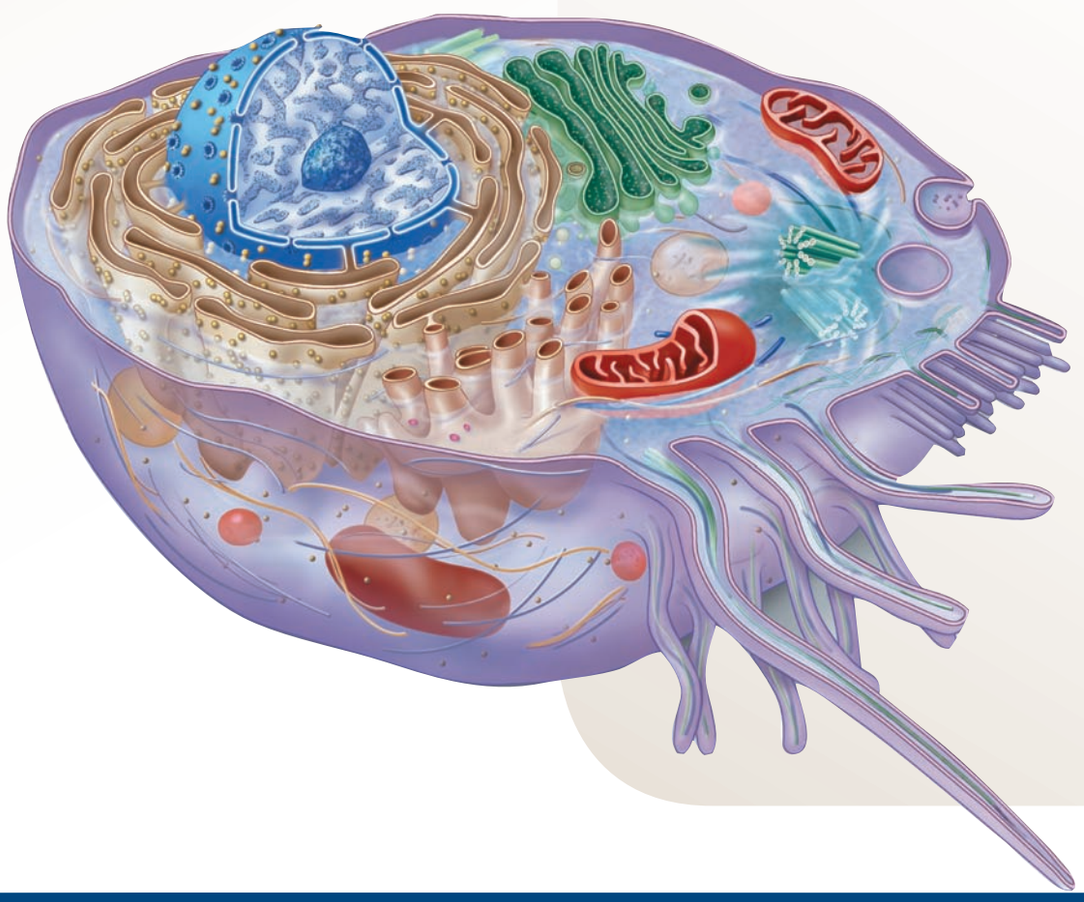
2

The Cell: Basic Unit of Structure and Function

OUTLINE

MODULE 2: CELLS & CHEMISTRY



Cells are the structural and functional units of all organisms, including humans. An adult human body contains about 75 trillion cells. Most cells are composed of characteristic parts that work together to allow them to perform specific body functions. There are approximately 200 different types of cells in the human body, but all of them share certain common characteristics:

- All cells perform the general housekeeping functions necessary to sustain life. Each cell must obtain nutrients and other materials essential for survival from its surrounding fluids. Recall from chapter 1 that the total of all the chemical reactions that occur in cells is called metabolism.
- Cells must dispose of the wastes they produce. If a cell didn't remove its waste products, this waste would build up in the cell and lead to its death.
- The shape and integrity of a cell is maintained by both its internal contents and its surrounding membrane.
- Most cells are capable of undergoing cell division to make more cells of the same type.

2.1 The Study of Cells

Learning Objectives:

1. **Compare and contrast the advantages and disadvantages of LM, TEM, and SEM.**
2. **Describe the relationship between structure and function in cells.**

The study of cells is called **cytology.** Throughout this chapter, we will examine the generalized structures and functions shared by all body cells. Subsequent chapters examine specialized cells and their unique functions.

2.1a Using the Microscope to Study Cells

The small size of cells is the greatest obstacle to determining their nature. Cells were discovered after microscopes were invented, and high-magnification microscopes are required to see the smallest human body cells. The dimensional unit often used to measure cell size is the micrometer (µm). One micrometer is equal to 1/10,000 of a centimeter (about 1/125,000 of an inch). For example, a red blood cell has a diameter of about 7–8 µm, whereas one of the largest human cells, an oocyte, has a diameter of about 120 µm. **Figure 2.1** compares the size of the smallest unit of structure in the human body (an atom) to various cell types as well as to other macroscopic structures, such as an ostrich egg and a human.

Microscopy is the use of the microscope. It has become a valuable asset in anatomic investigations. Most commonly used are the **light microscope (LM),** the **transmission electron microscope (TEM),** and the **scanning electron microscope (SEM).** Because specimen samples have no inherent contrast, they cannot be seen clearly under the microscope unless contrast is added. Therefore, colored-dye stains are used in light microscopy, and heavy-metal stain preparations are used in electron microscopy, which includes both TEM and SEM. **Figure 2.2** compares the images produced when each of these types of microscopes is used to examine the same specimen—in this case, the epithelium lining the respiratory tract.

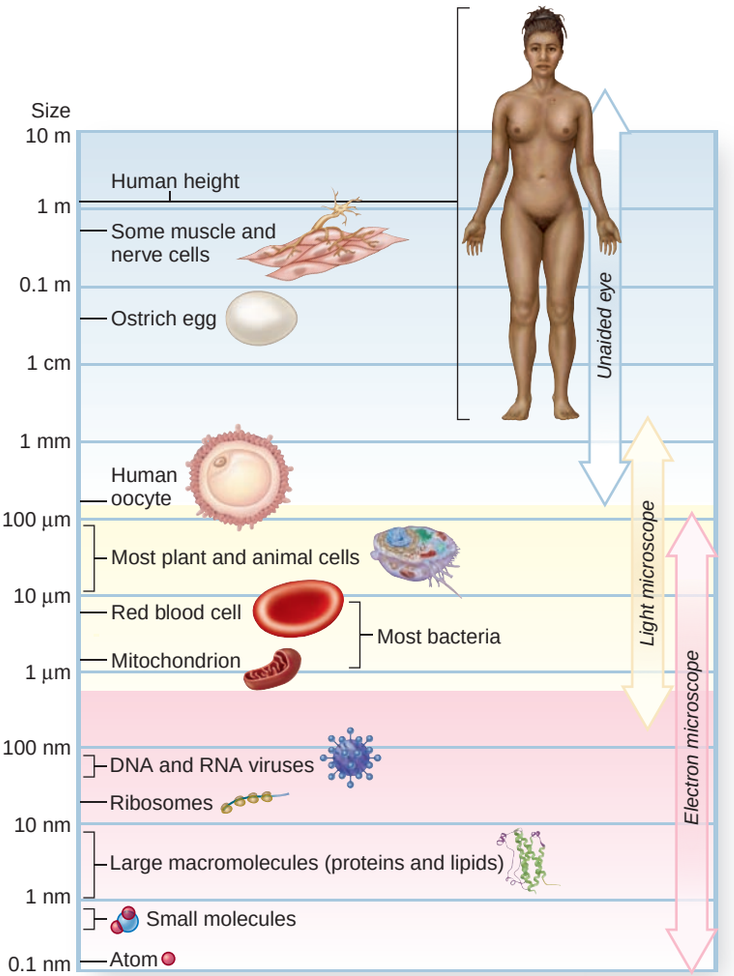


Figure 2.1

The Range of Cell Sizes. Most cells in the human body are between 1 micrometer (µm) and 100 µm in diameter. Individual cells are usually observed by light microscopy; subcellular structures are studied by electron microscopy.

The LM produces a two-dimensional image for study by passing visible light through the specimen. Glass lenses focus and magnify the image as it is projected toward the eye. Figure 2.2*a* shows the cellular structure of the epithelium as well as the hair-like structures (cilia) that project from its surface.

Electron microscopes use a beam of electrons to "illuminate" the specimen. Electron microscopes easily exceed the magnification obtained by light microscopy, but more importantly, they improve the resolution by more than a thousandfold. A TEM directs an electron beam through a thin-cut section of the specimen. The resultant two-dimensional image is focused onto a screen for viewing or onto photographic film to record the image. The TEM can show a close-up section of the cilia on the surface of the epithelial cells (figure 2.2*b*).

For a detailed three-dimensional study of the surface of the specimen, SEM analysis is the method of choice (figure 2.2*c*). Here,

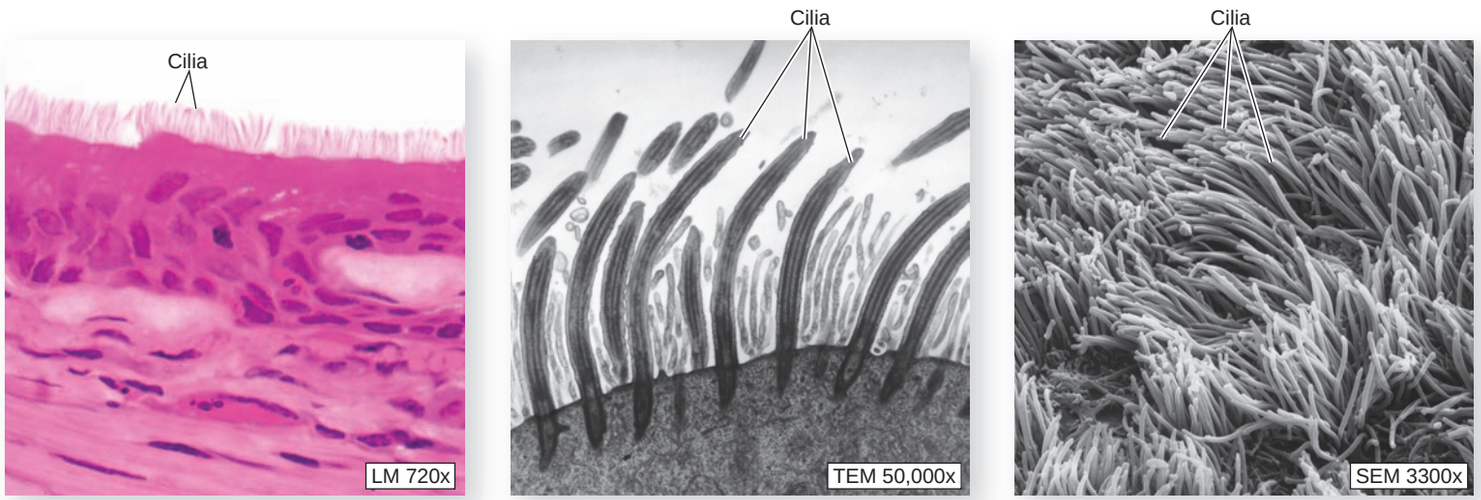


Figure 2.2

Microscopic Techniques for Cellular Studies. Different techniques are used to investigate cellular anatomy. (*a*) A light microscope (LM) shows hairlike structures, termed cilia, that project from the free membrane surfaces of the cells lining the respiratory tract. (*b*) A transmission electron microscope (TEM) reveals the ultrastructure of the cilia on the same type of cells. (*c*) A scanning electron microscope (SEM) shows the three-dimensional image of the cilia-covered surface of the same type of cells.

the electron beam is moved across the surface of the specimen, and reflected electrons generate a surface-topography image captured on a television screen.

2.1b General Functions of Human Body Cells

Besides differing in size, cells also vary in shape, which may be flat, cylindrical, oval, or quite irregular. Often, cells' functions are reflected in either their size or their shape. Among the general functions of cells are the following:

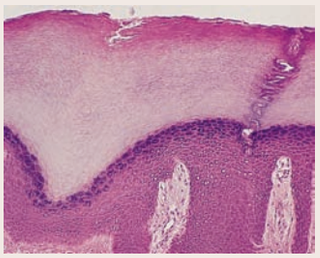
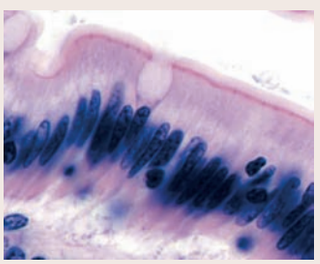
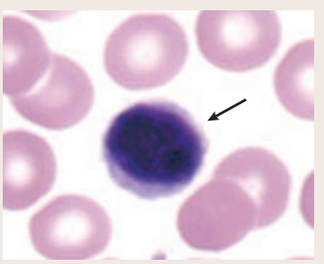
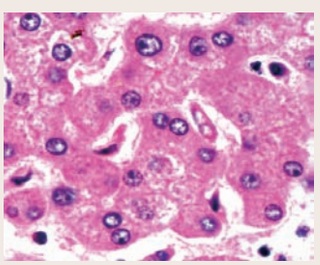
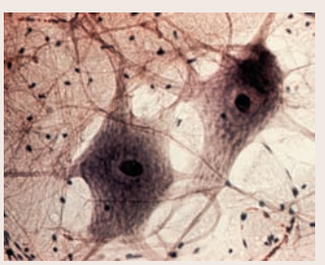
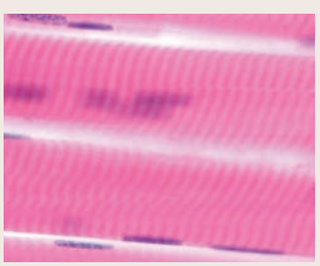
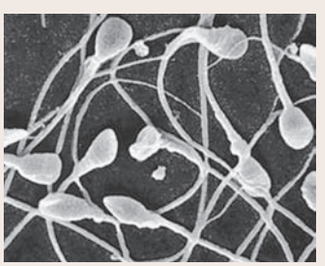
- **Covering.** Epithelial cells form a sheet to cover surfaces. For example, skin cells cover the external body surface.
- **Lining.** Epithelial cells line the internal surfaces of our organs, such as the small intestine.
- **Storage.** Some body cells, such as hepatocytes (liver cells) and adipocytes (fat cells), store nutrients or energy reserves for the body.
- **Movement.** Muscle cells are composed of contractile proteins that cause the muscle to shorten (contract), thereby allowing movement to occur. Skeletal muscle cells attach to the skeleton so that when these cells contract, they move the skeleton. In contrast, when the muscle cells in the heart wall contract, they are able to pump blood throughout the body.
- **Connection.** Multiple cell types are found in connective tissues, which help connect and support other tissues. For example, fibroblast cells produce protein fibers that are found in ligaments, the connective tissue that binds bone to bone.
- **Defense.** Many cell types protect the body against pathogens or antigens (anything perceived as foreign in the body). White blood cells (called leukocytes) are designed to recognize foreign material (antigens) and attack them. The process of attacking the foreign materials is called an immune response.
- **Communication.** Nerve cells (called neurons) transmit nerve impulses from one part of the body to another. The nerve impulse carries information between neurons within the nervous system, sensory information to the brain for processing, or motor information to make a muscle contract or a gland secrete.
- **Reproduction.** Some cells are designed solely to produce new individuals. For example, within the gonads, the sex cells (sperm and oocytes) are produced. They are specialized cells designed to join together and initiate the formation of a new individual. Additionally, within the bone marrow are stem cells that continuously produce new blood cells for the body.

Table 2.1 summarizes the types of cellular functions as they relate to cell structure. Now that we have mentioned that cells come in a variety of shapes and sizes and have different functions, let us examine the structures common to almost all cells.

WHAT DID YOU LEARN?

1. Describe an advantage of using TEM rather than LM to study intracellular structure.
2. What are some basic functions of human body cells?

Table 2.1 Selected Common Types of Cells and Their Functions

Functional Category	Example	Specific Functions	Functional Category	Example	Specific Functions
Covering	Epidermal cells in skin 	Protect outer surface of body	*Connection (attachment)*	Collagen (protein) fibers from fibroblasts 	Form ligaments that attach bone to bone
Lining	Epithelial cells in small intestine 	Regulate nutrient movement into body tissues	*Defense*	Lymphocytes 	Produce antibodies to target antigens or invading cells
Storage	Fat cells Liver cells 	Store lipid reserves Store carbohydrate nutrients as glycogen	*Communication*	Nerve cells 	Send information between regions of the brain
Movement	Muscle cells of heart Skeletal muscle cells 	Pump blood Move skeleton	*Reproduction*	Bone marrow stem cells Sperm and oocyte cells 	Produce new blood cells Produce new individual

2.2 A Prototypical Cell

Learning Objectives:

1. **Identify the characteristics of the plasma membrane, cytoplasm, and nucleus.**
2. **Describe the contents of a prototypical cell.**

The generalized cell in **figure 2.3** isn't an actual body cell, but rather a representation of a cell that combines features of several different types of body cells. Almost all mature human cells share the same three basic constituents, which can be described in terms of the prototypical cell:

- **Plasma membrane.** The plasma membrane, sometimes called the cell membrane, forms the outer, limiting barrier separating the internal contents of the cell from the external environment.
- **Cytoplasm.** Cytoplasm (sī′tō-plazm; *kytos* = a hollow, *plasma* = a thing formed) is a general term for all cellular contents located between the plasma membrane and the nucleus. The three components of the cytoplasm are cytosol (a viscous fluid), inclusions (nonfunctional, temporary structures that store cellular products), and organelles (tiny structures that perform specific cellular functions).
- **Nucleus.** The nucleus (noo′klē-ŭs; *nux* = the kernel or inside of a thing) is the cell's control center. It controls protein synthesis (production of new proteins), and in so doing, it directs the functional and structural characteristics of the cell.

The next three sections of this chapter describe the contents and specific functions of the plasma membrane, the cytoplasm, and the nucleus. As you read these descriptions, it may help to refer to **table 2.2**, which summarizes this information.

WHAT DID YOU LEARN?

