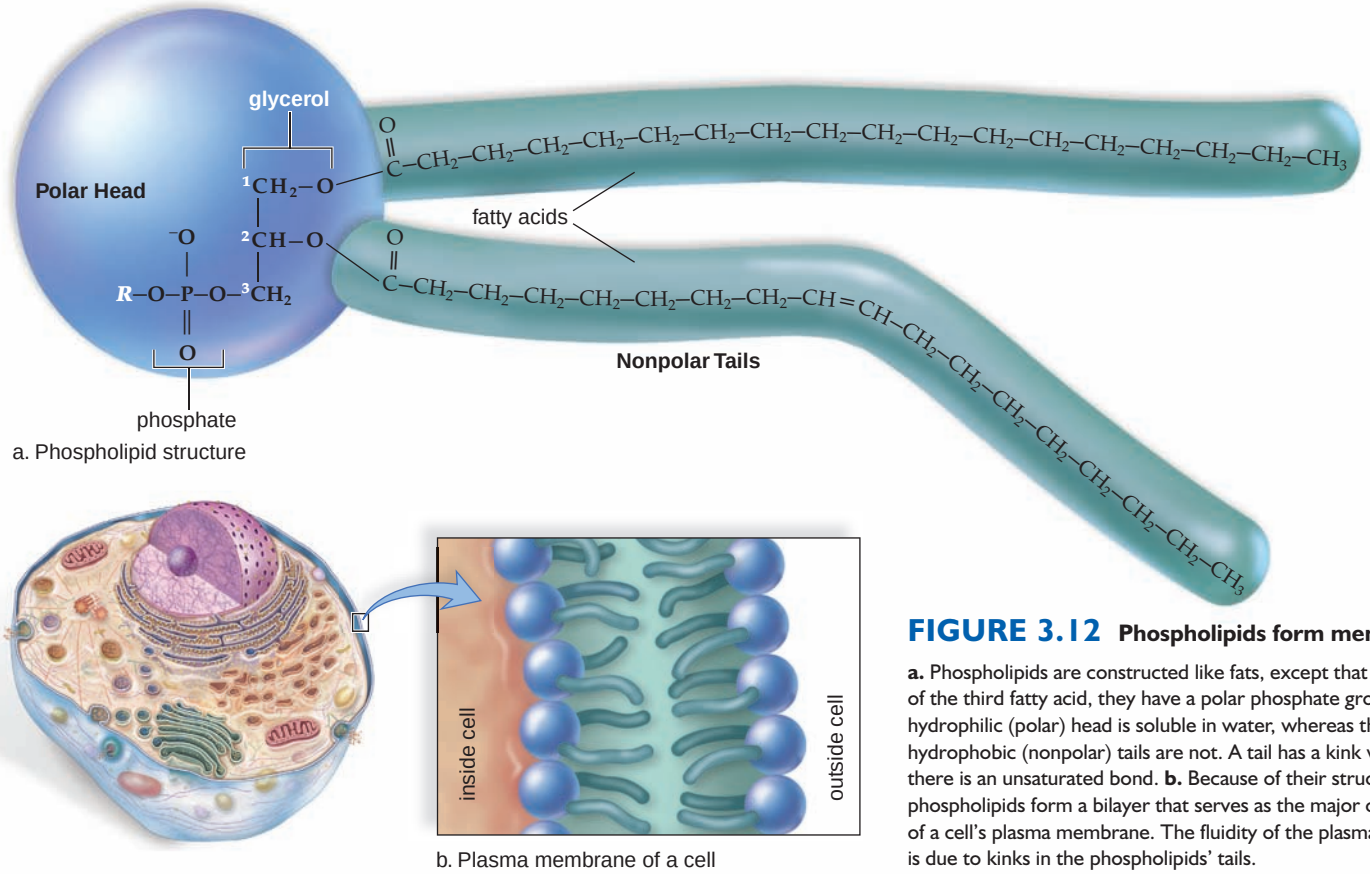


FIGURE 3.12 Phospholipids form membranes.

a. Phospholipids are constructed like fats, except that in place of the third fatty acid, they have a polar phosphate group. The hydrophilic (polar) head is soluble in water, whereas the two hydrophobic (nonpolar) tails are not. A tail has a kink wherever there is an unsaturated bond. **b.** Because of their structure, phospholipids form a bilayer that serves as the major component of a cell's plasma membrane. The fluidity of the plasma membrane is due to kinks in the phospholipids' tails.

Phospholipids: Membrane Components

Phospholipids [Gk. *phos,* light, and *lipos,* fat], as implied by their name, contain a phosphate group. Essentially, a phospholipid is constructed like a fat, except that in place of the third fatty acid attached to glycerol, there is a polar phosphate group. The phosphate group is usually bonded to another organic group, indicated by *R* in Figure 3.12*a.* This portion of the molecule becomes the polar head, while the hydrocarbon chains of the fatty acids become the nonpolar tails. Note that a double bond causes a tail to kink.

Because phospholipids have hydrophilic heads and hydrophobic tails, they tend to arrange themselves so that only the polar heads are adjacent to a watery medium. Therefore, when surrounded by water, phospholipids become a bilayer (double layer) in which the hydrophilic heads project outward and the hydrophobic tails project inward.

