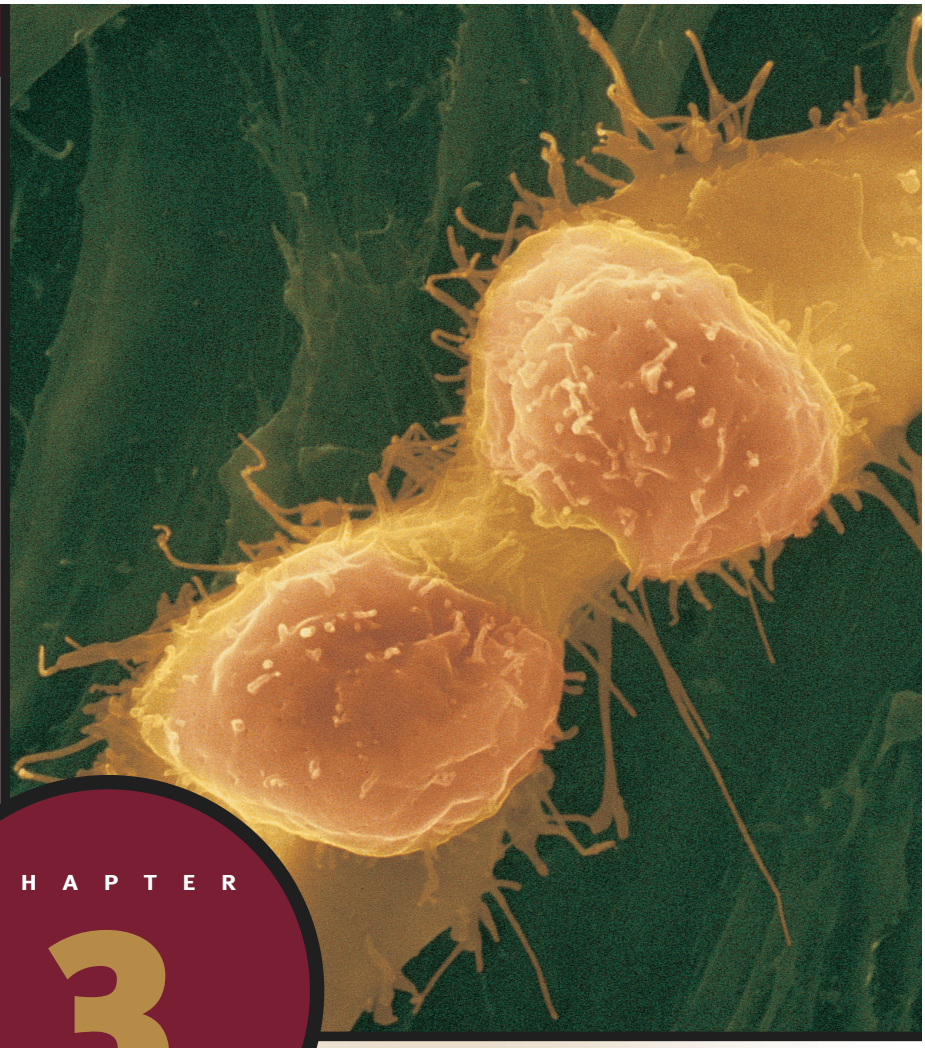
Structure and Function of the Cell



Colorized scanning electron micrograph (SEM) of a dividing cell.

CHAPTER 3

The cell is the basic structural and functional unit of all living organisms. The characteristic functions of cells include DNA replication, manufacture of macromolecules such as proteins and phospholipids, energy use, and reproduction. Cells are like very complex but minute factories that are always active, carrying out the functions of life. These microscopic factories are so small that an average-sized cell is only one-fifth the size of the smallest dot you can make on a sheet of paper with a sharp pencil. Each human body is made up of trillions of cells. If each cell was the size of a standard brick, the colossal human statue made from those bricks would be 5 1/2 miles (10 km) high!

All the cells of an individual originate from a single fertilized cell. During development, cell division and specialization give rise to a wide variety of cell types, such as nerve, muscle, bone, fat, and blood cells. Each cell type has important characteristics that are critical to the normal function of the body as a whole. One of the important reasons for maintaining homeostasis is to keep the trillions of cells that form the body functioning normally.

Although cells may have quite different structures and functions, they share several common characteristics (figure 3.1; table 3.1). The **plasma** (plazʹmă), or **cell, membrane** forms the outer boundary of the cell, through which the cell interacts with its external environment. The **nucleus** (nooʹklē-ŭs) is usually located centrally and functions to direct cell activities, most of which take place in the **cytoplasm** (sīʹtō-plazm), located between the plasma membrane and the nucleus. Within cells, specialized structures called **organelles** (orʹgă-nelz) perform specific functions.

This chapter outlines *functions of the cell* (59), *how we see cells* (59), and the composition of the *plasma membrane* (61). Then it addresses *movement through the plasma membrane* (65) and *endocytosis and exocytosis* (73). The chapter then addresses the *cytoplasm* (75), *organelles* (77), and *nucleus* (85). It then presents an *overview of cell metabolism* (87), *protein synthesis* (87), *cell life cycle* (90), and *meiosis* (94). Finally, *the cellular aspects of aging* are discussed (97).

Functions of the Cell

Objective

- ***Outline the major functions of the cell.***

The main functions of the cell include

1. *Basic unit of life.* The cell is the smallest part to which an organism can be reduced that still retains the characteristics of life.
2. *Protection and support.* Cells produce and secrete various molecules that provide protection and support of the body. For example, bone cells are surrounded by a mineralized material, making bone a hard tissue that protects the brain and other organs and that supports the weight of the body.
3. *Movement.* All the movements of the body occur because of molecules located within specific cells such as muscle cells.
4. *Communication.* Cells produce and receive chemical and electrical signals that allow them to communicate with one another. For example, nerve cells communicate with one another and with muscle cells, causing them to contract.
5. *Cell metabolism and energy release.* The chemical reactions that occur within cells are referred to collectively as cell metabolism. Energy released during metabolism is used for cell activities, such as the synthesis of new molecules, muscle contraction, and heat production, which helps maintain body temperature.
6. *Inheritance.* Each cell contains a copy of the genetic information of the individual. Specialized cells are responsible for transmitting that genetic information to the next generation.

How We See Cells

Objective

- ***Explain the differences between the two types of microscopes.***

Most cells are too small to be seen with the unaided eye. As a result, it is necessary to use microscopes to study them. **Light microscopes** allow us to visualize general features of cells. **Electron microscopes,** however, must be used to study the fine structure of cells. A **scanning electron microscope (SEM)** allows us to see features of the cell surface and the surfaces of internal structures. A **transmission electron microscope (TEM)** allows us to see "through" parts of the cell and thus to discover other aspects of cell structure. If you are not somewhat familiar with these types of microscopes, you should turn to the discussion on microscopic imaging on p. 107.

1. ***What are the major functions of the cell?***
2. ***What are the differences between light and electron microscopes?***

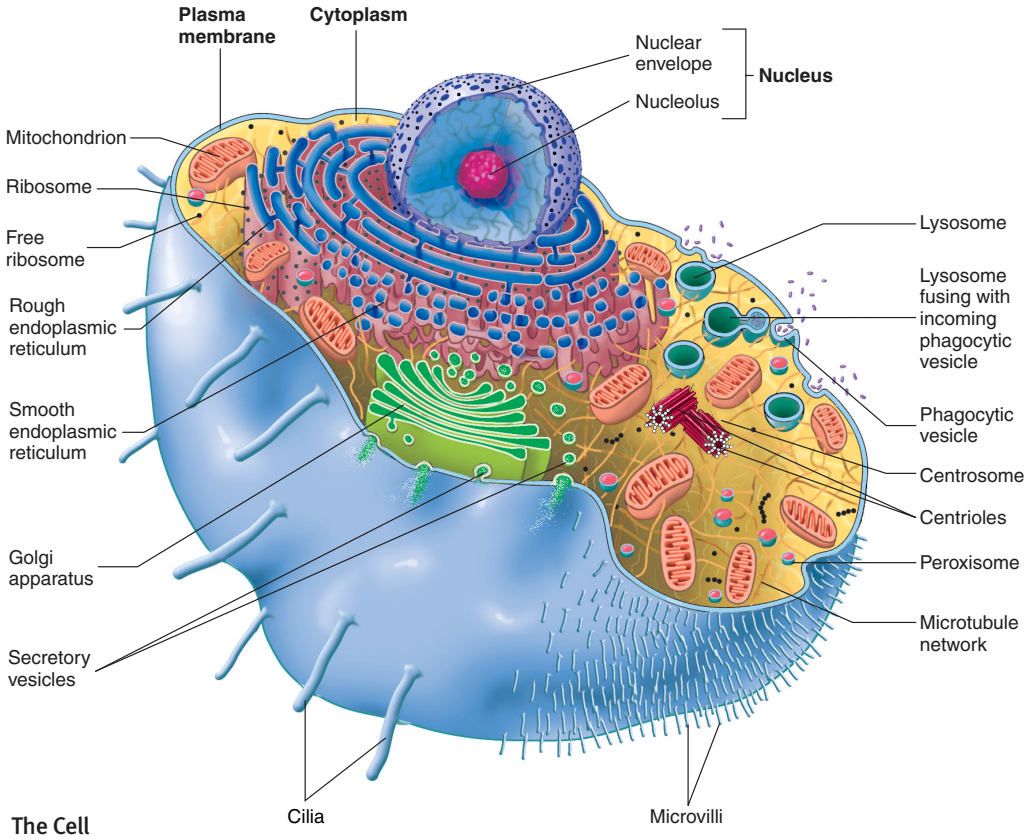


Figure 3.1 The Cell

A generalized human cell showing the plasma membrane, nucleus, and cytoplasm with its organelles. Although no single cell contains all these organelles, many cells contain a large number of them.

Table 3.1 Summary of Cell Parts

Cell Parts	Structure	Function
Plasma Membrane	Lipid bilayer composed of phospholipids and cholesterol with proteins that extend across or are buried in either surface of the lipid bilayer	Outer boundary of cells that controls entry and exit of substances; receptor molecules function in intercellular communication; marker molecules enable cells to recognize one another
Cytoplasm: Cytosol		
Fluid part	Water with dissolved ions and molecules; colloid with suspended proteins	Contains enzymes that catalyze decomposition and synthesis reactions; ATP is produced in glycolysis reactions
Cytoskeleton		
Microtubules	Hollow cylinders composed of the protein tubulin; 25 nm in diameter	Support the cytoplasm and form centrioles, spindle fibers, cilia, and flagella; responsible for cell movements
Actin filaments	Small fibrils of the protein actin; 8 nm in diameter	Support the cytoplasm, form microvilli, responsible for cell movements
Intermediate filaments	Protein fibers; 10 nm in diameter	Support the cytoplasm
Cytoplasmic inclusions	Aggregates of molecules manufactured or ingested by the cell; may be membrane-bound	Function depends on the molecules: energy storage (lipids, glycogen), oxygen transport (hemoglobin), skin color (melanin), and others
Cytoplasm: Organelles		
Centrioles	Pair of cylindrical organelles in the centrosome, consisting of triplets of parallel microtubules	Centers for microtubule formation; determine cell polarity during cell division; form the basal bodies of cilia and flagella
Spindle fibers	Microtubules extending from the centrosome to chromosomes and other parts of the cell (i.e., aster fibers)	Assist in the separation of chromosomes during cell division
Cilia	Extensions of the plasma membrane containing doublets of parallel microtubules; 10 µm in length	Move materials over the surface of cells
Flagellum	Extension of the plasma membrane containing doublets of parallel microtubules; 55 µm in length	In humans, responsible for movement of spermatozoa
Microvilli	Extension of the plasma membrane containing microfilaments	Increase surface area of the plasma membrane for absorption and secretion; modified to form sensory receptors
Ribosome	Ribosomal RNA and proteins form large and small subunits; attached to endoplasmic reticulum or free ribosomes are distributed throughout the cytoplasm	Site of protein synthesis
Rough endoplasmic reticulum	Membranous tubules and flattened sacs with attached ribosomes	Protein synthesis and transport to Golgi apparatus
Smooth endoplasmic reticulum	Membranous tubules and flattened sacs with no attached ribosomes	Manufactures lipids and carbohydrates; detoxifies harmful chemicals; stores calcium
Golgi apparatus	Flattened membrane sacs stacked on each other	Modification, packaging, and distribution of proteins and lipids for secretion or internal use
Secretory vesicle	Membrane-bounded sac pinched off Golgi apparatus	Carries proteins and lipids to cell surface for secretion
Lysosome	Membrane-bounded vesicle pinched off Golgi apparatus	Contains digestive enzymes
Peroxisome	Membrane-bound vesicle	One site of lipid and amino acid degradation and breaks down hydrogen peroxide
Proteasomes	Tube-like protein complexes in the cytoplasm	Break down proteins in the cytoplasm
Mitochondria	Spherical, rod-shaped, or threadlike structures; enclosed by double membrane; inner membrane forms projections called cristae	Major site of ATP synthesis when oxygen is available
Nucleus		
Nuclear envelope	Double membrane enclosing the nucleus; the outer membrane is continuous with the endoplasmic reticulum; nuclear pores extend through the nuclear envelope	Separates nucleus from cytoplasm and regulates movement of materials into and out of the nucleus
Chromatin	Dispersed thin strands of DNA, histones, and other proteins; condenses to form chromosomes during cell division	DNA regulates protein (e.g., enzyme) synthesis and therefore the chemical reactions of the cell; DNA is the genetic or hereditary material
Nucleolus	One to four dense bodies consisting of ribosomal RNA and proteins	Assembly site of large and small ribosomal subunits

Plasma Membrane

Objectives

- *Define intracellular, extracellular, glycocalyx, lipid bilayer, hydrophilic, and hydrophobic.*
- *Explain how phospholipids are arranged in the lipid bilayer. What is the function of cholesterol, and where is it found in the plasma membrane?*
- *What is the significance of the fluid nature of the lipid bilayer?*
- *Outline the function of membrane proteins as markers, attachment sites, channels, receptors, enzymes, and carriers.*

The plasma membrane is the outermost component of a cell. Substances inside the plasma membrane are **intracellular** and substances outside the cell are **extracellular.** Sometimes extracellular substances are referred to as **intercellular,** meaning between cells. The plasma membrane encloses and supports the cell contents. It attaches cells to the extracellular environment or to other cells. The ability of cells to recognize and communicate with each other takes place through the plasma membrane. In addition, the plasma membrane determines what moves into and out of cells. As a result, the intracellular contents of cells is different from the extracellular environment.

The regulation of ion movement by cells results in a charge difference across the plasma membrane called the **membrane potential.** The outside of the plasma membrane is positively charged compared to the inside because there are more positively charged ions immediately on the outside of the plasma membrane and more negatively charged ions inside. The membrane potential allows cells to function like tiny batteries with a positive and negative pole. It is an important feature of a living cell's normal function, which will be considered in greater detail in chapters 9 and 11.

The plasma membrane consists of 45%–50% lipids, 45%–50% proteins, and 4%–8% carbohydrates (figure 3.2). The carbohydrates combine with lipids to form **glycolipids** and with proteins to form **glycoproteins.** The **glycocalyx** (glī-kō-kā′liks) is the collection of glycolipids, glycoproteins, and carbohydrates on the outer surface of the plasma membrane. The glycocalyx also contains molecules absorbed from the extracellular environment, so there is often no precise boundary where the plasma membrane ends and the extracellular environment begins.

Membrane Lipids

The predominant lipids of the plasma membrane are phospholipids and cholesterol. **Phospholipids** readily assemble to form a **lipid bilayer,** a double layer of lipid molecules, because they have a polar

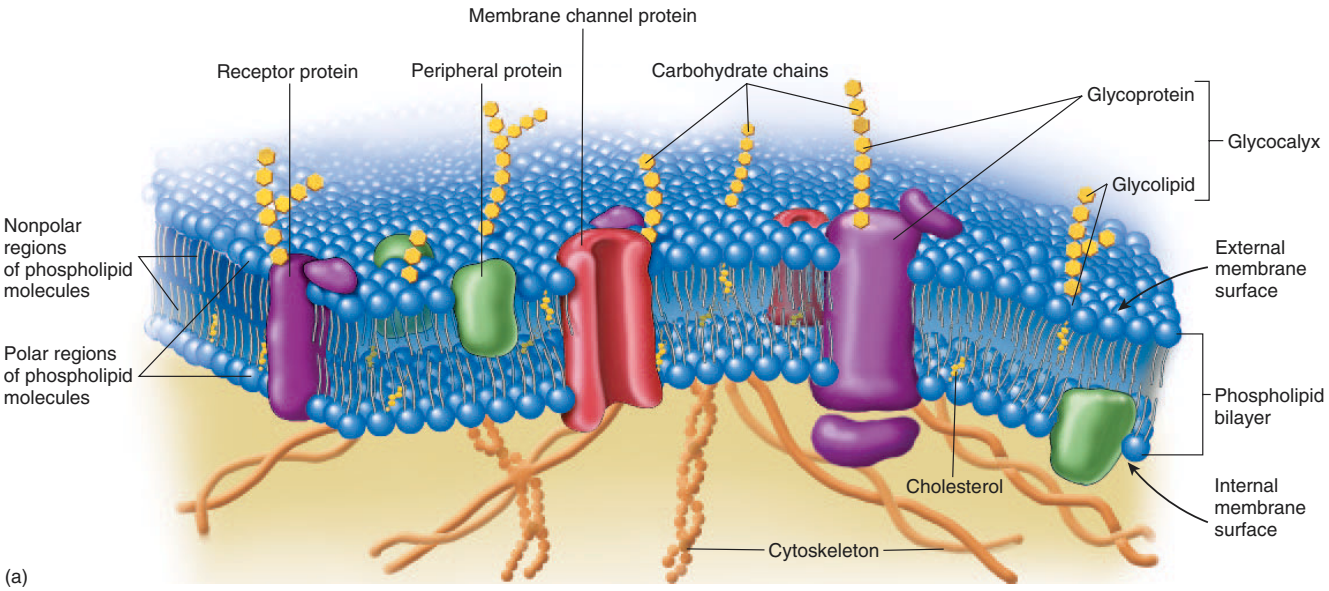


Figure 3.2 Plasma Membrane

(*a*) Fluid-mosaic model of the plasma membrane. The membrane is composed of a bilayer of phospholipids and cholesterol with proteins "floating" in the membrane. The nonpolar hydrophobic region of each phospholipid molecule is directed toward the center of the membrane and the polar hydrophilic region is directed toward the water environment either outside or inside the cell. (*b*) Transmission electron micrograph of a plasma membrane, with the membrane indicated by the *blue arrows.* Proteins at either surface of the lipid bilayer stain more readily than the lipid bilayer does and give the membrane the appearance of consisting of three parts: the two dark outer parts are proteins and the phospholipid heads, and the lighter central part is the phospholipid tails and cholesterol.

(charged) head and a nonpolar (uncharged) tail (see chapter 2). The polar **hydrophilic** (water-loving) heads are exposed to water inside and outside the cell, whereas the nonpolar **hydrophobic** (water-fearing) tails face one another in the interior of the plasma membrane. The other major lipid in the plasma membrane is **cholesterol** (see chapter 2), which is interspersed among the phospholipids and accounts for about a third of the total lipids in the plasma membrane. The hydrophilic OH group of cholesterol extends between the phospholipid heads to the hydrophilic surface of the membrane and the hydrophobic part of the cholesterol molecule lies within the hydrophobic region of the phospholipids. The amount of cholesterol in a given membrane is a major factor in determining the fluid nature of the membrane, which is critical to its function.

Membrane Proteins

The basic structure of the plasma membrane and some of its functions are determined by its lipids, but many functions of the plasma membrane are determined by its proteins. The modern concept of the plasma membrane, the **fluid-mosaic model,** suggests that the plasma membrane is neither rigid nor static in structure but is highly flexible and can change its shape and composition through time. The lipid bilayer functions as a liquid in which other molecules such as proteins are suspended. The fluid nature of the lipid bilayer has several important consequences. It provides an important means of distributing molecules within the plasma membrane. In addition, slight damage to the membrane can be repaired because the phospholipids tend to reassemble around damaged sites and seal them closed. The fluid nature of the lipid bilayer also enables membranes to fuse with one another.

Some protein molecules, called **integral,** or **intrinsic, proteins,** penetrate deeply into the lipid bilayer, in many cases, extending from one surface to the other (figure 3.3), whereas other proteins, called **peripheral,** or **extrinsic, proteins,** are attached to either the inner or outer surfaces of the lipid bilayer. Integral proteins consist of regions made up of amino acids with hydrophobic R groups and other regions of amino acids with hydrophilic R groups (see chapter 2). The hydrophobic regions are located within the hydrophobic part of the membrane, and the hydrophilic regions are located at the inner or outer surface of the membrane or line channels through the membrane. Peripheral proteins are usually bound to integral proteins. Membrane proteins are markers, attachment sites, channels, receptors, enzymes, or carriers. The ability of membrane proteins to function depends on their three-dimensional shapes and their chemical characteristics.

Marker Molecules

Marker molecules are cell surface molecules that allow cells to identify one another or other molecules. They are mostly **glycoproteins** (proteins with attached carbohydrates) or **glycolipids** (lipids with attached carbohydrates). The protein portions of glycoproteins may be either integral or peripheral proteins (figure 3.4). Examples include recognition of the oocyte by the sperm cell and the ability of the immune system to distinguish between self-cells and foreign cells, such as bacteria or donor cells in an organ transplant. Intercellular communication and recognition are important because cells are not isolated entities and they must work together to ensure normal body functions.

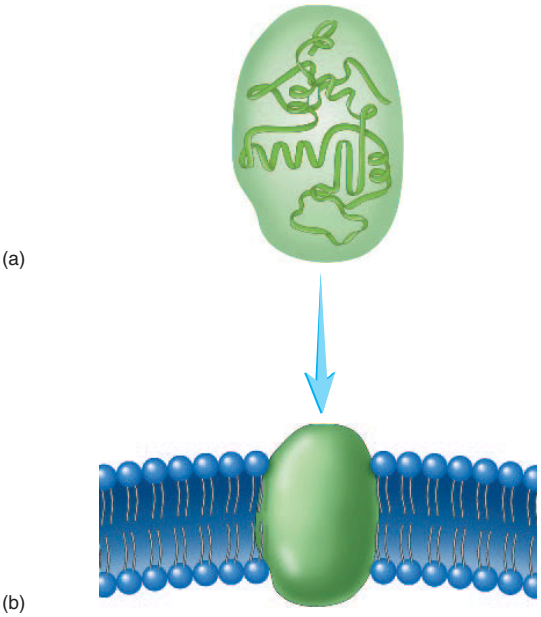


Figure 3.3 Globular Proteins in the Plasma Membrane

(*a*) Proteins are commonly depicted as ribbons (see chapter 2). The domain occupied by the protein ribbon can be enclosed by a three-dimensional shaded region. (*b*) The shaded region can be depicted as a three-dimensional globular integral protein inserted into the plasma membrane.

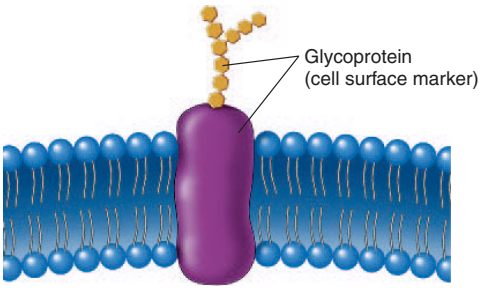


Figure 3.4 Cell Surface Marker

Glycoproteins on the cell surface allow cells to identify one another or other molecules.

Attachment Sites

Membrane-bound proteins, such as **integrins,** function as **attachment sites,** where cells attach to other cells or to extracellular molecules (figure 3.5). These membrane proteins also attach to intracellular molecules. Integrins function in pairs of two integral proteins, which interact with both intracellular and extracellular molecules.

Channel Proteins

Channel proteins are one or more integral proteins arranged so that they form a tiny channel through the plasma membrane (figure 3.6). The hydrophobic regions of the proteins face outward toward the hydrophobic part of the plasma membrane, and the

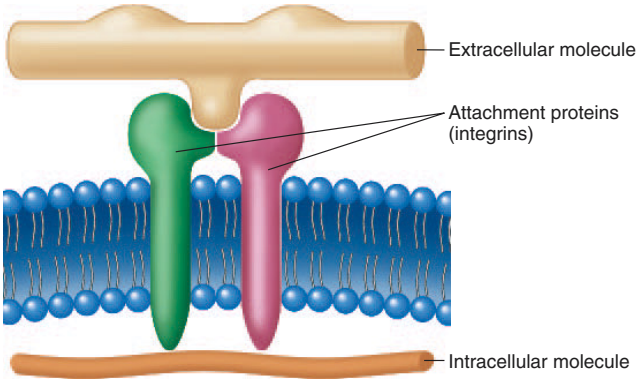


Figure 3.5 Attachment Sites

Proteins (integrins) in the plasma membrane attach to extracellular molecules.

hydrophilic regions of the protein face inward and line the channel. Small molecules or ions of the right shape, size, and charge can pass through the channel. The charges in the hydrophilic part of the channel proteins determine which types of ions can pass through the channel.

Some channel proteins, called **nongated ion channels,** are always open and are responsible for the permeability of the plasma membrane to ions when the plasma membrane is at rest. Other channels can be open or closed. Some channel proteins open in response to **ligands** (līg′andz, lī′gandz). Ligands are small molecules that bind to proteins or glycoproteins. This is called a **ligand-gated ion channel.** Other channel proteins open the channel when there is a change in charge across the plasma membrane. This is called a **voltage-gated ion channel.**

Receptor Molecules

Receptor molecules (figure 3.7) are proteins in the plasma membrane with an exposed **receptor site** on the outer cell surface, which can attach to specific ligand molecules. Some membrane receptors are part of ligand-gated channels. Many receptors and the ligands they bind are part of an intercellular communication system that facilitates coordination of cell activities.

For example, a nerve cell can release a chemical messenger that diffuses to a muscle cell and binds to its receptor. The binding acts as a signal that triggers a response, such as contraction in the muscle cell. The same chemical messenger would have no effect on other cells that lack the specific receptor molecule.

Receptors Linked to Channel Proteins

Some membrane-bound receptors are protein molecules that are part of ligand-gated ion channels in the plasma membrane. When ligands bind to the receptor sites of this type of receptor, the combination alters the three-dimensional structure of the proteins of the ion channels, causing the channels either to open or close. The result is a change in the permeability of the plasma membrane to the specific ions passing through the ion channels (figure 3.8). For example, acetylcholine released from nerve cells is a ligand that combines with membrane-bound receptors of skeletal muscle cells. The combination of acetylcholine molecules with the receptor sites of the membrane-bound receptors for acetylcholine opens Na^+ channels in the plasma membrane. Consequently, the ions diffuse into the skeletal muscle cells and trigger events that cause them to contract.