3 Briefly describe the three main constituents of a cell.

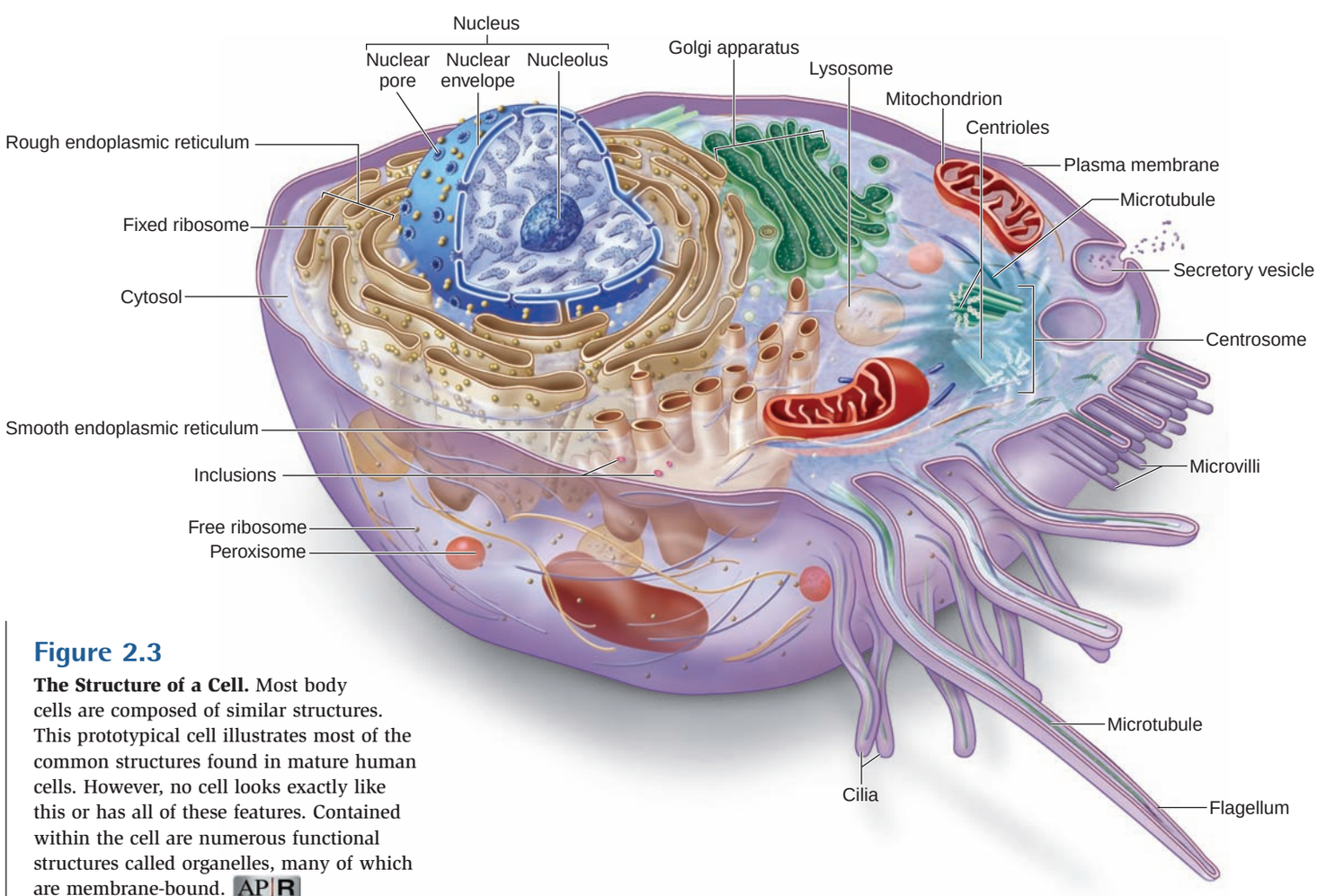


Figure 2.3

The Structure of a Cell. Most body cells are composed of similar structures. This prototypical cell illustrates most of the common structures found in mature human cells. However, no cell looks exactly like this or has all of these features. Contained within the cell are numerous functional structures called organelles, many of which are membrane-bound. AP|R

Table 2.2 Components of the Cell

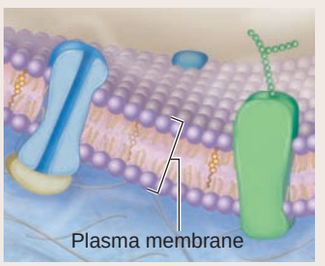
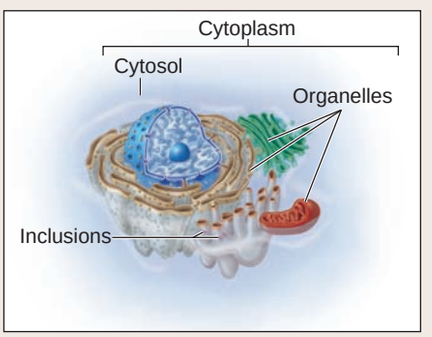
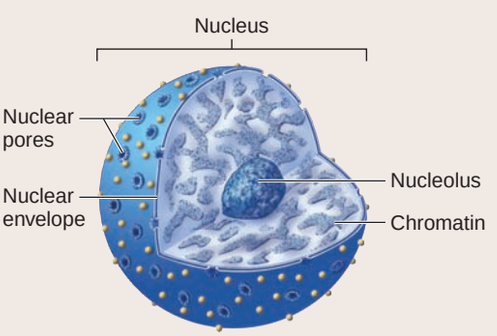
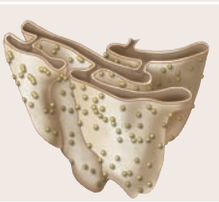
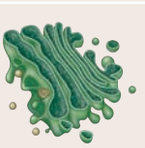
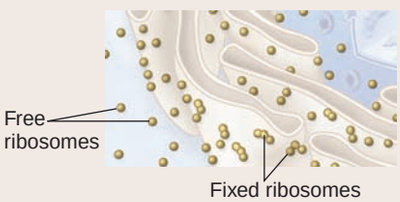
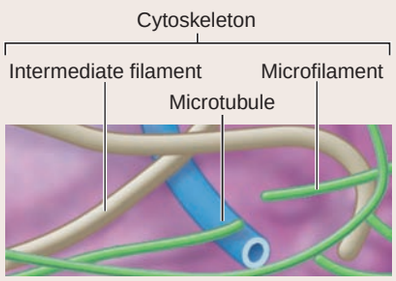
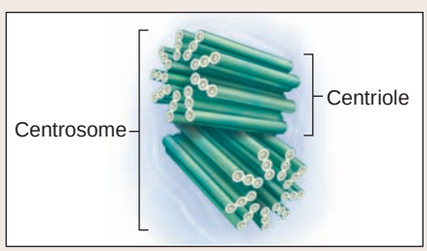
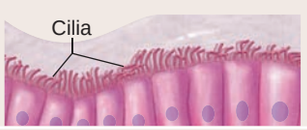
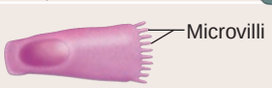
Component	Structure	Function	Appearance
MAJOR CELL COMPONENTS			
Plasma (cell) membrane	Phospholipid bilayer containing cholesterol and proteins (integral and peripheral) and some carbohydrates (externally)	Contains receptors for communication; forms intercellular connections; acts as physical barrier to enclose cell contents; regulates material movement into and out of the cell	
Cytoplasm	Contains cytosol, a viscous fluid, and inclusions and organelles	Place of many metabolic processes of the cell; stores nutrients and dissolved solutes	
Cytosol	Viscous fluid medium with dissolved solutes (ions, nutrients, proteins, carbohydrates, lipids, and other small molecules)	Provides support for organelles; serves as viscous medium through which diffusion occurs	
Organelles	Membrane-bound and non-membrane-bound structures that have unique functions and activities	Carry out specific metabolic activities of the cell	
Inclusions	Droplets of melanin, protein, glycogen granules, or lipid; usually non-membrane-bound	Store materials	
Nucleus	Surrounded by double membrane nuclear envelope (each membrane is a phospholipid bilayer); contains nucleolus and chromatin	Acts as cell control center; controls all genetic information (DNA); site of ribosome subunit assembly	
Nuclear envelope	Double membrane boundary between cytoplasm and nuclear contents	Pores in envelope regulate exchange of materials with the cytoplasm	
Nuclear pores	Openings through the nuclear envelope	Allow for passage of materials between nucleus and cytoplasm	
Nucleolus (or nucleoli)	Spherical, dark-staining, dense granular region in the nucleus	Synthesizes rRNA and assembles ribosomes in the nucleus	
Chromatin and chromosomes	Filamentous association of DNA and histone proteins	Site of genes in the DNA	
MEMBRANE-BOUND ORGANELLES			
Smooth endoplasmic reticulum (smooth ER)	Interconnected network of membrane tubules and vesicles; no ribosomes	Synthesizes lipids; metabolizes carbohydrates; detoxifies drugs, alcohol	
Rough endoplasmic reticulum (rough ER)	Flattened intracellular network of membrane sacs called cisternae; ribosomes attached on cytoplasmic surface	Synthesizes proteins for secretion, new proteins for the plasma membrane, and lysosomal enzymes; transports and stores molecules	
Golgi apparatus	Stacked series of flattened, smooth membrane sacs with associated transport vesicles (also called shuttle vesicles)	Modifies, packages, and sorts newly synthesized proteins for secretion, inclusion in new plasma membrane, or lysosomal enzyme synthesis	

Table 2.2 **Components of the Cell** *(continued)*

Component	Structure	Function	Appearance
MEMBRANE-BOUND ORGANELLES *(CONTINUED)*			
Lysosomes	Membrane sacs with digestive enzymes	Digest materials or microbes ingested by the cell; remove old/damaged organelles; self-destruct (autolyze)	
Peroxisomes	Membrane-enclosed sacs; usually contain large amounts of specific enzymes to break down harmful substances	Convert hydrogen peroxide formed during metabolism to water	
Mitochondria	Double membrane structures with cristae; fluid matrix contents at center	Synthesize most ATP during cellular respiration; "powerhouses of cell"	
NON-MEMBRANE-BOUND ORGANELLES			
Ribosomes	Dense cytoplasmic granules with two subunits (large and small); may be free in cytoplasm (free ribosomes) or bound to rough ER (fixed ribosomes)	Synthesize proteins for: 1. use in the cell (free ribosomes) 2. secretion, incorporation into plasma membrane, or lysosomes (fixed ribosomes)	
Cytoskeleton	Organized network of protein filaments or hollow tubules throughout the cell	Provides structural support; facilitates cytoplasmic streaming, organelle and cellular motility, transport of materials, and chromosomal movement and cell division	
Microfilaments	Actin protein monomers formed into filaments	Maintain cell shape; aid in muscle contraction and intracellular movement; separate dividing cells	
Intermediate filaments	Various protein components	Provide structural support; stabilize cell junctions	
Microtubules	Hollow cylinders of tubulin protein; able to lengthen and shorten	Support cell; hold organelles in place; maintain cell shape and rigidity; direct organelle movement within cell and cell motility as cilia and flagella; move chromosomes at cell division	
Centrosome	Amorphous region adjacent to nucleus; contains a pair of centrioles	Organizes microtubules; participates in spindle formation during cell division	
Centrioles	Paired perpendicular cylindrical bodies; composed of microtubule triplets	Organize microtubules during cell division for movement of chromosomes	
Cilia	Short, membrane-attached projections containing microtubules; occur in large numbers on exposed membrane surfaces	Move fluid, mucus, and materials over the cell surface	
Flagellum	Long, singular membrane extension containing microtubules	Propels sperm cells in human male	
Microvilli	Numerous thin membrane folds projecting from the free cell surface	Increase membrane surface area for increased absorption and/or secretion	

2.3 Plasma Membrane

Learning Objectives:

1. Describe the structure of the plasma membrane.
2. Understand the functions of selective permeability.
3. Identify the specific types of passive and active transport.

The **plasma membrane,** or *cell membrane,* forms the thin outer border of the cell. Also sometimes called the *plasmalemma* (plaz-mă-lem′ă; *plasma* = something formed, *lemma* = husk), the plasma membrane is a flexible and fluid molecular layer that separates the internal (intracellular) components of a cell from the external environment and extracellular materials. All materials that enter or leave the cell must pass across the plasma membrane. Therefore, the plasma membrane is a vital, selectively permeable barrier that functions as a "gatekeeper" to regulate the passage of gases, nutrients, and wastes between the internal and external environments. Selective permeability (sometimes called semipermeability) is essential to a cell's existence because it allows the entrance or exit of substances to be regulated or restricted.

Necessarily, the total surface area of the membrane must be extensive enough to permit all of these movements. As the cell grows larger, the surface area of the plasma membrane increases by square units, whereas the volume of cytoplasm within the cell increases by cubic units. It is possible that a cell may reach a point when it does not have the necessary area of membrane surface required to transport all of the materials it needs to maintain life processes. Thus, most cells necessarily remain small to acquire sufficient nutrients and dispose of their wastes.

2.3a Composition and Structure of Membranes

A plasma membrane is not a rigid layer of molecules. Rather, a typical plasma membrane is a fluid matrix composed of an approximately equal mixture, by weight, of lipids and proteins. While the lipids form the main structure of the plasma membrane, the proteins dispersed within it determine its primary function(s). In addition, the plasma membrane has an external carbohydrate (sugar) coat, called the **glycocalyx** (glī-kō-kā′liks; *glykys* = sweet, *kalyx* = husk). The following discussion explains how these components form the plasma membrane.

Lipids

Lipids are materials that are insoluble in water; examples are fats and oils, as well as steroids. The insolubility of the lipids within the plasma membrane ensures that the membrane will not simply "dissolve" when it comes in contact with water. The three types of lipids in the plasma membrane are phospholipids, cholesterol, and glycolipids.

Phospholipids Most of the plasma membrane lipids are **phospholipids,** which contain both water-soluble and water-insoluble regions as well as the element phosphate. These molecules are called *polar,* meaning that a charge is distributed unevenly through the molecule so that one region has a positive charge and another region has a negative charge. Often these molecules are portrayed in the membrane as a balloon with two tails. The balloonlike, polar "head" is charged and hydrophilic ("water-loving," or attracted to water). The two "tails" are uncharged, nonpolar, and hydrophobic ("water-hating," or repelled by water). Because all phospholipid molecules have these two regions with different water association properties, they readily associate to form two parallel sheets of phospholipid molecules lying tail-to-tail. The hydrophobic tails form the internal environment of the membrane, and their polar heads are directed outward. This basic structure of the plasma membrane is called the **phospholipid bilayer** (figure 2.4). It ensures that **intracellular fluid (ICF)** (fluid within the cell) remains inside the cell, and **extracellular fluid (ECF)** (fluid outside the cell) remains outside. One type of ECF is **interstitial fluid,** the thin layer of fluid that bathes the external surface of a cell.

Cholesterol **Cholesterol,** a type of lipid called a steroid, amounts to about 20% of the plasma membrane lipids. Cholesterol is scattered within the hydrophobic regions of the phospholipid bilayer, where it strengthens the membrane and stabilizes it at temperature extremes.

Glycolipids **Glycolipids,** lipids with attached carbohydrate groups, form about 5% to 10% of the membrane lipids. They are located only on the outer layer of the membrane, where they are exposed to the extracellular fluid. The glycocalyx (the carbohydrate portion of the glycolipid molecule mentioned earlier) helps these molecules participate in cell–cell recognition, intracellular adhesion, and communication.

Proteins

The other common molecular structures within the plasma membrane are proteins. **Proteins** are complex, diverse molecules composed of chains of smaller molecules called *amino acids.* Proteins play various structural and functional roles within the cell and within the body. They make up about half of the plasma membrane by weight. Most of the membrane's specific functions are determined by its resident proteins. Plasma membrane proteins are of two types: integral and peripheral.

Integral proteins are embedded within, and extend across, the phospholipid bilayer. Some species of integral proteins act as membrane channels, providing a pore (hole) in the membrane through which specific substances pass. Other integral proteins, termed **receptors,** serve as binding sites for molecules outside of the cell. Hydrophobic regions within the integral proteins interact with the hydrophobic interior of the membrane. In contrast, the hydrophilic regions of the integral proteins are exposed to the aqueous environments on either side of the membrane.

Peripheral proteins are not embedded in the phospholipid bilayer. They are attached loosely to either the external or internal surface of the membrane, often to the exposed parts of the integral proteins. Peripheral proteins can "float" and move about the bilayer, much like a beach ball floating on the surface in a swimming pool.

Study Tip!

Think of the glycoproteins and glycolipids as similar to your student ID card. This personal identification item supplies information about you and lets the school know you are supposed to be there. If a person doesn't have a student ID card, he or she is not allowed access to certain school facilities. Similarly, the glycoprotein and glycolipid molecules allow other cells in the body to recognize this cell and not confuse it with a foreign substance that must be destroyed.

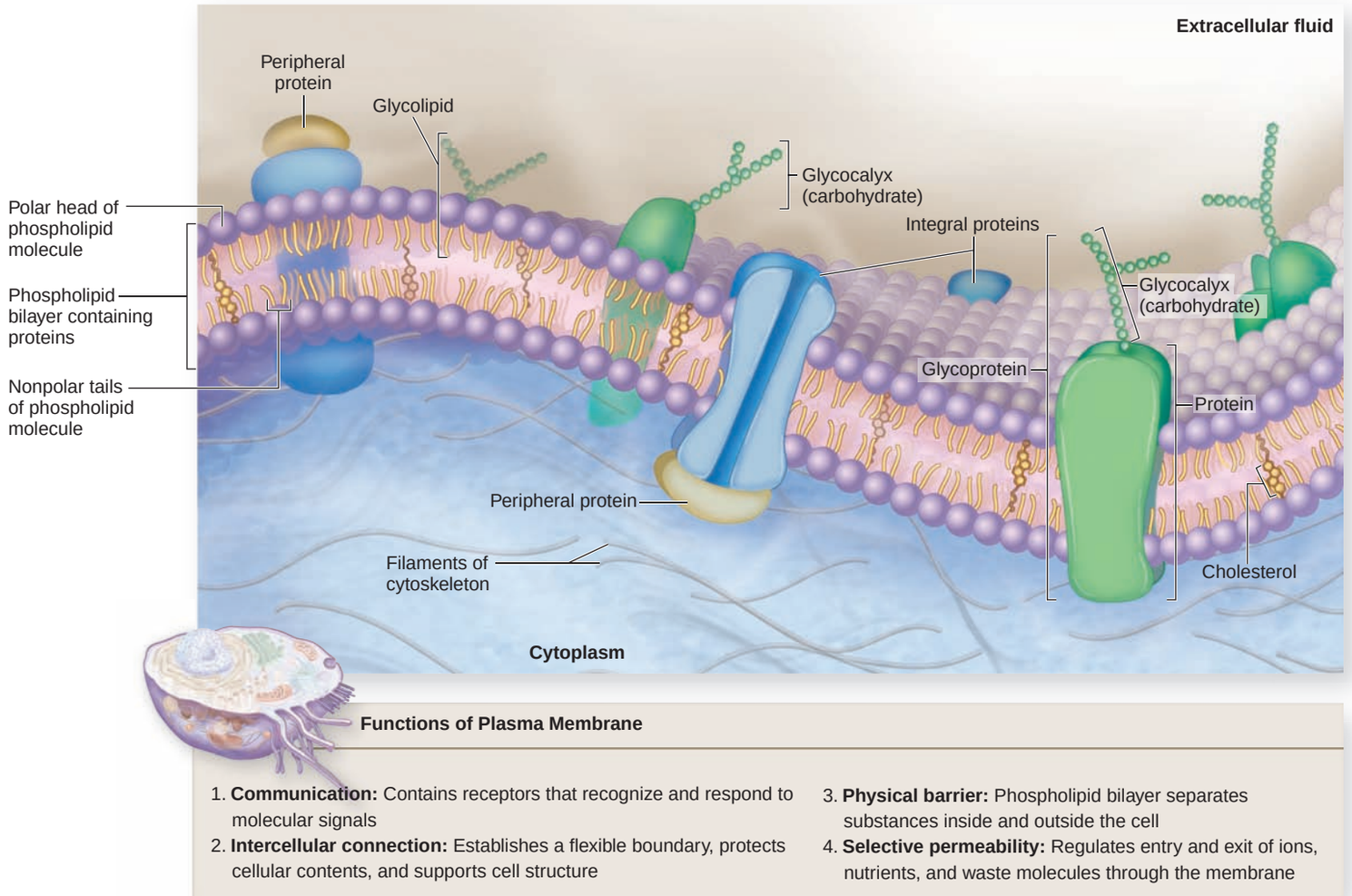


Figure 2.4

Structure of the Plasma Membrane. The plasma membrane is a phospholipid bilayer with cholesterol and proteins scattered throughout and associated with its surfaces. AP|R

Both integral and peripheral membrane proteins may serve as **enzymes,** which are also called catalysts. Enzymes are molecules that are important for functional or metabolic activities in the cell because they change the rate of a reaction without being affected by the reaction itself. An enzyme is the equivalent of an electric starter for a barbecue grill; the starter can repeatedly ignite the fire in the grill because it is unchanged by the fire itself.