The plasma membrane that surrounds cells consists primarily of a phospholipid bilayer (Fig. 3.12*b*). The presence of kinks in the tail cause the plasma membrane to be fluid in nature. A plasma membrane is absolutely essential to the structure and function of a cell, and this signifies the importance of phospholipids to living things.

Steroids: Four Fused Rings

Steroids are lipids that have entirely different structures from those of fats. Steroid molecules have skeletons of four fused carbon rings (Fig. 3.13*a*). Each type of steroid differs primarily by the types of functional groups attached to the carbon skeleton.

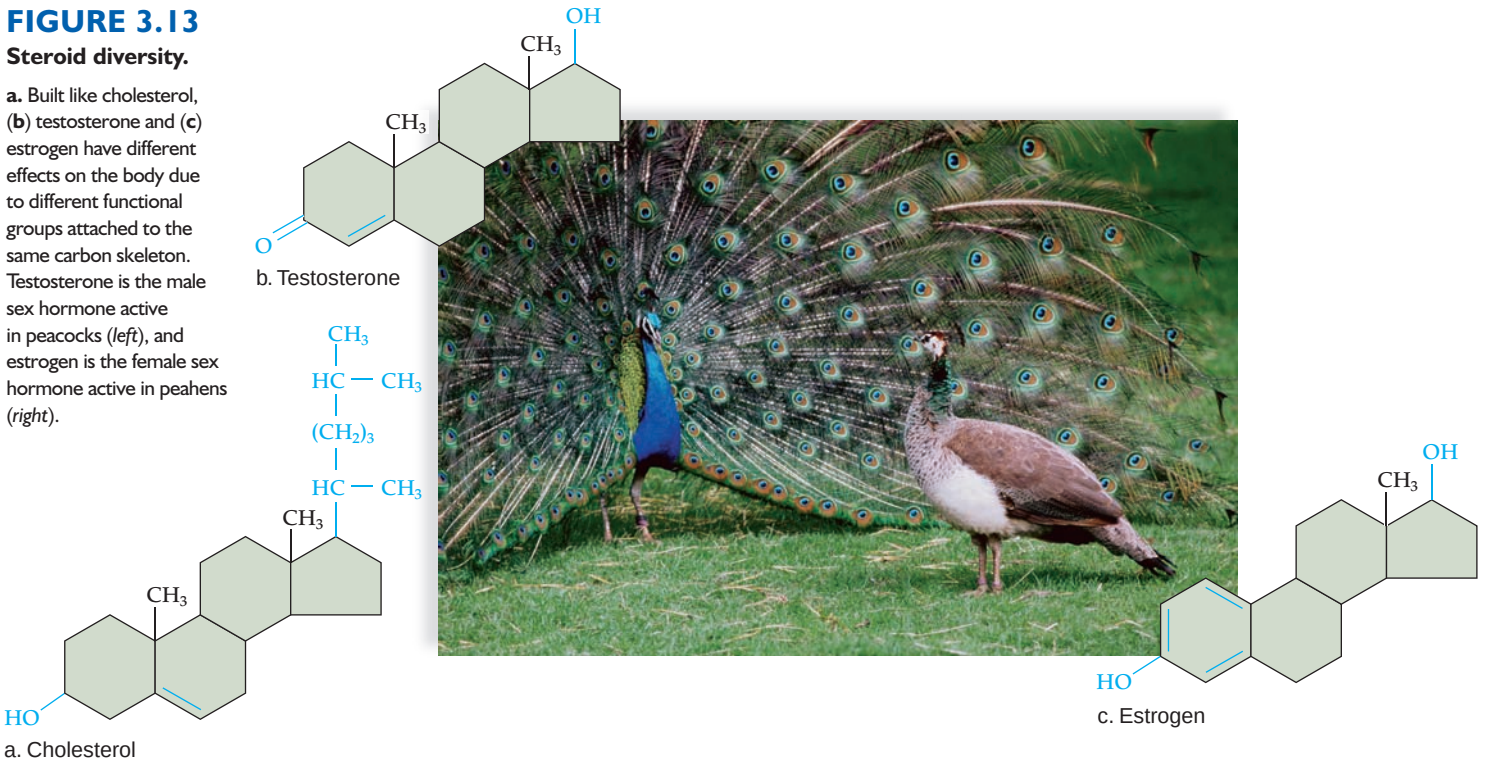
Cholesterol is an essential component of an animal cell's plasma membrane, where it provides physical stability. Cholesterol is the precursor of several other steroids, such as the sex hormones testosterone and estrogen (Fig. 3.13*b, c*). The male sex hormone, testosterone, is formed primarily in the testes, and the female sex hormone, estrogen, is formed primarily in the ovaries. Testosterone and estrogen differ only by the functional groups attached to the same carbon skeleton, and yet they each have their own profound effect on the body and the sexuality of an animal. Human and plant estrogen are similar in structure and, if estrogen therapy is recommended, some women prefer taking soy products in preference to estrogen from animals.