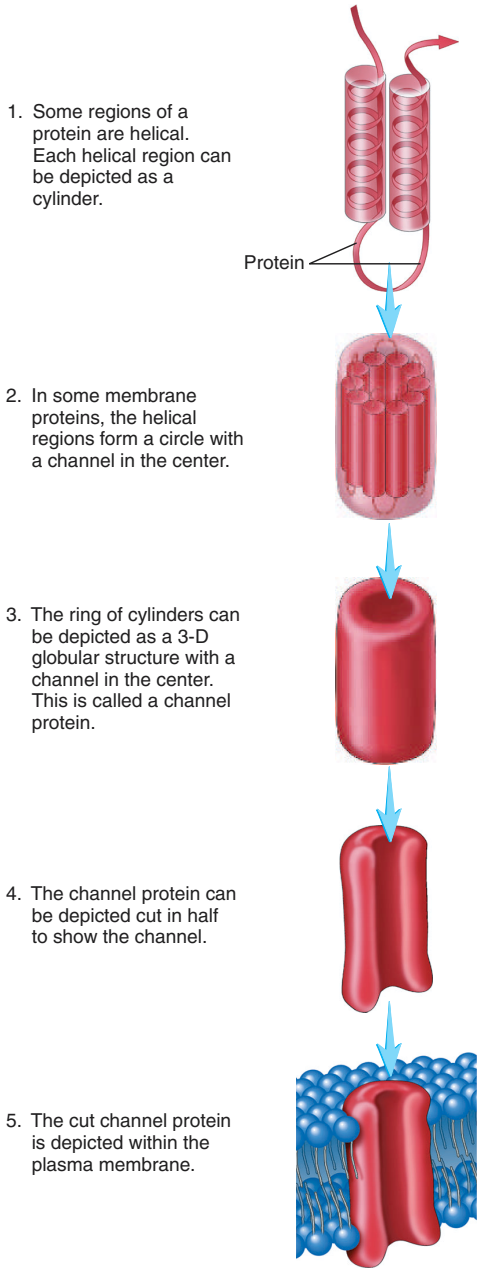


Figure 3.6 Channel Protein

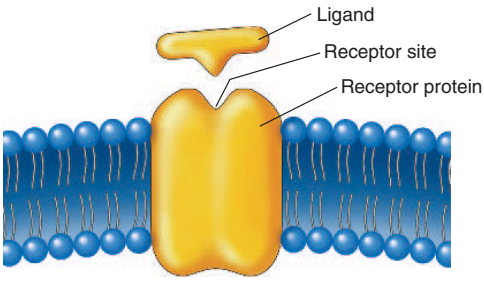
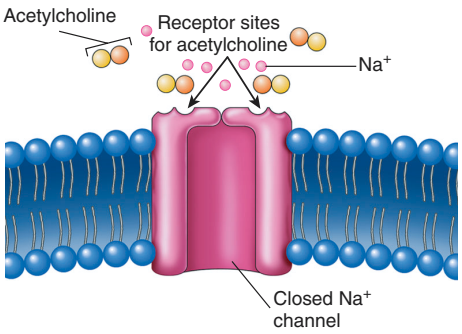
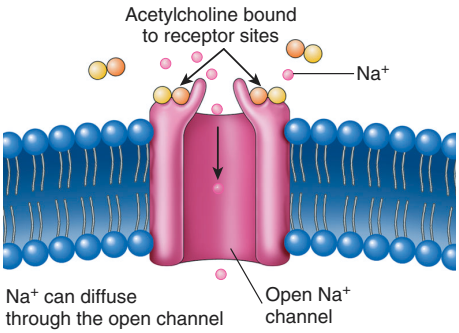


Figure 3.7 Receptor Protein

A protein in the plasma membrane with an exposed receptor site, which can attach to specific ligands.



(1) The Na^+ channel has receptor sites for the ligand, acetylcholine. When the receptor sites are not occupied by acetylcholine, the Na^+ channel remains closed.



(2) When two acetylcholine molecules bind to their receptor sites on the Na^+ channel, the channel opens to allow Na^+ to diffuse through the channel into the cell.

Process Figure 3.8 Receptors Linked to a Channel Protein

Cystic Fibrosis

Cystic fibrosis is a genetic disorder that affects chloride ion channels. Three types of cystic fibrosis exist. In about 70% of cases, a defective channel protein is produced that fails to reach the plasma membrane from its site of production inside the cell. In the remaining cases, the channel protein is incorporated into the plasma membrane but does not function normally. In some cases, the channel protein fails to bind ATP. In others, ATP binds to the channel protein, but the channel does not open. Failure of these ion channels to function results in the affected cells producing thick, viscous secretions. Although cystic fibrosis affects many cell types, its most profound effects are in the pancreas, causing an inability to digest certain types of food, and in the lungs, where it causes extreme difficulty in breathing.

Receptors Linked to G Proteins

Some membrane-bound receptor molecules function by altering the activity of a **G protein** complex located on the inner surface of the plasma membrane (figure 3.9). The G protein complex consists of three proteins, called the alpha, beta, and gamma proteins. A G protein attached to a receptor that does not have a ligand bound to it is inactive and has guanosine diphosphate (GDP) attached to it (figure 3.9 *1*). When a ligand attaches to the receptor, the G protein complex binds guanosine triphosphate (GTP) and is activated (figure 3.9 *2*). The activated G protein stimulates a cell response, often by means of intracellular chemical signals. Some G proteins open channels in the plasma membrane and others activate enzymes associated with the plasma membrane.

Drugs and Receptors

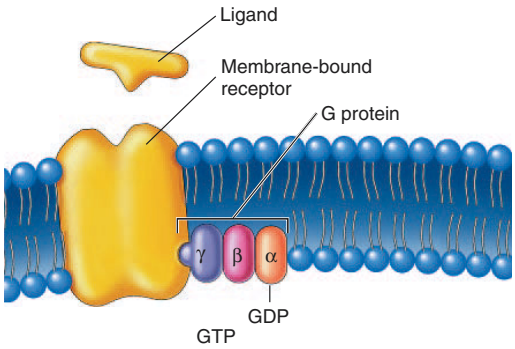
Drugs with structures similar to specific ligands may compete with those ligands for their receptor sites. Depending on the exact characteristics of a drug, it may either bind to a receptor site and activate the receptor or bind to a receptor site and inhibit the action of the receptor. For example, drugs exist that compete with the ligand epinephrine for its receptor sites. Some of these drugs activate epinephrine receptors and others inhibit them.

Enzymes in the Plasma Membrane

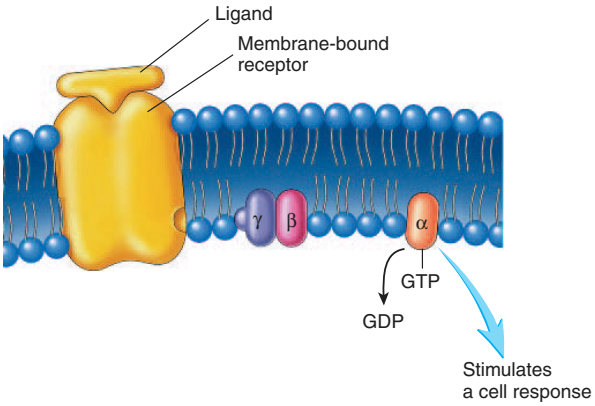
Some membrane proteins function as **enzymes,** which can catalyze chemical reactions on either the inner or outer surface of the plasma membrane. For example, some enzymes on the surface of cells in the small intestine break the peptide bonds of dipeptides (molecules consisting of two amino acids connected by a peptide bond) to form two single amino acids (figure 3.10). Some membrane-associated enzymes are always active. Others are activated by membrane-bound receptors or G proteins.

Carrier Proteins

Carrier proteins are integral membrane proteins that move ions or molecules from one side of the plasma membrane to the other. The carrier proteins have specific binding sites to which ions or molecules attach on one side of the plasma membrane. The carrier proteins change shape to move the bound ions or molecules to the other side of the plasma membrane where they are released (figure 3.11)



(1) A G protein attached to a receptor without a bound ligand has guanosine diphosphate (GDP) bound to it and is inactive.



(2) When a ligand attaches to the receptor, guanosine triphosphate (GTP) replaces GDP on the α-subunit of the G protein, which separates from the other subunits. The α-subunit, with GTP attached, stimulates a cell response.

Process Figure 3.9 A Receptor Linked to a G Protein

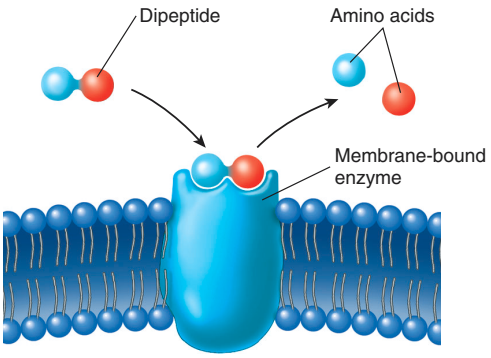
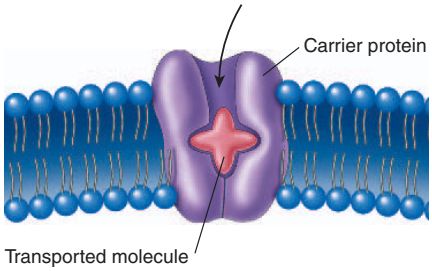
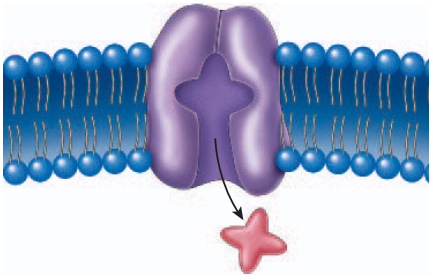


Figure 3.10 Enzyme in the Plasma Membrane

This enzyme in the plasma membrane breaks the peptide bond of a dipeptide to produce two amino acids.



1. The carrier protein binds with a molecule on one side of the plasma membrane.



2. The carrier protein changes shape and releases the molecule on the other side of the plasma membrane.

Process Figure 3.11 Carrier Protein

3. *Define glycolipid and glycoprotein. Describe the difference between integral and peripheral proteins in the plasma membrane.*
4. *List two functions of marker molecules.*
5. *Describe and give the function of integrins.*
6. *Define nongated ion channel, ligand-gated ion channel, and voltage-gated ion channel. What determines the function of a channel protein?*
7. *To what part of a receptor molecule does a ligand attach? Give two examples of how a ligand molecule can bind to a receptor in the plasma membrane and cause a response in the cell.*
8. *Give an example of the action of an enzyme in the plasma membrane.*

Movement Through the Plasma Membrane

Objectives

- *Describe the four ways by which substances can move through the plasma membrane.*
- *Describe the factors that affect the rate and the direction of diffusion of a solute in a solvent.*
- *Describe diffusion, osmosis, and filtration.*
- *Describe the processes of facilitated diffusion, active transport, and secondary active transport.*

The plasma membrane separates the extracellular material from the intracellular material and is **selectively permeable,** that is, it allows only certain substances to pass through it. The intracellular material has a different composition from the extracellular material, and the survival of the cell depends on the maintenance of these differences. Enzymes, other proteins, glycogen, and potassium ions are found in higher concentrations intracellularly; and sodium, calcium, and chloride ions are found in greater concentrations extracellularly. In addition, nutrients must continually enter the cell, and waste products must exit, but the volume of the cell remains unchanged. Because of the plasma membrane's permeability characteristics and its ability to transport molecules selectively, the cell is able to maintain homeostasis. Rupture of the membrane, alteration of its permeability characteristics, or inhibition of transport processes can disrupt the normal concentration differences across the plasma membrane and lead to cell death.

Molecules and ions can pass through the plasma membrane in four ways:

1. *Directly through the phospholipid membrane.* Molecules that are soluble in lipids, such as oxygen, carbon dioxide, and steroids, pass through the plasma membrane readily by dissolving in the lipid bilayer. The phospholipid bilayer acts as a barrier to most substances that are not lipid-soluble; but certain small, nonlipid-soluble molecules, such as water, carbon dioxide, and urea, can diffuse between the phospholipid molecules of the plasma membrane.
2. *Membrane channels.* There are several types of protein channels through the plasma membrane. Each channel type allows only certain molecules to pass through it. The size, shape, and charge of molecules determines whether they can pass through a given channel. For example, sodium ions pass through sodium channels, and potassium and chloride ions pass through potassium and chloride channels, respectively. Rapid movement of water across the cell membrane apparently occurs through membrane channels.
3. *Carrier molecules.* Large polar molecules that are not lipid-soluble, such as glucose and amino acids, cannot pass through the cell membrane in significant amounts unless they are transported by carrier molecules. Substances that are transported across the cell membrane by carrier molecules are said to be transported by **carrier-mediated processes.** Carrier proteins bind to specific molecules and transport them across the cell membrane. Carrier molecules that transport glucose across the cell membrane do not transport amino acids, and carrier molecules that transport amino acids do not transport glucose.
4. *Vesicles.* Large nonlipid-soluble molecules, small pieces of matter, and even whole cells can be transported across the cell membrane in a **vesicle,** which is a small sac surrounded by a membrane. Because of the fluid nature of membranes, the vesicle and the cell membrane can fuse, allowing the contents of the vesicle to cross the cell membrane.

Diffusion

A solution consists of one or more substances called **solutes** dissolved in the predominant liquid or gas, which is called the **solvent. Diffusion** is the movement of solutes from an area of higher concentration to an area of lower concentration in solution (figure 3.12). Diffusion is a product of the constant random motion of all atoms, molecules, or ions in a solution. Because more solute particles exist in an area of higher concentration than in an area of lower concentration and because the particles move randomly, the chances are greater that solute particles will move from the higher to the lower concentration than in the opposite direction. Thus the overall, or net, movement is from the area of higher concentration to that of lower concentration. At equilibrium, the net movement of solutes stops, although the random molecular motion continues, and the movement of solutes in any one direction is balanced by an equal movement in the opposite direction. The movement and distribution of smoke or perfume throughout a room in which no air currents exist or of a dye throughout a beaker of still water are examples of diffusion.

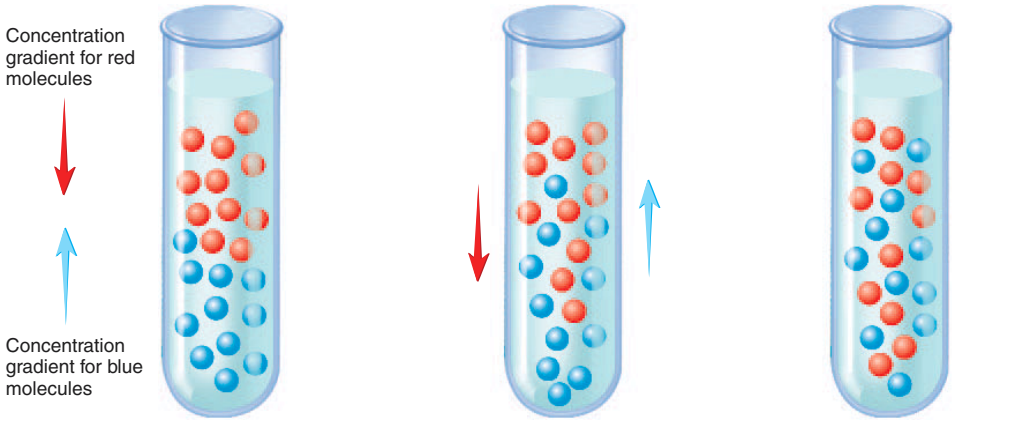
A concentration difference exists when the concentration of a solute is greater at one point than at another point in a solvent. The concentration difference between two points is called the **concentration,** or **density gradient.** Solutes diffuse with their concentration gradients (from a higher to a lower concentration) until an equilibrium is achieved. For a given concentration difference between two points in a solution, the concentration gradient is larger if the distance between the two points is small, and the concentration gradient is smaller if the distance between the two points is large.

The rate of diffusion is influenced by the magnitude of the concentration gradient, the temperature of the solution, the size of the diffusing molecules, and the viscosity of the solvent. The greater the concentration gradient, the greater is the number of solute particles moving from a higher to a lower concentration. As the temperature of a solution increases, the speed at which all molecules move increases, resulting in a greater diffusion rate. Small molecules diffuse through a solution more readily than do large ones. **Viscosity** is a measure of how easily a liquid flows; thick solutions, such as syrup, are more viscous than water. Diffusion occurs more slowly in viscous solvents than in thin, watery solvents.

Diffusion of molecules is an important means by which substances move between the extracellular and intracellular fluids in the body. Substances that can diffuse through either the lipid bilayer or the membrane channels can pass through the plasma membrane. Some nutrients enter and some waste products leave the cell by diffusion, and maintenance of the appropriate intracellular concentration of these substances depends to a large degree on diffusion. For example, if the extracellular concentration of oxygen is reduced, inadequate oxygen diffuses into the cell, and normal cell function cannot occur. Some lipid-soluble ligands can diffuse through the plasma membrane and attach to receptors inside the cell (figure 3.13).

PREDICT 1

Urea is a toxic waste produced inside cells. It diffuses from the cells into the blood and is eliminated from the body by the kidneys. What would happen to the intracellular and extracellular concentration of urea if the kidneys stopped functioning?



1. One solution (*red balls* representing one type of solute molecule) is layered onto a second solution (*blue balls* represent a second type of solute molecule). There is a concentration gradient for the red molecules from the red solution into the blue solution because there are no red molecules in the blue solution. There is also a concentration gradient for the blue molecules from the blue solution into the red solution because there are no blue molecules in the red solution.
2. Red molecules move down their concentration gradient into the blue solution (*red arrow*), and the blue molecules move down their concentration gradient into the red solution (*blue arrow*).
3. Red and blue molecules are distributed evenly throughout the solution. Even though the red and blue solute molecules continue to move randomly, an equilibrium exists, and no net movement occurs because no concentration gradient exists.

Process Figure 3.12 Diffusion

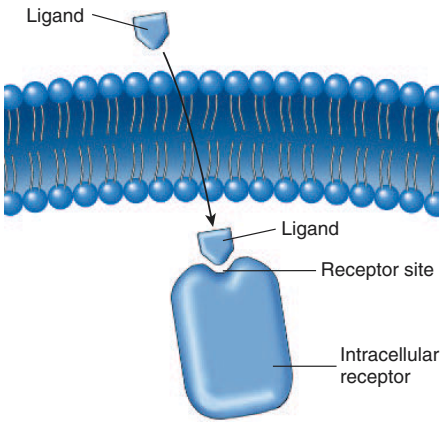


Figure 3.13 Intracellular Receptor

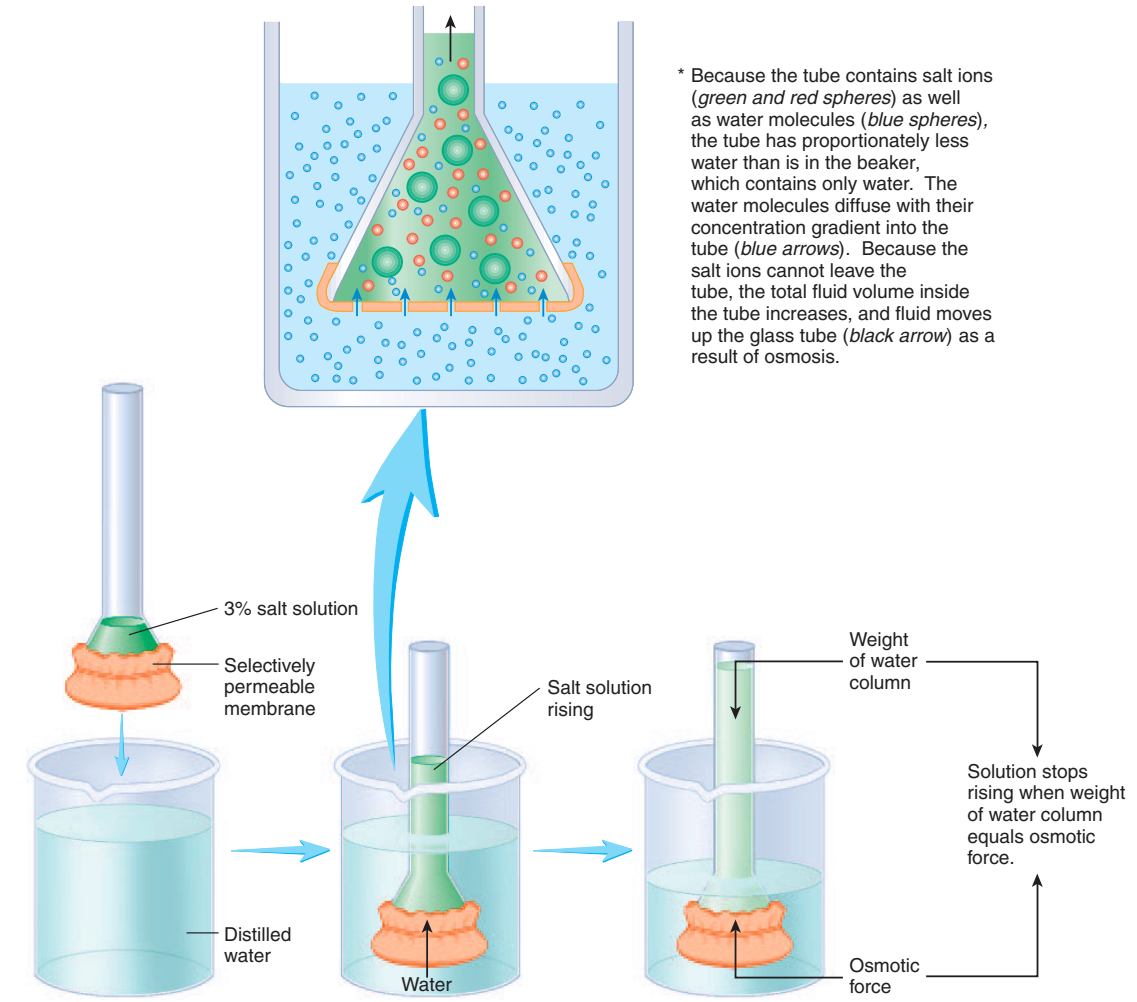
This small, lipid-soluble ligand diffuses through the plasma membrane and combines with the receptor site of an intracellular receptor.

Osmosis

Osmosis (os-mō′sis) is the diffusion of water (solvent) across a selectively permeable membrane, such as a plasma membrane. A selectively permeable membrane is a membrane that allows water but not all the solutes dissolved in the water to diffuse through the membrane. Water diffuses from a solution with proportionately more water, across a selectively permeable membrane, and into a solution with proportionately less water. Because solution concentrations are defined in terms of solute concentrations and not in terms of water content (see chapter 2), water diffuses from the less concentrated solution (fewer solutes, more water) into the more concentrated solution (more solutes, less water). Osmosis is important to cells because large volume changes caused by water movement disrupt normal cell function.

Osmotic pressure is the force required to prevent the movement of water by osmosis across a selectively permeable membrane. The osmotic pressure of a solution can be determined by placing the solution into a tube that is closed at one end by a selectively permeable membrane (figure 3.14). The tube is then immersed in distilled water. Water molecules move by osmosis through the membrane into the tube, forcing the solution to move up the tube. As the solution rises into the tube, its weight produces hydrostatic pressure that moves water out of the tube back into the distilled water surrounding the tube. At equilibrium, net movement of water stops, which means the movement of water into the tube by osmosis is equal to the movement of water out of the tube caused by hydrostatic pressure. The osmotic pressure of the solution in the tube is equal to the hydrostatic pressure that prevents net movement of water into the tube.

The osmotic pressure of a solution provides information about the tendency for water to move by osmosis across a selectively permeable membrane. Because water moves from less



Process Figure 3.14 Osmosis

concentrated solutions (fewer solutes, more water) into more concentrated solutions (more solutes, less water), the greater the concentration of a solution (the less water it has), the greater the tendency for water to move into the solution, and the greater the osmotic pressure to prevent that movement. Thus, the greater the concentration of a solution, the greater the osmotic pressure of the solution, and the greater the tendency for water to move into the solution.

P R E D I C T 2

Given the demonstration in figure 3.14, what would happen to osmotic pressure if the membrane were not selectively permeable but instead allowed all solutes and water to pass through it?

Three terms describe the osmotic pressure of solutions. Solutions with the same concentration of solute particles (see chapter 2) have the same osmotic pressure and are referred to as **isosmotic**

(ī′sos-mot′ik). The solutions are still isosmotic even if the types of solute particles in the two solutions differ from each other. If one solution has a greater concentration of solute particles and therefore a greater osmotic pressure than another solution, the first solution is said to be **hyperosmotic** (hī′per-oz-mot′ik) compared to the more dilute solution. The more dilute solution, with the lower osmotic pressure, is **hyposmotic** (hī-pos-mot′ik) compared to the more concentrated solution.

Three additional terms describe the tendency of cells to shrink or swell when placed into a solution. If a cell is placed into a solution in which it neither shrinks nor swells, the solution is said to be **isotonic** (ī-sō-ton′ik). If a cell is placed into a solution and water moves out of the cell by osmosis, causing the cell to shrink, the solution is called **hypertonic** (hī-per-ton′ik). If a cell is placed into a solution and water moves into the cell by osmosis, causing the cell to swell, the solution is called **hypotonic** (hī-pō-ton′ik) (figure 3.15*a*).

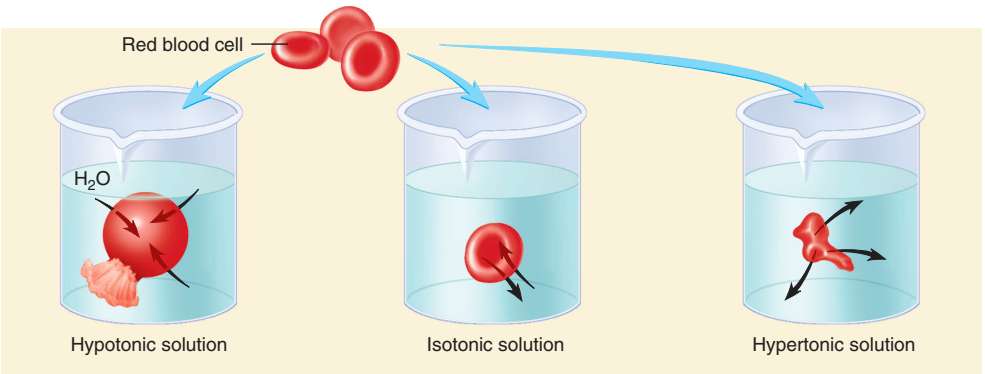
An isotonic solution may be isosmotic to the cytoplasm. Because isosmotic solutions have the same concentration of solutes and water as the cytoplasm of the cell, no net movement of water occurs, and the cell neither swells nor shrinks (figure 3.15*b*). Hypertonic solutions can be hyperosmotic and have a greater concentration of solute molecules and a lower concentration of water than the cytoplasm of the cell. Therefore water moves by osmosis from the cell into the hypertonic solution, causing the cell to shrink, a process called **crenation** (krē-nā′shŭn) (figure 3.15*c*). Hypotonic solutions can be hyposmotic and have a smaller concentration of solute molecules and a greater concentration of water than the cytoplasm of the cell. Therefore water moves by osmosis into the cell, causing it to swell. If the cell swells enough, it can rupture, a process called **lysis** (lī′sis) (see figure 3.15*a*). Solutions injected into the circulatory system or the tissues must be isotonic because crenation or swelling of cells disrupts their normal function and can lead to cell death.

The *-osmotic* terms refer to the concentration of the solutions, and the *-tonic* terms refer to the tendency of cells to swell or shrink. These terms should not be used interchangeably. Not all isosmotic solutions are isotonic. For example, it is possible to prepare a solution of glycerol and a solution of mannitol that are isosmotic to the cytoplasm of the cell. Because the solutions are isosmotic, they have the same concentration of solutes and water as the cytoplasm. Glycerol, however, can diffuse across the plasma membrane, and mannitol cannot. When glycerol diffuses into the cell, the solute concentration of the cytoplasm increases, and its water concentration decreases. Therefore, water moves by osmosis into the cell, causing it to swell, and the glycerol solution is both isosmotic and hypotonic. In contrast, mannitol cannot enter the cell, and the isosmotic mannitol solution is also isotonic.

Filtration

Filtration results when a partition containing small holes is placed in a stream of moving liquid. The partition works like a minute sieve. Particles small enough to pass through the holes move through the partition with the liquid, but particles larger than the holes are prevented from moving beyond the partition. In contrast to diffusion, filtration depends on a pressure difference on either side of the partition. The liquid moves from the side of the partition with the greater pressure to the side with the lower pressure.

Filtration occurs in the kidneys as a step in urine formation. Blood pressure moves fluid from the blood through a partition, or filtration membrane. Water, ions, and small molecules pass through the partition, whereas most proteins and blood cells remain in the blood.



(a) A hypotonic solution with a low solute concentration results in swelling (*black arrows*) and lysis (*puff of red in the lower left part of the cell*) of a red blood cell placed into the solution.