Many integral membrane proteins are **glycoproteins** (proteins with attached carbohydrate groups). They form about 90% of all the membrane molecules that have carbohydrates attached to their external surface. Together, the carbohydrate groups attached to both glycoproteins and the previously mentioned glycolipids form the fuzzy glycocalyx on the external surface of the plasma membrane.

WHAT DO YOU THINK?

1. What is the benefit to the cell of having a plasma membrane that is selectively permeable? What are some disadvantages of having a selectively permeable plasma membrane?

2.3b Protein-Specific Functions of the Plasma Membrane

The proteins of the plasma membrane perform a variety of important activities that promote its overall functions, including the following:

- **Transport.** A transmembrane protein spans the plasma membrane completely. It has an internal hydrophobic region and hydrophilic regions at both the internal and external membrane surfaces. This protein assists the movement of a particular substance across the membrane. Sometimes the transport of material across the membrane requires cellular energy. A molecule called **ATP (adenosine triphosphate)** provides the energy for that transport. ATP releases energy when the bond that attaches its third phosphate to the rest of the molecule is broken.
- **Intercellular connection**. Junctions form between some neighboring cells when proteins in the membranes of each cell attach. These junctions secure the cells to each other.

- **Anchorage for the cytoskeleton.** Cell shape is maintained by the attachment of structural proteins inside the cell (the cytoskeleton) to membrane proteins.
- **Enzyme (catalytic) activity.** Some membrane proteins are catalysts that change the rates of some metabolic reactions. The plasma membrane in most cells contains enzymes that increase the rate of ion movement across the membrane. Examples of such catalytic proteins are ion pumps, described later in this chapter.
- **Cell–cell recognition.** The carbohydrate components of both glycoproteins and glycolipids usually act as identification molecules that are specifically recognized by other cells.
- **Signal transduction.** Signal transduction is the transmission of a message from a molecule outside the cell to the inside of the cell. The cell then responds by changing its internal activities.

2.3c Transport Across the Plasma Membrane

As we've just discussed, the plasma membrane is selectively permeable, so it is able to regulate transport of materials into and out of the cell. The following factors influence membrane permeability:

- **Transport proteins.** Special integral membrane proteins attract specific molecules in both the internal and external environments of the cell and assist their transport across the membrane. For example, some transport proteins (also called *carrier proteins*) bind to specific carbohydrates and help them move across the membrane.
- **Plasma membrane structure.** Differences in the membrane phospholipids (both in the composition of the polar head and the length and composition of the tails) affect the ability of some molecules to cross that membrane. For example, because polar molecules such as water are small and able to interact with the phospholipids in the bilayer, they can pass through the phospholipid bilayer rapidly, while other polar molecules, such as simple sugars, cannot pass through the bilayer.
- **Concentration gradient.** Materials tend to move more rapidly when their concentrations are significantly different between two compartments. For example, if the intracellular fluid had a low concentration of a permeable substance, and the extracellular fluid had a high concentration of that substance, this substance would more easily pass through the membrane into the cell (where its original concentration was lower).
- **Ionic charge.** An **ion** (atom with a net negative or positive charge) may either be repulsed or attracted to the membrane structures. This ionic charge influences molecular movement across the membrane. For example, if the inside of the cell has a net negative charge, a negative ion outside the membrane might be repelled by the intracellular environment, whereas a positive ion might be attracted to the intracellular environment.
- **Lipid solubility.** Materials that are lipid-soluble easily dissolve through the phospholipid bilayer. Thus, lipid-soluble molecules can pass through the membrane more easily than non-lipid-soluble molecules can. For example, small nonpolar molecules called fatty acids readily move through the hydrophobic interior of the phospholipid bilayer and enter the cytoplasm of the cell, whereas larger, charged polar molecules, such as simple sugars or amino acids, are prevented from moving through the hydrophobic region of the plasma membrane.
- **Molecular size.** Smaller molecules move across the plasma membrane readily, while larger molecules need special transport systems to move them across the membrane. For example, some small molecules and ions move continuously across the plasma membrane by passing between the molecules that form the fabric of the membrane.

Passive Transport

The processes of transporting substances across plasma membranes are classified as either passive or active. In **passive transport,** substances move across a plasma membrane without the expenditure of energy by the cell. Materials move along a concentration gradient, meaning that they flow from a region of higher concentration of the material to a region of lower concentration. Passive transport is similar to floating downstream with the current; no cellular energy (ATP) is needed for it to occur. Passive processes that move material across the plasma membrane include simple diffusion, osmosis, facilitated diffusion, and bulk filtration.

Simple Diffusion **Diffusion** (di-fū′zhun; *diffundo* = to pour in different directions) is the tendency of molecules to move down their concentration gradient; that is, the molecules move from a region of higher concentration to a region of lower concentration. This movement continues until the molecules are spread out evenly into the available space on each side of the membrane, at which point the concentration of this molecule is said to be at **equilibrium.**

Simple diffusion occurs when substances move across membranes unaided because they are either small or nonpolar, or because they are both. As a result of simple diffusion, a **net movement** of specific molecules or ions takes place from a region of their higher concentration to a region of their lower concentration. This net movement continues until all of those molecules are evenly distributed in the environment (the point of equilibrium). At this point, the concentration gradient no longer exists. However, molecular movement does not cease. Those molecules still move continuously in all directions at an equal rate. For example, there is no net movement of molecule "A" during its equilibrium, which means that one molecule "A" enters the cell for every molecule "A" that leaves the cell. An example of diffusion in the body is the movement of respiratory gases between the air sacs in the lungs and the blood vessels in the lungs. Oxygen continually moves from the lung air sacs into the blood, while carbon dioxide moves in the opposite direction. This movement guarantees that the blood will receive oxygen and eliminate carbon dioxide as part of normal respiration. The process of simple diffusion can occur without the presence of a membrane. Thus, it also occurs within the cell to distribute substances throughout the cytoplasm. AP|R

Osmosis **Osmosis** (os-mō′sis; *osmos* = a thrusting) is a special type of simple diffusion in which water diffuses from one side of the selectively permeable membrane to the other. The net movement of

water across a semipermeable membrane continues from a region of high water concentration to a region of low water concentration until equilibrium is established. In the body, the movement of water between the blood and the extracellular fluid around cells occurs by osmosis. AP|R

Facilitated Diffusion **Facilitated diffusion** requires the participation of specific transport proteins that help specific substances move across the plasma membrane. These substances are either large molecules or molecules that are insoluble in lipids. The molecule to be moved binds to the transport protein in the membrane. This binding helps alter the shape of both the transport protein and the molecule to be moved, thus permitting it to pass across the membrane. For example, glucose and some amino acids move across the membrane by this means. Facilitated diffusion differs from simple diffusion in that a specific transport protein is required. Thus, transport is aided by a protein. AP|R

Bulk Filtration **Bulk filtration,** or *bulk movement,* involves the diffusion of solvents and solutes together across the selectively permeable membrane. **Solvents** are liquids that have substances called **solutes** dissolved in them. For example, water can be a solvent if it has a solute such as salt or sugar dissolved in it. An example of bulk filtration is when fluid and certain solutes are transported from the blood into the extracellular fluid. Bulk filtration works in this way: **Hydrostatic pressure** (hī-drō-stat′ik presh′ŭr) (fluid pressure exerted by blood pushing against the inside wall of a blood vessel) forces both water and small solutes from the blood across the plasma membranes of cells lining the capillaries (the smallest type of blood vessel). Only smaller molecules (glucose) and ions (such as sodium [Na^+] and potassium [K^+]) can be forced across the membrane by hydrostatic pressure. The largest molecules (called *macromolecules*) and large solid particles in the solvent must be transported through the membrane by another process, which we examine next.

Active Transport

Active transport is the movement of a substance across a plasma membrane *against* a concentration gradient, so materials must be moved from an area of low concentration to an area of high concentration. Active transport is similar to swimming upstream against a current, where you must exert energy (swim) to move against the water flow. To move materials against their concentration gradient, active transport requires cellular energy in the form of ATP (adenosine triphosphate) and sometimes a transport protein as well. ATP is continually synthesized by mitochondria, cell structures described later in this chapter. Active transport methods include ion pumps and several processes collectively known as bulk transport.

Ion Pumps Active transport processes that move ions across the membrane are called **ion pumps.** Ion pumps are a major factor in a cell's ability to maintain its internal concentrations of ions. One type of ion pump is the **sodium-potassium pump.** This transport mechanism is specifically called an exchange pump, because it moves one ion into the cell while simultaneously removing another type of ion from the cell **(figure 2.5)**. For example, compared to their surroundings, some human cells have much higher concentrations of potassium ions and much lower concentrations of sodium ions. The plasma membrane maintains these steep concentration gradient differences by continuously removing sodium ions from the cell and moving potassium ions into the cell. Figure 2.5 shows the steps in this process. The cell must expend energy in the form of ATP to maintain these sodium and potassium levels.

Bulk Transport Macromolecules, such as large proteins and polysaccharides, cannot move across the plasma membrane via ion pumps or even with the assistance of normal transport proteins. Instead, larger molecules or bulk structures move across the membrane via the active transport processes called exocytosis and endocytosis.

In **exocytosis** (ek′sō-sī-tō′sis; *exo* = outside, *kytos* = cell, *osis* = condition of), large molecules are secreted *from* the cell **(figure 2.6)**. Typically, the material for secretion is packaged within intracellular transport **vesicles** (ves′i-kl; *vesica* = bladder), which move toward the plasma membrane. When the vesicle and plasma membrane come into contact, the lipid molecules of the vesicle and plasma membrane bilayers rearrange themselves so that the two membranes fuse. The fusion of these lipid bilayers requires the cell to expend energy in the form of ATP. Following fusion, the vesicle contents are released to the outside of the cell. An example of this process occurs in the pancreas, where cells release digestive enzymes into a pancreatic duct for transport to the small intestine.

CLINICAL VIEW

Cystic Fibrosis and Chloride Channels

The inherited disease cystic fibrosis (CF) involves defective plasma membrane proteins that affect chloride ion (Cl^-) channels in the membrane. These channels are transport proteins that use facilitated diffusion to move chloride ions across the plasma membrane. The genetic defect that causes CF results in the formation of abnormal chloride channel proteins in the membranes of cells lining the respiratory passageways and ducts in glands, such as the pancreas. The primary defect in these chloride channels results in an abnormal flow of chloride ions across the membrane, causing salt to be trapped within the cytoplasm of affected cells. Ultimately, the normal osmotic flow of water across the plasma membrane breaks down. The concentration of salt within the cytoplasm of these cells causes an increase in the osmotic flow of water into the cell, thereby resulting in thickening of the mucus in the respiratory passageways and the pancreatic ducts. The aggregation of thickened mucus plugs the airways of the lungs, leading to breathing problems and increasing the risk of infection. Therefore, a single genetic and biochemical defect in a transport protein produces significant health problems.

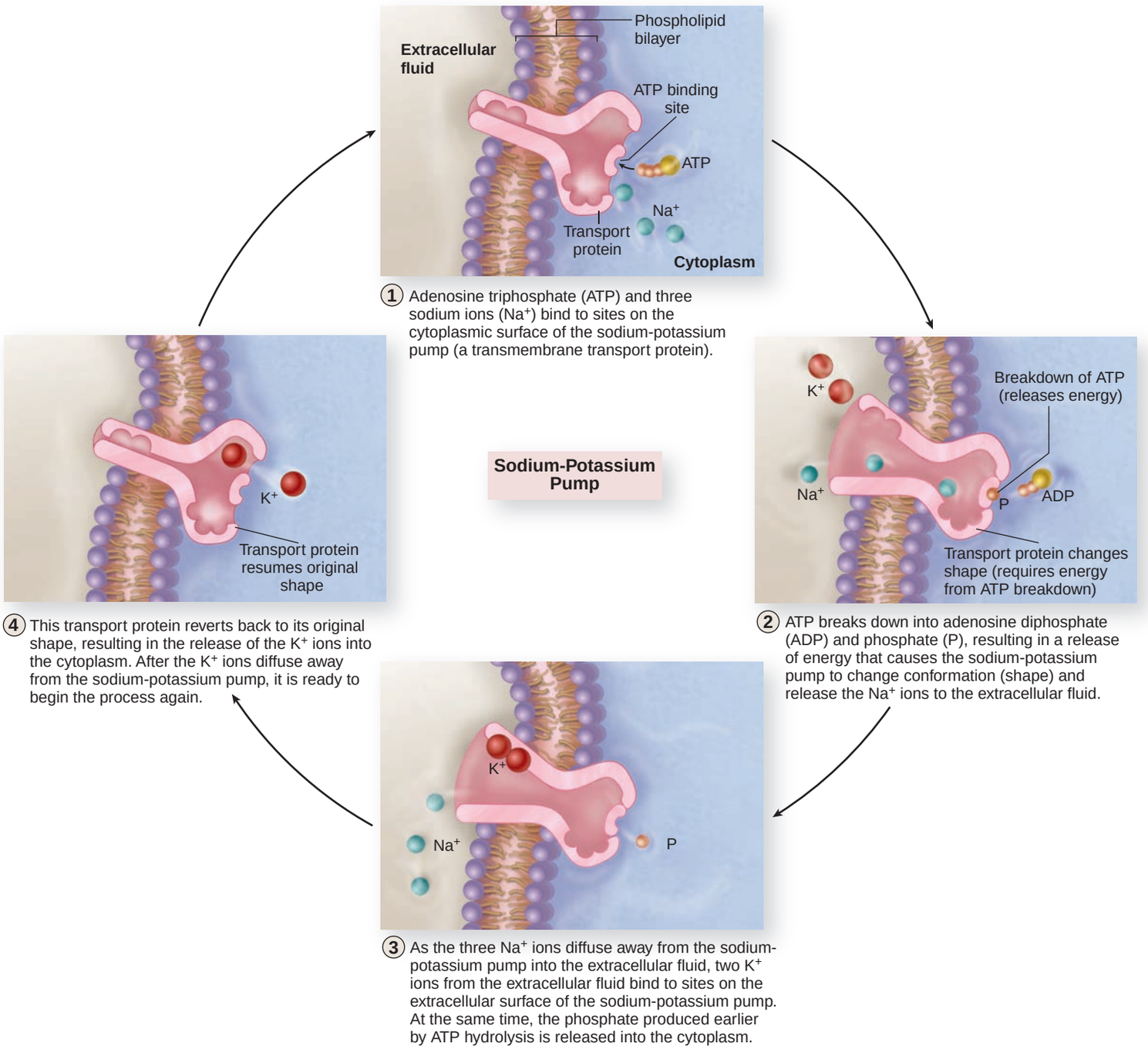
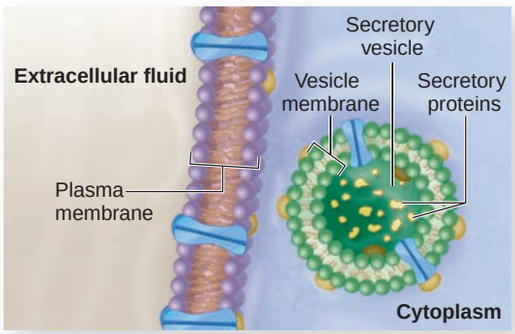


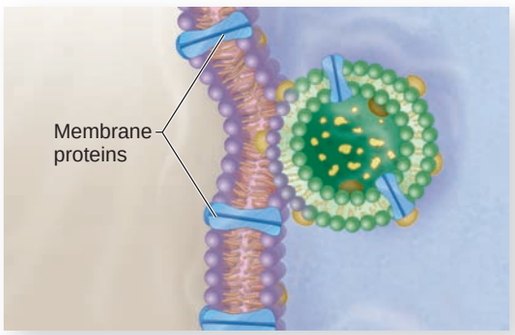
Figure 2.5

Sodium-Potassium Pump. A sodium-potassium pump has a transmembrane transport protein that uses energy to transport Na^+ and K^+ ions through the membrane from a region of low concentration to a region of high concentration. This continuous, active transport process can be broken down into four steps. AP|R

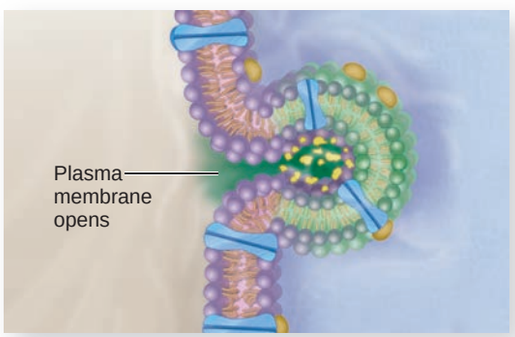
By contrast, large particulate substances and macromolecules are taken *into* the cell via **endocytosis** (en′dō-sī-tō′sis; *endon* = within). The steps of endocytosis are similar to those of exocytosis, only in reverse. In endocytosis, extracellular macromolecules and large particulate matter are packaged in a vesicle that forms at the cell surface for internalization into the cell. A small area of plasma membrane folds inward to form a pocket, or **invagination** (in-vaj′i-nā-shun; *in* = in, *vagina* = a sheath), which deepens and pinches off as the lipid bilayer fuses. This fusion of the lipid bilayer is the energy-expending step. A new intracellular vesicle is formed containing material that was formerly outside the cell. There are three types of endocytosis: phagocytosis, pinocytosis, and receptor-mediated endocytosis **(figure 2.7)**.



