height (cm)	Stem thickness (cm)
WT1	9.667±0.333	1.975±0.095
WT2	11.867±0.376	2.238±0.204
TG1	15.420±1.146	2.723±0.261
TG2	15.600±0.909	2.903±0.323
TG3	14.925±0.767	2.633±0.073
TG4	16.100±0.682	3.160±0.169

Table 5.4

A. **Analyze** the data. Are the heights and stem thicknesses in the transgenic plants significantly different than in the wild type plant? **Justify** your claim with evidence.

B. Are the heights and stem thicknesses among the transgenic plants significantly different? **Justify** your claim with evidence.

C. Plants from which these data were taken were grown in 10 mM NaCl solutions. **Pose one question** that researchers can investigate by growing the same varieties in a series of lower-salinity conditions.

D. The Na+/H+ antiporter is an active transport system. Briefly **explain** negative feedback regulation of the movement of sodium into the vacuole of rye cells.