(b) An isotonic solution with a concentration of solutes equal to that inside the cell results in a normally shaped red blood cell. Water moves into and out of the cell in equilibrium (*black arrows*), but there is no net water movement.

(c) A hypertonic solution, with a high solute concentration, causes shrinkage (crenation) of the red blood cell as water moves out of the cell and into the hypertonic solution (*black arrows*).

Figure 3.15 Effects of Hypotonic, Isotonic, and Hypertonic Solutions on Red Blood Cells

9. *List four ways that substances move across the plasma membrane.*
10. *Define solute, solvent, and concentration gradient. Do solutes diffuse with or against their concentration gradient?*
11. *How is the rate of diffusion affected by an increased concentration gradient? By increased temperature of a solution? By increased viscosity of the solvent?*
12. *Define osmosis and osmotic pressure. As the concentration of a solution increases, what happens to its osmotic pressure and to the tendency for water to move into it?*
13. *Compare isosmotic, hyperosmotic, and hyposmotic solutions to isotonic, hypertonic, and hypotonic solutions. What type of solution causes crenation of a cell? What type of solution causes lysis of a cell?*
14. *Define filtration and give an example of where it occurs in the body.*

Mediated Transport Mechanisms

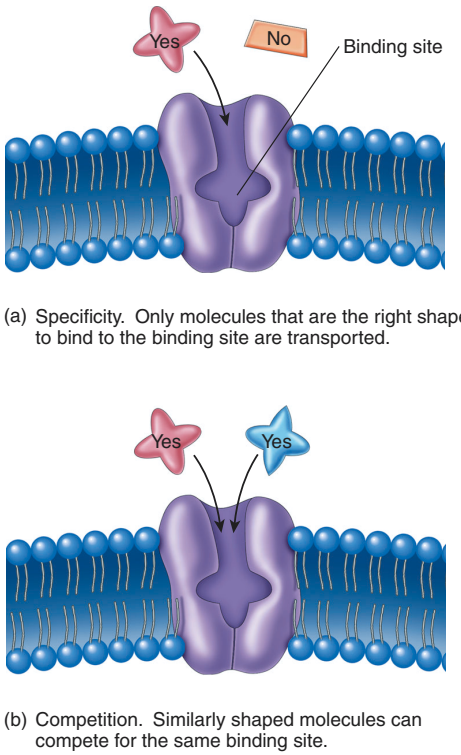
Many essential molecules, such as amino acids and glucose, cannot enter the cell by simple diffusion, and many products, such as proteins, cannot exit the cell by diffusion. **Mediated transport mechanisms** involve carrier proteins within the plasma membrane that move large, water-soluble molecules or electrically charged molecules across the plasma membrane. Once a molecule to be transported binds to the carrier protein on one side of the membrane, the three-dimensional shape of the carrier protein changes, and the transported molecule is moved to the opposite side of the membrane (see figure 3.11). The carrier protein then resumes its original shape and is available to transport other molecules.

Mediated transport mechanisms have three characteristics: specificity, competition, and saturation. **Specificity** means that each carrier protein binds to and transports only a single type of molecule. For example, the carrier protein that transports glucose does not bind to amino acids or ions. The chemical structure of the binding site determines the specificity of the carrier protein (see figure 3.11). **Competition** is the result of similar molecules binding to the carrier protein. Although the binding sites of carrier proteins exhibit specificity, closely related substances may bind to the same binding site. The substance in the greater concentration or the substance that binds to the binding site more readily is transported across the plasma membrane at the greater rate (figure 3.16*b*). **Saturation** means that the rate of transport of molecules across the membrane is limited by the number of available carrier proteins. As the concentration of a transported substance increases, more carrier proteins have their binding sites occupied. The rate at which the substance is transported increases; however, once the concentration of the substance is increased so that all the binding sites are occupied, the rate of transport remains constant, even though the concentration of the substance increases further (figure 3.17).

Three kinds of mediated transport exist: facilitated diffusion, active transport, and secondary active transport.

Facilitated Diffusion

Facilitated diffusion is a carrier-mediated process that moves substances into or out of cells from a higher to a lower concentration. Facilitated diffusion does not require metabolic energy to transport substances across the plasma membrane. The rate at which molecules are transported is directly proportional to their concentration gradient up to the point of saturation, when all the carrier proteins are occupied. Then the rate of transport remains constant at its maximum rate.



(a) Specificity. Only molecules that are the right shape to bind to the binding site are transported.

(b) Competition. Similarly shaped molecules can compete for the same binding site.

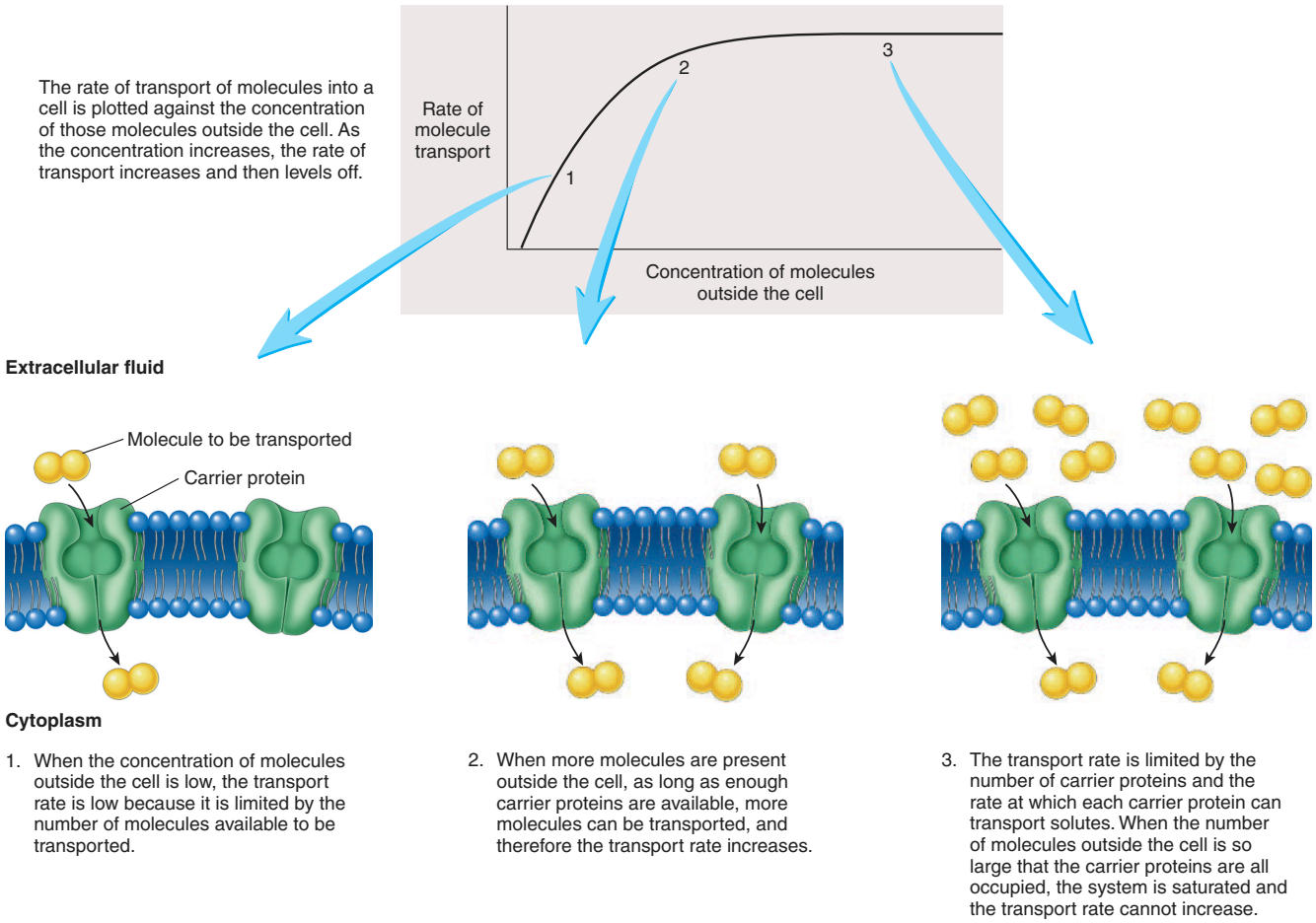
Figure 3.16 Mediated Transport: Specificity and Competition

PREDICT 3

The transport of glucose into and out of most cells, such as muscle and fat cells, occurs by facilitated diffusion. Once glucose enters a cell, it is rapidly converted to other molecules, such as glucose-6-phosphate or glycogen. What effect does this conversion have on the ability of the cell to acquire glucose? Explain.

Active Transport

Active transport is a mediated transport process that requires energy provided by ATP (figure 3.18). Movement of the transported substance to the opposite side of the membrane and its subsequent release from the carrier protein are fueled by the breakdown of ATP. The maximum rate at which active transport proceeds depends on the number of carrier proteins in the plasma membrane and the availability of adequate ATP. Active-transport processes are important because they can move substances against their concentration gradients, that is, from lower concentrations to higher concentrations. Consequently, they have the ability to accumulate



Process Figure 3.17 Saturation of a Carrier Protein

substances on one side of the plasma membrane at concentrations many times greater than those on the other side. Active transport can also move substances from higher to lower concentrations.

Some active-transport mechanisms exchange one substance for another. For example, the sodium–potassium exchange pump moves sodium out of cells and potassium into cells (figure 3.18). The result is a higher concentration of sodium outside the cell and a higher concentration of potassium inside the cell.

15. ***What is mediated transport? What types of molecules are moved through the plasma membrane by mediated transport?***
16. ***Describe specificity, competition, and saturation as characteristics of mediated transport mechanisms.***
17. ***Contrast facilitated diffusion and active transport in relation to energy expenditure and movement of substances with or against their concentration gradients.***
18. ***What are secondary active transport, cotransport, and countertransport?***

Secondary Active Transport

Secondary active transport involves the active transport of an ion such as sodium out of a cell, establishing a concentration gradient, with a higher concentration of the ions outside the cell. The tendency for the ions to move back into the cell, down their concentration gradient, provides the energy necessary to transport a different ion or some other molecule into the cell. For example, glucose is transported from the lumen of the intestine into epithelial cells by secondary active transport (figure 3.19). This process requires two carrier proteins: (1) a sodium–potassium exchange pump actively transports Na^+ out of the cell, and (2) the other carrier protein facilitates the movement of Na^+ and glucose into the cell. Both Na^+ and glucose are necessary for the carrier protein to function.

The movement of Na^+ down their concentration gradient provides the energy to move glucose molecules into the cell against their concentration gradient. Thus glucose can accumulate at concentrations higher inside the cell than outside. Because the movement of glucose molecules against their concentration

1. Three sodium ions (Na^+) and adenosine triphosphate (ATP) bind to the carrier protein.

2. The ATP breaks down to adenosine diphosphate (ADP) and a phosphate (P) and releases energy.

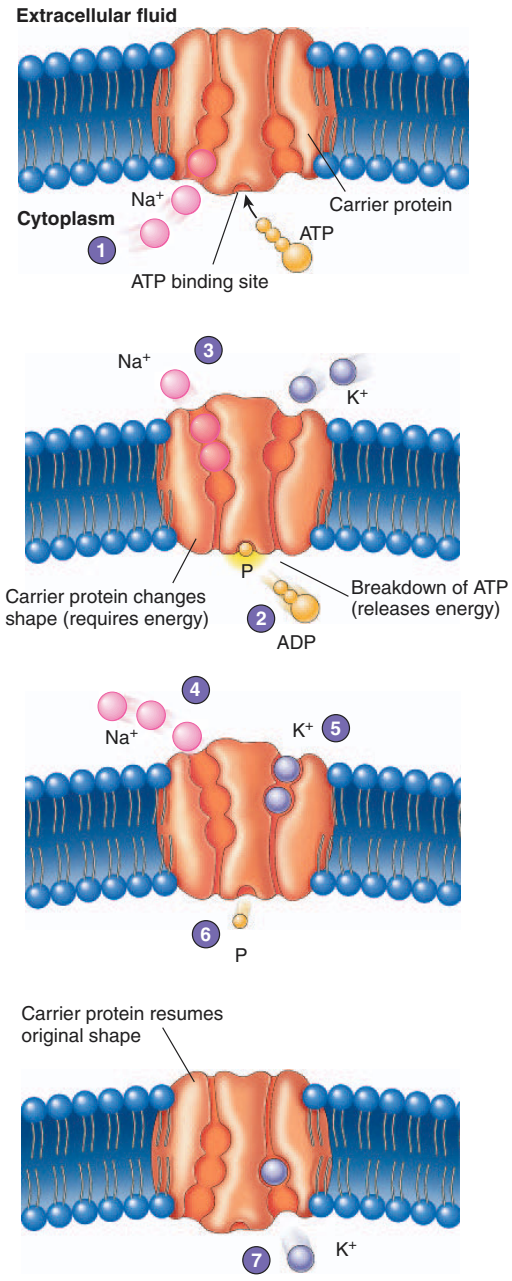
3. The carrier protein changes shape, and the Na^+ are transported across the membrane.

4. The Na^+ diffuse away from the carrier protein.

5. Two potassium ions (K^+) bind to the carrier protein.

6. The phosphate is released.

7. The carrier protein changes shape, transporting K^+ across the membrane, and the K^+ diffuse away from the carrier protein. The carrier protein can again bind to Na^+ and ATP.



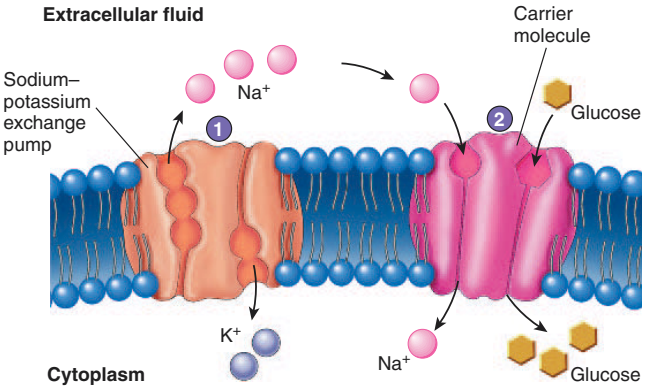
Process Figure 3.18 Sodium–Potassium Exchange Pump

gradient results from the formation of a concentration gradient of Na^+ by an active transport mechanism, the process is called secondary active transport.

The ions or molecules moved by secondary active transport can move in the same direction as or in a different direction across the membrane than the ion that enters the cell by diffusion down its concentration gradient. **Cotransport,** or **symport,** is a type of secondary active transport where movement is in the same direction. For example, glucose, fructose, and amino acids move with Na^+ into cells of the intestine and kidneys. **Countertransport,** or **antiport,** is a type of secondary active transport where ions or molecules move in opposite directions. For example, the internal pH of cells is maintained by countertransport, which moves H^+ out of the cell as Na^+ move into the cell.

This example shows cotransport of Na^+ and glucose.

1. A sodium–potassium exchange pump maintains a concentration of Na^+ that is higher outside the cell than inside.
2. Na^+ move back into the cell by a carrier protein that also moves glucose. The concentration gradient for Na^+ provides energy required to move glucose against its concentration gradient.



Process Figure 3.19 Secondary Active Transport

PREDICT 4

In cardiac (heart) muscle cells, the concentration of intracellular Ca^{2+} affects the force of heart contraction. The higher the intracellular Ca^{2+} concentration, the greater the force of contraction. Na^+/Ca^{2+} countertransport helps to regulate intracellular Ca^{2+} levels by transporting Ca^{2+} out of cardiac muscle cells. Given that digitalis slows the transport of Na^+, should the heart beat more or less forcefully when exposed to this drug? Explain.

Endocytosis and Exocytosis

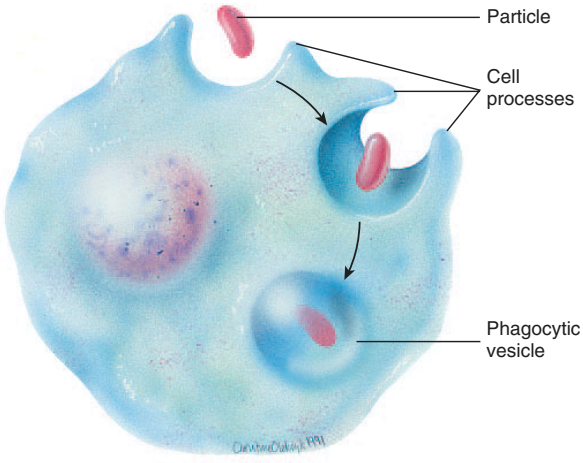
Objective

- ***Describe the processes of endocytosis and exocytosis.***

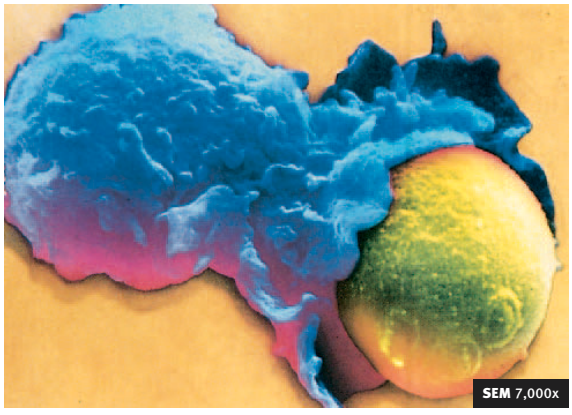
Endocytosis (en′dō-sī-tō′sis), or the internalization of substances, includes both phagocytosis and pinocytosis and refers to the bulk uptake of material through the plasma membrane by the formation of a vesicle. A **vesicle** is a membrane-bounded sac found within the cytoplasm of a cell. A portion of the plasma membrane wraps around a particle or droplet and fuses so that the particle or droplet is surrounded by a membrane. That portion of the membrane then "pinches off" so that the particle or droplet, surrounded by a membrane, is within the cytoplasm of the cell, and the plasma membrane is left intact.

Phagocytosis (fāg-ō-sī-tō′sis) literally means cell-eating (figure 3.20) and applies to endocytosis when solid particles are ingested and phagocytic vesicles are formed. White blood cells and some other cell types phagocytize bacteria, cell debris, and foreign particles. Phagocytosis is therefore important in the elimination of harmful substances from the body.

Pinocytosis (pin′ō-sī-tō′sis) means cell-drinking and is distinguished from phagocytosis in that smaller vesicles are formed and they contain molecules dissolved in liquid rather than particles (figure 3.21). Pinocytosis often forms vesicles near the tips of deep invaginations of the plasma membrane. It is a common transport



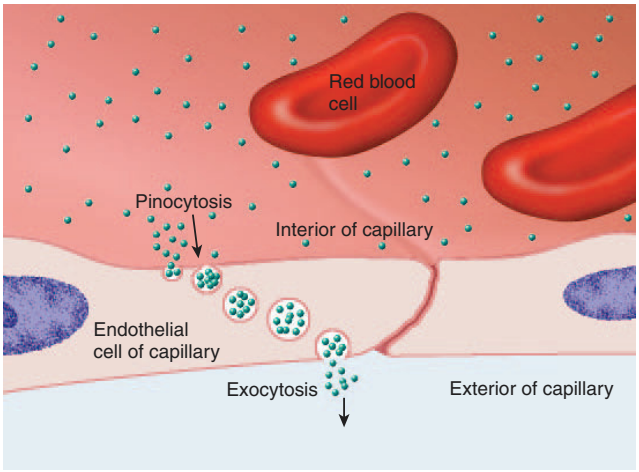
(a)



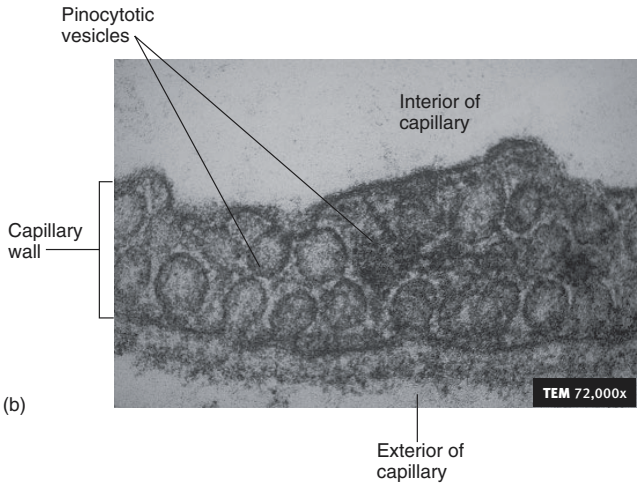
(b)

Figure 3.20 Endocytosis

(*a*) Phagocytosis. (*b*) Transmission electron micrograph of phagocytosis.



(a)



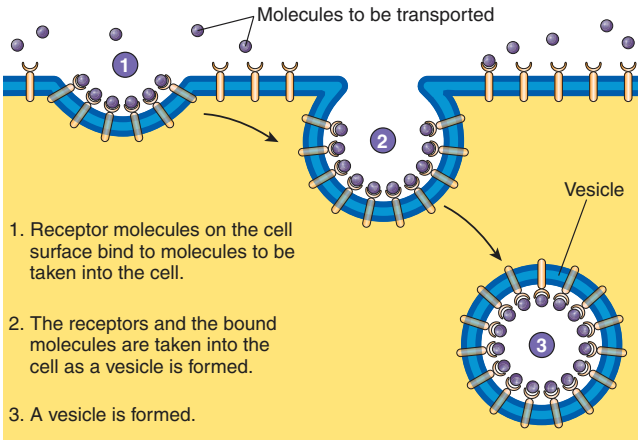
(b)

Figure 3.21 Pinocytosis

(*a*) Pinocytosis is much like phagocytosis, except the cell processes and therefore the vesicles formed are much smaller and the material inside the vesicle is liquid rather than particulate. Pinocytotic vesicles form on the internal side of a capillary, are transported across the cell, and open by exocytosis outside the capillary. (*b*) Transmission electron micrograph of pinocytosis.

phenomenon in a variety of cell types and occurs in certain cells of the kidneys, epithelial cells of the intestines, cells of the liver, and cells that line capillaries.

Endocytosis can exhibit specificity. For example, cells that phagocytize bacteria and necrotic tissue do not phagocytize healthy cells. The plasma membrane may contain specific receptor molecules that recognize certain substances and allow them to be transported into the cell by phagocytosis or pinocytosis. This is called **receptor-mediated endocytosis,** and the receptor sites combine only with certain molecules (figure 3.22). This mechanism increases the rate at which specific substances are taken up by



Process Figure 3.22 Receptor-Mediated Endocytosis

the cells. Cholesterol and growth factors are examples of molecules that can be taken into a cell by receptor-mediated endocytosis. Both phagocytosis and pinocytosis require energy in the form of ATP and therefore are active processes. Because they involve the bulk movement of material into the cell, however, phagocytosis and pinocytosis do not exhibit either the degree of specificity or saturation that active transport exhibits.

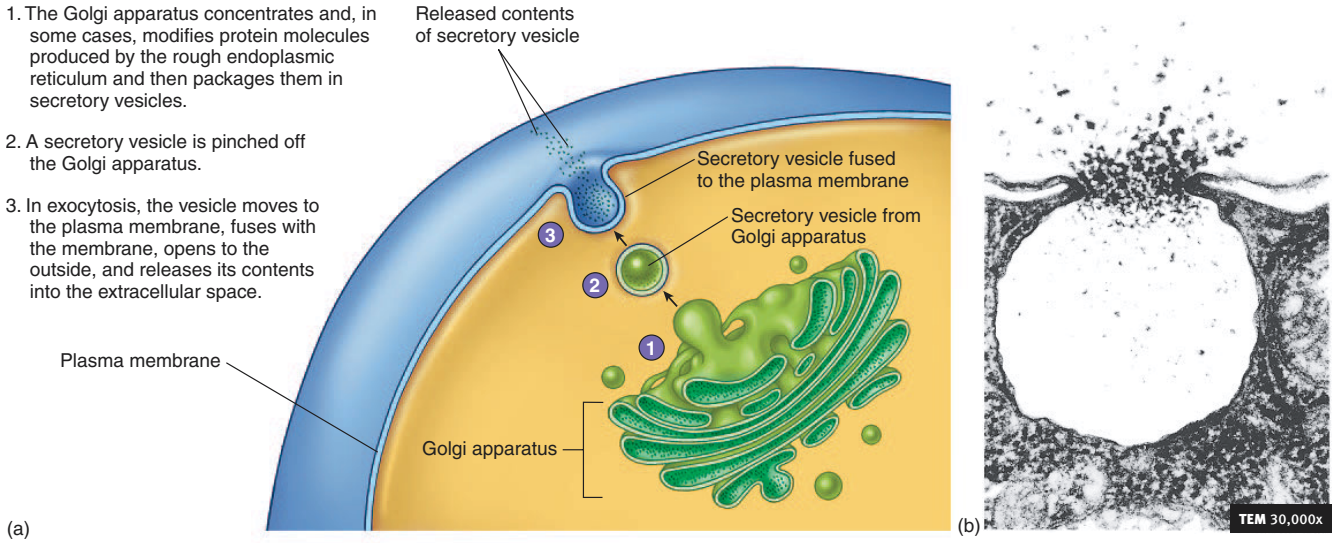
Hypercholesterolemia

Hypercholesterolemia is a common genetic disorder affecting 1 in every 500 adults in the United States. It consists of a reduction in or absence of low-density lipoprotein (LDL) receptors on cell surfaces. This interferes with receptor-mediated endocytosis of LDL cholesterol. As a result of inadequate cholesterol uptake, cholesterol synthesis within these cells is not regulated, and too much cholesterol is produced. The excess cholesterol accumulates in blood vessels, resulting in atherosclerosis. Atherosclerosis can result in heart attacks or strokes.

In some cells, secretions accumulate within vesicles. These secretory vesicles then move to the plasma membrane, where the membrane of the vesicle fuses with the plasma membrane and the content of the vesicle is expelled from the cell. This process is called **exocytosis** (ek′sō-sī-tō′sis) (figure 3.23). Secretion of digestive enzymes by the pancreas, of mucus by the salivary glands, and of milk by the mammary glands are examples of exocytosis. In some respects the process is similar to phagocytosis and pinocytosis but occurs in the opposite direction.

Table 3.2 summarizes and compares the mechanisms by which different kinds of molecules are transported across the plasma membrane.

- *19. Define endocytosis and vesicle. How do phagocytosis and pinocytosis differ from each other?*
- *20. What is receptor-mediated endocytosis?*
- *21. Describe and give examples of exocytosis.*



Process Figure 3.23 Exocytosis

(*a*) Example of exocytosis. (*b*) Transmission electron micrograph of exocytosis.

Cytoplasm

Objective

- ***Describe the cytosol and cytoskeleton of the cell.***

Cytoplasm, the cellular material outside the nucleus but inside the plasma membrane, is about half cytosol and half organelles.

Cytosol

Cytosol (sī′tō-sol) consists of a fluid portion, a cytoskeleton, and cytoplasmic inclusions. The fluid portion of cytosol is a solution with dissolved ions and molecules and a colloid with suspended molecules, especially proteins. Many of these proteins are enzymes that catalyze the breakdown of molecules for energy or the synthesis of sugars, fatty acids, nucleotides, amino acids, and other molecules.

Cytoskeleton

The **cytoskeleton** supports the cell and holds the nucleus and organelles in place. It is also responsible for cell movements, such as changes in cell shape or movement of cell organelles. The cytoskeleton consists of three groups of proteins: microtubules, actin filaments, and intermediate filaments (figure 3.24).

Microtubules are hollow tubules composed primarily of protein units called **tubulin.** The microtubules are about 25 nanometers (nm) in diameter, with walls about 5 nm thick. Microtubules vary in length but are normally several micrometers (μm) long. Microtubules play a variety of roles within cells. They help provide support and structure to the cytoplasm of the cell, much like an internal scaffolding. They are involved in the process of cell division, transport of intracellular materials, and form essential components of certain cell organelles, such as centrioles, spindle fibers, cilia, and flagella.