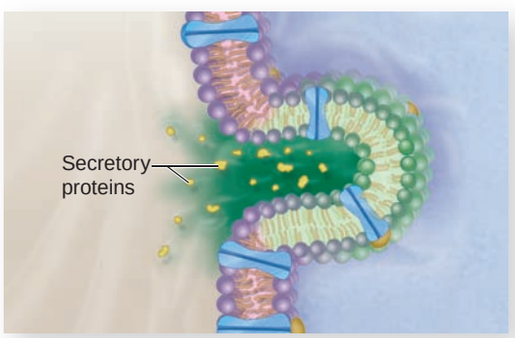
1 Vesicle nears plasma membrane



2 Fusion of vesicle membrane with plasma membrane



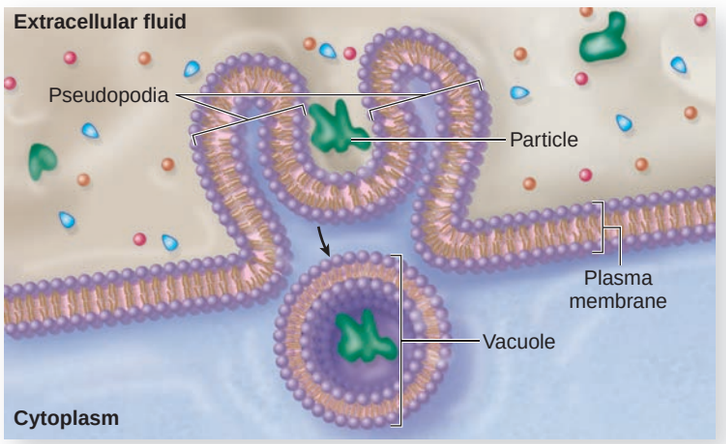
3 Exocytosis as plasma membrane opens externally



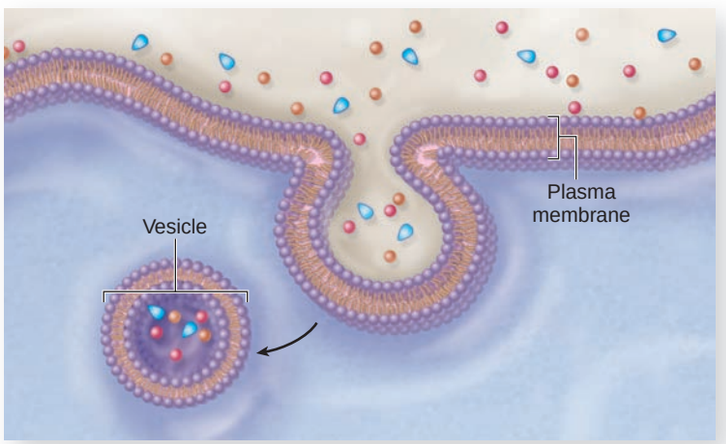
4 Release of vesicle components into the extracellular fluid and integration of vesicle membrane components into the plasma membrane

Figure 2.6

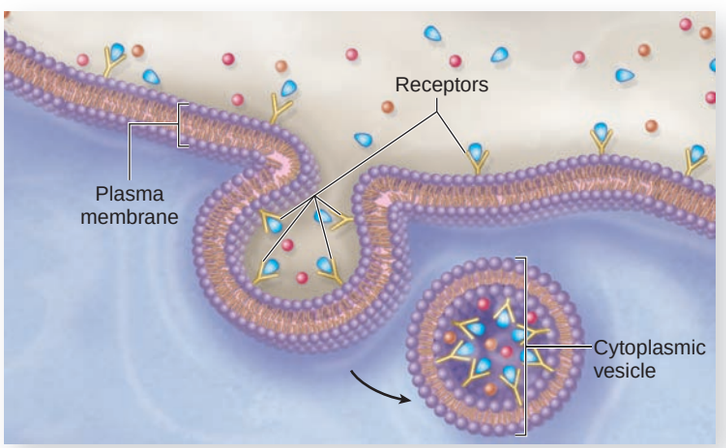
Exocytosis. In exocytosis, the cell secretes bulk volumes of materials into the extracellular fluid.



(a) Phagocytosis



(b) Pinocytosis



(c) Receptor-mediated endocytosis

Figure 2.7

Three Forms of Endocytosis. Endocytosis is a process whereby the cell acquires materials from the extracellular fluid. (*a*) Phagocytosis occurs when membrane extensions, termed pseudopodia, engulf a particle and internalize it into a vacuole. (*b*) Pinocytosis is the incorporation of droplets of extracellular fluid into the cell via the formation of small vesicles. (*c*) In receptor-mediated endocytosis, receptors with specific molecules bound to them aggregate within the membrane, and then an invagination forms around them to create a cytoplasmic vesicle.

Phagocytosis (fag′ō-sī-tō′sis; *phago* = to eat, *kytos* = cell, *osis* = condition) means "cellular eating." It is a nonspecific process that occurs when a cell engulfs or captures a large particle external to the cell by forming membrane extensions, called **pseudopodia** (sing., *pseudopodium*; soo-dō-pō′dē-ūm, -pō′dē-ă; *pous* = foot), or *false feet,* to surround the particle (figure 2.7*a*). Once the particle is engulfed by the pseudopodia, it is packaged within an enclosed membrane sac. If large enough, this sac is classified as a **vacuole** (vak′oo-ōl; *vacuum* = an empty space). The contents of the vacuole are broken down chemically (digested) after it fuses with a *lysosome* (lī′sō-sōm; *lysis* = a loosening, *soma* = body), which contains specific digestive enzymes that split large molecules into smaller ones. Only a few types of cells are able to perform phagocytosis. For example, phagocytosis occurs regularly when a white blood cell engulfs and digests a bacterium.

Pinocytosis (pin′ō-sī-tō′sis [or pī′nō-]; *pineo* = to drink, *kytos* = cell, *osis* = condition) is known as "cellular drinking." This process occurs when the cell internalizes a very small droplet of extracellular fluid into tiny internal vesicles (figure 2.7*b*). This process is nonspecific because all solutes dissolved in the droplet are taken into the cell. Most cells perform this type of transport across the membrane. Pinocytosis is similar to bulk filtration in that both types of transport move similar materials. However, it differs from bulk filtration because pinocytosis moves materials against a concentration gradient. An example of pinocytosis occurs within cells that form a capillary (tiny blood vessel) wall, where vesicles fill with a fluid droplet containing small solutes from the blood, carry this droplet to the other side of the cell, and then expel its contents outside the capillary wall.

Receptor-mediated endocytosis is the movement of specific molecules from the extracellular environment into a cell by way of a newly formed vesicle. This process begins when molecules in the extracellular fluid bind to their specific integral membrane protein receptors. (Recall that a membrane receptor is a protein that acts as a binding site for molecules outside the cell.) This process is different from the nonspecific transport mechanisms discussed earlier. It is considered a specific mechanism because the endocytosis is stimulated by the binding of the specific molecules to their specific membrane receptors. The receptor proteins then cluster in one region of the membrane to begin the process of endocytosis. The plasma membrane housing the bound specific molecules from the extracellular fluid folds inward to form a pocket, or invagination (figure 2.7*c*). This membrane pocket deepens and pinches off as the lipid bilayers fuse. The fusion of these lipid bilayers requires the cell to expend energy in the form of ATP. An example of receptor-mediated endocytosis occurs when human cells contain receptors that bind to and internalize cholesterol, which is required for new membrane synthesis. Cholesterol travels in our blood bound to proteins called low-density lipoproteins (LDLs). LDL particles bind to LDL receptors in the membrane. Receptor-mediated endocytosis enables the cell to obtain bulk quantities of specific substances, even though those substances may not be very concentrated in the extracellular fluid.

Table 2.3 summarizes passive and active transport mechanisms. AP|R

WHAT DID YOU LEARN?

4. What types of lipids are found in the plasma membrane?
5. In general, what materials may cross a selectively permeable membrane?
6. What is diffusion?
7. Describe the process of osmosis.
8. Discuss the similarities between facilitated diffusion and receptor-mediated endocytosis.

2.4 Cytoplasm

Learning Objectives:

1. **Identify the characteristics of the three parts of a cell's cytoplasm.**
2. **Describe the structures and functions of cellular organelles.**

Cytoplasm is a nonspecific term for all of the materials contained within the plasma membrane and surrounding the nucleus. The cytoplasm includes three separate parts: cytosol, inclusions, and organelles (except the nucleus).

2.4a Cytosol

The **cytosol** (sī′tō-sol; *kytos* = cell, *sol* = abbrev. of soluble), also called the *cytoplasmic matrix* or *intracellular fluid*, is the viscous, syruplike fluid of the cytoplasm. It has a high water content and contains many dissolved solutes, including ions, nutrients, proteins, carbohydrates, lipids, and other small molecules. Many cytoplasmic proteins are the enzymes that act as catalysts in cellular reactions. The cytosol's carbohydrates and lipids serve as an energy source for the cell. Many of the small molecules in the cytosol are the building blocks of large macromolecules. For example, amino acids are small molecules dissolved in the cytosol that the cell uses to synthesize new proteins.

2.4b Inclusions

The cytosol of some cells contains **inclusions,** a large and diverse group of chemical substances that these cells store temporarily. Most inclusions are not bound by a membrane. Cellular inclusions include pigments, such as melanin; protein crystals; and nutrient stores, such as glycogen and triglycerides. **Melanin** (mel′ă-nin; *melas* = black), a stored pigment in some skin, hair, and eye cells, protects the body from the sun's ultraviolet light. **Glycogen** is a polysaccharide (a type of carbohydrate [sugar]) that is stored primarily in liver and skeletal muscle cells.

2.4c Organelles

Organelles (or′gă-nel; *organon* = organ, *elle* = the diminutive suffix), meaning "little organs," are complex, organized structures with unique, characteristic shapes. Each type of organelle performs a different function for the cell. Collectively, the specialized functions of all organelles are essential for normal cellular structure and activities. These unique structures permit the cell to carry on different activities simultaneously. This division of labor prevents interference between cellular activities and promotes maximal functional efficiency in the cell. Organelles assume specific roles

Table 2.3 Transport Processes Across a Plasma Membrane

Process	Type of Movement	Energy Source	Example
PASSIVE TRANSPORT	Movement of substance *along* a concentration gradient; ATP not required		
Simple diffusion	Unaided net movement of a substance due to molecular motion down its concentration gradient across selectively permeable membrane; continues until equilibrium is reached	Molecular movement	Exchange of oxygen and carbon dioxide between blood and body tissues
Osmosis	Diffusion of water across a selectively permeable membrane; direction is determined by relative solute concentrations; continues until equilibrium is reached	Molecular movement	Water in small kidney tubules moves across a cell barrier back into the blood from the tubular fluid that eventually forms urine
Facilitated diffusion	Movement of materials too large to pass through membrane channels; relies on transport proteins	Molecular movement requiring carrier assistance by a transport protein	Transport of glucose into cells
Bulk filtration	Bulk movement of solvents and solutes from an area of high concentration to an area of low concentration as a result of hydrostatic pressure differences across the membrane	Hydrostatic pressure	Transport of nutrients and fluids from the blood into body tissues
ACTIVE TRANSPORT	Movement of substances *against* a concentration gradient; requires ATP; requires assistance to move across the membrane, often by a transport protein and sometimes by bulk movement in vesicles.		
Ion pumps	Transport of ions across the membrane against a concentration gradient by transmembrane protein pumps	ATP	Sodium-potassium exchange pump
Bulk transport	Membrane vesicles form around materials for transport	ATP	
Exocytosis	Bulk movement of substances *out* of the cell by fusion of secretory vesicles with the plasma membrane	ATP	Release of digestive enzymes by pancreatic cells
Endocytosis	Bulk movement of substances *into* a cell by vesicles forming at the plasma membrane	ATP	
Phagocytosis	Type of endocytosis in which particulate materials move into a cell after being engulfed by pseudopodia at the cell surface; vesicles form at the inside of the plasma membrane; large sacs are called vacuoles	ATP	White blood cell engulfing a bacterium
Pinocytosis	Type of endocytosis in which plasma membrane folds inward to capture extracellular fluid droplet and its dissolved contents, forming a small new vesicle inside the cell	ATP	Formation of small vesicles in capillary wall to move fluid and small particulate materials out of the blood
Receptor-mediated endocytosis	Type of endocytosis in which specific molecule-receptor complexes in the plasma membrane stimulate the clustering of bound molecule-receptor complexes; vesicles containing specific molecules bound to receptors in the membrane stimulate internalization of the bound molecules	ATP	Uptake of cholesterol into cells

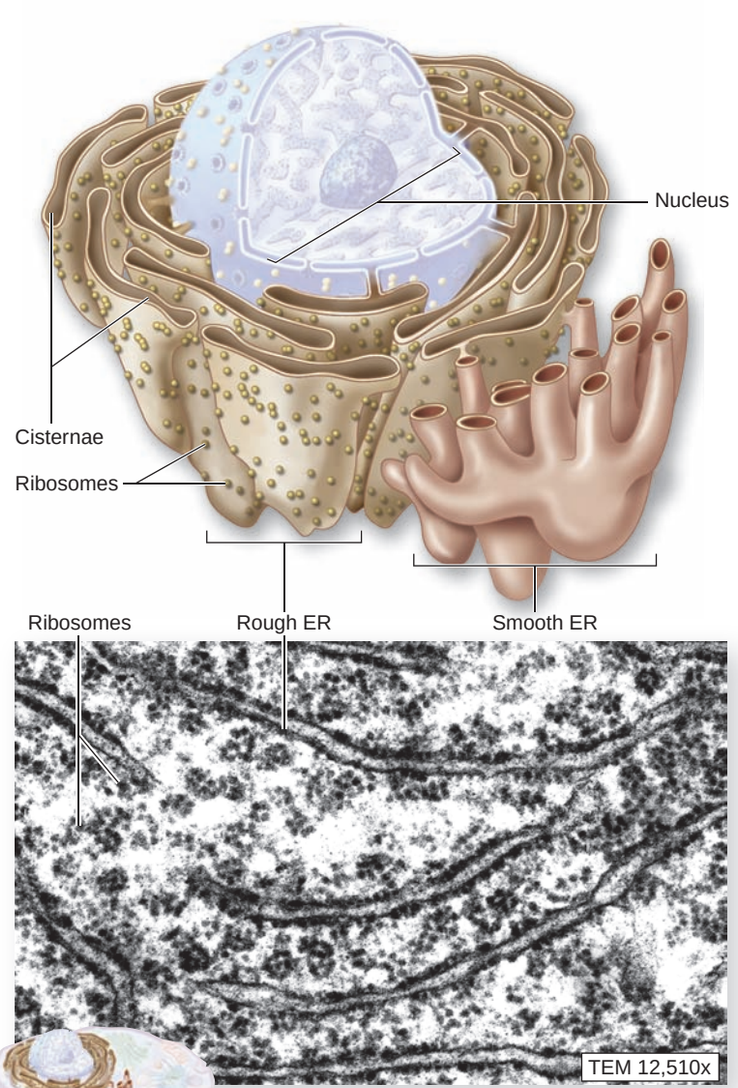
in growth, repair, and cellular maintenance. The distribution and numbers of different types of organelles are determined by organelle function and vary among cells, depending upon the needs of the cells. Two categories of organelles are recognized: membrane-bound organelles and non-membrane-bound organelles.

Membrane-Bound Organelles

Some organelles are surrounded by a membrane and thus are called **membrane-bound organelles,** or *membranous organelles*. This membrane is similar to the plasma membrane surrounding the cell in that it is composed of a phospholipid bilayer with diverse associated proteins. Note that every membrane exhibits a unique protein-lipid composition, which confers a unique function(s) to that membrane. The membrane separates the organelle's contents from the cytosol so that the activities of the organelle can proceed without disrupting other cellular activities. Membrane-bound organelles include the endoplasmic reticulum, the Golgi apparatus, lysosomes, peroxisomes, and mitochondria.

Endoplasmic Reticulum The **endoplasmic reticulum** (re-tik′ū-lum; *rete* = net) **(ER)** is an extensive intracellular membrane network throughout the cytoplasm. ER is composed of two distinct regions that differ in structure and function: smooth endoplasmic reticulum (smooth ER, or SER) and rough endoplasmic reticulum (rough ER, or RER; **figure 2.8**). The amount of either kind of ER varies, depending on the specific functions of the cell.

Smooth ER is continuous with the rough ER. Because no ribosomes are attached to the smooth ER membranes, the walls have a smoother appearance than those of rough ER. Smooth ER resembles multiple interconnected branches of tubules. The smooth ER of



Functions of Endoplasmic Reticulum

1. **Synthesis:** Provides a place for chemical reactions
   a. Smooth ER is the site of lipid synthesis and carbohydrate metabolism
   b. Rough ER synthesizes proteins for secretion, incorporation into the plasma membrane, and as enzymes within lysosomes
2. **Transport:** Moves molecules through cisternal space from one part of the cell to another; sequestered away from the cytoplasm
3. **Storage:** Stores newly synthesized molecules
4. **Detoxification:** Smooth ER detoxifies both drugs and alcohol

Figure 2.8

Endoplasmic Reticulum (ER). A drawing and TEM show that the ER is a membranous network of flattened membrane sacs (cisternae) and interconnected tubules that is continuous with the nuclear envelope. Smooth ER, which is not shown on this TEM, consists of even-surfaced, interconnected tubules, and it lacks associated ribosomes. Rough ER, by contrast, is composed of cisternal membranes with ribosomes attached to their cytoplasmic surfaces. However, the two types of ER are continuous.

various cell types functions in diverse metabolic processes, including synthesis, transport, and storage of lipids; metabolism of carbohydrates; and detoxification of drugs, alcohol, and poisons. The amount of smooth ER is greater in cells that synthesize steroid hormones. In addition, the liver contains abundant amounts of smooth ER to process digested nutrients and detoxify drugs and alcohol.

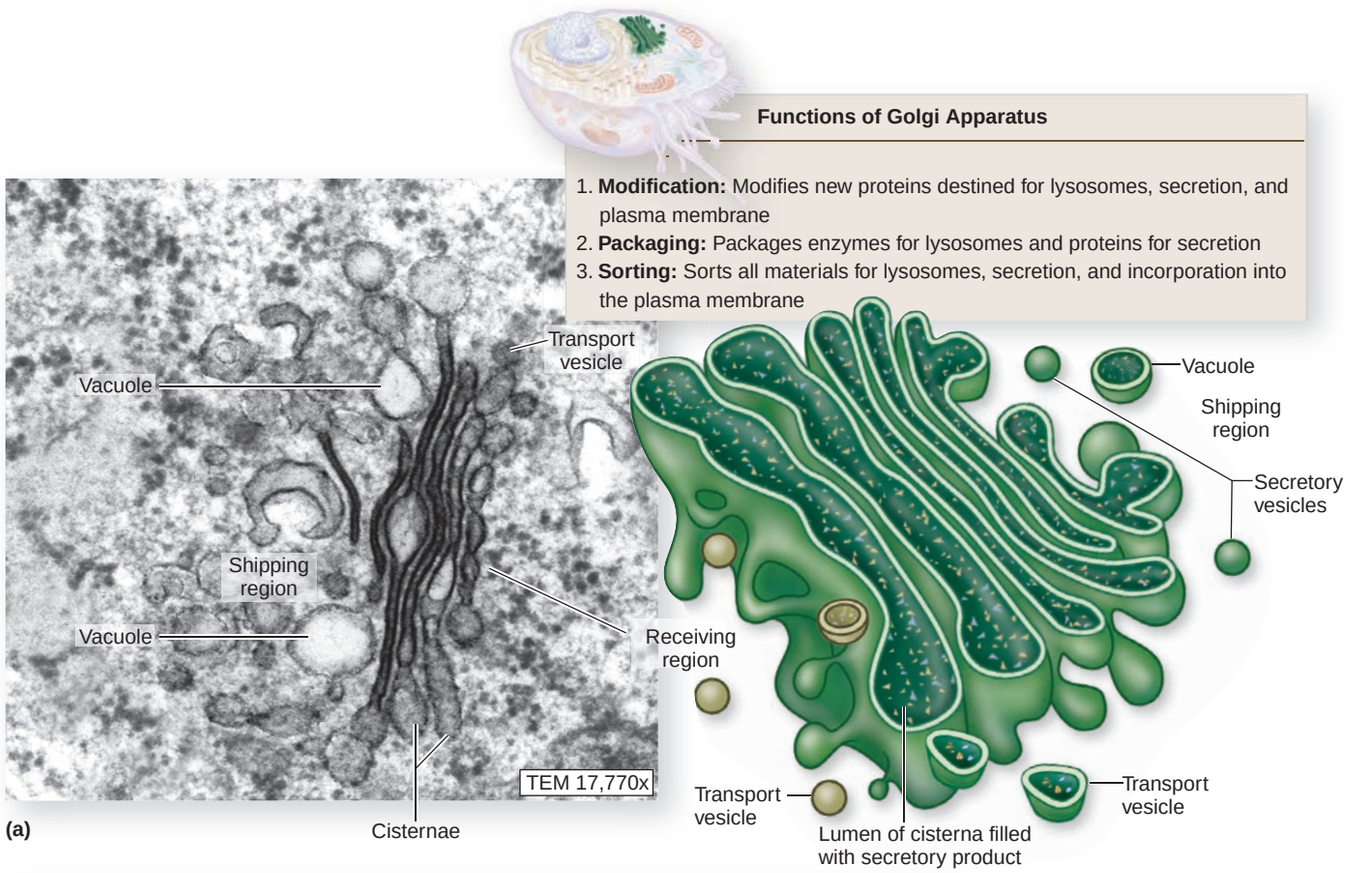
Rough ER is responsible for producing, transporting, and storing proteins to be exported outside the cell, proteins to be incorporated into the plasma membrane, and enzymes that are housed within lysosomes. Rough ER consists of profiles of parallel membranes enclosing spaces called **cisternae** (sis′tern-ā; *cisterna* = cistern). Ribosomes are the small structures attached to the cytoplasmic sides (called faces) of these membranes. These ribosomes are called fixed ribosomes because they are attached to the membrane surface of the ER, thus forming the rough ER. These ribosomes synthesize the proteins targeted for cell export, insertion into the plasma membrane, or inclusion within a lysosome as a catalyst. As new proteins are synthesized by the fixed ribosomes, they pass through the membrane of the rough ER and enter its cisternae, where their original structure changes by either adding other molecules or removing part of what was originally synthesized. These modified proteins are packaged into small, enclosed membrane sacs that pinch off from the ER. These sacs, termed **transport vesicles,** shuttle proteins from the rough ER to another organelle, the Golgi apparatus (discussed later) for further modification. For a seamless interaction and transition between organelles, transport vesicles, and the plasma membrane, the membranes of each structure have the same general lipid and protein composition and organization. However, as mentioned earlier, the molecules within these membranes also have some unique characteristics that are associated with the specific function(s) of each structure. The amount of rough ER is greater in cells producing large amounts of protein for secretion, such as a cell in the pancreas that secretes enzymes for digesting materials in the small intestine.