Actin filaments, or **microfilaments,** are small fibrils about 8 nm in diameter that form bundles, sheets, or networks in the cytoplasm of cells. These filaments have a spiderweb-like appearance within the cell. Actin filaments provide structure to the cytoplasm and mechanical support for microvilli. Actin filaments support the plasma membrane and define the shape of the cell. Changes in cell shape involve the breakdown and reconstruction of actin filaments. These changes in shape allow some cells to move about. Muscle cells contain a large number of highly organized actin filaments responsible for the muscle's contractile capabilities (see chapter 9).

Intermediate filaments are protein fibers about 10 nm in diameter. They provide mechanical strength to cells. For example, intermediate filaments support the extensions of nerve cells, which have a very small diameter but can be a meter in length.

Cytoplasmic Inclusions

The cytosol also contains **cytoplasmic inclusions,** which are aggregates of chemicals either produced by the cell or taken in by the cell. For example, lipid droplets or glycogen granules store energy-rich molecules; hemoglobin in red blood cells transports oxygen; melanin is a pigment that colors the skin, hair, and eyes; and **lipochromes** (lip′ō-krōmz) are pigments that increase in amount with age. Dust, minerals, and dyes can also accumulate in the cytoplasm.

- ***22. Define cytoplasm and cytosol.***
- ***23. What are the two general functions of the cytoskeleton?***
- ***24. Describe and list the functions of microtubules, actin filaments, and intermediate filaments.***
- ***25. Define and give examples of cytoplasmic inclusions. What are lipochromes?***

Table 3.2 Comparison of Membrane Transport Mechanisms

Transport Mechanism	Description	Substances Transported	Example
Diffusion	Random movement of molecules results in net movement from areas of higher to lower concentration.	Lipid-soluble molecules dissolve in the lipid bilayer and diffuse through it; ions and small molecules diffuse through membrane channels.	Oxygen, carbon dioxide, and lipids such as steroid hormones dissolve in the lipid bilayer; Cl^- and urea move through membrane channels.
Osmosis	Water diffuses across a selectively permeable membrane.	Water diffuses through the lipid bilayer.	Water moves from the stomach into the blood.
Filtration	Liquid moves through a partition that allows some, but not all, of the substances in the liquid to pass through it; movement is due to a pressure difference across the partition.	Liquid and substances pass through holes in the partition.	Filtration in the kidneys allows removal of everything from the blood except proteins and blood cells.
Facilitated diffusion	Carrier molecules combine with substances and move them across the plasma membrane; no ATP is used; substances are always moved from areas of higher to lower concentration; it exhibits the characteristics of specificity, saturation, and competition.	Some substances too large to pass through membrane channels and too polar to dissolve in the lipid bilayer are transported.	Glucose moves by facilitated diffusion into muscle cells and fat cells.
Active transport	Carrier molecules combine with substances and move them across the plasma membrane; ATP is used; substances can be moved from areas of lower to higher concentration; it exhibits the characteristics of specificity, saturation, and competition.	Substances too large to pass through channels and too polar to dissolve in the lipid bilayer are transported; substances that are accumulated in concentrations higher on one side of the membrane than on the other are transported.	Ions such as Na^+, K^+, and Ca^{2+} are actively transported.
Secondary active transport	Ions are moved across the plasma membrane by active transport, which establishes a concentration gradient; ATP is required; ions then move back down their concentration gradient by facilitated diffusion, and another ion or molecule moves with the diffusion ion (cotransport) or in the opposite direction (countertransport).	Some sugars, amino acids, and ions are transported.	A concentration gradient for Na^+ exists in intestinal epithelial cells. This gradient provides the energy for the cotransport of glucose. As Na^+ enter the cell, down their concentration gradient, glucose also enters the cell. In many cells, H^+ is countertransported (in the opposite direction) with Na^+.
Endocytosis	The plasma membrane forms a vesicle around the substances to be transported, and the vesicle is taken into the cell; this requires ATP; in receptor-mediated endocytosis specific substances are ingested.	Phagocytosis takes in cells and solid particles; pinocytosis takes in molecules dissolved in liquid.	Immune system cells called phagocytes ingest bacteria and cellular debris; most cells take in substances through pinocytosis.
Exocytosis	Materials manufactured by the cell are packaged in secretory vesicles that fuse with the plasma membrane and release their contents to the outside of the cell; this requires ATP.	Proteins and other water-soluble molecules are transported out of cells.	Digestive enzymes, hormones, neurotransmitters, and glandular secretions are transported, and cell waste products are eliminated.

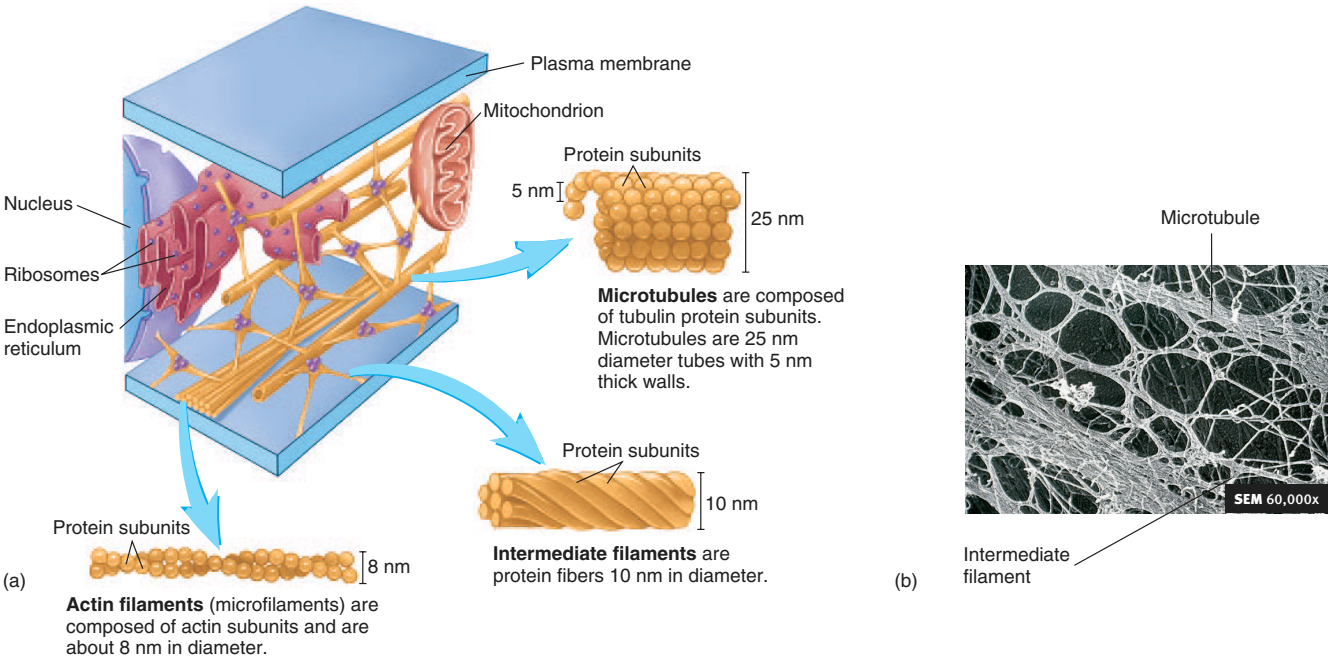


Figure 3.24 Cytoskeleton

(*a*) Diagram of the cytoskeleton. (*b*) Scanning electron micrograph of the cytoskeleton.

Organelles

Objectives

- ***Describe centrioles, spindle fibers, cilia, flagella, and microvilli.***
- ***Explain the structure and function of ribosomes, rough endoplasmic reticulum, smooth endoplasmic reticulum, Golgi apparatus, and secretory vesicles.***
- ***Distinguish between lysosomes, peroxisomes, and proteasomes.***
- ***Describe the structure and function of mitochondria.***

Organelles are small structures within cells that are specialized for particular functions, such as manufacturing proteins or producing ATP. Organelles can be thought of as individual workstations within the cell, each responsible for performing specific tasks. Most, but not all organelles have membranes that are similar to the plasma membrane. The membranes separate the interior of the organelles from the rest of the cytoplasm, creating a subcellular compartment with its own enzymes that is capable of carrying out its own unique chemical reactions. The nucleus is an example of an organelle.

The number and type of cytoplasmic organelles within each cell are related to the specific structure and function of the cell. Cells secreting large amounts of protein contain well-developed organelles that synthesize and secrete protein, whereas cells actively transporting substances such as sodium ions across their plasma membrane contain highly developed organelles that produce ATP. The following sections describe the structure and main functions of the major cytoplasmic organelles found in cells.

Centrioles and Spindle Fibers

The **centrosome** (sen′trō-sōm) is a specialized zone of cytoplasm close to the nucleus that is the center of microtubule formation. It contains two **centrioles** (sen′trē-ōlz). Each centriole is a small, cylindrical organelle about 0.3–0.5 μm in length and 0.15 μm in diameter, and the two centrioles are normally oriented perpendicular to each other within the centrosome (see figure 3.1). The wall of the centriole is composed of nine evenly spaced, longitudinally oriented, parallel units, or triplets. Each unit consists of three parallel microtubules joined together (figure 3.25).

Microtubules appear to influence the distribution of actin and intermediate filaments. Through its control of microtubule formation, the centrosome is therefore closely involved in determining cell shape and movement. The microtubules extending from the centrosomes are very dynamic—constantly growing and shrinking.

Before cell division, the two centrioles double in number, the centrosome divides into two, and one centrosome, containing two centrioles, moves to each end of the cell. Microtubules called **spindle fibers** extend out in all directions from the centrosome. These microtubules grow and shrink even more rapidly than those of nondividing cells. If the extended end of a spindle fiber comes in contact with a **kinetochore** (ki-nē′tō-kōr, ki-net′ō-kōr), a specialized region on each chromosome, the spindle fiber attaches to the kinetochore and stops growing or shrinking. Eventually spindle fibers from each centromere bind to the kinetochores of all the chromosomes. During cell division, the microtubules facilitate the movement of chromosomes toward the two centrosomes (see the section on "Cell Division" near the end of the chapter).

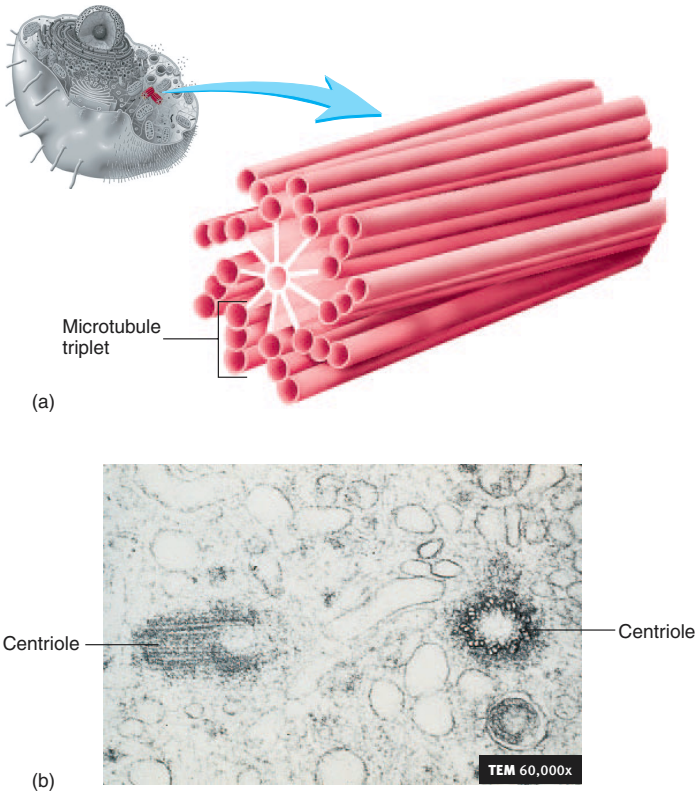


Figure 3.25 Centriole

(*a*) Structure of a centriole, which comprises nine triplets of microtubules. Each triplet contains one complete microtubule fused to two incomplete microtubules. (*b*) Transmission electron micrograph of a pair of centrioles, which are normally located together near the nucleus. One is shown in cross section and one in longitudinal section.

Cilia and Flagella

Cilia (sil′ē-ă) are appendages that project from the surface of cells and are capable of movement. They are usually limited to one surface of a given cell and vary in number from one to thousands per cell. Cilia are cylindrical in shape, about 10 μm in length and 0.2 μm in diameter, and the shaft of each cilium is enclosed by the plasma membrane. Two centrally located microtubules and nine peripheral pairs of fused microtubules, the so-called 9+2 arrangement, extend from the base to the tip of each cilium (figure 3.26). Movement of the microtubules past each other, a process that requires energy from ATP, is responsible for movement of the cilia. **Dynein arms,** proteins connecting adjacent pairs of microtubules, push the microtubules past each other. A **basal body** (a modified centriole) is located in the cytoplasm at the base of the cilium. Cilia are numerous on surface cells that line the respiratory tract and the female reproductive tract. In these regions cilia move in a coordinated fashion, with a power stroke in one direction and a recovery stroke in the opposite direction (figure 3.27). Their motion moves materials over the surface of the cells. For example, cilia in the trachea move mucus embedded with dust particles upward and away from the lungs. This action helps keep the lungs clear of debris.

Flagella (flă-jel′ă) have a structure similar to cilia but are longer (55 μm), and usually only one exists per sperm cell. Furthermore, whereas cilia move small particles across the cell surface, flagella move the cell. For example, each sperm cell is propelled by a single flagellum. In contrast to cilia, which have a power stroke and a recovery stroke, flagella move in a wavelike fashion.

Microvilli

Microvilli (mī-krō-vil′ī) (figure 3.28) are cylindrically shaped extensions of the plasma membrane about 0.5–1.0 μm in length and 90 nm in diameter. Normally many microvilli are on each cell, and they function to increase the cell surface area. A student looking at photographs may confuse microvilli with cilia. Microvilli, however, are only one-tenth to one-twentieth the size of cilia. Individual microvilli can usually only be seen with an electron microscope, whereas cilia can be seen with a light microscope. Microvilli do not move, and they are supported with actin filaments, not microtubules. Microvilli are found in the intestine, kidney, and other areas in which absorption is an important function. In certain locations of the body, microvilli are highly modified to function as sensory receptors. For example, elongated microvilli in hair cells of the inner ear respond to sound.

26. *Define organelles.*
27. *Describe and list the functions of centrosomes. Explain the structure of centrioles.*
28. *What are spindle fibers? Explain the relationship between centrosomes, spindle fibers, and the kinetochores of chromosomes during cell division.*
29. *Contrast the structure and function of cilia and flagella.*
30. *Describe the structure and function of microvilli. How are microvilli different from cilia?*

Ribosomes

Ribosomes (rī′bō-sōms) are the sites of protein synthesis. Each ribosome is composed of a large subunit and a smaller one. The ribosomal subunits, which consist of **ribosomal RNA (rRNA)** and proteins, are produced separately in the nucleolus of the nucleus. The ribosomal subunits then move through the nuclear pores into the cytoplasm, where they assemble to form the functional ribosome during protein synthesis (figure 3.29). Ribosomes can be found free in the cytoplasm or associated with a membrane called the endoplasmic reticulum. **Free ribosomes** primarily synthesize proteins used inside the cell, whereas endoplasmic reticulum ribosomes can produce proteins that are secreted from the cell.

Endoplasmic Reticulum

The outer membrane of the nuclear envelope is continuous with a series of membranes distributed throughout the cytoplasm of the cell, collectively referred to as the **endoplasmic reticulum** (en′dō-plas′mik re-tik′ū-lŭm; network inside the cytoplasm) (figure 3.30). The endoplasmic reticulum consists of broad, flattened, interconnecting sacs and tubules. The interior spaces of those sacs and tubules are called **cisternae** (sis-ter′nē) and are isolated from the rest of the cytoplasm.

Rough endoplasmic reticulum is endoplasmic reticulum with attached ribosomes. The ribosomes of the rough endoplasmic reticulum are sites where proteins are produced and modified for

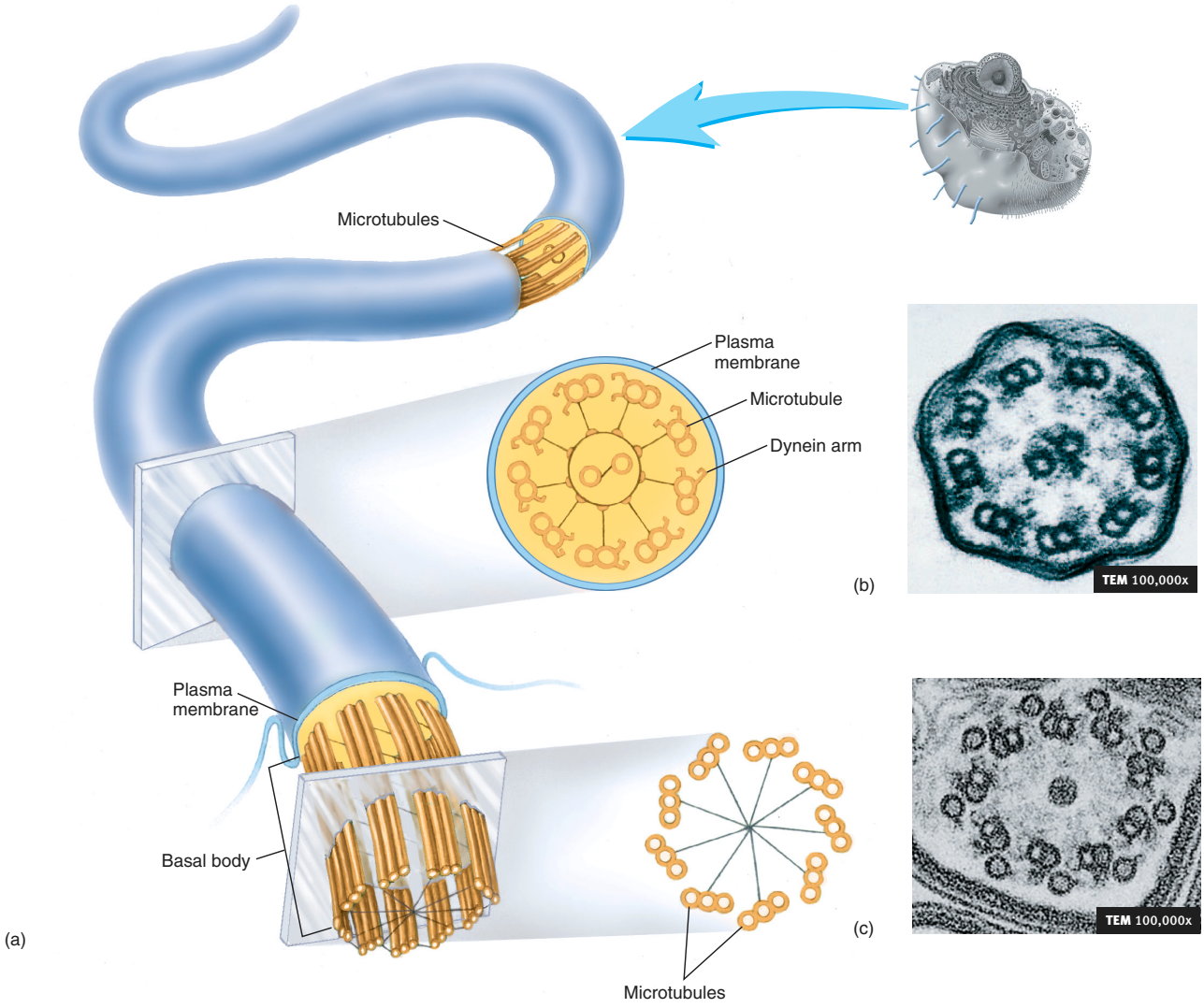


Figure 3.26 Cilia and Flagella

(*a*) Ciliary or flagellar structures. The shaft is composed of nine microtubule doublets around its periphery and two in the center. Dynein arms are proteins that connect one pair of microtubules to another pair. Dynein arm movement, which requires ATP, causes the microtubules to slide past each other, resulting in bending or movement of the cilium or flagellum. A basal body attaches the cilium or flagellum to the plasma membrane. (*b*) TEM through cilium. (*c*) TEM through basal body of cilium.

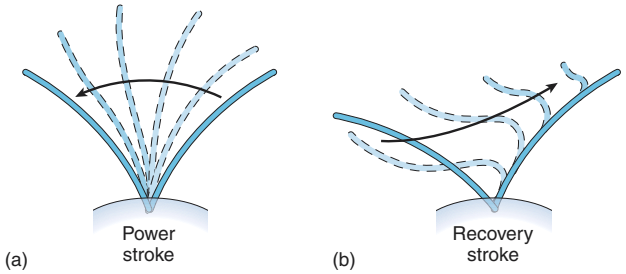


Figure 3.27 Ciliary Movement

(*a*) Power and (*b*) recovery strokes.

secretion and for internal use. The amount and configuration of the endoplasmic reticulum within the cytoplasm depend on the cell type and function. Cells with abundant rough endoplasmic reticulum synthesize large amounts of protein that are secreted for use outside the cell.

Smooth endoplasmic reticulum, which is endoplasmic reticulum without attached ribosomes, manufactures lipids, such as phospholipids, cholesterol, steroid hormones, and carbohydrates like glycogen. Many phospholipids produced in the smooth endoplasmic reticulum help form vesicles within the cell and contribute to the plasma membrane. Cells that synthesize large amounts of lipid contain dense accumulations of smooth endoplasmic reticulum. Enzymes required for lipid synthesis are

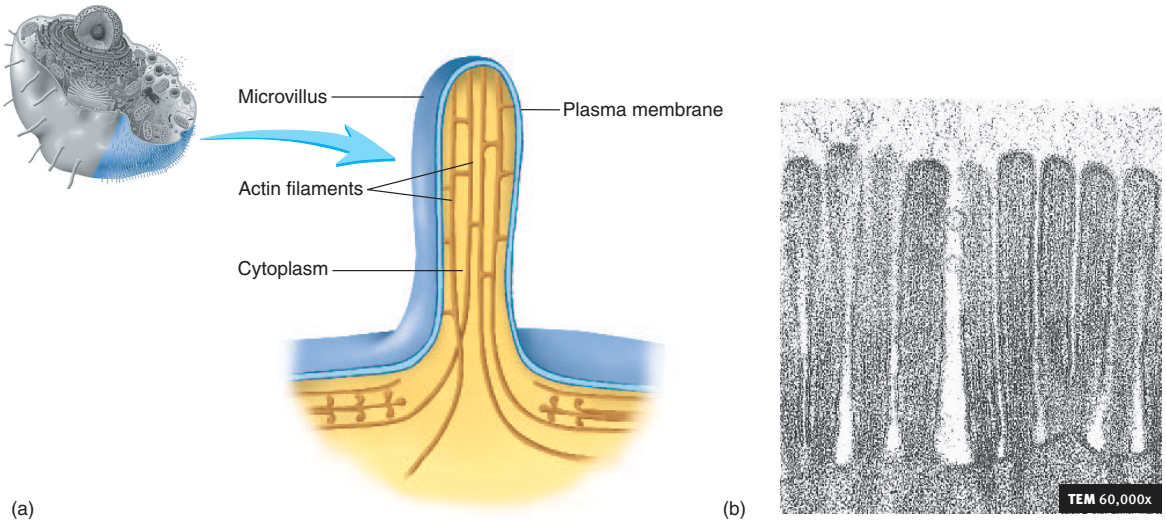
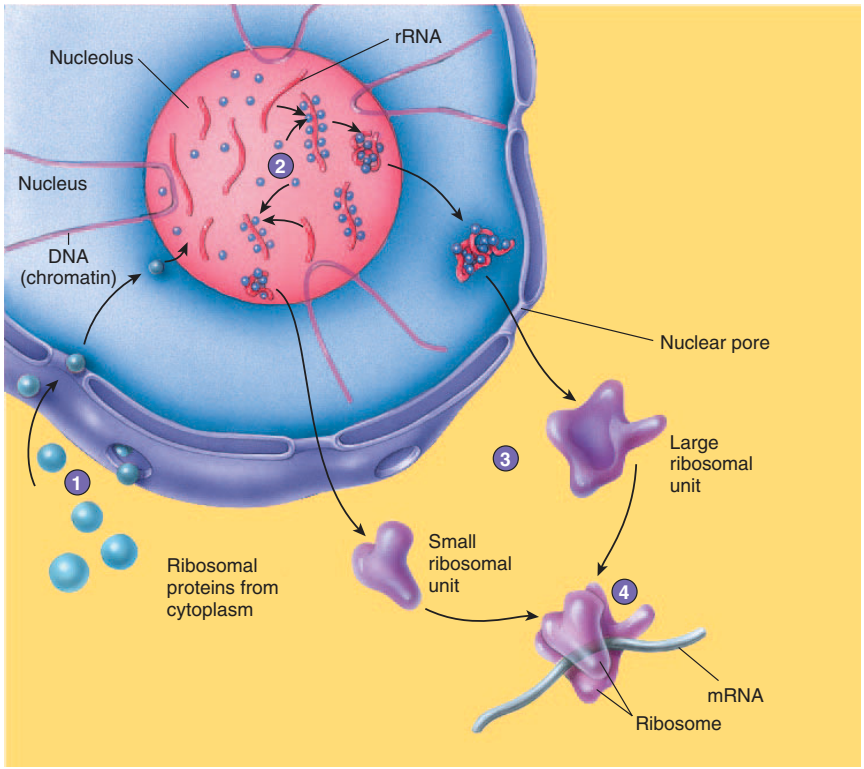


Figure 3.28 Microvillus

(*a*) A microvillus is a tiny tubular extension of the cell and contains cytoplasm and some actin filaments (microfilaments). (*b*) Transmission electron micrograph of microvilli.

1. Ribosomal proteins, produced in the cytoplasm, are transported through nuclear pores into the nucleolus.
2. rRNA, most of which is produced in the nucleolus, is assembled with ribosomal proteins to form small and large ribosomal subunits.
3. The small and large ribosomal subunits leave the nucleolus and the nucleus through nuclear pores.
4. The small and large subunits, now in the cytoplasm, combine with each other and with mRNA.



Process Figure 3.29 Production of Ribosomes

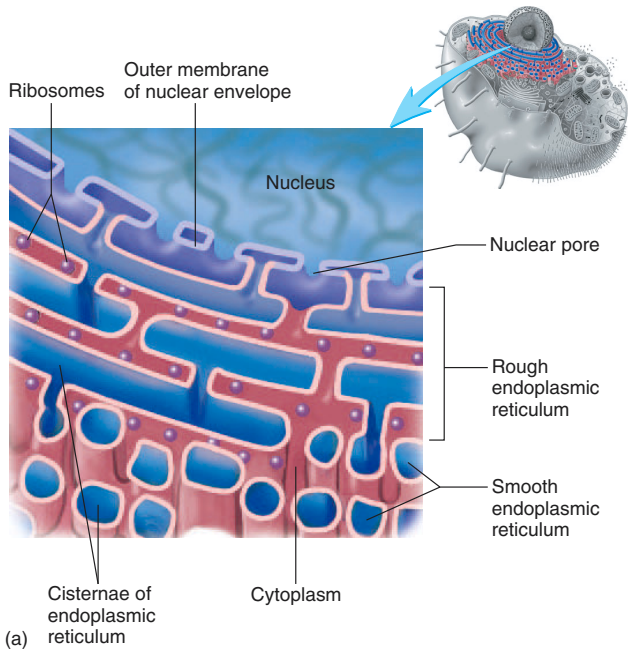


Figure 3.30 The Endoplasmic Reticulum

(*a*) The endoplasmic reticulum is continuous with the nuclear envelope and can exist as either rough endoplasmic reticulum (with ribosomes) or smooth endoplasmic reticulum (without ribosomes). (*b*) Transmission electron micrograph of the rough endoplasmic reticulum.

associated with the membranes of the smooth endoplasmic reticulum. Smooth endoplasmic reticulum also participates in the detoxification processes by which enzymes act on chemicals and drugs to change their structure and reduce their toxicity. The smooth endoplasmic reticulum of skeletal muscle stores calcium ions that function in muscle contraction.

Golgi Apparatus

The **Golgi** (gōl′jē) **apparatus** (figure 3.31) is composed of flattened membranous sacs, containing cisternae, that are stacked on each other like dinner plates. The Golgi apparatus can be thought of as a packaging and distribution center because it modifies, packages, and distributes proteins and lipids manufactured by the rough and smooth endoplasmic reticula (figure 3.32). Proteins produced at the ribosomes of the rough endoplasmic reticulum enter the endoplasmic reticulum and, then, are surrounded by a **vesicle** (ves′i-kl), or little sac, that forms from the membrane of the endoplasmic reticulum. This vesicle, called a **transport vesicle,** moves to the Golgi apparatus, fuses with its membrane, and releases the protein into its cisterna. The Golgi apparatus concentrates and, in some cases, chemically modifies the proteins by synthesizing and attaching carbohydrate molecules to the proteins to form glycoproteins or attaching lipids to proteins to form lipoproteins. The proteins are then packaged into vesicles that pinch off from the margins of the Golgi apparatus and are distributed to various locations. Some vesicles carry proteins to the plasma membrane, where the proteins are secreted from the cell by exocytosis; other vesicles contain proteins that become part of the plasma membrane; and still other vesicles contain enzymes that are used within the cell.

The Golgi apparatuses are most numerous and most highly developed in cells that secrete large amounts of protein or glycoproteins, such as cells in the salivary glands and the pancreas.

31. *What kinds of molecules are in ribosomes? Where are ribosomal subunits formed and assembled?*
32. *Compare the functions of free ribosomes and endoplasmic reticulum ribosomes.*
33. *How is the endoplasmic reticulum related to the nuclear envelope? How are the cisternae of the endoplasmic reticulum related to the rest of the cytoplasm?*
34. *What are the functions of smooth endoplasmic reticulum?*
35. *Describe the structure and function of the Golgi apparatus.*
36. *Describe the production of a protein at the endoplasmic reticulum and its distribution to the Golgi apparatus. Name three ways in which proteins are distributed from the Golgi apparatus.*

Secretory Vesicles

The membrane-bounded **secretory vesicles** (see figure 3.31) that pinch off from the Golgi apparatus move to the surface of the cell, their membranes fuse with the plasma membrane, and the contents of the vesicle are released to the exterior by exocytosis. The membranes of the vesicles are then incorporated into the plasma membrane.

Secretory vesicles accumulate in many cells, but their contents frequently are not released to the exterior until a signal is received by the cell. For example, secretory vesicles that contain the hormone insulin do not release it until the concentration of glucose in the blood increases and acts as a signal for the secretion of insulin from the cells.

Lysosomes

Lysosomes (lī′sō-sōmz) are membrane-bound vesicles that pinch off from the Golgi apparatus (see figure 3.31). They contain a variety of hydrolytic enzymes that function as intracellular digestive systems. Vesicles taken into the cell fuse with the lysosomes to form one vesicle and to expose the phagocytized materials to hydrolytic enzymes (figure 3.33). Various enzymes within lysosomes digest nucleic acids, proteins, polysaccharides, and lipids. Certain white blood cells have large numbers of lysosomes that contain enzymes to digest phagocytized bacteria. Lysosomes also digest organelles of the cell that are no longer functional in a process called **autophagia** (aw-tō-fā′jē-ă; self-eating). Furthermore, when tissues are damaged,

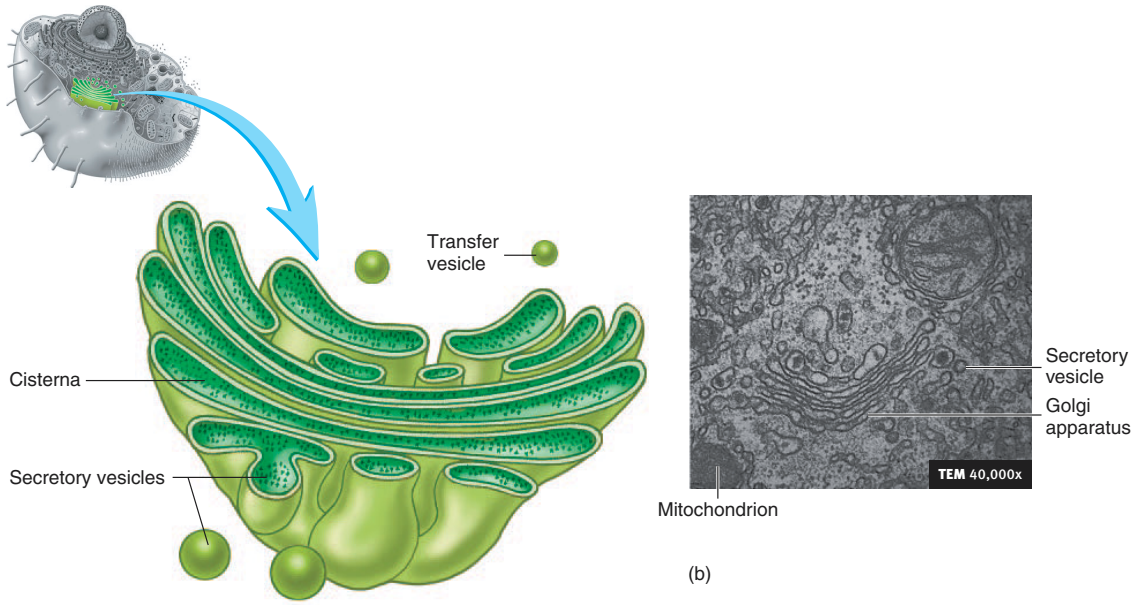
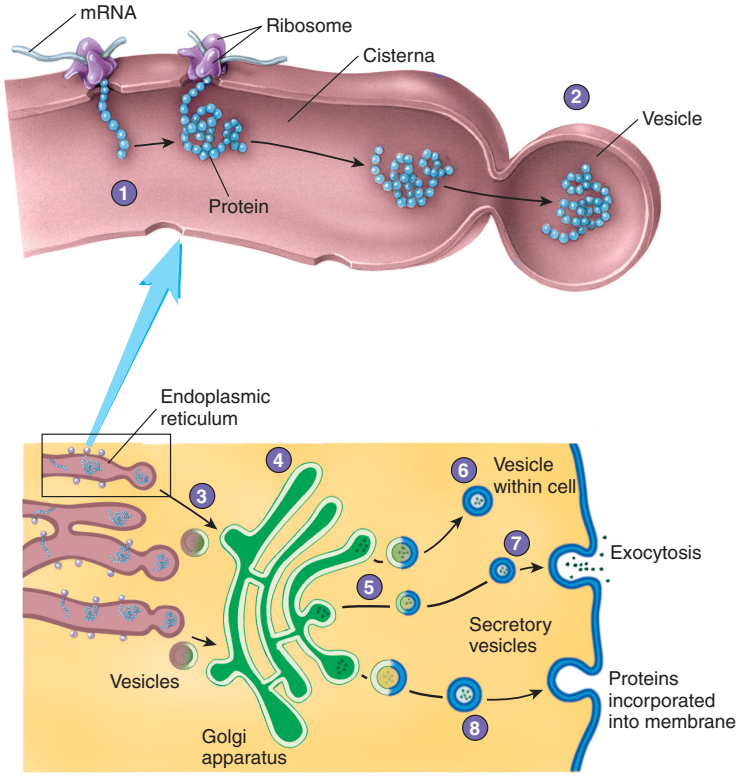


Figure 3.31 Golgi Apparatus

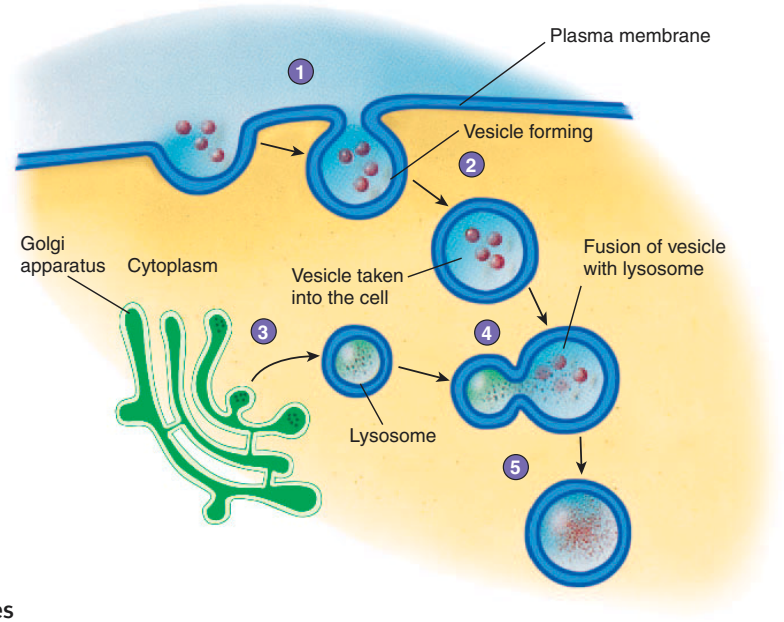
(*a*) The Golgi apparatus is composed of flattened membranous sacs, containing cisternae, and resembles a stack of dinner plates or pancakes. (*b*) Transmission electron micrograph of the Golgi apparatus.

1. Some proteins are produced at ribosomes on the surface of the rough endoplasmic reticulum and are transferred into the cisterna as they are produced.
2. The proteins are surrounded by a vesicle that forms from the membrane of the endoplasmic reticulum.
3. The vesicle moves from the endoplasmic reticulum to the Golgi apparatus, fuses with its membrane and releases the proteins into its cisterna.
4. The Golgi apparatus concentrates and, in some cases, modifies the proteins into glycoproteins or lipoproteins.
5. The proteins are packaged into vesicles that form from the membrane of the Golgi apparatus.
6. Some vesicles, such as lysosomes, contain enzymes that are used within the cell.
7. Secretory vesicles carry proteins to the plasma membrane, where the proteins are secreted from the cell by exocytosis.
8. Some vesicles contain proteins that become part of the plasma membrane.



Process Figure 3.32 Function of the Golgi Apparatus

1. A vesicle forms around material outside the cell.
2. The vesicle is pinched off from the plasma membrane and becomes a separate vesicle inside the cell.
3. A lysosome is pinched off the Golgi apparatus.
4. The lysosome fuses with the vesicle.
5. The enzymes from the lysosome mix with the material in the vesicle, and the enzymes digest the material.



Process Figure 3.33 Action of Lysosomes

ruptured lysosomes within the damaged cells release their enzymes, which digest both damaged and healthy cells. In other cells, the lysosomes move to the plasma membrane, and the enzymes are secreted by exocytosis. For example, the normal process of bone remodeling involves the breakdown of bone tissue by specialized bone cells. Enzymes responsible for that degradation are released into the extracellular fluid from lysosomes produced by those cells.

Diseases of Lysosomal Enzymes

Some diseases result from nonfunctional lysosomal enzymes. For example, **Pompe's disease** results from the inability of lysosomal enzymes to break down glycogen. The glycogen accumulates in large amounts in the heart, liver, and skeletal muscles, an accumulation that often leads to heart failure. **Familial hyperlipoproteinemia** is a group of genetic disorders characterized by the accumulation of large amounts of lipids in phagocytic cells that lack the normal enzymes required to break down the lipid droplets. Symptoms include abdominal pain, enlargement of the spleen and liver, and eruption of yellow nodules in the skin filled with the affected phagocytic cells. **Mucopolysaccharidoses,** such as **Hurler's syndrome,** are diseases in which lysosomal enzymes are unable to break down mucopolysaccharides (glycosaminoglycans), so these molecules accumulate in the lysosomes of connective tissue cells and nerve cells. People affected by these diseases suffer mental retardation and skeletal deformities.

Peroxisomes

Peroxisomes (per-ok′si-sōmz) are membrane-bounded vesicles that are smaller than lysosomes. Peroxisomes contain enzymes that break down fatty acids and amino acids. Hydrogen peroxide (H_2O_2), which can be toxic to the cell, is a by-product of that breakdown. Peroxisomes also contain the enzyme **catalase,** which breaks down hydrogen peroxide to water and oxygen. Cells that are active in detoxification, such as liver and kidney cells, have many peroxisomes.

Proteasomes

Proteasomes (prō′tē-ă-sōmz) consist of large protein complexes, including several enzymes that break down and recycle proteins within the cell. Proteasomes are not surrounded by membranes. They are tunnel-like structures, similar to channel protein complexes; the inner surfaces of the tunnel have enzymatic regions that break down proteins. Smaller protein subunits close the ends of the tunnel and regulate which proteins are taken into it for digestion.

Mitochondria

Mitochondria (mī-tō-kon′drē-ă) provide energy for the cell. Consequently, they are often called the cell's power plants. Mitochondria are usually illustrated as small, rod-shaped structures (figure 3.34). In living cells, time-lapse photomicrography reveals that mitochondria constantly change shape from spherical to rod-shaped or even to long, threadlike structures. Mitochondria are the major sites of ATP production, which is the major energy source for most energy-requiring chemical reactions within the cell. Each mitochondrion has an inner and outer membrane separated by an intermembranous space. The outer membrane has a smooth contour, but the inner membrane has numerous infoldings called **cristae** (kris′tē) that project like shelves into the interior of the mitochondria.

A complex series of mitochondrial enzymes forms two major enzyme systems that are responsible for oxidative metabolism and most ATP synthesis (see chapter 25). The enzymes of the citric acid (or Krebs) cycle are found in the **matrix,** which is the substance located in the space formed by the inner membrane. The enzymes of the electron transport chain are embedded within the inner membrane. Cells with a greater energy requirement have more mitochondria with more cristae than cells with lower energy requirements. Within the cytoplasm of a given cell, the mitochondria are more numerous in areas in which ATP is used. For example,

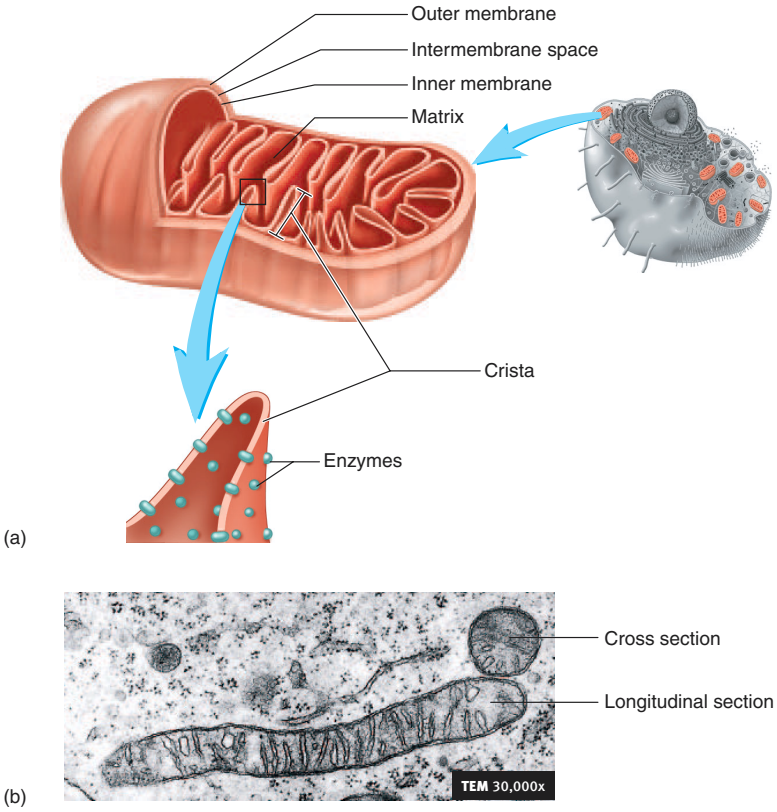


Figure 3.34 Mitochondrion

(*a*) Typical mitochondrion structure. (*b*) Transmission electron micrograph of mitochondria in longitudinal and cross section.

mitochondria are numerous in cells that perform active transport and are packed near the membrane where active transport occurs.

Increases in the number of mitochondria result from the division of preexisting mitochondria. When muscles enlarge as a result of exercise, the number of mitochondria within the muscle cells increases to provide the additional ATP required for muscle contraction.

The information for making some mitochondrial proteins is stored in DNA contained within the mitochondria themselves, and those proteins are synthesized on ribosomes within the mitochondria. The structure of many other mitochondrial proteins is determined by nuclear DNA, however, and these proteins are synthesized on ribosomes within the cytoplasm and then transported into the mitochondria. Both the mitochondrial DNA and mitochondrial ribosomes are very different from those within the nucleus and cytoplasm of the cell, respectively. Mitochondrial DNA is a closed circle of about 16,500 base pairs (bp) coding for 37 genes, compared with the open strands of nuclear DNA, which is composed of 3 billion bp coding for 30,000 genes. In addition, unlike nuclear DNA, mitochondrial DNA does not have associated proteins.

PREDICT 5

Describe the structural characteristics of cells that are highly specialized to do the following: (a) synthesize and secrete proteins, (b) actively transport substances into the cell, (c) synthesize lipids, and (d) phagocytize foreign substances.

Mitochondrial DNA

Half of the nuclear DNA of an individual is derived from the mother, and half is derived from the father; but all, or nearly all, mitochondrial DNA comes from the mother. The mitochondria of the sperm cell from the father are not incorporated into the oocyte at the time of fertilization. Because only the mother's mitochondrial DNA is passed down from generation to generation, maternal pedigrees are much easier to trace using mitochondrial DNA than with nuclear DNA. This unique quality of mitochondria has been used in a number of studies, from reuniting mothers or grandmothers with lost children to searching for the origins of the human species. A number of degenerative disorders affecting the nervous system, heart, or kidneys have been linked to mutations in mitochondrial DNA. The study of these disorders is providing valuable clues to the aging process.

37. *Define secretory vesicles.*
38. *Describe the process by which lysosomal enzymes digest phagocytized materials. Define autophagia.*
39. *What is the function of peroxisomes? How does catalase protect cells?*
40. *Describe the structure and function of proteasomes.*
41. *What is the function of mitochondria? What enzymes are found on the cristae and in the matrix? How can the number of mitochondria in a cell increase?*

Nucleus

Objective

- ***Describe the structure and function of the nucleus and nucleolus.***

The **nucleus,** which contains most of the genetic information of the cell, is a large, membrane-bounded structure usually located near the center of the cell. It may be spherical, elongated, or lobed, depending on the cell type. All cells of the body have a nucleus at some point in their life cycle, although some cells, such as red blood cells (also called red blood corpuscles or erythrocytes), lose their nuclei as they develop. Other cells, such as skeletal muscle cells and certain bone cells, called osteoclasts, contain more than one nucleus. The nucleus consists of **nucleoplasm** surrounded by a **nuclear envelope** (figure 3.35) composed of two membranes separated by a space. At many points on the surface of the nuclear envelope, the inner and outer membranes fuse to form porelike structures, the **nuclear pores.** Molecules move between the nucleus and the cytoplasm through these nuclear pores.

Deoxyribonucleic acid (DNA) and associated proteins are dispersed throughout the nucleus as thin strands about 4–5 nm in diameter. The proteins include **histones** (his′tōnz) and other proteins that play a role in the regulation of DNA function. The DNA and protein strands can be stained with dyes and are called **chromatin** (krō′ma-tin; colored material) (figure 3.36). Chromatin is distributed throughout the nucleus but is more condensed and more readily stained in some areas than in others. The more highly condensed chromatin apparently is less functional than the more evenly distributed chromatin, which stains lighter. During cell division, the chromatin condenses to form the more densely coiled bodies called **chromosomes** (colored bodies).

DNA ultimately determines the structure of proteins (protein synthesis is described later in this chapter). Many structural components of the cell and all the enzymes, which regulate most chemical reactions in the cell, are proteins. By determining protein structure, DNA therefore ultimately controls the structural and functional characteristics of the cell. DNA does not leave the nucleus but functions by means of an intermediate, **ribonucleic acid (RNA),** which can leave the nucleus. DNA determines the structure of messenger RNA (mRNA), ribosomal RNA (rRNA), and transfer RNA (tRNA) (all described in more detail later). mRNA moves out of the nucleus through the nuclear pores into the cytoplasm, where it determines the structure of proteins.

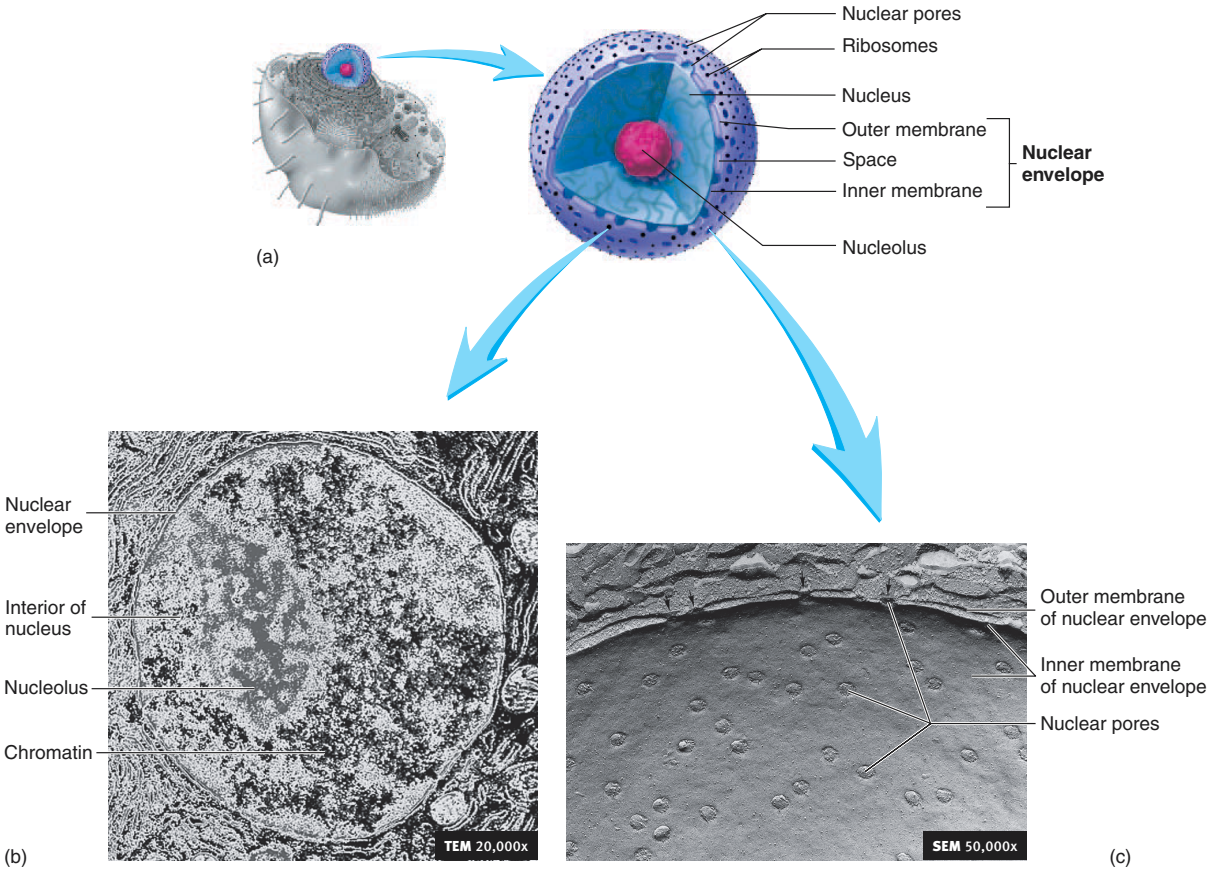


Figure 3.35 The Nucleus

(*a*) The nuclear envelope consists of inner and outer membranes that become fused at the nuclear pores. The nucleolus is a condensed region of the nucleus not bounded by a membrane and consisting mostly of RNA and protein. (*b*) Transmission electron micrograph of the nucleus. (*c*) Scanning electron micrograph showing the inner surface of the nuclear envelope and the nuclear pores.

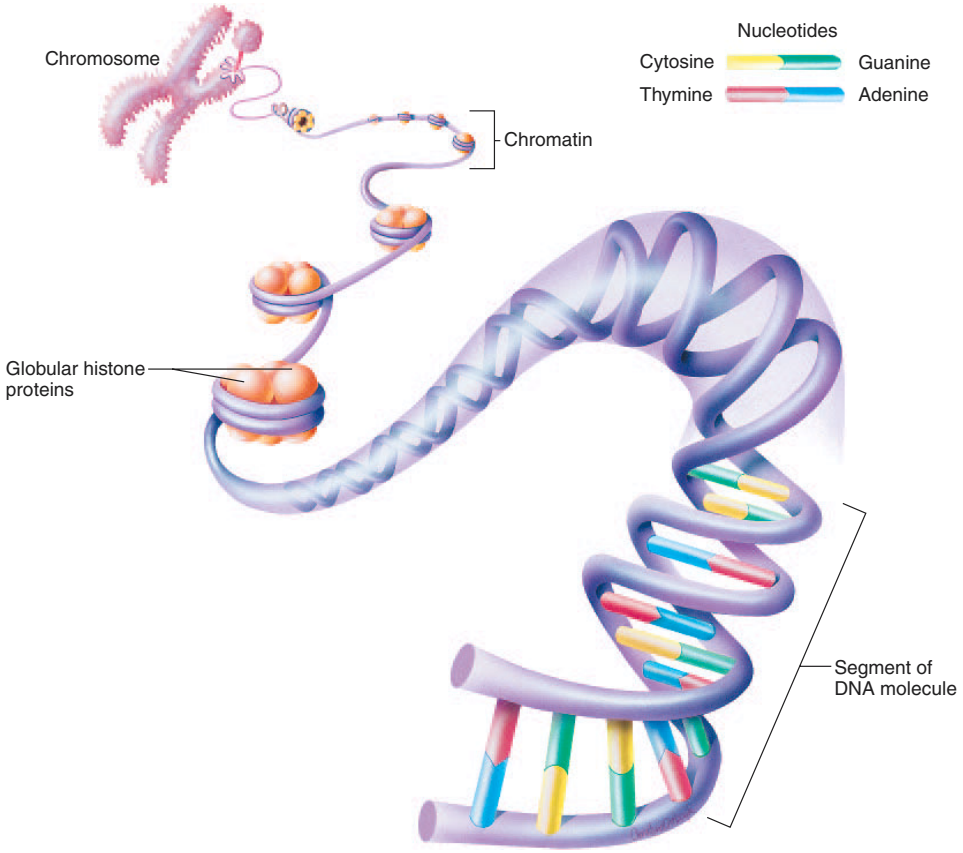


Figure 3.36 Chromosome Structure

DNA is associated with globular histone proteins. Usually the DNA molecule is stretched out, resembling a string of beads, and is called chromatin. During cell division, however, the chromatin condenses to become bodies called chromosomes.

Human Genome Project

The **Human Genome Project** is an ambitious international project, which began in 1990, with the 15-year goal of mapping and sequencing the entire human genome. The **genome** is the total of all the genes contained within each cell. One goal of the Human Genome Project is to construct a map indicating where each of the approximately 27,000–30,000 genes is located on the human chromosomes. The other major goal of the project is to determine the sequence of the estimated 3 billion base pairs (bp) that make up the human DNA molecules. The sequencing is now complete, and the mapping continues. It is hoped that by knowing for what proteins the genes implicated in genetic disorders are coded, and by determining the functions of those proteins, we will be able to more effectively treat these disorders.

Because mRNA synthesis occurs within the nucleus, cells without nuclei accomplish protein synthesis only as long as the mRNA produced before the nucleus degenerates remains functional. The nuclei of developing red blood cells are expelled from the cells before the red blood cells enter the blood, where they survive without a nucleus for about 120 days. In comparison, many cells with nuclei, such as nerve and skeletal muscle cells, survive as long as the individual person survives.