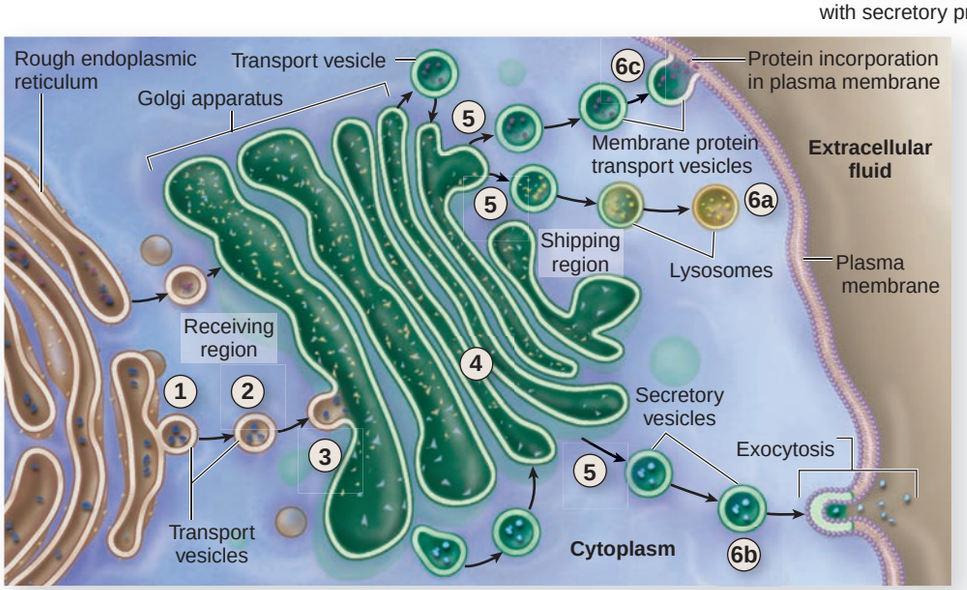
Golgi Apparatus The **Golgi apparatus,** also called the *Golgi complex,* is a center for modifying, packaging, and sorting materials that arrive from the RER in transport vesicles. The Golgi apparatus is especially extensive and active in cells specialized for secretion.

The Golgi apparatus is composed primarily of a series of cisternae, which are arranged in a stack **(figure 2.9*a*)**. The edges of each sac bulge, and many small transport vesicles are clustered around the expanded edges of the individual sacs. The vesicles concentrated at the periphery of the Golgi apparatus are active in transporting and transferring material between the individual sacs of the Golgi apparatus as well as between the Golgi apparatus and other cellular structures.

The Golgi apparatus exhibits a distinct polarity: The membranes of the cisternae at opposite ends of a stack differ in thickness and molecular composition. These two poles of the Golgi apparatus are called the **receiving region** (or *cis*-face) and the **shipping region** (or *trans*-face), respectively. The diameter of the flattened sac is larger in the receiving region than in the shipping region. The products of the rough ER move through the Golgi apparatus via transport vesicles, going from the receiving region to the shipping region. Normally, materials move through the Golgi apparatus as shown in figure 2.9*b* and described here:

1. Newly synthesized proteins in the rough ER cisternae are sequestered into a transport vesicle.
2. The vesicle pinches off the ER and travels to the Golgi apparatus.





1. RER proteins in transport vesicle
2. Vesicle from RER moves to Golgi apparatus
3. Vesicle fuses with Golgi apparatus receiving region
4. Proteins are modified as they move through Golgi apparatus
5. Modified proteins are packaged in shipping region
6. Vesicles become either (a) lysosomes, (b) secretory vesicles that undergo exocytosis, or (c) plasma membrane

Figure 2.9

Golgi Apparatus. Each Golgi apparatus is composed of several flattened membrane sacs (cisternae), with some associated transport vesicles at the periphery of these sacs. The arrangement of sacs exhibits both structural and functional polarity. (*a*) A TEM and a drawing provide different views of the Golgi apparatus along with a list of its functions. (*b*) The receiving region receives incoming transport vesicles from the rough ER; large vesicles carrying finished product exit the shipping region.

3. Newly arrived transport vesicles fuse with the receiving region of the Golgi apparatus.
4. Protein modification occurs as the proteins are moved by transport vesicles sequentially through the Golgi apparatus cisternae from the receiving region to the shipping region.
5. Modified proteins are packaged in secretory vesicles.
6. Vesicles leaving the shipping region become (a) lysosomes, which contain proteins called digestive enzymes, (b) secretory vesicles that undergo exocytosis, or (c) new parts of the plasma membrane.

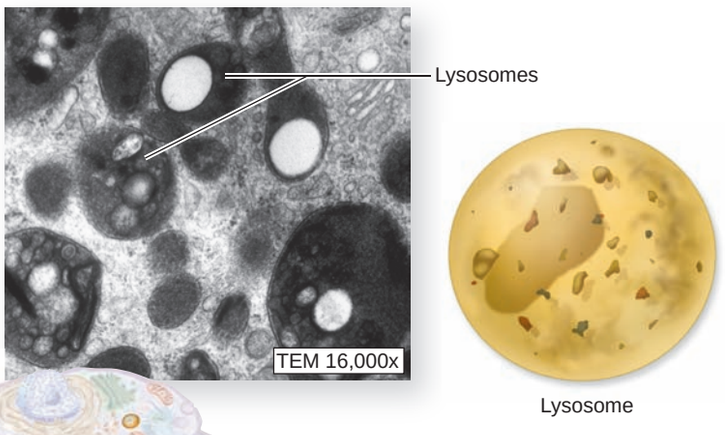


Figure 2.10

Lysosomes. A drawing and TEM show lysosomes, which are membrane-bound, spherical sacs in the cytoplasm of a cell. Lysosomes house enzymes for intracellular digestion, as well as performing the other functions listed here. AP|R

Lysosomes **Lysosomes** (lī′sō-sōm; *lysis* = a loosening, *soma* = body) are membrane sacs formed by the Golgi apparatus **(figure 2.10)**. Lysosomes contain enzymes used by the cell to digest waste products and ingested macromolecules. These enzymes break down large molecules, such as proteins, fats, polysaccharides, and nucleic acids, into smaller molecules. Lysosomes are sometimes referred to as the "garbagemen" of the cell because they digest and remove waste products.

Some substances digested by lysosomal enzymes enter the cell by endocytosis. Lysosomes fuse with internalized endocytic vesicles, and their enzymes combine with the internalized materials. The products resulting from these digestive activities are released from the lysosome into the cytosol, where they are recycled for various future uses. For example, a large protein is broken down into its component amino acids, which may be used to synthesize a new, different protein needed by that cell.

Lysosomes also remove the cell's damaged parts. An internal membrane encloses these damaged structures, and then it fuses with the lysosomes. Thus, old organelles are removed via a process called **autophagy** (aw-tōf′ă-jē; *autos* = self, *phago* = to eat). When a cell is damaged or dies, enzymes from all lysosomes are eventually released into the cell, resulting in the rapid digestion of the cell itself. This process is called **autolysis** (aw-tol′i-sis; *autos* = self, *lysis* = dissolution).

WHAT DO YOU THINK?

2. What would happen to a cell if it didn't contain any lysosomes (or if its lysosomes weren't functioning)? Would the cell be able to survive?

CLINICAL VIEW

Tay-Sachs Disease

Tay-Sachs is a "lysosomal storage disease" that results in the buildup of fatty material in nerve cells. Healthy, properly functioning lysosomes are essential for the health of the cells and the whole body. Tay-Sachs disease occurs because one of the more than 40 different lysosomal enzymes is missing or nonfunctional. Lysosomes in affected individuals lack an enzyme that is needed to break down a complex membrane lipid. As a result, the complex lipid accumulates within cells. The cellular signs of Tay-Sachs disease are swollen lysosomes due to accumulation of the complex lipid that cannot be digested. Affected infants appear normal at birth, but begin to show signs of the disease by the age of 6 months. The nervous system bears the brunt of the damage. Paralysis, blindness, and deafness typically develop over a period of one or two years, followed by death by the age of 4. Unfortunately, there is no treatment or cure for this deadly disease.

Peroxisomes **Peroxisomes** (per-oḱsi-sōm) are membrane-enclosed sacs that are usually smaller in diameter than lysosomes **(figure 2.11)**. They are formed by pinching off vesicles from the rough ER. Peroxisomes use oxygen to catalytically detoxify specific harmful substances either produced by the cell or taken into the cell. For example, the peroxisome is able to convert hydrogen peroxide (a toxic compound) that is sometimes produced by cells into

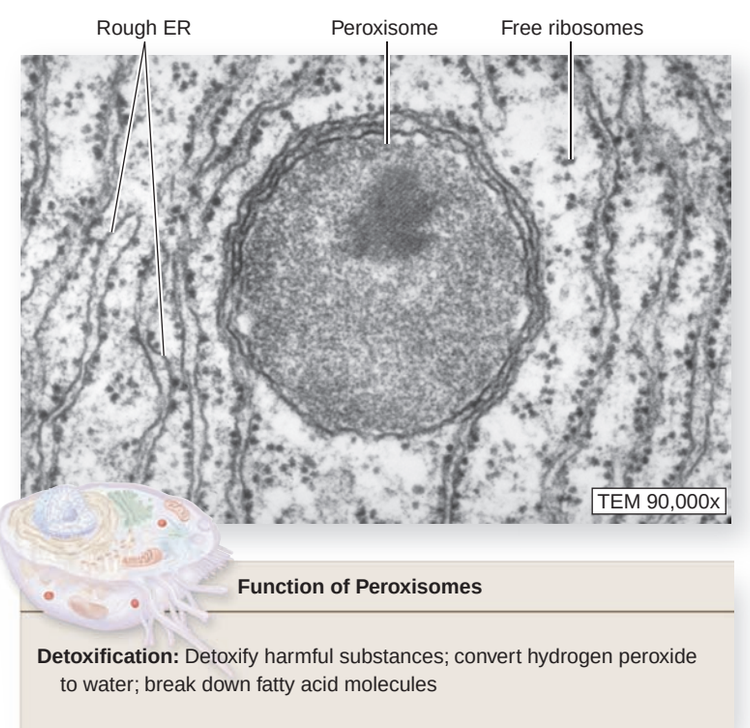


Figure 2.11

Peroxisomes. A TEM shows a peroxisome in a cell. Peroxisomes are small, membrane-bound organelles that degrade harmful substances, including hydrogen peroxide, during cellular reactions. They also break down fatty acid molecules.

CLINICAL VIEW

Adrenoleukodystrophy (ALD)

Adrenoleukodystrophy is a rare inherited disorder that became widely known after the release of the movie *Lorenzo's Oil* in 1993. The movie chronicles the true story of Lorenzo Odone, a boy diagnosed with ALD, and his family's efforts to find a treatment and cure. ALD is caused when a membrane protein is missing in the peroxisome. In the healthy state, this protein transports into the peroxisome an enzyme that controls the breakdown of very-long-chain fatty acids, which are part of the neutral fats in our diets. When the enzyme cannot enter the peroxisome because the transport protein is missing, the peroxisomes cannot function normally, and so the very-long-chain fatty acids accumulate in cells of the central nervous system, eventually stripping these cells of their myelin covering. The absence of this myelin covering prevents the normal transmission of messages through the nerve cell, and the messages "short-circuit." The very-long-chain fatty acids also build up in the adrenal glands, causing them to malfunction.

ALD exists in several forms, but the most severe kind affects young boys between the ages of 4 and 10. Typically, the first signs of ALD are lethargy, weakness, and dizziness. Additionally, the patient's skin may darken, blood sugar levels decrease, heart rhythm is altered, and the levels of electrolytes in the body fluids become imbalanced. Control over the limbs deteriorates. In the severe form of ALD, the patient loses all motor function and becomes paralyzed. Eventually, the patient becomes blind, loses basic reflex actions, such as swallowing, and enters a vegetative state. Death often results.

There is no cure for ALD, but dietary modification (to reduce the amounts of very-long-chain fatty acids in the diet) and use of "Lorenzo's oil" (an oleic acid/rapeseed oil blend discovered by Lorenzo Odone's family) helps control the very-long-chain fatty acid buildup. Most recently, some research has indicated that statins (medicines that control cholesterol levels) may help prevent the buildup of the very-long-chain fatty acids. Researchers have also learned that the severity of the disease is reduced if new therapies are applied at an early age. In addition, new, noninvasive diagnostic techniques have been developed, and diagnosis has been further improved by recognizing different phenotypes (since ALD can be misdiagnosed as attention deficit hyperactivity disorder [ADHD] in some boys).

water before it can damage the cell. It does this using the enzyme catalase, which is a component of the peroxisome. Peroxisomes are most abundant in liver cells, where they break down fatty acids and detoxify some toxic materials, such as alcohol, that are absorbed in the digestive tract.

Mitochondria **Mitochondria** (mī-tō-kon′drē-ă; sing., *mitochondrion*, mī-tō-kon′drē-on′; *mitos* = thread, *chondros* = granule) are organelles with a double membrane that are involved in producing large amounts of the cell's energy currency, ATP. For this reason, mitochondria are called the "powerhouses" of the cell. A mitochondrion is completely surrounded by an outer membrane, while a second, or inner membrane, is folded internally into the space at the center of the organelle. These folds, called **cristae** (kris′tă, -tē; *crista* = crest), increase the surface area that is exposed to the internal fluid contents, termed the **matrix** (figure 2.12). Inner membrane proteins are on the cristae.

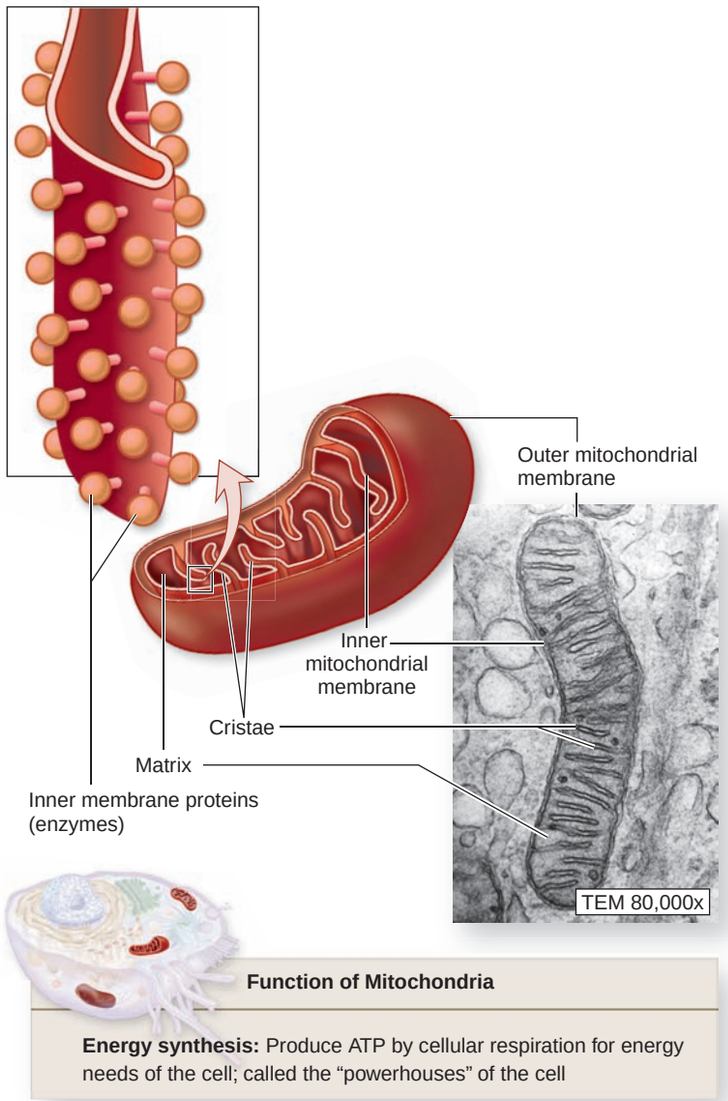


Figure 2.12

Mitochondria. A drawing and TEM show the parts of a mitochondrion. Mitochondria are double-membrane-bound organelles that produce ATP for cellular work.

The number of mitochondria in a cell depends upon the cell's energy needs. Because mitochondria can self-replicate, the numbers of mitochondria are greater in cells that have a high energy demand. For example, muscle cells with a high rate of energy usage have a large number of mitochondria in their cytoplasm. Mitochondria numbers increase with increased demands for ATP. Additionally, mitochondria contain a small, unique fragment of DNA, the genetic material (described later in this chapter). In the mitochondria, this piece of DNA contains genes for producing mitochondrial proteins. Mitochondrial shape also varies among cells. Interestingly, the head of a sperm cell contains no mitochondria because that portion has no energy need. Instead, there are mitochondria in the midpiece of the sperm cell, the region responsible for propelling the sperm.

WHAT DO YOU THINK?

3. While examining a cell by microscope, you observe that the cell has few mitochondria. What does this imply about the cell's energy requirements?

CLINICAL VIEW

MELAS and Mitochondria

MELAS syndrome is a neurogenerative disorder named for its features: **M**itochondrial myopathy (mī-op′ă-thē), a weakness in muscle caused by reduced ATP production; **E**ncephalopathy, a brain disorder; **L**actic **A**cidosis, accumulation of lactic acid in tissues because of an inability to produce normal amounts of ATP; and **S**troke, impaired cerebral (brain) circulation. The abnormal mitochondrial function is the result of a single mutation in the mitochondrial DNA that makes affected individuals unable to synthesize some of the proteins needed for energy transactions. This mutation also leads to the elevated levels of lactic acid, brain pathology, and recurring strokes. The syndrome typically first presents with stroke (often between the ages of 4 and 15 years), a symptom that is followed by episodes of fatigue, developmental delays, and seizures. Low muscle tone and muscle weakness are common. Often patients have uncoordinated and numb hands or feet, as well as diabetes mellitus. MELAS is a progressive disorder that has a high rate of morbidity (illness) and mortality (death). There is no cure for MELAS, and drug therapies have been only minimally effective.