A **nucleolus** (noo-klē′ō-lŭs) is a somewhat rounded dense region within the nucleus that lacks a surrounding membrane (see figure 3.35). Usually one nucleolus exists per nucleus, but several smaller, accessory nucleoli may also be seen in some nuclei, especially during the latter phases of cell division. The nucleolus incorporates portions of 10 chromosomes (five pairs), called **nucleolar organizer regions.** These regions contain DNA from which rRNA is produced. Within the nucleolus, the subunits of ribosomes are manufactured (see preceding section on "Ribosomes").

42. *Describe the structure of the nucleus and nuclear envelope. What is the function of the nuclear pores?*
43. *What molecules are found in chromatin? How does chromatin become a chromosome?*
44. *List the types of RNA whose structure is determined by DNA. How can DNA control the structural and functional characteristics of the cell without leaving the nucleus?*
45. *Describe the nucleolus. Define and give the function of the nucleolar organizer regions.*

Overview of Cell Metabolism

Objective

- ***Define cell metabolism, and contrast aerobic and anaerobic respiration.***

Cell metabolism is the sum of all the catabolic (decomposition) and anabolic (synthesis) reactions in the cell. The breakdown of food molecules such as carbohydrates, lipids, and proteins releases energy that is used to synthesize ATP. Each ATP molecule contains a portion of the energy originally stored in the chemical bonds of the food molecules. The ATP molecules are smaller "packets" of energy that, when released, can be used to drive other chemical reactions or processes such as active transport.

The production of ATP takes place in the cytosol and in mitochondria through a series of chemical reactions (see chapter 25 for details). Energy from food molecules is transferred to ATP in a controlled fashion. If the energy in food molecules were released all at once, the cell literally would burn up.

The breakdown of the sugar glucose, such as from sugar found in a candy bar, is used to illustrate the production of ATP from food molecules. Once glucose is transported into a cell, a series of reactions takes place within the cytosol. These chemical reactions, collectively called **glycolysis** (glī-kol′i-sis), convert the glucose to pyruvic acid. Pyruvic acid can enter different biochemical pathways, depending on oxygen availability (figure 3.37).

Aerobic (ār-ō′bik) **respiration** occurs when oxygen is available. The pyruvic acid molecules enter mitochondria and, through another series of chemical reactions, collectively called the citric acid cycle and the electron-transport chain, are converted to carbon dioxide and water. Aerobic respiration can produce up to 38 ATP molecules from the energy contained in each glucose molecule.

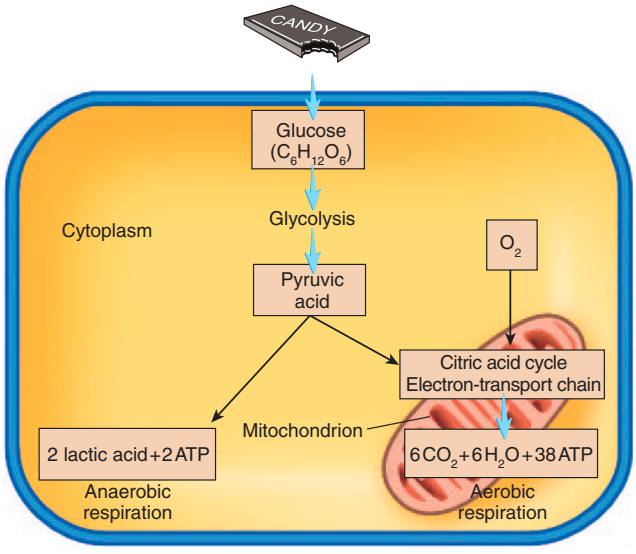


Figure 3.37 Overview of Cell Metabolism

Aerobic respiration requires oxygen and produces more ATP per glucose molecule than does anaerobic metabolism.

Several important points should be noted about aerobic respiration. First, the quantities of ATP produced through aerobic respiration are absolutely necessary to maintain the energy-requiring chemical reactions of life in human cells. Second, aerobic respiration requires oxygen because the last chemical reaction that takes place in aerobic respiration is the combination of oxygen with hydrogen to form water. If this reaction does not take place, the reactions immediately preceding it do not occur either. This explains why breathing oxygen is necessary for human life: without oxygen, aerobic respiration is inhibited, and the cells do not produce enough ATP to sustain life. Finally, during aerobic respiration the carbon atoms of food molecules are separated from one another to form carbon dioxide. Thus the carbon dioxide humans breathe out comes from the food they eat.

Anaerobic (an-ār-ō′bik) **respiration** occurs without oxygen and includes the conversion of pyruvic acid to lactic acid. A net production of two ATP molecules occurs for each glucose molecule used. Anaerobic respiration does not produce as much ATP as aerobic respiration, but it does allow the cells to function for short periods when oxygen levels are too low for aerobic respiration to provide all the needed ATP. For example, during intense exercise, when aerobic respiration has depleted the oxygen supply, anaerobic respiration can provide additional ATP.

46. ***Define cell metabolism. What molecule is synthesized using the energy released by the breakdown of food molecules?***
47. ***Define glycolysis, aerobic respiration, and anaerobic respiration.***
48. ***How many ATP molecules are produced from one glucose molecule in aerobic and anaerobic respiration?***
49. ***During aerobic respiration, what happens to the oxygen we breathe in? Where does the carbon dioxide we breathe out come from?***
50. ***Besides ATP, what molecule is produced as a result of anaerobic respiration? Under what conditions is anaerobic respiration necessary?***

Protein Synthesis

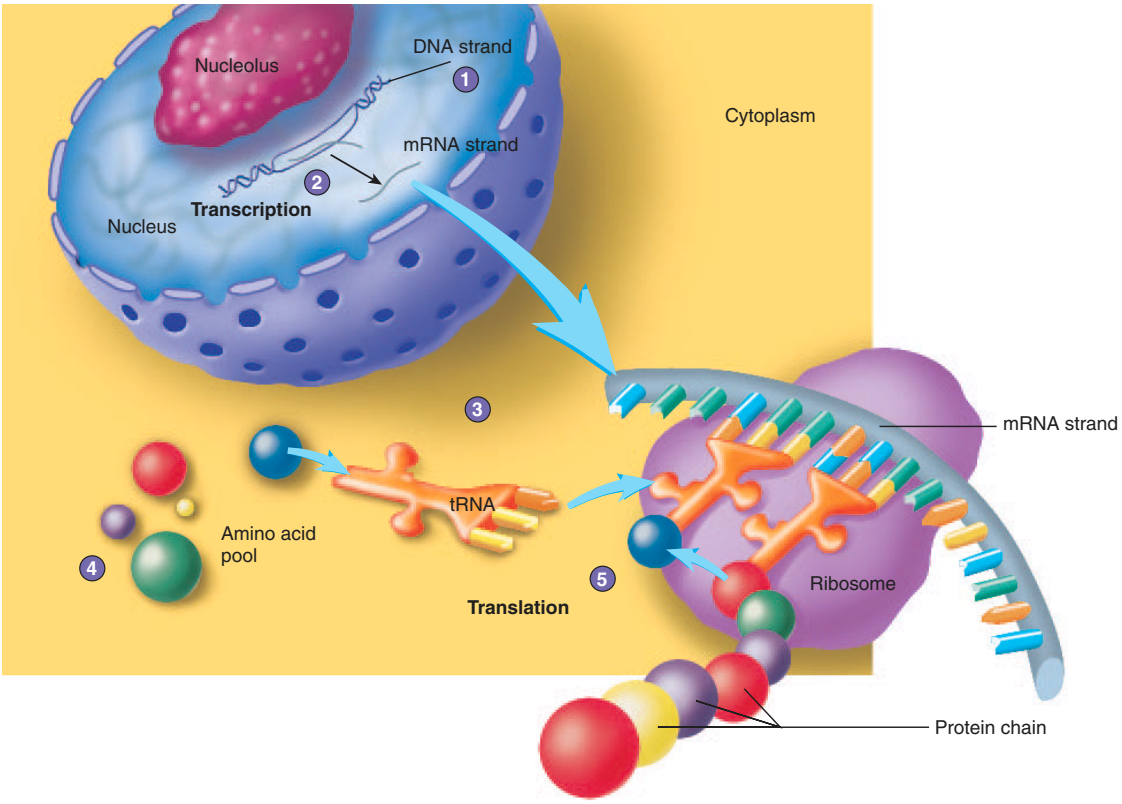
Objective

- ***Describe the process of protein synthesis.***

Normal cell structure and function would not be possible without proteins (figure 3.38), which form the cytoskeleton and other structural components of cells and function as transport molecules, receptors, and enzymes. In addition, proteins secreted from cells perform vital functions: collagen is a structural protein that gives tissues flexibility and strength, enzymes control the chemical reactions of food digestion in the intestines, and protein hormones regulate the activities of many tissues.

Ultimately, the production of all the proteins in the body is under the control of DNA. Recall from chapter 2 that the building blocks of DNA are nucleotides containing adenine (A), thymine (T), cytosine (C), and guanine (G). The nucleotides form two antiparallel strands of nucleic acids. The term *antiparallel* means that the strands are parallel but extend in opposite directions. Each strand has a 5′ (phosphate) end and a 3′ (hydroxyl) end. The

1. DNA contains the information necessary to produce proteins.
2. Transcription of DNA results in mRNA, which is a copy of the information in DNA needed to make a protein.
3. The mRNA leaves the nucleus and goes to a ribosome.
4. Amino acids, the building blocks of proteins, are carried to the ribosome by tRNAs.
5. In the process of translation, the information contained in mRNA is used to determine the number, kinds, and arrangement of amino acids in the protein.



Process Figure 3.38 Overview of Protein Synthesis

sequence of the nucleotides in the DNA is a method of storing information. Every three nucleotides, called a **triplet,** code for an amino acid, and amino acids are the building blocks of proteins. All of the triplets required to code for the synthesis of a specific protein are called a **gene.**

The production of proteins from the stored information in DNA involves two steps: transcription and translation, which can be illustrated with an analogy. Suppose a cook wants a recipe that is found only in a reference book in the library. Because the book cannot be checked out, the cook makes a handwritten copy, or **transcription,** of the recipe. Later, in the kitchen the information contained in the copied recipe is used to prepare the meal. The changing of something from one form to another (from recipe to meal) is called **translation.** In this analogy, DNA is the reference book that contains many recipes for making different proteins. DNA, however, is too large a molecule to pass through the nuclear envelope to go to the ribosomes (the kitchen), where the proteins are prepared. Just as the reference book stays in the library, DNA remains in the nucleus. Therefore, through transcription, the cell makes a copy of the information in DNA (the recipe) necessary to make a particular protein (the meal). The copy, which is called **messenger RNA (mRNA),** travels from the nucleus to ribosomes in the cytoplasm, where the information in the copy is used to construct a protein (i.e., translation). Of course, to turn a recipe into a meal, the actual ingredients are needed. The ingredients necessary to synthesize a protein are amino acids. Specialized transport molecules, called **transfer RNA (tRNA),** carry the amino acids to the ribosome (figure 3.39).

In summary, the synthesis of proteins involves transcription, making a copy of part of the stored information in DNA, and translation, converting that copied information into a protein. The details of transcription and translation are considered next.

Transcription

Transcription is the synthesis of mRNA on the basis of the sequence of nucleotides in DNA. It occurs when the double strands of a DNA segment separate, one of its strands serves as a template, and RNA nucleotides pair with DNA nucleotides of the template (figure 3.39). Nucleotides pair with each other according to the following rule: adenine pairs with thymine or uracil, and cytosine pairs with guanine. DNA contains thymine, but uracil replaces thymine in RNA. Adenine, thymine, cytosine, and guanine nucleotides of DNA therefore pair with uracil, adenine, guanine, and cytosine nucleotides of mRNA, respectively.

This pairing relationship between nucleotides ensures that the information in DNA is transcribed correctly to mRNA. The RNA nucleotides combine through dehydration reactions catalyzed by RNA polymerase enzymes to form a long mRNA segment. The elongation of all nucleic acids, both DNA and RNA, occurs in the same chemical direction: from the 5′ to the 3′ end of

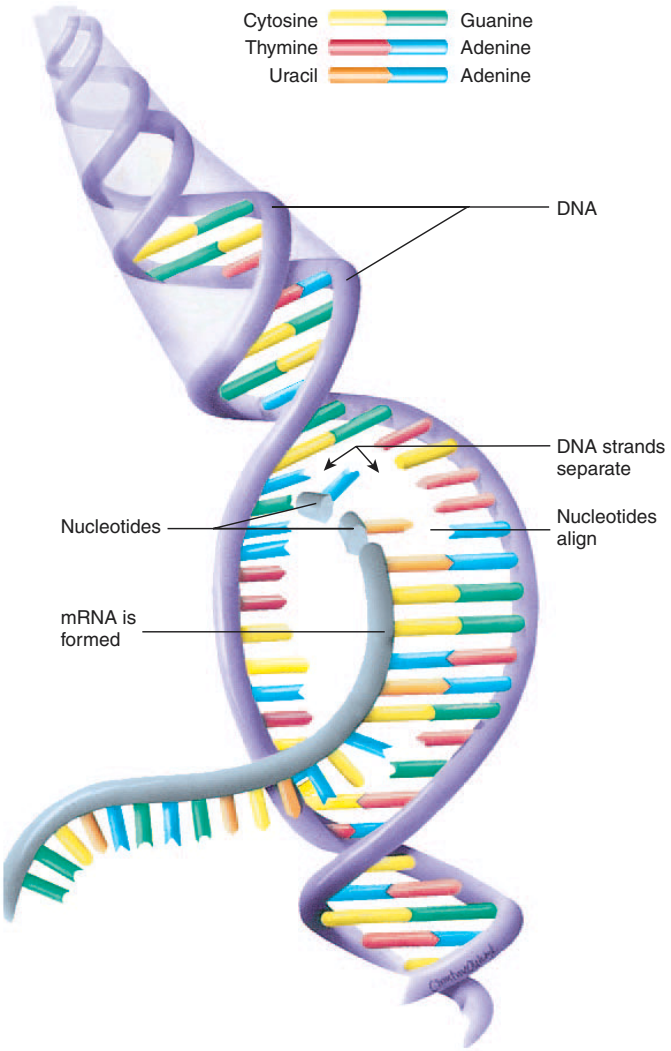


Figure 3.39 Formation of mRNA by Transcription of DNA

A segment of the DNA molecule is opened, and RNA polymerase (an enzyme that is not shown) assembles nucleotides into mRNA according to the base-pair combinations shown in the inset. Thus the sequence of nucleotides in DNA determines the sequence of nucleotides in mRNA. As nucleotides are added, an mRNA molecule is formed.

the molecule. The mRNA molecule contains the information required to determine the sequence of amino acids in a protein. The information, called the **genetic code,** is carried in groups of three nucleotides called **codons.**

The number and sequence of codons in the mRNA are determined by the number and sequence of sets of three nucleotides, called triplets, in the segments of DNA that were transcribed. For example, the triplet code of CTA in DNA results in the codon GAU in mRNA, which codes for aspartic acid. Each codon codes for a specific amino acid. Sixty-four possible mRNA codons exist, but only 20 amino acids are in proteins. As a result, the genetic code is redundant because more than one codon codes for some amino acids. For example, CGA, CGG, CGT, and CGC all code for the amino acid alanine, and UUU and UAC both code for phenylalanine. Some codons do not code for amino acids but perform other functions. AUG and sometimes GUG act as signals for starting the transcription of a stretch of DNA to RNA. Three codons, UAA, UGA, and UAG, act as signals for stopping the transcription of DNA to RNA.

The region of a DNA molecule between the codon starting transcription and the codon stopping transcription is transcribed into a stretch of RNA and is called a **transcription unit.** A transcription unit codes for a protein or part of a protein. A transcription unit is not necessarily a gene. A gene is a functional unit, and some regulatory genes don't code for proteins. A molecular definition of a **gene** is all of the nucleic acid sequences necessary to make a functional RNA or protein.

Not all of a continuous stretch of DNA may code for parts of a protein. Regions of the DNA that code for parts of the protein are called **exons,** whereas those regions of the DNA that do not code for portions of the protein are called **introns.** Both the exon and intron regions of the DNA may be transcribed into mRNA. An mRNA containing introns is called a **pre-mRNA.** After a stretch of pre-mRNA has been transcribed, the introns can be removed and the exons spliced together by enzyme complexes called **spliceosomes** to produce the functional mRNA (figure 3.40). These changes in the mRNA are called **posttranscriptional processing.**

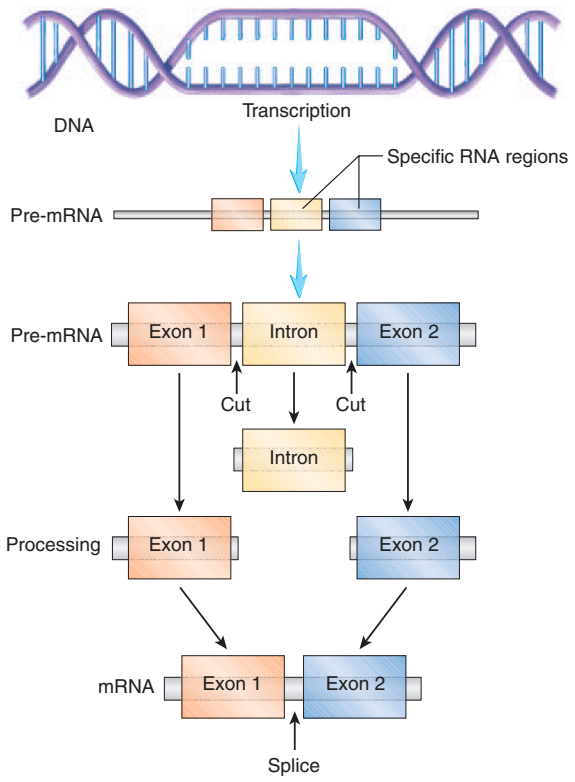


Figure 3.40 Posttranscriptional Change in mRNA

An intron is cleaved from between two exons and is discarded. The exons are spliced together by spliceosomes to make the functional mRNA.

Thalassemia

Hemoglobin is an oxygen-carrying protein molecule composed of four polypeptides. **Thalassemia** is a group of genetic disorders in which one or more of the polypeptides of hemoglobin is produced in decreased amounts as the result of defective posttranscriptional processing. The decreased amount of hemoglobin in the blood causes anemia, which reduces the oxygen-carrying capacity of the blood.

Translation

The synthesis of a protein at the ribosome in response to the codons of mRNA is called translation. In addition to mRNA, translation requires ribosomes and tRNA. Ribosomes consist of **ribosomal RNA (rRNA)** and proteins. Like mRNA, tRNA and rRNA are produced in the nucleus by transcription.

The function of tRNA is to match a specific amino acid to a specific codon of mRNA. To do this, one end of each kind of tRNA combines with a specific amino acid. Another part of the tRNA has an **anticodon,** which consists of three nucleotides. On the basis of the pairing relationships between nucleotides, the anticodon can combine only with its matched codon. For example, the tRNA that binds to aspartic acid has the anticodon CUA, which combines with the codon GAU of mRNA. Therefore the codon GAU codes for aspartic acid.

Ribosomes align the codons of the mRNA with the anticodons of tRNA and then join the amino acids of adjacent tRNA molecules. As the amino acids are joined together, a chain of amino acids, or a protein, is formed. The step-by-step process of protein synthesis at the ribosome is described in detail in figure 3.41.

Many proteins are longer when first made than they are in their final, functional state. These proteins are called **proproteins,** and the extra piece of the molecule is cleaved off by enzymes to make the proprotein into a functional protein. Many proteins are enzymes, and the proproteins of those enzymes are called **proenzymes.** If many proenzymes were made within cells as functional enzymes, they could digest the cell that made them. Instead, they are made as proenzymes and are not converted to active enzymes until they reach a protected region of the body, such as inside the small intestine, where they are functional. Many proteins have side chains, such as polysaccharides, added to them following translation. Some proteins are composed of two or more amino acid chains that are joined after each chain is produced on separate ribosomes. These various modifications to proteins are referred to as **posttranslational processing.**

After the initial part of mRNA is used by a ribosome, another ribosome can attach to the mRNA and begin to make a protein. The resulting cluster of ribosomes attached to the mRNA is called a **polyribosome.** Each ribosome in a polyribosome produces an identical protein, and polyribosomes are an efficient way to use a single mRNA molecule to produce many copies of the same protein.

PREDICT 6

Explain how changing one nucleotide within a DNA molecule of a cell could change the structure of a protein produced by that cell. What effect would this change have on the protein's function?

Regulation of Protein Synthesis

All of the cells in the body, except for sex cells, have the same DNA. The transcription of mRNA in cells is regulated, however, so that all portions of all DNA molecules are not continually transcribed. The proteins associated with DNA in the nucleus play a role in regulating the transcription. As cells differentiate and become specialized for specific functions during development, part of the DNA becomes nonfunctional and is not transcribed, whereas other segments of DNA remain very active. For example, in most cells the DNA coding for hemoglobin is nonfunctional, and little if any hemoglobin is synthesized. In developing red blood cells, however, the DNA coding for hemoglobin is functional, and hemoglobin synthesis occurs rapidly.

Protein synthesis in a single cell is not normally constant, but it occurs more rapidly at some times than others. Regulatory molecules that interact with the nuclear proteins can either increase or decrease the transcription rate of specific DNA segments. For example, thyroxine, a hormone released by cells of the thyroid gland, enters cells such as skeletal muscle cells, interacts with specific nuclear proteins, and increases specific types of mRNA transcription. Consequently, the production of certain proteins increases. As a result, an increase in the number of mitochondria and an increase in metabolism occur in these cells.

51. *What type of molecule is produced as a result of transcription? Of translation? Where do these events take place?*
52. *In what molecules are triplets, codons, and anticodons found? What is the genetic code?*
53. *How are triplets, transcription units, and genes related?*
54. *Describe the role of mRNA, rRNA, and tRNA in the production of a protein at a ribosome. What is a polyribosome?*
55. *What are exons and introns? How are they related to pre-mRNA and posttranscriptional processing?*
56. *Define proprotein, proenzyme, and posttranslational processing.*
57. *State two ways the cell controls what DNA is transcribed.*

Cell Life Cycle

Objective

- *Explain what is accomplished during mitosis and cytokinesis.*

The **cell life cycle** includes the changes a cell undergoes from the time it is formed until it divides to produce two new cells. The life cycle of a cell has two stages, an interphase and a cell division stage (figure 3.42).

Interphase

Interphase is the phase between cell divisions. Ninety percent or more of the life cycle of a typical cell is spent in interphase. During this time the cell carries out the metabolic activities necessary for life and performs its specialized functions such as secreting digestive enzymes. In addition, the cell prepares to divide. This preparation includes an increase in cell size, because many cell

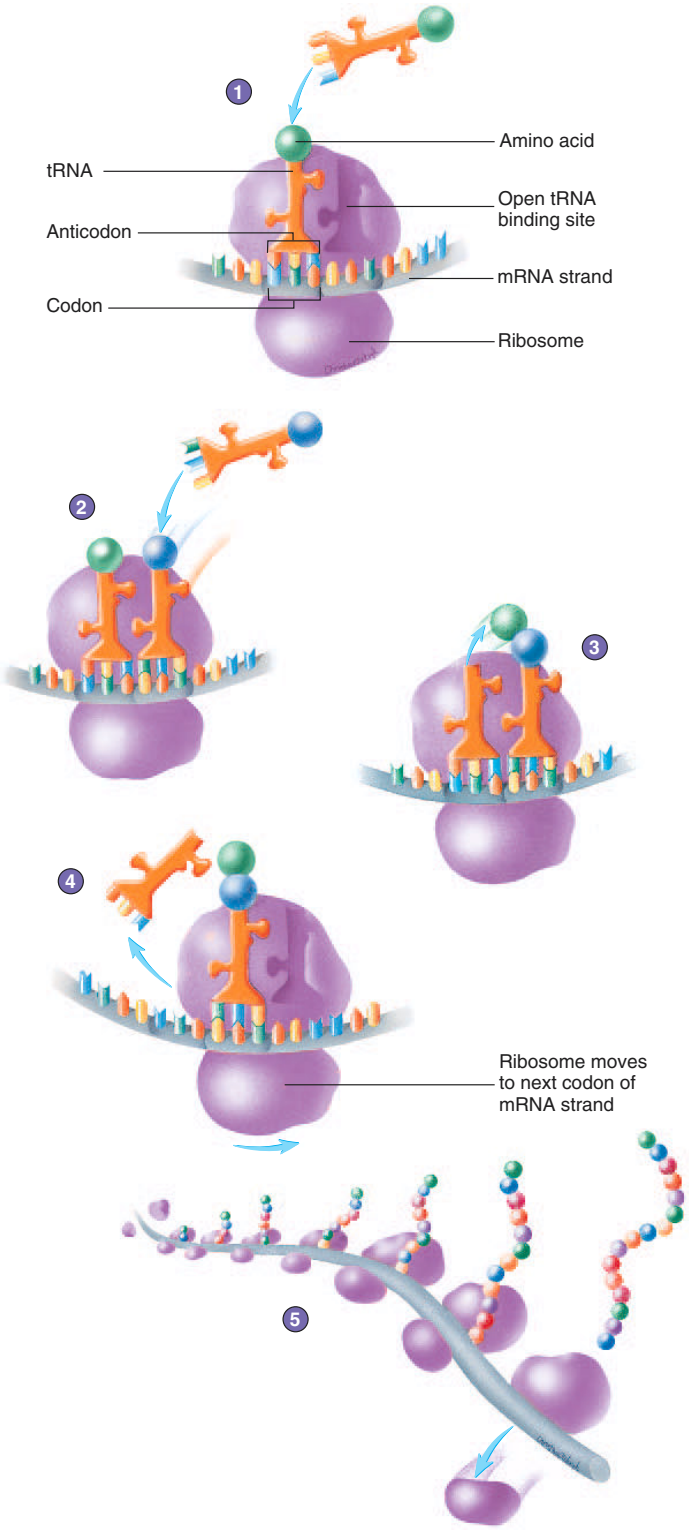
1. To start protein synthesis a ribosome binds to mRNA. The ribosome also has two binding sites for tRNA, one of which is occupied by a tRNA with its amino acid. Note that the codon of mRNA and the anticodon of tRNA are aligned and joined. The other tRNA binding site is open.

2. By occupying the open tRNA binding site the next tRNA is properly aligned with mRNA and with the other tRNA.

3. An enzyme within the ribosome catalyzes a synthesis reaction to form a peptide bond between the amino acids. Note that the amino acids are now associated with only one of the tRNAs.

4. The ribosome shifts position by three nucleotides. The tRNA without the amino acid is released from the ribosome, and the tRNA with the amino acids takes its position. A tRNA binding site is left open by the shift. Additional amino acids can be added by repeating steps *2* through *4*. Eventually a stop codon in the mRNA ends the production of the protein, which is released from the ribosome.

5. Multiple ribosomes attach to a single mRNA. As the ribosomes move down the mRNA, proteins attached to the ribosomes lengthen and eventually detach from the mRNA.



Process Figure 3.41 Translation of mRNA to Produce a Protein

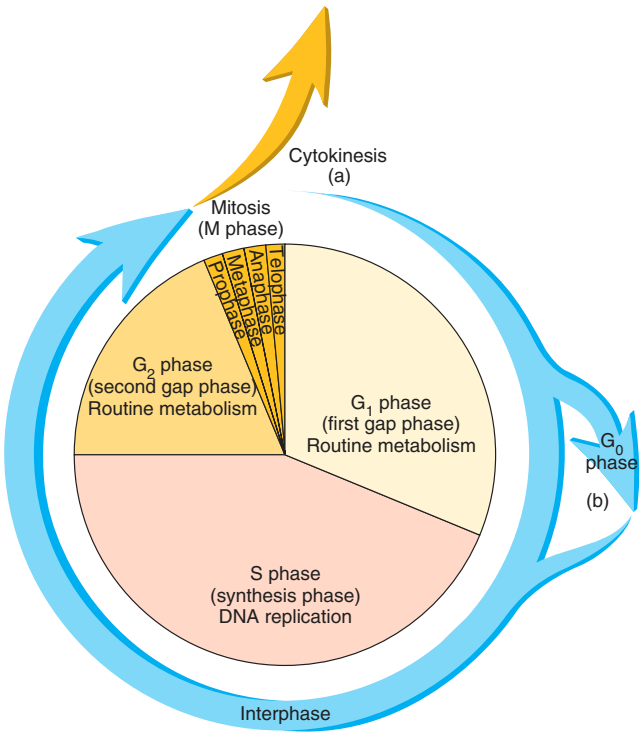


Figure 3.42 Cell Cycle

The cell cycle is divided into interphase and mitosis. Interphase is divided into G_1, S, and G_2 subphases. During G_1 and G_2, the cell carries out routine metabolic activities. During the S phase DNA is replicated. (*a*) Following mitosis, two cells are formed by the process of cytokinesis. Each new cell begins a new cell cycle. (*b*) Many cells exit the cell cycle and enter the G_0 phase, where they remain until stimulated to divide, at which point they reenter the cell cycle.

components double in quantity, and a replication of the cell's DNA. The centrioles within the centrosome are also duplicated. Consequently, when the cell divides, each new cell receives the organelles and DNA necessary for continued functioning.

Interphase can be divided into three subphases, called G_1, S, and G_2. During G_1(the first *gap* phase) and G_2 (the second *gap* phase), the cell carries out routine metabolic activities. During the S phase (the *synthesis* phase), the DNA is replicated (new DNA is synthesized). Many cells in the body do not divide for days, months, or even years. These "resting" cells exit the cell cycle and enter what is called the G_0 phase, in which they remain unless stimulated to divide.

DNA Replication

DNA **replication** is the process by which two new strands of DNA are made, using the two existing strands as templates. During interphase, DNA and its associated proteins appear as dispersed chromatin threads within the nucleus. When DNA replication begins, the two strands of each DNA molecule separate from each other for some distance (figure 3.43). Each strand then functions as a template, or pattern, for the production of a new strand of DNA, which is formed as new nucleotides pair with the existing nucleotides of each strand of the separated DNA molecule. The production of the new nucleotide strands is catalyzed by DNA **polymerase,** which adds new nucleotides at the 3′ end of the growing strands. One strand, called the **leading strand,** is formed as a continuous strand, whereas the other strand, called the **lagging strand,** is formed in short segments going in the opposite direction. The short segments are then spliced by **DNA ligase.** As a result of DNA replication, two identical DNA molecules are produced. Each of the two new DNA molecules has one strand of nucleotides derived from the original DNA molecule and one newly synthesized strand.

P R E D I C T 7

Suppose a molecule of DNA separates, forming strands 1 and 2. Part of the nucleotide sequence in strand 1 is ATGCTA. From this template, what would be the sequence of nucleotides in the DNA replicated from strand 1 and strand 2?

Cell Division

New cells necessary for growth and tissue repair are produced by cell division. A parent cell divides to form two daughter cells, each of which has the same amount and type of DNA as the parent cell. Because DNA determines cell structure and function, the daughter cells have the same structure and perform the same functions as the parent cell.

Cell division involves two major events: the division of the nucleus to form two new nuclei, and the division of the cytoplasm to form two new cells. Each of the new cells contains one of the newly formed nuclei. The division of the nucleus occurs by mitosis, and the division of the cytoplasm is called cytokinesis.

Mitosis

Mitosis (mī-tō′sis) is the division of the nucleus into two nuclei, each of which has the same amount and type of DNA as the original nucleus. The DNA, which was dispersed as chromatin in interphase, condenses in mitosis to form chromosomes. All human **somatic** (sō-mat′ik) cells, which include all cells except the sex cells, contain 46 chromosomes, which are referred to as a **diploid** (dip′loyd) number of chromosomes. Sex cells have half the number of chromosomes as somatic cells (see section on "Meiosis"). The 46 chromosomes in somatic cells are organized into 23 pairs of chromosomes. Twenty-two of these pairs are called **autosomes.** Each member of an autosomal pair of chromosomes looks structurally alike, and together they are called a **homologous** (hŏ-mol′ō-gŭs) pair of chromosomes. One member of each autosomal pair is derived from the person's father, and the other is derived from the mother. The remaining pair of chromosomes are the sex chromosomes. In females, the sex chromosomes look alike, and each is called an **X chromosome.** In males, the sex chromosomes do not look alike. One chromosome is an X chromosome, and the other is smaller and is called a **Y chromosome.** One X chromosome of a female is derived from her mother and the other is derived from her father. The X chromosome of a male is derived from his mother and the Y chromosome is derived from his father.

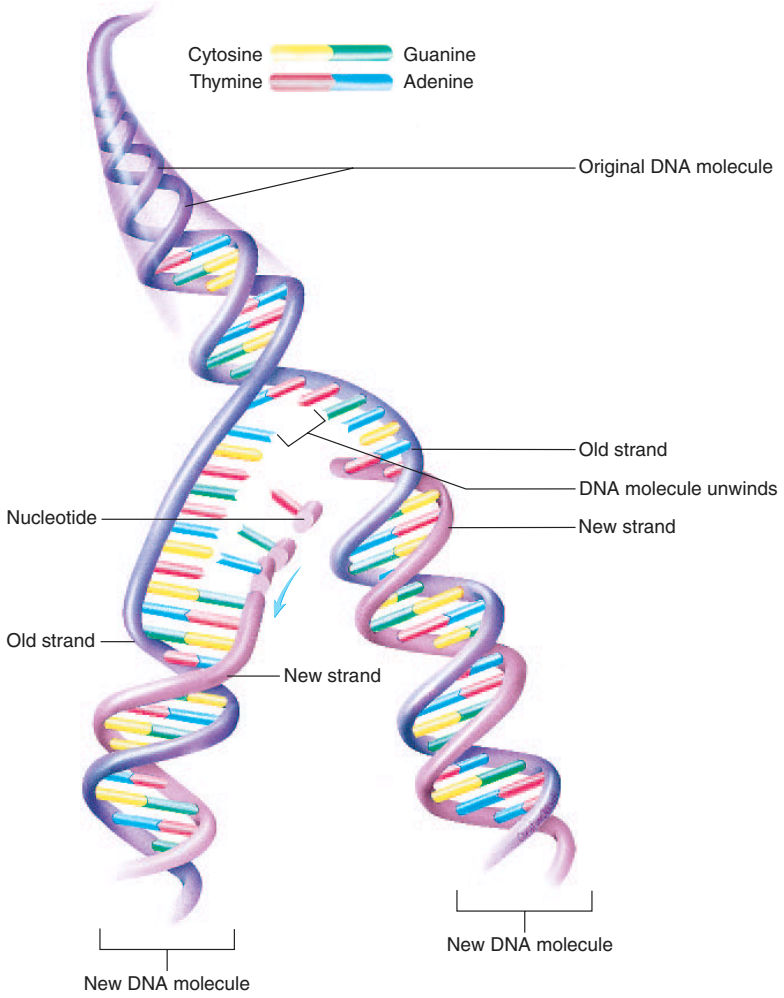


Figure 3.43 Replication of DNA

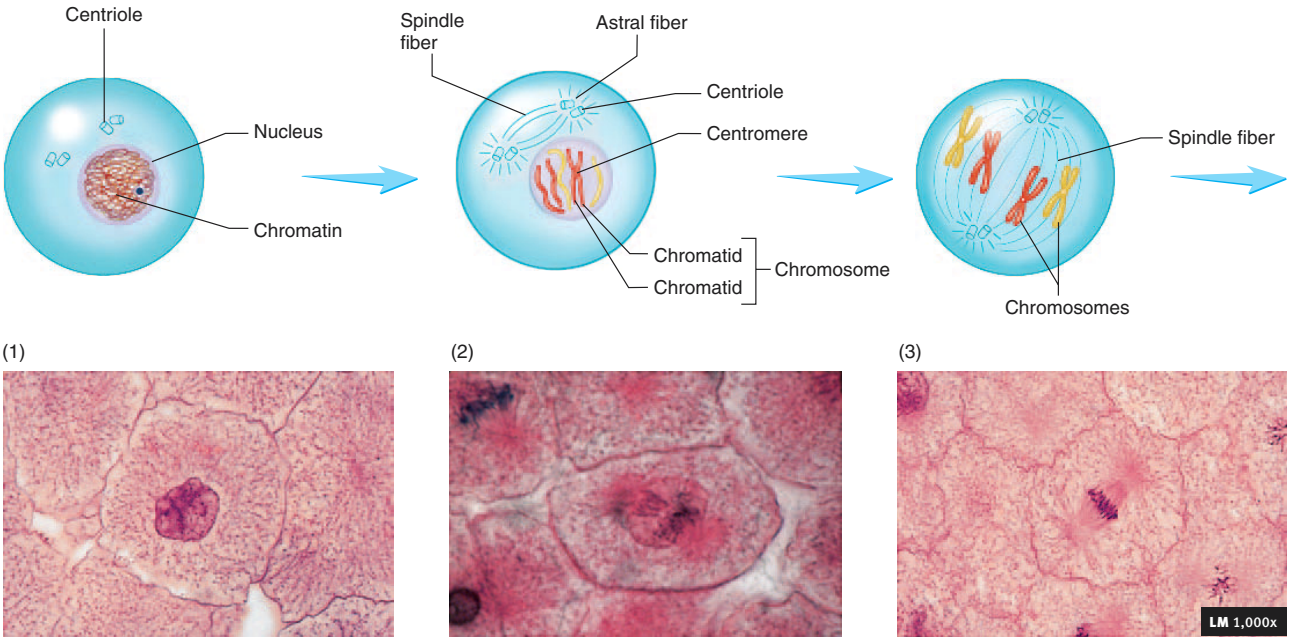
Replication of DNA during interphase produces two identical molecules of DNA. The strands of the DNA molecule separate from each other, and each strand functions as a template on which another strand is formed. The base-pairing relationship between nucleotides determines the sequence of nucleotides in the newly formed strands.

For convenience of discussion, mitosis is divided into four phases: **prophase, metaphase, anaphase,** and **telophase** (tel′ō-fāz). Although each phase represents major events, mitosis is a continuous process, and no discrete jumps occur from one phase to another. Learning the characteristics associated with each phase is helpful, but a more important concept is how each daughter cell obtains the same number and type of chromosomes as the parent cell. The major events of mitosis are summarized in figure 3.44.

Cytokinesis

Cytokinesis (sī′tō-ki-nē′sis) is the division of the cytoplasm of the cell to produce two new cells. Cytokinesis begins in anaphase, continues through telophase, and ends in the following interphase (see figure 3.45). The first sign of cytokinesis is the formation of a **cleavage furrow,** or puckering of the plasma membrane, which forms midway between the centrioles. A contractile ring composed primarily of actin filaments pulls the plasma membrane inward, dividing the cell into two halves. Cytokinesis is complete when the membranes of the two halves separate at the cleavage furrow to form two separate cells.

- *58. Define interphase. What percent of the cell life cycle is typically spent in interphase?*
- *59. Describe the cell's activities during G_1, S, and G_2 phases of the cell life cycle.*
- *60. Describe the process of DNA replication. What are the functions of DNA polymerase and DNA ligase?*
- *61. Define mitosis. How do the two nuclei that are produced in mitosis compare to the original nucleus?*
- *62. How many chromosomes are contained in a human somatic cell? How are the chromosomes of males and females the same? How are they different?*
- *63. List the events that occur during interphase, prophase, metaphase, anaphase, and telophase of mitosis.*
- *64. Describe cytokinesis.*



Process Figure 3.44 Mitosis

(*1*) **Interphase.** DNA, which is dispersed as chromatin, replicates. The two strands of each DNA molecule separate, and a copy of each strand is made. Consequently, two identical DNA molecules are produced. The pair of centrioles replicates to produce two pairs of centrioles.
(*2*) **Prophase.** Chromatin strands condense to form chromosomes. Each chromosome is composed of two identical strands of chromatin called **chromatids,** which are joined together at one point by a specialized region called the **centromere.** Each chromatid contains one of the DNA molecules replicated during interphase. One pair of centrioles moves to each side, or pole, of the cell. Microtubules form near the centrioles and project in all directions. Some of the microtubules end blindly and are called **astral fibers.** Others, known as **spindle fibers** project toward an invisible line, called the **equator,** and either overlap with fibers from other centrioles or attach to the centromeres of the chromosomes. At the end of prophase the nuclear envelope degenerates, and the nucleoli disappear.
(*3*) **Metaphase.** The chromosomes align along the equator with spindle fibers from each pair of centrioles, located at opposite poles of the cell, attached to their centromeres.

Cloning

Through the process of differentiation, cells become specialized to certain functions and are no longer capable of producing an entire organism if isolated. Over 30 years ago, however, it was demonstrated in frogs that if the nucleus is removed from a differentiated cell and is transferred to an oocyte with the nucleus removed, a complete, normal frog can develop from that oocyte. This process, called **cloning,** demonstrated that during differentiation, genetic information is not irrevocably lost. Because mammalian oocytes are considerably smaller than frog oocytes, cloning of mammalian cells has been technically much more difficult. Dr. Ian Wilmut and his colleagues at the Roslin Institute in Edinburgh, Scotland, overcame those technical difficulties in 1996, when they successfully cloned the first mammal, a sheep. Since that time, several other mammalian species have been cloned.

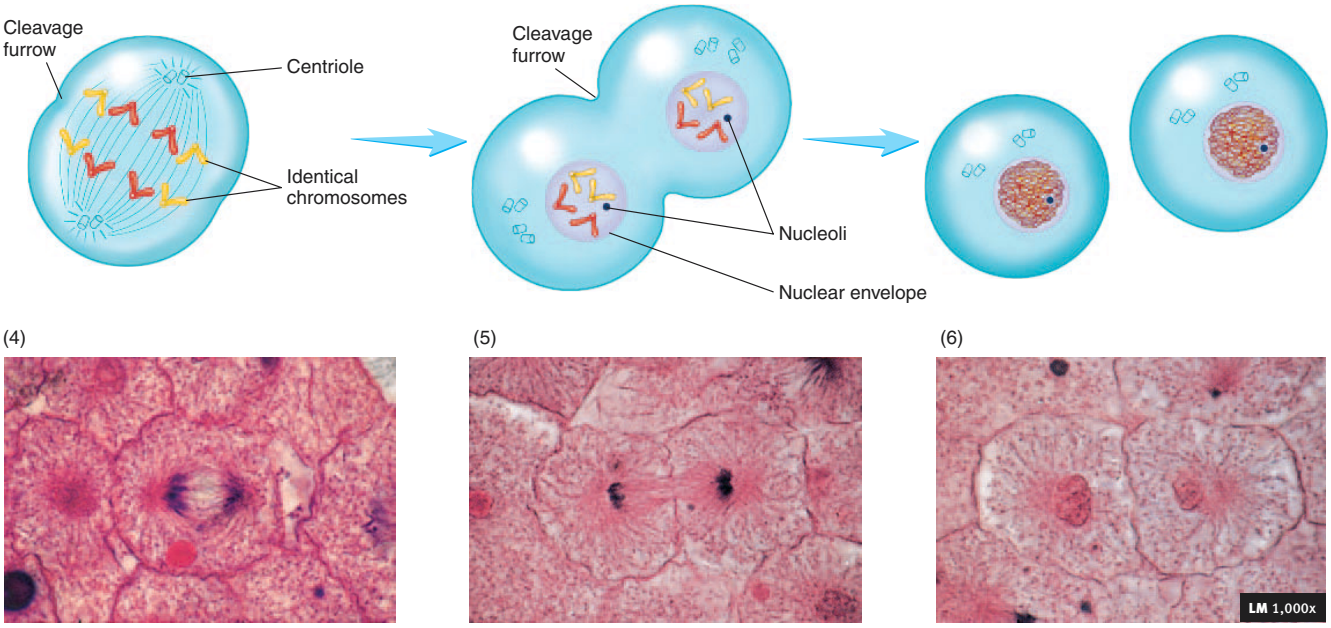
Meiosis

Objective

- ***Describe the events of meiosis, and explain how they result in the production of genetically unique individuals.***

All cells of the body, except sex cells, are formed by mitosis. Sex cells are formed by **meiosis** (mī-ō′sis). In meiosis the nucleus undergoes two divisions resulting in four nuclei, each containing half as many chromosomes as the parent cell. The daughter cells that are produced by cytokinesis differentiate into **gametes** (gam′ētz), or sex cells. The gametes are reproductive cells—**sperm cells** in males and **oocytes** (egg cells) in females. Each gamete not only has half the number of chromosomes found in a somatic cell but also has one chromosome from each of the homologous pairs found in the parent cell. The complement of chromosomes in a gamete is referred to as a **haploid** number. Oocytes contain one autosomal chromosome from each of the 22 homologous pairs and an X chromosome. Sperm cells have 22 autosomal chromosomes and either an X or Y chromosome. During fertilization, when a sperm cell fuses with an oocyte, the normal number of 46 chromosomes in 23 pairs is reestablished. The sex of the baby is determined by the sperm cell that fertilizes the oocyte. The sex is male if a Y chromosome is carried by the sperm cell that fertilizes the oocyte and female if the sperm cell carries an X chromosome.

The first division during meiosis is divided into four phases: prophase I, metaphase I, anaphase I, and telophase I (figure 3.45). As in prophase of mitosis, the nuclear envelope degenerates, spindle fibers form, and the already duplicated chromosomes become visible. Each chromosome consists of two chromatids joined by a centromere. In prophase I, however, the four chromatids of a homologous pair of chromosomes join together, or **synapse,** (sin-aps, sĭ-naps′), to form a **tetrad** (four). In metaphase I the tetrads align at



Process Figure 3.44 *(continued)*

(*4*) **Anaphase.** The centromeres separate, and each chromatid is then referred to as a chromosome. Thus, when the centromeres divide, the chromosome number doubles, and there are two identical sets of chromosomes. The two sets of chromosomes are pulled by the spindle fibers toward the poles of the cell. Separation of the chromatids signals the beginning of anaphase, and by the time anaphase has ended, the chromosomes have reached the poles of the cell. The beginning of cytokinesis is evident during anaphase; along the equator of the cell the cytoplasm becomes narrower as the plasma membrane pinches inward.
(*5*) **Telophase.** The migration of each set of chromosomes is complete. A new nuclear envelope develops from the endoplasmic reticulum, and the nucleoli reappear. During the latter portion of telophase the spindle fibers disappear, and the chromosomes unravel to become less distinct chromatin threads. The nuclei of the two daughter cells assume the appearance of interphase nuclei, and the process of mitosis is complete.
(*6*) **Interphase.** Cytokinesis, which continued from anaphase through telophase, becomes complete when the plasma membranes move close enough together at the equator of the cell to fuse, completely separating the two new daughter cells, each of which now has a complete set of chromosomes (a diploid number of chromosomes) identical to the parent cell.

the equatorial plane, and in anaphase I each pair of homologous chromosomes separate and move toward opposite poles of the cell. For each pair of homologous chromosomes, one daughter cell receives one member of the pair, and the other daughter cell receives the other member. Thus each daughter cell has 23 chromosomes, each of which is composed of two chromatids. Telophase I, with cytokinesis, is similar to telophase of mitosis, and two daughter cells are produced.

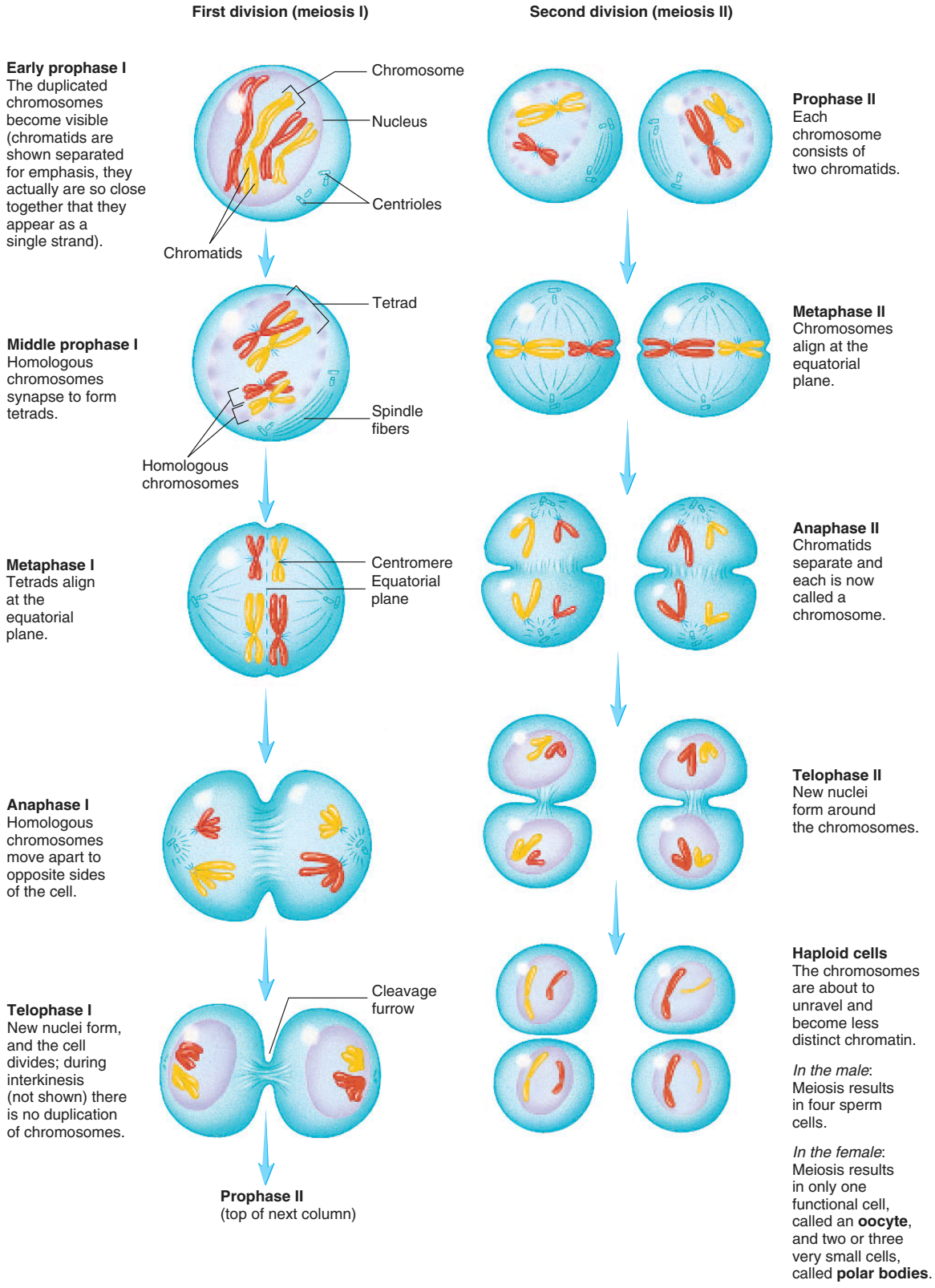
Interkinesis (in′ter-ki-nē′sis) is the phase between the formation of the daughter cells and the second meiotic division. No duplication of DNA occurs during interkinesis. The second division of meiosis also has four phases: prophase II, metaphase II, anaphase II, and telophase II. These stages occur much as they do in mitosis, except that 23 chromosomes are present instead of 46. The chromosomes align at the equatorial plane in metaphase II, and their chromatids split apart in anaphase II. The chromatids then are called chromosomes, and each new cell receives 23 chromosomes. Table 3.3 compares mitosis and meiosis.

In addition to reducing the number of chromosomes in a cell from 46 to 23, meiosis is also responsible for genetic diversity for two reasons. First, a random distribution of the chromosomes is received from each parent. One member of each homologous pair of chromosomes was derived from the person's father and the other member from the person's mother. The homologous chromosomes align randomly during metaphase I; when they split apart, each daughter cell receives some of the father's and some of the mother's chromosomes. The number of chromosomes each daughter cell receives from each parent is determined by chance, however.

Second, when tetrads are formed, some of the chromatids may break apart, and part of one chromatid from one homologous pair may be exchanged for part of another chromatid from the other homologous pair (figure 3.46). This exchange is called **crossing-over;** as a result, chromatids with different DNA content are formed.

With random assortment of homologous chromosomes and crossing-over, the possible number of gametes with different genetic makeup is practically unlimited. When the different gametes of two individuals unite, it is virtually certain that the resulting genetic makeup never has occurred before and never will occur again. The genetic makeup of each new human being is unique.

65. ***Compare meiosis and mitosis, including types of cells involved, number of divisions, number of nuclei produced, and number of chromosomes in each nucleus.***
66. ***Define gamete, sperm cell, and oocyte.***
67. ***What is a tetrad? Name two processes in meiosis that increase genetic diversity.***



Process Figure 3.45 Meiosis

Table 3.3 Comparison of Mitosis and Meiosis

Feature	Mitosis	Meiosis
Time of DNA replication	Interphase	Interphase
Number of cell divisions	One	Two; no replication of DNA occurs in between the two meiotic divisions.
Cell produced	The two daughter cells are genetically identical to the parent cell; each daughter cell has a diploid number of chromosomes.	Gametes are each different from the parent cell and from each other; the gametes have a haploid number of chromosomes; in males, four gametes (sperm cells); in females, one gamete (oocyte) and two or three polar bodies, which eventually disintegrate.
Function	New cells are formed during growth or tissue repair; new cells have identical DNA and can perform the same functions as the parent cells.	Gametes are produced for reproduction; during fertilization the chromosomes from the haploid gametes unite to restore the diploid number typical of somatic cells; genetic variability is increased because of random distribution of chromosomes during meiosis and crossing-over.

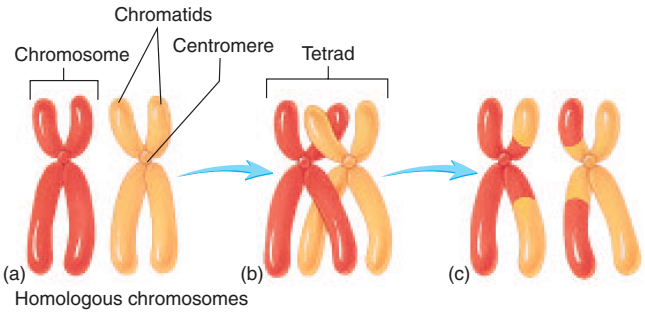


Figure 3.46 Crossing-Over

Crossing-over may occur during prophase I of meiosis. (*a*) A pair of replicated homologous chromosomes. (*b*) Chromatids of the homologous chromosomes form a tetrad. The chromatids are crossed in two places. The chromatids may break at the points of crossing and become fused to the opposite chromosome, resulting in crossing-over. (*c*) Genetic material is exchanged following crossing-over of the chromatids.

Apoptosis (Programmed Cell Death)

Apoptosis (ap′op-tō′sis, ap′ō-tō′sis), or **programmed cell death,** is a normal process by which cell numbers within various tissues are adjusted and controlled. During development, extra cells are removed by apoptosis, such as cells between the developing fingers and toes, to fine-tune the contours of the developing fetus. The number of cells in most adult tissues is maintained at a specific level. Apoptosis eliminates excess cells produced by proliferation within some adult tissues to maintain a constant number of cells within the tissue. Damaged or potentially dangerous cells, virus-infected cells, and potential cancer cells are also eliminated by apoptosis.

Apoptosis is regulated by specific genes. The proteins coded for by those genes initiate events within the cell that ultimately lead to the cell's death. As apoptosis begins, the chromatin within the nucleus condenses and fragments. This is followed by fragmentation of the nucleus and finally by death and fragmentation of the cell. The cell fragments are cleaned up by specialized cells called macrophages.

Cellular Aspects of Aging

Objective

- ***Outline the major theories of aging.***

A number of cellular structures and/or events appear to be involved in the process of aging. The major theories of aging concentrate on molecules within the cell, such as lipids, proteins, and nucleic acids. It is estimated that at least 35% of the factors affecting aging are genetic.