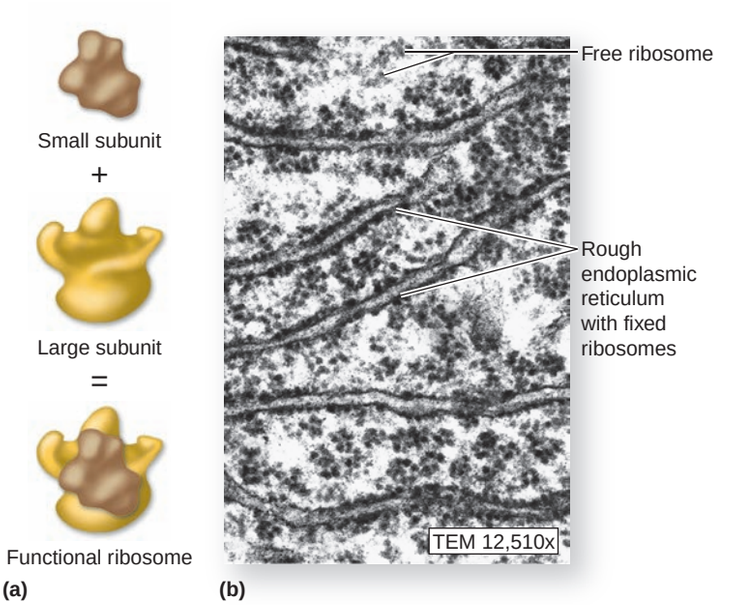
Non-Membrane-Bound Organelles

Organelles that are always in direct contact with the cytosol are called either **non-membrane-bound organelles** or *nonmembranous organelles*.

Ribosomes **Ribosomes** (rī′bō-sōm; *ribos* = reference to a 5-carbon sugar, *soma* = body) are very small, dense granules that are responsible for protein production (synthesis). Each ribosome has a small subunit and a large subunit **(figure 2.13*a*)**; the small subunit is about one-half the size of the large subunit. The parts of the subunits are formed in the nucleus, and the subunits are assembled within the cytosol at the time when a new protein is about to be synthesized. Once ribosomes are assembled, those that float freely within the cytosol of the cell are called **free ribosomes,** while those that are attached to the rough endoplasmic reticulum are called **fixed ribosomes** (figure 2.13*b*). Free ribosomes are responsible for the synthesis of proteins that remain within the cytosol of the cell. Fixed ribosomes produce proteins that are exported outside the cell, incorporated into the plasma membrane, or housed as enzymes within a new lysosome.

Cytoskeleton The **cytoskeleton** is composed of protein subunits organized either as filaments or hollow tubes. The cytoskeleton has three separate components—microfilaments, intermediate filaments, and microtubules—which differ in their structures and functions **(figure 2.14)**.

Microfilaments (mī-krō-fil′ă-ment; *micros* = small) are the smallest components of the cytoskeleton. They are about 7 nanometers (nm) in diameter and are composed of thin protein filaments (actin proteins) organized into two intertwined strands. They form an interlacing network on the cytoplasmic side of the plasma membrane. Microfilaments help maintain cell shape, support changes in cell shape, participate in muscle contraction, separate the two cells formed during cell division, and facilitate cytoplasmic streaming, which is the movement of the cytoplasm associated with changing cell shape.



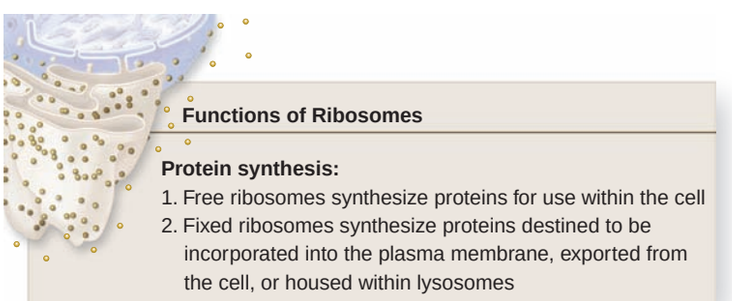


Figure 2.13

Ribosomes. Ribosomes are small, dense, cytoplasmic granules where proteins are synthesized within the cell. *(a)* Ribosomes consist of both small and large subunits. *(b)* A TEM shows fixed and free ribosomes in the cell cytoplasm.

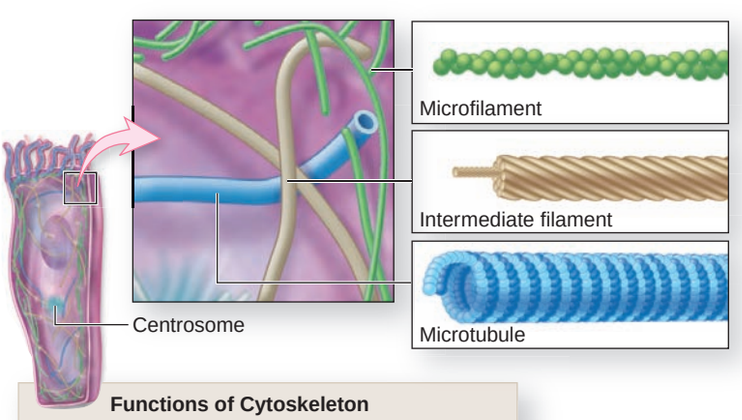
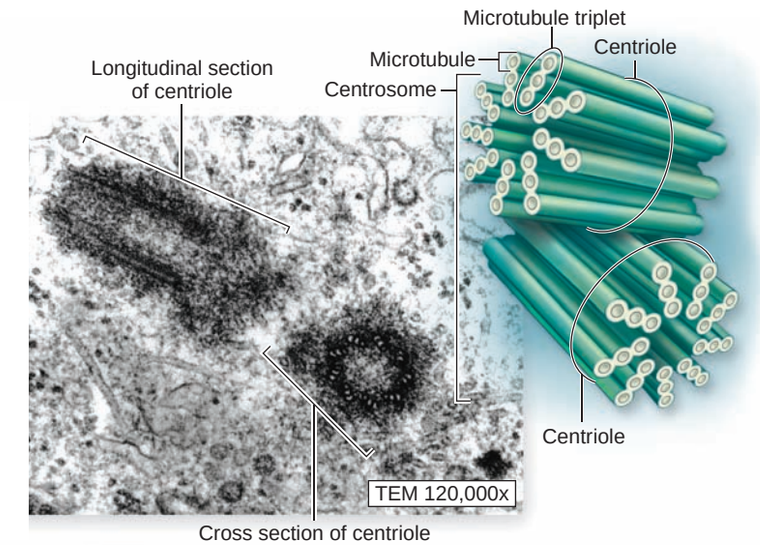


Figure 2.14

Cytoskeleton. Filamentous proteins form the cytoskeleton, which helps give the cell its shape and coordinate cellular movements. The three cytoskeletal elements are microfilaments, intermediate filaments, and microtubules.



Functions of Centrosomes and Centrioles

1. **Microtubule support:** Organizes microtubules and supports their growth in nondividing cells
2. **Cell division:** Directs formation of mitotic spindle in dividing cells

Figure 2.15

Centrosome and Centrioles. A drawing and TEM show that a region of the cytoplasm called the centrosome surrounds a centriole pair immediately adjacent to the nucleus.

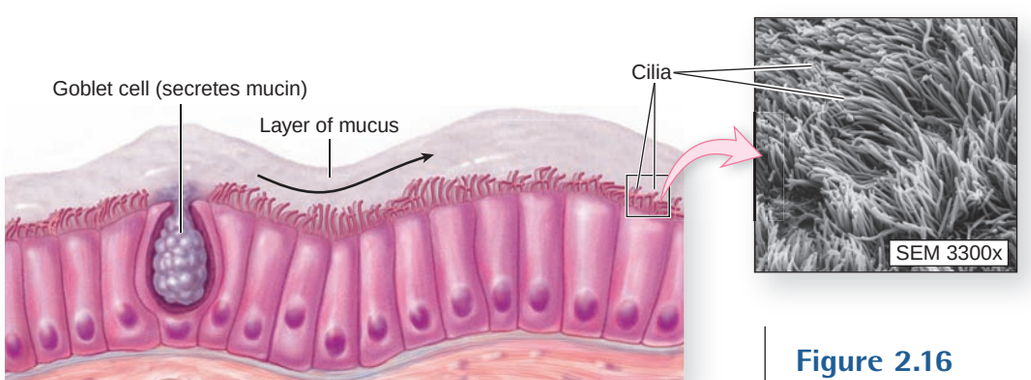
Intermediate filaments are between 8 nm and 12 nm in diameter, and are more rigid than microfilaments. They support cells structurally and stabilize junctions between cells. Their protein component differs, depending upon the cells in which they are found in the body.

Microtubules (mī-krō-too′būl; *micros* = small, *tubus* = tube) are hollow tubules, about 25 nm in diameter, composed of long chains of a protein called tubulin. Microtubules radiate from the centrosome (discussed next) and help hold organelles in place, maintain cell shape and rigidity, direct organelle movement between different regions of the cell, provide a means of cell motility using structures called cilia or flagella, and move chromosomes during the process of cell division. Microtubules are not permanent structures, and they can be elongated or shortened as needed to complete their functions.

Centrosome and Centrioles Closely adjacent to the nucleus in most cells is a nonmembranous, spherical structure called the **centrosome.** The matrix of this region is a microtubule organization center that supports the growth and elongation of microtubules. Within the region of the centrosome are a pair of cylindrical **centrioles** (sen′trē-ōl; *kentron* = a point, center) that lie perpendicular to one another. Each centriole is composed of nine sets of three closely aligned microtubules, called *microtubule triplets,* that are arranged in a circle **(figure 2.15)**. The centrioles replicate immediately prior to cell division (mitosis). During mitosis (described on page 47), they are responsible for organizing microtubules that are a part of the mitotic spindle. Some of these microtubules attach to chromosomes to facilitate their movement.

Cilia and Flagella **Cilia** (sil′ē-ă; sing., *cilium*, sil′ē-ŭm; an eyelid) and **flagella** (flă-jel′ă; sing., *flagellum*, flă-jel′ŭm; a whip) are projections extending from the cell. They are composed of cytoplasm and supportive microtubules, and they are enclosed by the plasma membrane.

Cilia are usually found in large numbers on the exposed surfaces of certain cells **(figure 2.16*a*)**. For example, cells having cilia on their exposed surfaces line parts of the respiratory passageways. Here, these ciliated cells are always associated with mucin-secreting goblet cells. Mucus that is formed from the secreted mucin appears as a sticky film on the free surface of ciliated cells. The beating of the cilia moves the mucus and any adherent particulate material along the cell surface toward the throat, where it may then be expelled from the body.



(a)

(b)

Figure 2.16

Cilia and Flagella. Cilia and flagella are appendages extending from the surface of some cells. (*a*) Cilia usually occur in large numbers; they work together to move materials or fluids along the surface of a cell. (*b*) Flagella are longer than cilia, and usually occur as single appendages. In human sperm cells, the flagellum is the apparatus that enables the sperm to "swim."

Flagella are similar to cilia in basic structure; however, they are longer and usually appear alone (figure 2.16*b*). The function of a flagellum is to help propel or move an entire cell. In humans, the only example of a cell with a flagellum is the sperm cell.

Microvilli **Microvilli** are thin, microscopic projections extending from the surface of the plasma membrane. They are much smaller than cilia, much more densely packed together, and do not have powered movement (see figure 2.3). The main function of microvilli is to increase the surface area of the plasma membrane. In essence, these projections create a more extensive plasma membrane surface for molecules to travel across. Just as not all cells have cilia, not all cells have microvilli. Cells with microvilli occur throughout the small intestine, where increased surface area is needed to absorb digested nutrients.

WHAT DID YOU LEARN?

9. Describe the characteristics of the cytosol.
10. Describe the functions of lysosomes, mitochondria, and centrioles.
11. Contrast the fates of proteins synthesized on free ribosomes versus those synthesized on fixed ribosomes.
12. What is the function of cilia?

2.5 Nucleus

Learning Objectives:

1. Describe the contents and function of the nucleus.
2. Compare and contrast the relationship between chromatin and chromosomes.

The **nucleus** is the core, or the control center, of cellular activities. Usually, it is the largest structure within the cell, averaging about 5 µm to 7 µm in diameter **(figure 2.17)**. Generally, its shape mirrors the shape of the cell. For example, a cuboidal cell has a spherical nucleus in the center of the cell, while a thin, elongated cell's nucleus is elongated in the same direction as the cell itself. Some cells contain uniquely shaped nuclei. For example, neutrophils, a type of white blood cell, have a multilobed nucleus—one that has three or more bulges.

The nucleus contains three basic structures: a nuclear envelope, nucleoli, and chromatin.

2.5a Nuclear Envelope

The nucleus is enclosed by a double membrane structure called the **nuclear envelope.** This boundary controls the entry and exit of materials between the nucleus and the cytoplasm. Each layer of the nuclear envelope is a phospholipid bilayer, similar in structure to the plasma membrane. The nuclear envelope has ribosomes attached to

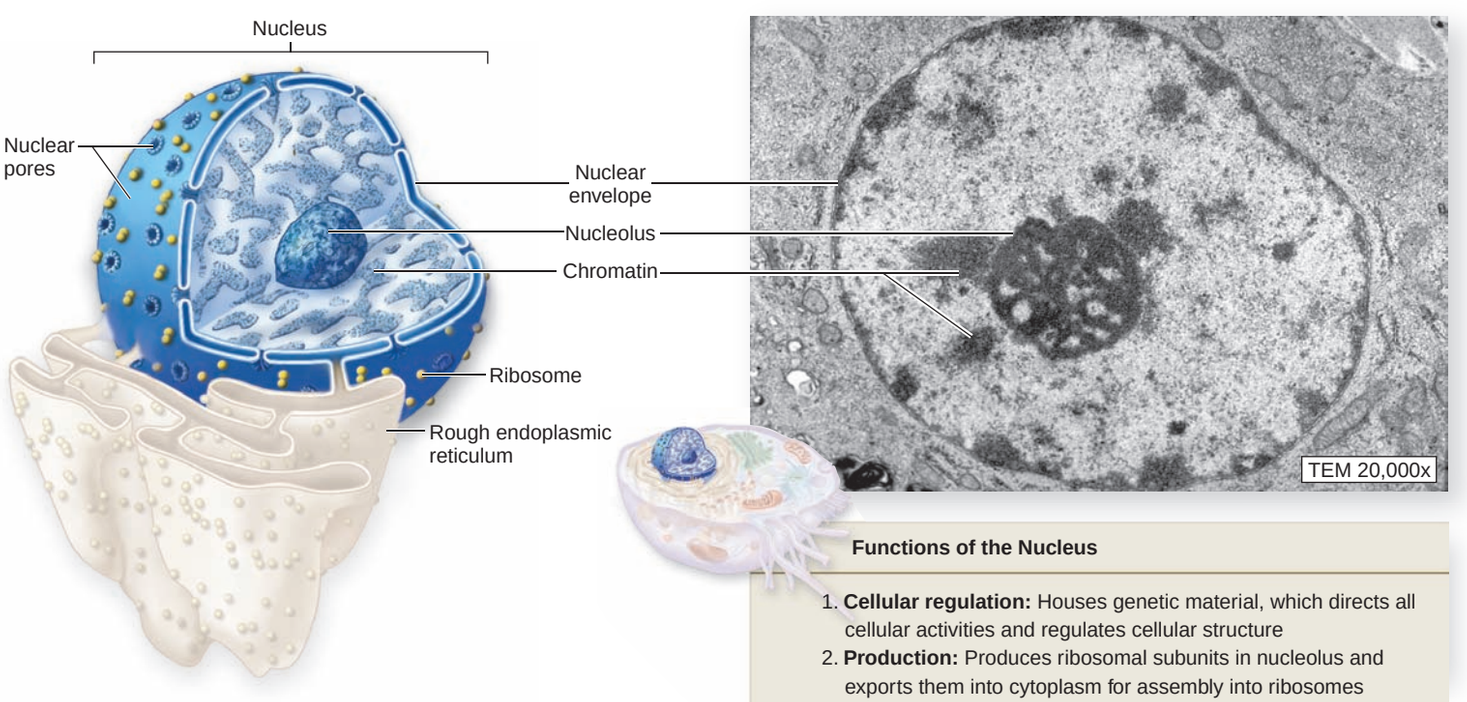


Figure 2.17

Nucleus. A drawing and TEM compare the structures of the nucleus within a cell. Control of cellular activities is centered in the nucleus.

its cytoplasmic surface, and it is continuous with the rough ER in the cytoplasm. **Nuclear pores** are open passageways that penetrate fused regions of the double membrane throughout the entire nuclear envelope. Nuclear pores allow the nuclear membrane to be selectively permeable and permit most ions and water-soluble molecules to shuttle between the nucleus and the cytoplasm.

2.5b Nucleoli

The cell nucleus may contain one or more dark-staining, usually spherical bodies called **nucleoli** (figure 2.17). (The singular term is *nucleolus* [noo-klē′ō-lŭs; pl., *nucleoli*, noo-klē′ō-lī].) Nucleoli are made up of RNA, enzymes, and other proteins. Nucleoli are responsible for making the small and large subunits of ribosomes. These subunits are exported outside the nucleus into the cytoplasm, where they are then assembled to form ribosomes. You can think of the ribosomal subunits as puzzle pieces that are made in the nucleolus. Arrangement of the puzzle pieces into one complete puzzle (ribosome) occurs in the cytoplasm.

Not all cells contain a nucleolus. The presence and number of nucleoli indicate the protein synthetic activity of a cell. For example, nerve cells contain nucleoli because they produce many proteins. In contrast, sperm cells have no nucleoli because they produce no proteins.

2.5c DNA, Chromatin, and Chromosomes

The nucleus houses **deoxyribonucleic acid (DNA),** an enormous macromolecule that contains the genetic material of the cell. The DNA within the nucleus, termed **nuclear DNA,** is much more complex than the DNA in mitochondria. DNA is organized into discrete units called **genes.** Genes provide the instructions for the production of specific proteins, and thereby direct all of the cell's activities.

DNA is in the shape of a double helix, or a ladder twisted into a spiral shape. The building blocks that form this double helix are called **nucleotides** (noo′klē-ō-tīd; *nucleus* = a little nut or kernel) **(figure 2.18*a*)**. A nucleotide contains a sugar (called a deoxyribose sugar), a phosphate molecule, and a nitrogen-containing base. There are four different types of nucleotides, each having one of four different bases: adenine (A), cytosine (C), guanine (G), and thymine (T). These nucleotides are arranged to form the unique double-helical shape of DNA. If you think of the DNA as a ladder, the sugar and phosphate components of the nucleotides form the

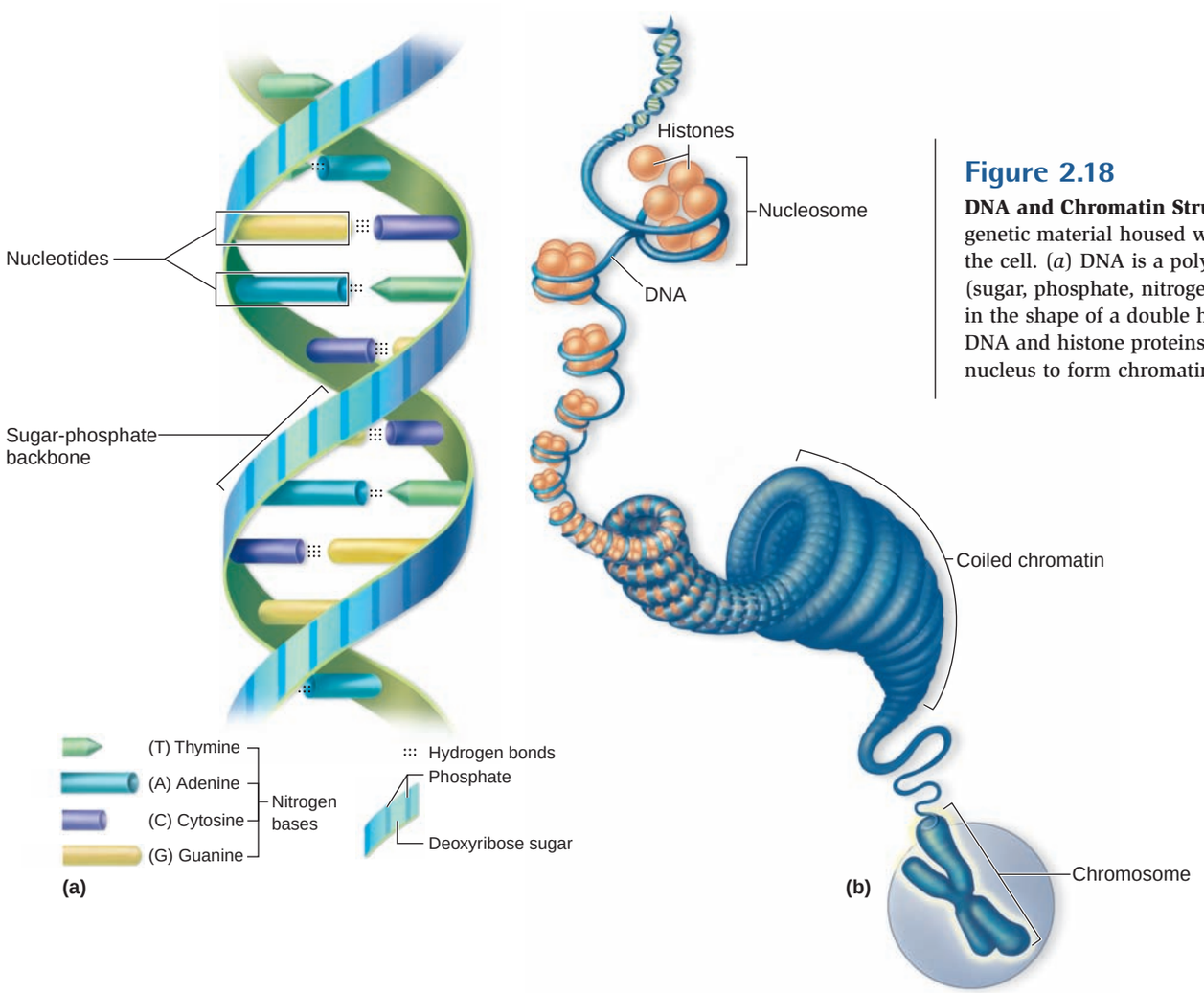


Figure 2.18

DNA and Chromatin Structure. DNA is the genetic material housed within the nucleus of the cell. (*a*) DNA is a polymer of nucleotides (sugar, phosphate, nitrogen-containing base) in the shape of a double helix. (*b*) Strands of DNA and histone proteins associate within the nucleus to form chromatin. AP|R

vertical "struts" of the ladder, while pairs of nucleotide bases interconnected by weak hydrogen bonds form the horizontal "rungs." Note that the base guanine interconnects only with the base cytosine, while the base adenine pairs only with the base thymine. The specific order of the bases in the nucleotides "codes for" specific proteins the body needs.

When a cell is not dividing, the DNA and its associated proteins are in the form of an unwound, finely filamented mass called **chromatin** (krō′ma-tin; *chroma* = color). Dark-staining chromatin in the nucleus of a nondividing cell is condensed chromatin. Other, light-staining regions of the nucleus contain chromatin that is uncoiled and spread out in fine strands of DNA and protein. When the cell is not dividing, the DNA remains unwound in fine, uncoiled chromatin, so that the genes within the DNA can direct the production of cellular proteins. This is not possible when the DNA is condensed and organized into a chromosome at the time of cell division.

Once the cell begins to divide, the chromatin rearranges itself in more precise and identifiable elongated structures called chromosomes. The **chromosome** (krō′mō-sōm; *chroma* = color, *soma* = body) is the most organized level of genetic material. Each chromosome contains a single, long molecule of DNA and associated proteins. Chromosomes become visible only when the cell is dividing. As a cell prepares for division, the DNA and protein in the chromatin coil, wrap, and twist to form the chromosomes, which resemble relatively short, thick rods. The long DNA double helix winds around a cluster of special nuclear proteins called **histones,** forming a complex known as a **nucleosome** (figure 2.18*b*). The degree of coiling of the DNA around the histone proteins ultimately determines the length and thickness of the chromosome.

WHAT DID YOU LEARN?

13. What is the function of the nuclear envelope?
14. What is the difference between chromatin and chromosomes?

2.6 Life Cycle of the Cell

Learning Objectives:

1. **Describe the events that occur during interphase.**
2. **Identify and define the phases of mitosis and the activities that occur during each phase.**

Producing the trillions of cells that form a human body—and replacing the aging, damaged, or dead ones—requires continuous cell division. In cell division, one cell divides to produce two identical cells, called **daughter cells.** There are two types of cell division: mitosis and meiosis. **Mitosis** (mī-tō′sis; *mitos* = thread) is the cell division process that takes place in the **somatic cells,** which are all of the cells in the body except the sex cells. (Meiosis occurs in the sex cells, which give rise to sperm or oocytes ["eggs"], and is discussed in chapter 3.)

The events of cell division make up the **cell cycle.** The cell cycle has two phases: interphase and the mitotic (M) phase. **Interphase** is the time between cell divisions when the cell maintains and carries out normal metabolic activities and may also prepare for division. The **mitotic (M) phase** is the time when the cell divides into two cells **(figure 2.19)**.

The lives of cells vary, depending on their specific type and their environment. For example, blood cells and epithelial skin cells

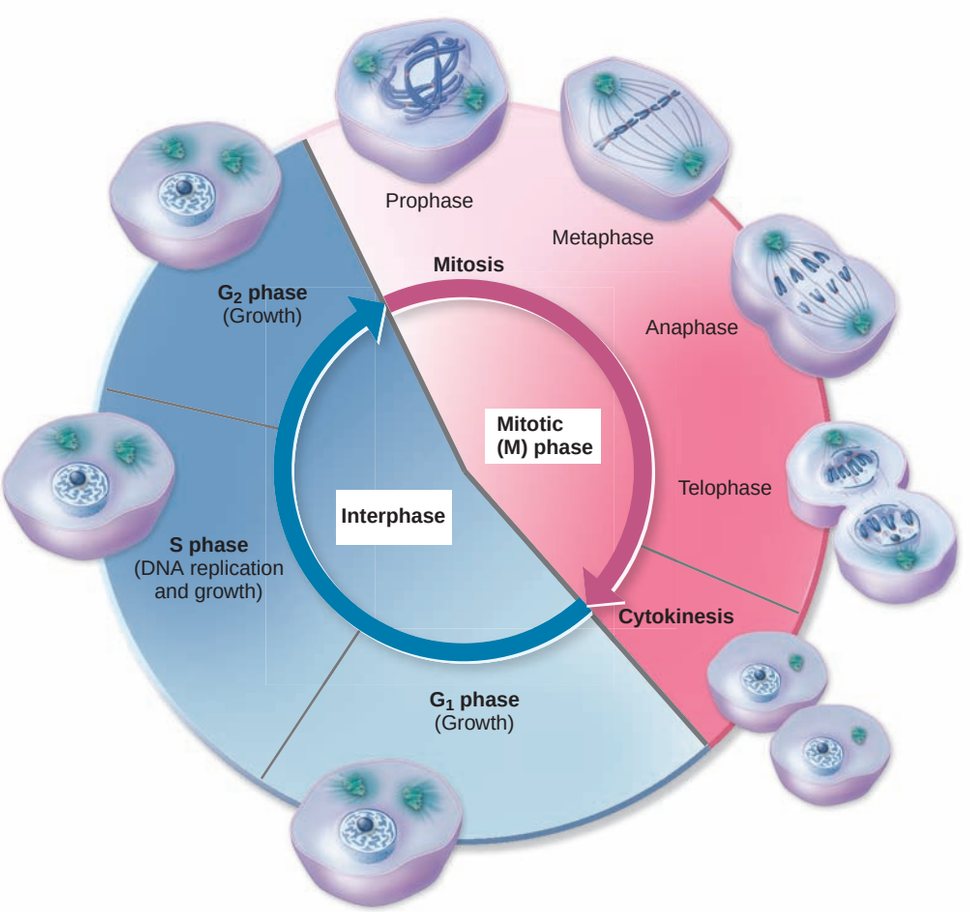


Figure 2.19

The Cell Cycle. A cell capable of division undergoes two general phases: interphase and the mitotic (M) phase. Interphase is a growth period that is subdivided into G_1, S, and G_2. Cell growth in preparation for division occurs during the G_1 and G_2 stages, and both cell growth and DNA replication occur during the S phase. The mitotic phase is composed of two processes: mitosis, during which the nucleus divides, and cytokinesis, when the cytoplasm divides. AP|R

are replaced frequently, so the cells that produce them undergo frequent cell division. Other cells, such as most nerve cells, undergo cell division infrequently or not at all. However, all somatic cells that divide go through the same stages, as described next.

2.6a Interphase

Most cells are in interphase during the majority of their lives. Interphase is a time when the cell appears to be resting because no overt activity is observed. However, while the cell carries on its normal activities, it may also be preparing for division. Interphase is a time for growth and making new cellular parts, replicating DNA and centrioles, and producing the proteins, RNA, and organelles needed for cell division. Interphase is divided into three distinct phases: G_1, S, and G_2 (figure 2.19).

G_1 Phase

During the **G_1 phase** (the first "growth" or gap stage), cells grow, produce new organelles, carry out specific metabolic activities, and produce proteins required for division. Near the end of G_1, the centrioles begin to replicate in preparation for cell division. Nondividing cells never finish G_1, and remain in a state of arrested development termed G_0. Most nerve cells appear to be in this state and do not enter cell division.

S Phase

The **S phase** ("synthesis" phase) is the next period of interphase for cells that will eventually be dividing. During this short phase, each DNA molecule replicates (makes an exact copy of itself) completely. Replication is in preparation for cell division and provides for the partitioning of all of the hereditary material of a parent cell into two identical daughter cells. A parent DNA molecule has two strands of DNA that are complementary, meaning that each base on one strand is paired with a specific partner: Adenine (A) pairs with thymine (T), and cytosine (C) pairs with guanine (G) (see figure 2.18*a*). The first steps in replication are the unwinding of the helix followed by the separation, or "unzipping," of the two strands of DNA in the parent molecule. Once separated, each parent strand serves as a template for the order of bases in the new complementary strand according to the base-pairing pattern just described. Each new DNA molecule now consists of one parent strand and one new strand. AP|R

G_2 Phase

The last part of interphase, called the **G_2 phase** (or the second "growth" or gap phase), is brief. During this phase, centriole replication is completed, organelle production continues, and enzymes needed for cell division are synthesized.

2.6b Mitotic (M) Phase

Cell division is necessary to provide the large number of cells essential for the growth and survival of a human. Cells divide at different rates through specific stages in their life cycle. Following interphase, cells enter the M (mitotic) phase **(figure 2.20)**. Two distinct events occur during this phase: **mitosis,** or division of the nucleus, followed by **cytokinesis** (sī′tō-ki-nē′sis; *kytos* = cell, *kinesis* = movement), division of the cytoplasm.

Mitotic cell division produces two daughter cells that are identical to the original (parent) cell. The nucleus divides such that the replicated DNA molecules of the original parent cell are apportioned into the two new daughter cells, with each receiving an identical copy of the DNA of the original cell.

Four consecutive phases take place during mitosis: prophase, metaphase, anaphase, and telophase. Each phase merges smoothly into the next in a nonstop process. The duration of mitosis varies according to cell type, but it typically lasts about 2 hours.

Prophase

Prophase is the first stage of mitosis (figure 2.20*b*). Chromatin becomes supercoiled into relatively short, dense chromosomes, which are more maneuverable during cell division than the long, delicate chromatin strands. Remember that the DNA replicated itself during interphase, so during prophase each chromosome (called a *duplicated chromosome*) contains two copies of its DNA. A duplicated chromosome consists of two genetically identical structures, called **sister chromatids.** Each sister chromatid is composed of an identical DNA double helix, and the two sister chromatids are joined together by proteins at a constricted region called the **centromere** (sen′trō-mēr; *kentron* = center, *meros* = part).

During prophase, the nucleolus breaks down and disappears. The chromosomes form a big puffy ball within the nucleus. Elongated microtubules called **spindle fibers** begin to grow from the centrioles, and this event pushes the two centriole pairs apart. Eventually, the centrioles come to lie at opposite poles of the cell. The end of prophase is marked by the dissolution of the nuclear envelope, which permits the chromosomes to move freely into and through the cytoplasm.

Metaphase

Metaphase occurs when the chromosomes line up along the equatorial plate of the cell (figure 2.20*c*). Spindle fibers grow from each centriole toward the chromosomes, and some attach to the centromere of each chromosome. The collection of spindle fibers extending from the centrioles to the chromosomes forms an oval-structured array termed the **mitotic spindle.** This arrangement remains in place until the next phase begins.

Anaphase

Anaphase begins as spindle fibers pull sister chromatids apart at the centromere (figure 2.20*d*). The spindle fibers shorten, and each "reels in" a chromatid, like a fishing line reeling in a fish. After the chromatids are pulled apart, each chromatid is called a **single-stranded chromosome,** as each forms its own unique centromere. Thus, a pair of single-stranded chromosomes is pulled apart from sister chromatids, and each migrates to the opposite end of the cell (cell pole). As each single-stranded chromosome migrates toward the cell pole, its centromere leads the way, and the arms of the chromosome trail behind. In most cases, cytokinesis, the division of the cytoplasm, begins in late anaphase.

Telophase

Telophase begins with the arrival of a group of single-stranded chromosomes at each cell pole (figure 2.20*e*). A new nuclear envelope forms around each set of chromosomes, and the chromosomes begin to uncoil and return to the form of dispersed threads of chromatin. The mitotic spindle breaks up and disappears. Each new nucleus forms nucleoli.

Telophase signals the end of nuclear division and it overlaps with cytokinesis. A contractile ring of protein filaments at the periphery of the cell equator pinches the mother cell into two separate cells. The resulting **cleavage furrow** indicates where the cytoplasm is dividing. The two new daughter cells then enter the interphase of their life cycle, and the process continues.

Table 2.4 summarizes the events of the somatic cell cycle.

INTERPHASE AND MITOSIS

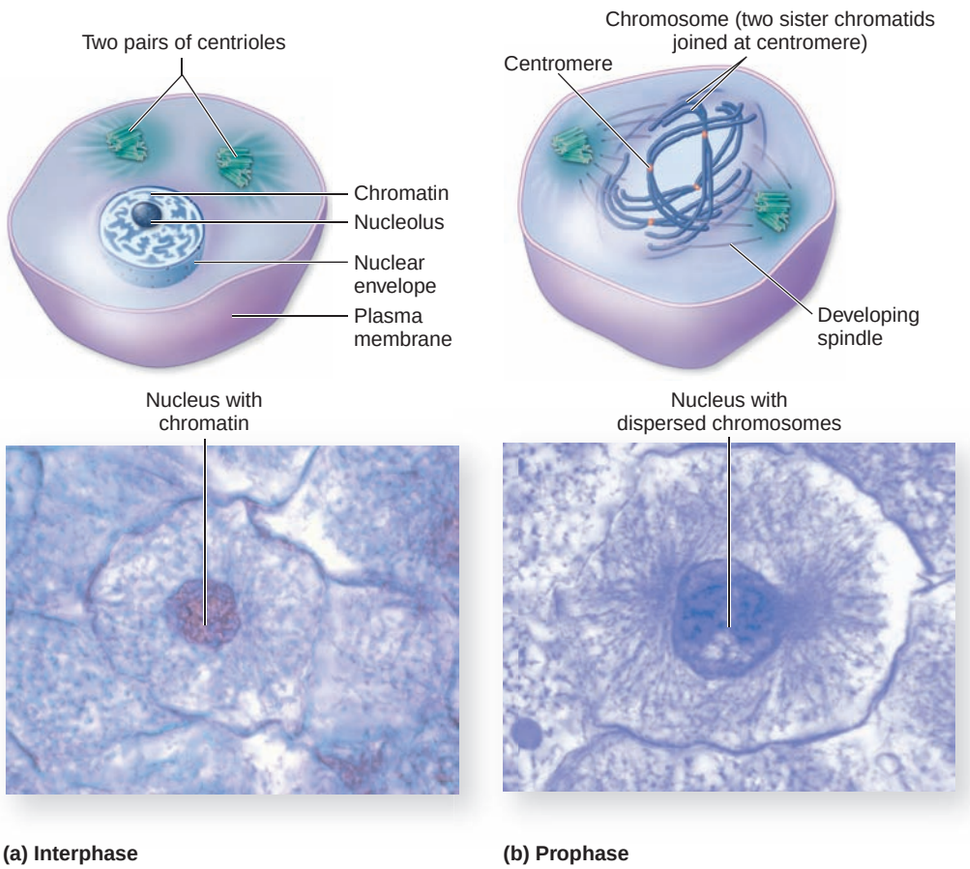
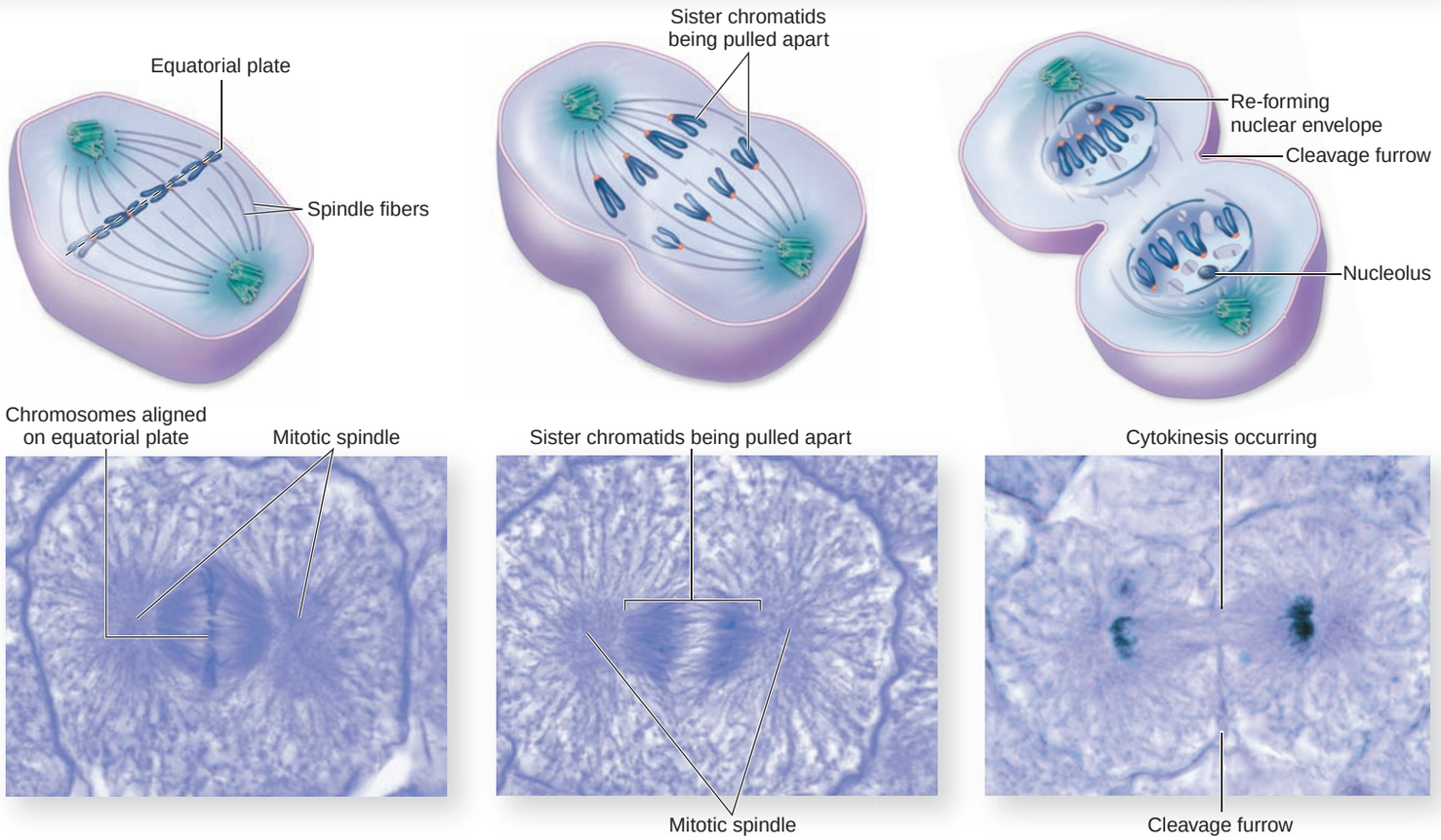


Figure 2.20

Interphase and Mitosis. Drawings and micrographs depict what happens inside a cell during the stages of *(a)* interphase and *(b–e)* mitotic cell division.