1. *Cellular clock.* One theory of aging suggests that there is a cellular clock, which, after a certain passage of time or a certain number of cell divisions, results in death of the cell line.
2. *Death genes.* Another theory suggests that there are "death genes," which turn on late in life, or sometimes prematurely, causing cells to deteriorate and die.
3. *DNA damage.* Other theories suggest that through time, DNA is damaged, resulting in cell degeneration and death. It may be that DNA is protected from damage by a specific sequence of nucleotides, TTAGGG, called a **telomere** (tel′ō-mēr), at the end of chromosomes. Apparently, during DNA replication, nucleotides are lost at the extreme distal end of the DNA molecule. Telomeres, at this extreme end, take the brunt of this replicative loss, thereby protecting regions of DNA that code for essential proteins. **Telomerase** is an enzyme that mediates the repair and maintains the integrity of the telomeric region of chromosomes. The enzyme can even add additional nucleotides to the telomeric region. Telomerase appears to be lost from aging populations of somatic cells. Without telomerase to repair the telomeres, they tend to degenerate during replication, and eventually, critical, functional regions of DNA are lost during replication, resulting in cell death.
4. *Free radicals.* The DNA in somatic cells may also be susceptible to more direct damage, resulting in somatic mutations, which may result in cellular dysfunction and, ultimately, cell death. One of the major sources of DNA

Clinical Focus Genetic Engineering

We are living in an exciting era, when the genetic bases of many human illnesses are rapidly being revealed. As we discover the defective genes associated with these diseases and learn the nature and function of the proteins they encode, our ability to understand and therefore to treat many of these diseases is improved. Once we have learned the basis of a given disease, a number of approaches are possible for treating it, such as genetic engineering or other molecular techniques. For example, the gene for insulin has been inserted into a bacterial genome, thereby enabling the bacterium to produce large quantities of human insulin, which increases its availability and functional quality. Antibodies are being developed that will target specific cells or cell surface marker molecules associated with diseases such as arthritis or cancer. Clinical trials are underway to test the efficacy of introducing a functional copy of a gene into the cells of a person who has a defective gene.

A negative side exists to this technology, however. Many people are concerned that the introduction of foreign genes into bacteria and human cells may have unexpected side effects. Many genes have multiple functions, and a danger exists that we may begin using gene therapy before we know all the ramifications. Some people are greatly concerned about how far genetic engineering should be allowed to go. What range of "genetic defects" should humanity be allowed to change, or should no limit be established? For example, when we discover the genes involved in controlling human height, should parents be allowed to use gene therapy to increase a child's height so that he or she can be better at basketball? An even more immediate concern is to what extent a person's genetic code should be made public. For example, should a medical insurance company or employer be allowed to see a person's genetic profile to set insurance premiums or make employment judgments? If a person is shown to have a gene for muscular dystrophy, should the person's insurance company be given that information? Also of concern is whether a person or company should be able to patent and thus to own a human gene.

damage is apparently from **free radicals,** which are atoms or molecules with an unpaired electron.

5. *Mitochondrial damage.* It may be that mitochondrial DNA is more sensitive to free-radical damage than is nuclear DNA. Mitochondrial DNA damage may result in loss of proteins critical to mitochondrial function. Because the mitochondria are the power plants of cells, loss of mitochondrial function could result in the loss of energy critical to cell function and, ultimately, to cell death. One proposal suggests that reduced caloric intake may reduce free radical damage to mitochondria.

68. How might a cellular clock, death genes, DNA damage, free radicals, or mitochondrial damage contribute to cellular aging?

S U M M A R Y

1. The plasma membrane forms the outer boundary of the cell.
2. The nucleus directs the activities of the cell.
3. Cytoplasm, between the nucleus and plasma membrane, is where most cell activities take place.

Functions of the Cell (p. 59)

1. Cells are the basic unit of life.
2. Cells provide protection and support.
3. Cells allow for movement.
4. Cells provide a means of communication.
5. Cells metabolize and release energy.
6. Cells provide for inheritance.

How We See Cells (p. 59)

1. Light microscopes allow us to visualize general features of cells.
2. Electron microscopes allow us to visualize the fine structure of cells.

Plasma Membrane (p. 61)

1. The plasma membrane passively or actively regulates what enters or leaves the cell.
2. The plasma membrane is composed of a phospholipid bilayer in which proteins are suspended (fluid-mosaic model).

Membrane Lipids

Lipids give the plasma membrane most of its structure and some of its function.

Membrane Proteins

1. Membrane proteins function as markers, attachment sites, channels, receptors, enzymes, and carriers.
2. Some receptor molecules are linked to and control channel proteins.
3. Some receptor molcules are linked to G proteins, which, in turn, control numerous cellular activities.

Movement Through the Plasma Membrane (p. 65)

1. Lipid-soluble molecules pass through the plasma membrane readily by dissolving in the lipid bilayer.
2. Small molecules pass through membrane channels. Most channels are positively charged, allowing negatively charged ions and neutral molecules to pass through more readily than positively charged ions.
3. Large polar substances (e.g., glucose and amino acids) are transported through the membrane by carrier molecules.
4. Larger pieces of material enter cells in vesicles.

Diffusion

1. Diffusion is the movement of a substance from an area of higher concentration to one of lower concentration (with a concentration gradient).
2. The concentration gradient is the difference in solute concentration between two points divided by the distance separating the points.
3. The rate of diffusion increases with an increase in the concentration gradient, an increase in temperature, a decrease in molecular size, and a decrease in viscosity.
4. The end result of diffusion is a uniform distribution of molecules.
5. Diffusion requires no expenditure of energy.

Osmosis

1. Osmosis is the diffusion of water (solvent) across a selectively permeable membrane.
2. Osmotic pressure is the force required to prevent the movement of water across a selectively permeable membrane.
3. Isosmotic solutions have the same concentration of solute particles, hyperosmotic solutions have a greater concentration, and hyposmotic solutions have a lesser concentration of solute particles than a reference solution.
4. Cells placed in an isotonic solution neither swell nor shrink. In a hypertonic solution they shrink (crenate), and in a hypotonic solution they swell and may burst (lyse).

Filtration

1. Filtration is the movement of a liquid through a partition with holes that allow the liquid, but not everything in the liquid, to pass through them.
2. Liquid movement results from a pressure difference across the partition.

Mediated Transport Mechanisms

1. Mediated transport is the movement of a substance across a membrane by means of a carrier molecule. The substances transported tend to be large, water-soluble molecules.
   - The carrier molecules have binding sites that bind with either a single transport molecule or a group of similar transport molecules. This selectiveness is called specificity.
   - Similar molecules can compete for carrier molecules, with each reducing the rate of transport of the other.
   - Once all the carrier molecules are in use, the rate of transport cannot increase further (saturation).
2. Three kinds of mediated transport can be identified.
   - Facilitated diffusion moves substances with their concentration gradient and does not require energy expenditure (ATP).
   - Active transport can move substances against their concentration gradient and requires ATP. An exchange pump is an active-transport mechanism that simultaneously moves two substances in opposite directions across the plasma membrane.
   - In secondary active transport, an ion is moved across the plasma membrane by active transport, and the energy produced by the ion diffusing back down its concentration gradient can transport another molecule, such as glucose, against its concentration gradient.

Endocytosis and Exocytosis

1. Endocytosis is the bulk movement of materials into cells.
   - Phagocytosis is the bulk movement of solid material into cells by the formation of a vesicle.
   - Pinocytosis is similar to phagocytosis, except that the ingested material is much smaller or is in solution.
2. Exocytosis is the secretion of materials from cells by vesicle formation.
3. Endocytosis and exocytosis use vesicles, can be specific (receptor-mediated endocytosis) for the substance transported, and require energy.

Cytoplasm (p. 75)

The cytoplasm is the material outside the nucleus and inside the plasma membrane.

Cytocol

1. Cytosol consists of a fluid part (the site of chemical reactions), the cytoskeleton, and cytoplasmic inclusions.
2. The cytoskeleton supports the cell and enables cell movements. It consists of protein fibers.
   - Microtubules are hollow tubes composed of the protein tubulin. They form spindle fibers and are components of centrioles, cilia, and flagella.
   - Actin filaments are small protein fibrils that provide structure to the cytoplasm or cause cell movements.
   - Intermediate filaments are protein fibers that provide structural strength to cells.
3. Cytoplasmic inclusions, such as lipochromes, are not surrounded by membranes.

Organelles (p. 77)

Organelles are subcellular structures specialized for specific functions.

Centrioles and Spindle Fibers

1. Centrioles are cylindrical organelles located in the centrosome, a specialized zone of the cytoplasm. The centrosome is the site of microtubule formation.
2. Spindle fibers are involved in the separation of chromosomes during cell division.

Cilia and Flagella

1. Movement of materials over the surface of the cell is facilitated by cilia.
2. Flagella, much longer than cilia, propel sperm cells.

Microvilli

Microvilli increase the surface area of the plasma membrane for absorption or secretion.

Ribosomes

1. Ribosomes consist of small and large subunits manufactured in the nucleolus and assembled in the cytoplasm.
2. Ribosomes are the sites of protein synthesis.
3. Ribosomes can be free or associated with the endoplasmic reticulum.

Endoplasmic Reticulum

1. The endoplasmic reticulum is an extension of the outer membrane of the nuclear envelope and forms tubules or sacs (cisternae) throughout the cell.
2. The rough endoplasmic reticulum has ribosomes and is a site of protein synthesis and modification.
3. The smooth endoplasmic reticulum lacks ribosomes and is involved in lipid production, detoxification, and calcium storage.

Golgi Apparatus

The Golgi apparatus is a series of closely packed, modified cisternae that function to modify, package, and distribute lipids and proteins produced by the endoplasmic reticulum.

Secretory Vesicles

Secretory vesicles are membrane-bound sacs surrounded by membranes that carry substances from the Golgi apparatus to the plasma membrane, where the contents of the vesicle are released by exocytosis.

Lysosomes

1. Lysosomes are membrane-bounded sacs containing hydrolytic enzymes. Within the cell, the enzymes break down phagocytized material and nonfunctional organelles (autophagia).

2. Enzymes released from the cell by lysis or enzymes secreted from the cell can digest extracellular material.

Peroxisomes

Peroxisomes are membrane-bounded sacs containing enzymes that digest fatty acids and amino acids and enzymes that catalyze the breakdown of hydrogen peroxide.

Proteasomes

Proteasomes are large multienzyme complexes, not bound by membranes, which digest selected proteins within the cell.

Mitochondria

1. Mitochondria are the major sites of the production of ATP, which is used as an energy source by cells.
2. The mitochondria have a smooth outer membrane and an inner membrane that is infolded to produce cristae.
3. Mitochondria contain their own DNA, can produce some of their own proteins, and can replicate independently of the cell.

Nucleus (p. 85)

1. The nuclear envelope consists of two separate membranes with nuclear pores.
2. DNA and associated proteins are found inside the nucleus as chromatin. DNA is the hereditary material of the cell and controls the activities of the cell by producing proteins through RNA.
3. Proteins play a role in the regulation of DNA activity.
4. Nucleoli consist of RNA and proteins and are the sites of ribosomal subunit assembly.

Overview of Cell Metabolism (p. 87)

1. Aerobic respiration requires oxygen and produces carbon dioxide, water, and up to 38 ATP molecules from a molecule of glucose.
2. Anaerobic respiration does not require oxygen and produces lactic acid and two ATP molecules from a molecule of glucose.

Protein Synthesis (p. 87)

1. Transcription: information stored in DNA is copied to mRNA.
2. Translation: the mRNA goes to ribosomes, where it directs the synthesis of proteins.

Transcription

1. DNA unwinds and, through nucleotide pairing, produces mRNA (transcription).
2. The genetic code, which codes for amino acids, consists of codons, which are sequences of three nucleotides in mRNA.
3. Introns are removed and exons are spliced by spliceosomes during posttranscriptional processing.

Translation

1. The mRNA moves through the nuclear pores to ribosomes.
2. Transfer RNA (tRNA), which carries amino acids, interacts at the ribosome with mRNA. The anticodons of tRNA bind to the codons of mRNA, and the amino acids are joined to form a protein (translation).
3. Proproteins, some of which are proenzymes, are modified into proteins, some of which are enzymes, during posttranslational processing.

Regulation of Protein Synthesis

1. Cells become specialized because of inactivation of certain parts of the DNA molecule and activation of other parts.
2. The level of DNA activity and thus protein production can be controlled internally or can be affected by regulatory substances secreted by other cells.

Cell Life Cycle (p. 90)

The cell life cycle has two stages: interphase and mitosis.

Interphase

Interphase is the period between cell divisions.

DNA Replication

DNA unwinds, and each strand produces a new DNA molecule during replication.

Cell Division

Cell division includes nuclear division and cytoplasmic division.

Mitosis

1. Mitosis is the replication of the nucleus of the cell, and cytokinesis is division of the cytoplasm of the cell.
2. Humans have 22 pairs of homologous chromosomes called autosomes. Females also have two X chromosomes, and males also have an X chromosome and a Y chromosome.
3. Mitosis is a continuous process divided into four phases.
   - *Prophase.* Chromatin condenses to become visible as chromosomes. Each chromosome consists of two chromatids joined at the centromere. Centrioles move to opposite poles of the cell, and astral fibers and spindle fibers form. Nucleoli disappear, and the nuclear envelope degenerates.
   - *Metaphase.* Chromosomes align at the equatorial plane.
   - *Anaphase.* The chromatids of each chromosome separate at the centromere. Each chromatid then is called a chromosome. The chromosomes migrate to opposite poles.
   - *Telophase.* Chromosomes unravel to become chromatin. The nuclear envelope and nucleoli reappear.

Cytokinesis

Cytokinesis begins with the formation of the cleavage furrow during anaphase. It is complete when the plasma membrane comes together at the equator, thus producing two new daughter cells.

Meiosis (p. 94)

1. Meiosis results in the production of gametes (oocytes or sperm cells).
2. All gametes receive one-half of the homologous autosomes (one from each homologous pair). Oocytes also receive an X chromosome. Sperm cells have an X or a Y chromosome.
3. Two cell divisions occur in meiosis. Each division has four phases (prophase, metaphase, anaphase, and telophase) similar to those in mitosis.
   - In the first division tetrads form, crossing-over occurs, and homologous chromosomes are distributed randomly. Two cells are formed, each with 23 chromosomes. Each chromosome has two chromatids.
   - In the second division, the chromatids of each chromosome separate, and each cell receives 23 chromatids, which then are called chromosomes.
4. Genetic variability is increased by crossing-over and random assortment of chromosomes.

Cellular Aspects of Aging (p. 97)

There are five major theories of aging:

1. *Cellular clock.* A cell line may die out after a certain time or a certain number of cell divisions.
2. *Death genes.* There may be "death genes," which turn on late in life, causing cells to die.
3. *DNA damage.* Telomeres normally protect DNA from damage during replication, and telomerase protects these telomeres. Aging cells lack telomerase and telomeres, and other DNA, become open to damage.
4. *Free radicals.* Free radicals may also damage DNA.
5. *Mitochondrial damage.* Mitochondrial DNA may be the most sensitive to free-radical damage.

REVIEW AND COMPREHENSION

1. In the plasma membrane, _____ form(s) the lipid bilayer, _____ determine(s) the fluid nature of the membrane, and _____ mainly determine(s) the function of the membrane.
   a. phospholipids, cholesterol, proteins
   b. phospholipids, proteins, cholesterol
   c. proteins, cholesterol, phospholipids
   d. cholesterol, phospholipids, proteins
   e. cholesterol, proteins, phospholipids
2. Which of the following are functions of the proteins found in the plasma membrane?
   a. channel proteins
   b. marker molecules
   c. receptor molecules
   d. enzymes
   e. all of the above
3. Integrins in the plasma membrane function as
   a. channel proteins.
   b. marker molecules.
   c. attachment sites.
   d. enzymes.
   e. receptor molecules.
4. In general, lipid-soluble molecules diffuse through the _____; small, water-soluble molecules diffuse through the _____.
   a. membrane channels, membrane channels
   b. membrane channels, lipid bilayer
   c. lipid bilayer, carrier molecules
   d. lipid bilayer, membrane channels
   e. carrier proteins, membrane channels
5. Small pieces of matter, and even whole cells, can be transported across the plasma membrane in
   a. membrane channels.
   b. carrier molecules.
   c. receptor molecules.
   d. marker molecules.
   e. vesicles.
6. The rate of diffusion increases if the
   a. concentration gradient decreases.
   b. temperature of a solution decreases.
   c. viscosity of a solution decreases.
   d. all of the above.
7. Concerning the process of diffusion, at equilibrium
   a. the net movement of solutes stops.
   b. random molecular motion continues.
   c. there is an equal movement of solute in opposite directions.
   d. concentration of solute is equal throughout the solution.
   e. all of the above.
8. Which of these statements about osmosis is true?
   a. Osmosis always involves a membrane that allows water and all solutes to diffuse through it.
   b. The greater the solute concentration, the smaller the osmotic pressure of a solution.
   c. Osmosis moves water from a greater solute concentration to a lesser solute concentration.
   d. The greater the osmotic pressure of a solution, the greater the tendency for water to move into the solution.
   e. Osmosis occurs because of hydrostatic pressure outside the cell.
9. If a cell is placed in a _____ solution, lysis of the cell may occur.
   a. hypertonic
   b. hypotonic
   c. isotonic
   d. isosmotic
10. Container A contains a 10% salt solution, and container B contains a 20% salt solution. If the two solutions are connected, the net movement of water by diffusion is from _____ to _____, and the net movement of salt by diffusion is from _____ to _____.
    a. A,B; A,B
    b. A,B; B,A
    c. B,A; A,B
    d. B,A; B,A
11. Suppose that a woman ran a long-distance race in the summer. During the race she lost a large amount of hyposmotic sweat. You would expect her cells to
    a. shrink.
    b. swell.
    c. stay the same
12. Suppose that a man is doing heavy exercise in the hot summer sun. He sweats profusely. He then drinks a large amount of distilled water. After he drank the water, you would expect his tissue cells to
    a. shrink.
    b. swell.
    c. remain the same.
13. Unlike diffusion and osmosis, filtration depends on a _____ on the two sides of the partition.
    a. concentration gradient
    b. pressure difference
    c. difference in electric charge
    d. difference in osmotic pressure
    e. hyposmotic solution
14. Which of these statements about facilitated diffusion is true?
    a. In facilitated diffusion, net movement is with the concentration gradient.
    b. Facilitated diffusion requires the expenditure of energy.
    c. Facilitated diffusion does not require a carrier protein.
    d. Facilitated diffusion moves materials through membrane channels.
    e. Facilitated diffusion moves materials in vesicles.
15. Which of these statements concerning contransport of glucose into cells is true?
    a. The sodium-potassium exchange pump moves Na^+ into cells.
    b. The concentration of Na^+ outside cells is less than inside cells.
    c. A carrier protein moves Na^+ into cells and glucose out of cells.
    d. The concentration of glucose can be greater inside cells than outside cells.
    e. As Na^+ is actively transported into the cell, glucose is carried along.
16. A white blood cell ingests solid particles by forming vesicles. This describes the process of
    a. exocytosis.
    b. facilitated diffusion.
    c. secondary active transport.
    d. phagocytosis.
    e. pinocytosis.
17. Given these characteristics:
    1. requires energy
    2. requires carrier proteins
    3. requires membrane channels
    4. requires vesicles

    Choose the characteristics that apply to exocytosis.
    a. 1, 2
    b. 1, 4
    c. 1, 3, 4
    d. 1, 2, 3
    e. 1, 2, 3, 4

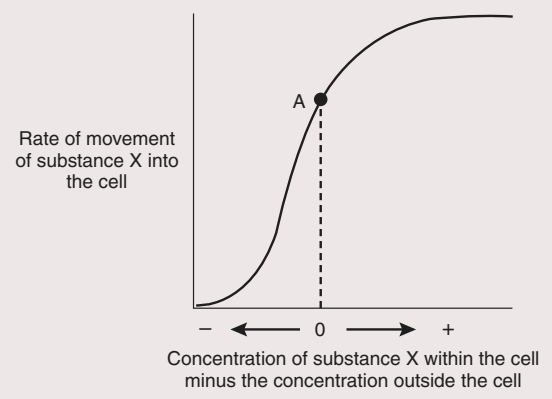
18. Cytoplasm is found
    a. in the nucleus.
    b. outside the nucleus and inside the plasma membrane.
    c. outside the plasma membrane.
    d. inside mitochondria.
    e. everywhere in the cell.
19. Which of these elements of the cytoskeleton is composed of tubulin and forms essential components of centrioles, spindle fibers, cilia, and flagella?
    a. actin filaments
    b. intermediate filaments
    c. microtubules
20. Cylindrically shaped extensions of the plasma membrane that do not move, and are supported with actin filaments; they may function in absorption or as sensory receptors. This describes
    a. centrioles.
    b. spindle fibers.
    c. cilia.
    d. flagella.
    e. microvilli.
21. A large structure, normally visible in the nucleus of a cell, where ribosomal subunits are produced.
    a. endoplasmic reticulum.
    b. mitochondria.
    c. nucleolus.
    d. lysosome.
22. A cell that synthesizes large amounts of protein for use outside the cell has a large
    a. number of cytoplasmic inclusions.
    b. number of mitochondria.
    c. amount of rough endoplasmic reticulum.
    d. amount of smooth endoplasmic reticulum.
    e. number of lysosomes.
23. Which of these organelles produces large amounts of ATP?
    a. nucleus
    b. mitochondria
    c. ribosomes
    d. endoplasmic reticulum
    e. lysosomes
24. Mature red blood cells cannot
    a. synthesize ATP.
    b. transport oxygen.
    c. synthesize new protein.
    d. use glucose as a nutrient.
25. For each glucose molecule, aerobic respiration may produce up to _____ ATP and 6 CO_2 molecules, whereas anaerobic respiration produces _____ ATP and 2 lactic acid molecules.
    a. 2, 2
    b. 2, 4
    c. 2, 38
    d. 38, 2
    e. 38, 38
26. A portion of an mRNA molecule that determines one amino acid in a polypeptide chain is called a
    a. nucleotide.
    b. gene.
    c. codon.
    d. exon.
    e. intron.
27. In which of these organelles is mRNA synthesized?
    a. nucleus
    b. ribosome
    c. endoplasmic reticulum
    d. nuclear envelope
    e. peroxisome
28. During the cell life cycle, DNA replication occurs during the
    a. G_1 phase.
    b. G_2 phase.
    c. M phase.
    d. S phase.
29. Given the following activities:
    1. repair
    2. growth
    3. gamete production
    4. differentiation

    Which of the activities are the result of mitosis?
    a. 2
    b. 3
    c. 1, 2
    d. 3, 4
    e. 1, 2, 4
30. Which of these processes does *not* occur during meiosis?
    a. crossing-over
    b. interkinesis
    c. tetrad formation
    d. production of chromatids
    e. production of gametes with the diploid number of chromosomes

Answers in Appendix F

CRITICAL THINKING

1. Why does a surgeon irrigate a surgical wound from which a tumor has been removed with sterile distilled water rather than with sterile isotonic saline?
2. Solution A is hyperosmotic to solution B. If solution A is separated from solution B by a selectively permeable membrane, does water move from solution A into solution B or vice versa? Explain.
3. A dialysis membrane is selectively permeable, and substances smaller than proteins are able to pass through it. If you wanted to use a dialysis machine to remove only urea (a small molecule) from blood, what could you use for the dialysis fluid?
    a. a solution that is isotonic and contains only large molecules, such as protein
    b. a solution that is isotonic and contains the same concentration of all substances except that it has no urea
    c. distilled water, which contains no ions or dissolved molecules
    d. blood, which is isotonic and contains the same concentration of all substances, including urea
4. A researcher wants to determine the nature of the transport mechanism that moved substance X into a cell. She could measure the concentration of substance X in the extracellular fluid and within the cell, as well as the rate of movement of substance X into the cell. She does a series of experiments and gathers the data shown in the graph. Choose the transport process that is consistent with the data.
    a. diffusion
    b. active transport
    c. facilitated diffusion
    d. not enough information to make a judgment



Graph depicting the rate of movement of substance X from a fluid into a cell (*y* axis) versus the concentration of substance X within the cell (*x* axis). At point *A* the extracellular concentration of substance X is equal to the intracellular concentration of substance X (designated *0* on the *x* axis).

5. Predict the consequence of a reduced intracellular K^+ concentration on the resting membrane potential.
6. If you had the ability to inhibit mRNA synthesis with a drug, explain how you could distinguish between proteins released from secretory vesicles in which they had been stored and proteins released from cells in which they have been newly synthesized.
7. Given the following data from electron micrographs of a cell, predict the major function of the cell:
   - moderate number of mitochondria;
   - well-developed rough endoplasmic reticulum;
   - moderate number of lysosomes;
   - well-developed Golgi apparatus;
   - dense nuclear chromatin;
   - numerous vesicles.

Answers in Appendix G

ANSWERS TO PREDICT QUESTIONS

1. Urea is continually produced by metabolizing cells and diffuses from the cells into the interstitial spaces and from the interstitial spaces into the blood. If the kidneys stop eliminating urea, it begins to accumulate in the blood. Because the concentration of urea increases in the blood, urea cannot diffuse from the interstitial spaces. As urea accumulates in the interstitial spaces, the rate of diffusion from cells into the interstitial spaces slows because the urea must pass from a higher to a lower concentration by the process of diffusion. the urea finally reaches concentrations high enough to be toxic to cells, thereby causing cell damage followed by cell death.
2. If the membrane is freely permeable, the solutes in the tube diffuse from the tube (higher concentration of solutes) into the beaker (lower concentration of solutes) until equal amounts of solutes exist inside the tube and beaker (i.e., equilibrium). In a similar fashion, water in the beaker diffuses from the beaker (higher concentration of water) into the tube (lower concentration of water) until equal amounts of water are inside the tube and beaker. Consequently, the solution concentrations inside the tube and beaker are the same because they both contain the same amounts of solutes and water. Under these conditions, no net movement of water into the tube occurs. This simple experiment demonstrates that osmosis and osmotic pressure require a membrane that is selectively permeable.
3. Glucose transported by facilitated diffusion across the plasma membrane moves from a higher to a lower concentration. If glucose molecules are quickly converted to some other molecule as they enter the cell, a steep concentration gradient is maintained. The rate of glucose transport into the cell is directly proportional to the magnitude of the concentration gradient.
4. Digitalis should increase the force of heart concentration. By interfering with Na^+ transport, digitalis decreases the concentration gradient for Na^+ because fewer ions are pumped out of cells by active transport. Consequently, fewer ions diffuse into cells, and fewer Ca^{2+} ions move out of the cells by countertransport. The higher intracellular levels of Ca^{2+} promote more forceful concentrations.
5. a. Cells highly specialized to synthesize and secrete proteins have large amounts of rough endoplasmic reticulum (ribosomes attached to endoplasmic reticulum) because these organelles are important for protein synthesis. Golgi apparatuses are well developed because they package materials for release in secretory vesicles. Also, numerous secretory vesicles exist in the cytoplasm.
   b. Cells highly specialized to actively transport substances into the cell have a large surface area exposed to the fluid from which substances are actively transported, and numerous mitochondria are present near the membrane across which active transport occurs.
   c. Cells highly specialized to synthesize lipids have large amounts of smooth endoplasmic reticulum. Depending on the kind of lipid produced, lipid droplets may accumulate in the cytoplasm.
   d. Cells highly specialized to phagocytize foreign substances have numerous lysosomes in their cytoplasm and evidence of phagocytic vesicles.
6. By changing a single nucleotide within a DNA molecule, a change in the nucleotide of mRNA produced from that segment of DNA also occurs, and a different amino acid is placed in the amino acid chain for which the mRNA provides direction. Because a change in the amino acid sequence of a protein could change its structure, one substitution of a nucleotide in a DNA chain could result in altered protein structure and function.
7. Because adenine pairs with thymine (no uracil exists in DNA) and cytosine pairs with guanine, the sequence of DNA replicated from strand 1 is TACGAT. This sequence is also the sequence of DNA in the original strand 2. A replicate of strand 2 is therefore ATGCTA, which is the same as the original strand 1.