Table 2.4 Somatic Cell Cycle Events

Phase	Cellular Events
INTERPHASE	A time of normal metabolic activities with no noticeable change in either the cytoplasm or nucleus; cell is not dividing, and chromosomes are not visible by light microscopy
G_1 phase	First growth phase: Protein synthesis and metabolic activity occur; new organelles are produced; centriole replication begins at end of this phase
S phase	Nuclear DNA is replicated
G_2 phase	Second growth phase: Brief growth period for production of cell division enzymes; centriole replication finishes; organelle replication continues
MITOTIC (M) PHASE	Nuclear and cytoplasmic events produce two identical daughter cells from one parent cell
Mitosis	Division of the nucleus: Continuous series of nuclear events that distribute two sets of chromosomes into two daughter nuclei
Prophase	Chromatin threads appear due to coiling and condensation; elongated duplicated chromosomes consisting of identical sister chromatids become visible Nuclear envelope disappears at the end of this stage Nucleolus disappears Microtubules begin to form mitotic spindle Centrioles move toward opposing cell poles
Metaphase	Chromosomes line up at the equatorial plate of the cell Microtubules from the mitotic spindle attach to the centromeres of the chromosomes from the centrioles
Anaphase	Centromeres that held sister chromatid pairs together separate; they are now single-stranded chromosomes Identical pairs of single-stranded chromosomes are pulled toward opposite ends of the cell



(c) Metaphase **(d) Anaphase** **(e) Telophase**

Table 2.4 **Somatic Cell Cycle Events** *(continued)*

Phase	Cellular Events
MITOTIC (M) PHASE	Nuclear and cytoplasmic events produce two identical daughter cells from one parent cell *(continued)*
Telophase	Chromosomes arrive at cell poles and stop moving Nuclear envelope reappears, mitotic spindle disintegrates, chromosomes uncoil, disappear and become thin chromatin threads within boundary of the new nuclear envelope Nucleoli reappear
Cytokinesis	Usually begins in late anaphase and ends after telophase ends; cleavage furrow is formed from a contractile ring of microfilaments; cytoplasm divides, completing the formation of two daughter cells

Study Tip!

Use these study tips to help you remember some of the hallmark events that occur during each phase of mitosis:

- The **p** in **p**rophase stands for the **puffy** ball of chromosomes that forms in the center of the cell.
- The **m** in **m**etaphase stands for **middle:** During this phase, the chromosomes align along the **middle** of the cell.
- The **a** in **a**naphase stands for **apart:** During this phase, the sister chromatids are pulled **apart**.
- The **t** in **t**elophase stands for **two:** During this phase, **two** new cells begin to form as a cleavage furrow divides the cytoplasm.

WHAT DID YOU LEARN?

15. Observation shows that most cells are suspended in interphase for most of their lives. Identify the parts of interphase, and describe an event that occurs during each part.
16. List the stages of mitosis in order of occurrence. Describe a unique activity associated with each stage.

2.7 Aging and the Cell

Learning Objectives:

1. Describe the effects of aging on cells.
2. Identify two causes of cell death.

Aging is a normal, continuous process that often exhibits obvious body signs. However, at the cellular level, changes within cells due to aging are neither obvious nor well understood. Often, reduced metabolic functions of normal cells have wide-ranging effects throughout the body, including cells' decreased ability to maintain homeostasis. These signs of aging reflect a reduced number of normal functional body cells, and may even suggest abnormal function in the remaining cells. Affected cells may exhibit alteration in either the structure or the number of specific organelles. For example, if mitochondrial function begins to fail, the cell's ability to synthesize ATP will diminish. Additionally, changes in the distribution and structure of the chromatin and chromosomes within the nucleus may occur. Often, both chromatin and chromosomes clump, shrink, or fragment as a result of repeated divisions.

Some cancers (e.g., prostate cancer) appear with greater frequency in elderly individuals. Cancer is essentially caused by cells that undergo uncontrolled cell division and fail to "turn off" the cell division process. Thus, as we age, the whole mechanism of cell division becomes more faulty, making cancers more prevalent. Further, pregnant women over the age of 35 are at greater risk for giving birth to a child with a birth defect than are younger pregnant women. One reason for this greater risk is that older women's sex cells (oocytes) are older, and their mechanisms for completing sex cell division and maturation may not operate properly.

Essentially, cells die by one of two mechanisms: (1) They are killed by harmful agents or mechanical damage, in a process called **necrosis** (nĕ-krō′sis; *nekrosis* = death), wherein the damage is irreversible and there is an inflammatory response; or (2) they are induced to commit suicide, a process of programmed cell death called **apoptosis** (ap′op-tō′sis; *apo* = off, *ptosis* = a falling). Cells in apoptosis exhibit nuclear changes (chromatin degradation), shrinkage in volume, and abnormal development in both organelle and plasma membrane structure.

Programmed cell death both promotes proper development and removes harmful cells. For example, in a human embryo, the proper development of fingers and toes begins with the formation of a paddlelike structure at the distal end of the developing limb. In order for our digits to form correctly, programmed death removes the cells and tissues between the true fingers and toes developing within this paddle structure. Additionally, programmed cell death sometimes destroys harmful cells, reducing potential health threats. For example, the cells of our immune system promote programmed cell death in some virus-infected cells to reduce the further spread of infection. Often, cells with damaged DNA appear to promote events leading to apoptosis, presumably to prevent these cells from causing developmental defects or becoming cancerous. Additionally, some cancer therapy treatments lead to apoptosis in certain types of cancer cells.

Precise control of cell division is required to maintain healthy, normal-functioning cells. The quality-control mechanisms inherent within normal cellular processes are meant to ensure continuous removal of unnecessary cells, old cells, or abnormal cells as normal aging progresses.

WHAT DID YOU LEARN?

17. What name is given to programmed cell death?
18. In general, what is the main characteristic of cancer?

CLINICAL VIEW: In Depth

Characteristics of Cancer Cells

Normal tissue development exhibits a balance between cell division and cell death. If this balance is upset and cells multiply faster than they die, abnormal growth results in a new cell mass called a neoplasm, or tumor. ***Neoplasms*** (nē′ō-plazm; *neos* = new, *plasma* = thing formed) are classified as benign or malignant, based on their cytologic and histologic features.

Benign (bē-nīn′; *benignus* = kind) neoplasms usually grow slowly and are confined within a connective tissue capsule. Cells within these tumors **dedifferentiate**—that is, they revert to a less specialized state and cause an increase in their own vascular supply to support their growth. These tumors are usually not lethal, but they have the potential to become life-threatening if they compress brain tissue, nerves, blood vessels, or airways.

Malignant (mă-lig′nănt; *maligno* = to do maliciously) neoplasms are unencapsulated, contain cells that dedifferentiate, increase their vascular supply, grow rapidly, and are able to spread easily to other organs by way of the blood or lymph, a phenomenon called ***metastasis*** (mĕ-tas′tă-sis; *meta* = in the midst of, *stasis* = a placing).

Cancer is the general term used to describe a group of diseases characterized by various types of malignant neoplasms. A ***carcinogen*** is any infectious agent or substance shown to cause changes within a normal cell that results in the formation of a cancer cell. Cancer cells resemble undifferentiated or primordial cell types. Generally, they do not mature before they divide and are not capable of maintaining normal function. They use energy very inefficiently, and their growth comes at the expense of normal cells and tissues. The characteristics of cancer include the following:

- Cancer cells lose control of their cell cycle. Cells divide too frequently and grow out of control. A ***mutagen*** is any agent or factor that causes a change in genes; it may be responsible for stimulating the development of a cancerous cell.
- Cancer cells lose contact inhibition, meaning that they overgrow one another and lack the ability to stop growing and dividing when they crowd other cells.
- Cancer cells often exhibit dedifferentiation and revert to an earlier, less specialized developmental state.
- Cancer cells often produce chemicals that cause local blood vessel formation (a process called *angiogenesis*), resulting in increased blood vessels in the developing tumor.
- Cancer cells have the ability to squeeze into any space, a property called *invasiveness*. This permits cancer cells to leave their place of origin and travel elsewhere in the body.
- Cancer cells acquire the ability to metastasize—that is, spread to other organs in the body.

Clinical Terms

anaplasia Obvious loss of cellular or structural differentiation and change in cells' orientation to each other and to blood vessels; seen in most malignant neoplasms.

dysplasia (dis-plā′zē-ă; *dys* = bad, *plasis* = a molding) Abnormal development of a tissue; a pathologic condition resulting in a change in the shape, size, and organization of adult cells; development of cellular and tissue elements that are not normal.

hyperplasia Increase in the normal number of cells within a tissue or organ; an excessive proliferation of normal cells; does not include tumor formation.

hypertrophy Generalized increase in the bulk or size of a part of an organ, not as a consequence of tumor formation.

malignant tumor An abnormal growth of cells that invades surrounding tissues.

metaplasia Abnormal transformation of a fully differentiated adult tissue into a differentiated tissue of another kind.

Chapter Summary

2.1 The Study of Cells 24

- Cytology is the study of anatomy at the cellular level.

2.1a Using the Microscope to Study Cells 24

- Variations in magnification and resolution exist when comparing light microscopy (LM) and electron microscopy (TEM and SEM).

2.1b General Functions of Human Body Cells 25

- Cells vary in shape and size, often related to various cellular functions.

2.2 A Prototypical Cell 27

- A cell is surrounded by a thin layer of extracellular fluid. Interstitial fluid is a type of extracellular fluid forming a thin layer on the outside of the cell. Most mature human cells have an outer boundary called the plasma (cell) membrane, general cell contents termed cytoplasm, and a nucleus that serves as the cell's control center.

2.3 Plasma Membrane 30

- The plasma membrane acts as a gatekeeper to regulate movement of material into and out of the cell.

2.3a Composition and Structure of Membranes 30

- Plasma membranes are composed of an approximately equal mixture of lipids and proteins.
- The primary membrane lipids are phospholipids, arranged as a bilayer.
- Membrane proteins are of two types: integral proteins and peripheral proteins. Some integral membrane proteins have carbohydrate molecules attached to their external surfaces.
- The glyocalyx is the carbohydrate component of the plasma membrane attached to either lipid (glycolipid) or protein (glycoprotein) components. It functions in cell–cell recognition and communication.

2.3b Protein-Specific Functions of the Plasma Membrane 31

- Plasma membrane proteins function in transport, intercellular attachment, cytoskeleton anchorage, catalytic (enzyme) activity, cell–cell recognition, and signal transduction.

2.3c Transport Across the Plasma Membrane 32

- Plasma membrane permeability is influenced by transport proteins, membrane structure, concentration gradient across the membrane, ionic charge, lipid solubility of materials, and molecular size.
- Passive transport is the movement of a substance across a membrane at no energy cost to the cell; it includes diffusion (simple diffusion, osmosis, and facilitated diffusion) and bulk filtration.
- All active transport processes require energy in the form of ATP. Two active processes are ion pumps and bulk transport in vesicles (exocytosis and endocytosis).
- Bulk transport includes exocytosis, a mechanism to export packaged materials from the cell, and endocytosis, a mechanism by which materials are imported into the cell.

2.4 Cytoplasm 36

- The cytoplasm is all the material between the plasma membrane and the nucleus. It contains cytosol, inclusions, and organelles.

2.4a Cytosol 36

- Cytosol is a viscous intracellular fluid containing ions, nutrients, and other molecules necessary for cell metabolism.

2.4b Inclusions 36

- Inclusions are storage bodies in the cytoplasm.

2.4c Organelles 36

- Membrane-bound organelles include endoplasmic reticulum (both rough and smooth), the Golgi apparatus, lysosomes, peroxisomes, and mitochondria.
- Non-membrane-bound organelles include ribosomes (both free and fixed), the cytoskeleton, the centrosome, and centrioles, cilia, flagella, and microvilli.

(continued on next page)

Chapter Summary *(continued)*

2.5 Nucleus 44	■ The nucleus is the cell's control center. **2.5a Nuclear Envelope 44** ■ The nuclear envelope is a double membrane boundary surrounding the nucleus. Nuclear pores are openings that penetrate the nuclear envelope and permit direct communication with the cytosol. **2.5b Nucleoli 45** ■ A nucleolus is a dark-staining, usually spherical body in the nucleus that produces the subunits that will form ribosomes. **2.5c DNA, Chromatin, and Chromosomes 45** ■ Chromatin is the name of the fine, uncoiled strands of DNA in the nucleus. As the cell prepares to divide, the DNA strands begin to coil and wind to form large, microscopically identifiable structures termed chromosomes.
2.6 Life Cycle of the Cell 46	■ Cell division in somatic cells is called mitosis, and cell division in sex cells (sperm and oocytes) is called meiosis. **2.6a Interphase 47** ■ Somatic cells spend the majority of their time in interphase, a time of maintenance and growth that occurs between cell divisions. **2.6b Mitotic (M) Phase 47** ■ The division of the somatic cell nucleus is called mitosis, whereas the division of the cytoplasm following mitosis is called cytokinesis. Both mitosis and cytokinesis represent the mitotic phase. ■ Four consecutive phases comprise mitosis: prophase, metaphase, anaphase, and telophase (see figure 2.20).
2.7 Aging and the Cell 50	■ Aging is a normal process that is often marked by changes in normal cells. ■ Cells may be killed by harmful agents or mechanical damage, or they may undergo programmed cell death, called apoptosis.

Challenge Yourself

Matching

Match each numbered item with the most closely related lettered item.

_____ 1. ribosomes
_____ 2. lysosomes
_____ 3. peripheral proteins
_____ 4. Golgi apparatus
_____ 5. exocytosis
_____ 6. cytoskeleton
_____ 7. osmosis
_____ 8. S phase
_____ 9. pinocytosis
_____ 10. nucleus

a. endocytosis of small amounts of fluid
b. organelle that sorts and packages molecules
c. diffusion of water across a semipermeable membrane
d. process of bulk export from the cell
e. responsible for synthesizing proteins
f. control center; stores genetic information
g. organelles housing digestive enzymes
h. not embedded in phospholipid bilayer
i. the time when DNA replication occurs
j. internal protein framework in cytoplasm

Multiple Choice

Select the best answer from the four choices provided.

_____ 1. When a cell begins to divide, its chromatin forms
a. nucleoli.
b. chromosomes.
c. histones.
d. None of these are correct.

_____ 2. Which of the following describes integral membrane proteins?
a. They only permit water movement into or out of the cell.
b. They only transport large proteins into the cell.
c. They extend across the phospholipid bilayer.
d. They are attached to the external plasma membrane surface.

_____ 3. Facilitated diffusion differs from active transport in that facilitated diffusion
a. expends no ATP.
b. moves molecules from an area of higher concentration to one of lower concentration.
c. does not require a carrier protein for transport.
d. moves molecules in vesicles across a semipermeable membrane.

_____ 4. Which plasma membrane structures serve in cell recognition and act as a "personal ID card" for the cell?
a. integral proteins and peripheral proteins
b. glycolipids and glycoproteins
c. phospholipids and cholesterol
d. cholesterol and integral proteins

_____ 5. _____ increase the outer surface area of the plasma membrane to increase absorption.
a. Centrioles
b. Cilia
c. Microvilli
d. Flagella

_____ 6. The major functions of the Golgi apparatus are
a. diffusion and osmosis.
b. detoxification of substances and removal of waste products.
c. synthesis of new proteins for the cytoplasm.
d. packaging, sorting, and modification of new molecules.

_____ 7. Interphase of the cell cycle consists of the following parts:
a. prophase, metaphase, anaphase, and telophase.
b. G_1, S, and G_2.
c. mitosis and cytokinesis.
d. All of these are correct.

_____ 8. The organelle that provides most of the ATP needed by the cell is the
a. endoplasmic reticulum.
b. mitochondrion.
c. lysosome.
d. Golgi apparatus.

_____ 9. During which phase of mitosis do the sister chromatids begin to move apart from each other at the middle of the cell?
a. prophase
b. metaphase
c. anaphase
d. telophase

_____ 10. A peroxisome uses oxygen to
a. detoxify harmful substances.
b. make ATP.
c. help make proteins.
d. package secretory materials.

Content Review

1. Describe the three main regions common to all cells, and briefly discuss the composition of each region.
2. Describe the structure and the function of the plasma membrane.
3. What is meant by passive transport of materials into a cell? Describe the passive processes by which substances enter and leave cells.
4. How does active transport differ from passive transport? What are the three specific forms of the active transport mechanism termed endocytosis?
5. Discuss the two categories of organelles and the main differences between these groups.
6. Compare and contrast the structure and functions of the SER and the RER.
7. Identify the three parts of the cytoskeleton, and describe the structure and function of each component.
8. What are the basic components of the nucleus, and what are their functions?
9. What is interphase? What role does it serve in the cell cycle?
10. Identify the phases of mitosis, and briefly discuss the events that occur during each phase.

Developing Critical Reasoning

1. You place some cells into a solution of unknown content and then observe them on a microscope slide. After a short period, all of the cells appear shrunken, and their plasma membranes look wrinkled. What took place, and why?
2. Why is it efficient for some organelles to be enclosed by a membrane similar to a plasma membrane?

Answers to "What Do You Think?"

1. A selectively permeable plasma membrane allows some materials to enter the cell and blocks the entry of other materials that may be detrimental to the cell. However, a selectively permeable plasma membrane may inadvertently block some beneficial material. In these cases, active transport methods (e.g., endocytosis) are needed to bring the material into the cell.
2. Most cells would not be able to function without lysosomes. Lysosomes are necessary for breaking down and removing waste products. If lysosomes do not function properly, the waste products build up in the cell and cause cell death.
3. The number of mitochondria is positively related to the metabolic activity of the cell. A cell with few mitochondria is probably not as active metabolically as a cell with numerous mitochondria.