Not only saturated fats, but also cholesterol can contribute to circulatory disorders. The presence of cholesterol encourages the accumulation of fatty material inside the lining of blood vessels and, therefore, high blood pressure. Cholesterol-lowering medication is available.

FIGURE 3.13

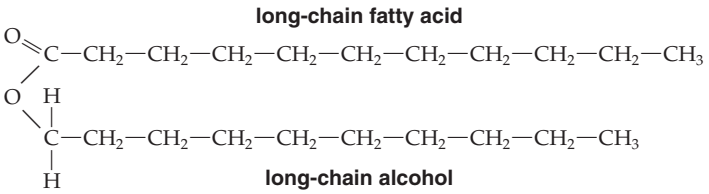
Steroid diversity.

a. Built like cholesterol, (**b**) testosterone and (**c**) estrogen have different effects on the body due to different functional groups attached to the same carbon skeleton. Testosterone is the male sex hormone active in peacocks (*left*), and estrogen is the female sex hormone active in peahens (*right*).



Waxes

In **waxes,** long-chain fatty acids bond with long-chain alcohols:



Waxes are solid at normal temperatures because they have a high melting point. Being hydrophobic, they are also waterproof and resistant to degradation. In many plants, waxes, along with other molecules, form a protective cuticle (covering) that retards the loss of water for all exposed parts (Fig. 3.14*a*). In many animals, waxes are involved in skin and fur maintenance. In humans, wax is produced by glands in the outer ear canal. Earwax contains cerumin, an organic compound that at the very least repels insects, and in some cases even kills them. It also traps dust and dirt, preventing them from reaching the eardrum.

A honeybee produces beeswax in glands on the underside of its abdomen. Beeswax is used to make the six-sided cells of the comb where honey is stored (Fig. 3.14*b*). Honey contains the sugars fructose and glucose, breakdown products of the sugar sucrose.

Humans have found a myriad of uses for waxes, from making candles to polishing cars, furniture, and floors.

Check Your Progress 3.3

1. **a.** Compare and contrast a saturated fatty acid with an unsaturated fatty acid. **b.** Which of these is preferred in the diet and why?
2. Explain why phospholipids form a bilayer in a watery medium.

FIGURE 3.14 Waxes.

Waxes are a type of lipid. **a.** Fruits are protected by a waxy coating that is visible on these plums. **b.** Bees secrete the wax that allows them to build a comb where they store honey. This bee has collected pollen (yellow) to feed growing larvae.

a.

b.

3.4 Proteins

Proteins [Gk. *proteios,* first place], as their Greek derivation implies, are of primary importance to the structure and function of cells. As much as 50% of the dry weight of most cells consists of proteins. Presently, over 100,000 proteins have been identified. Here are some of their many functions in animals:

Metabolism Enzymes bring reactants together and thereby speed chemical reactions in cells. They are specific for one particular type of reaction and can function at body temperature.

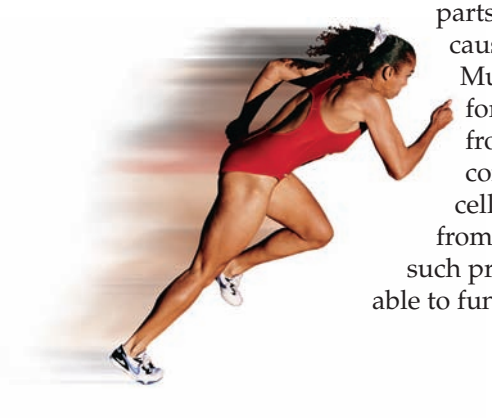
Support Some proteins have a structural function. For example, keratin makes up hair and nails, while collagen lends support to ligaments, tendons, and skin.

Transport Channel and carrier proteins in the plasma membrane allow substances to enter and exit cells. Some other proteins transport molecules in the blood of animals; **hemoglobin** is a complex protein that transports oxygen.

Defense Antibodies are proteins. They combine with foreign substances, called antigens. In this way, they prevent antigens from destroying cells and upsetting homeostasis.

Regulation Hormones are regulatory proteins. They serve as intercellular messengers that influence the metabolism of cells. The hormone insulin regulates the content of glucose in the blood and in cells; the presence of growth hormone determines the height of an individual.

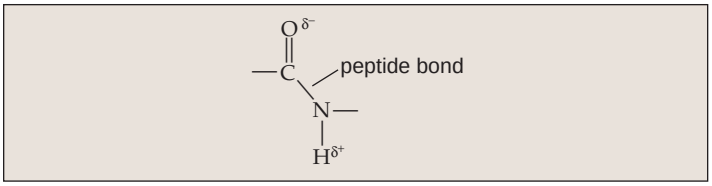
Motion The contractile proteins actin and myosin allow parts of cells to move and cause muscles to contract. Muscle contraction accounts for the movement of animals from place to place. All cells contain proteins that allow cell components to move from place to place. Without such proteins, cells would not be able to function.



Proteins are such a major part of living organisms that tissues and cells of the body can sometimes be characterized by the proteins they contain or produce. For example, muscle cells contain large amounts of actin and myosin for contraction; red blood cells are filled with hemoglobin for oxygen transport; and support tissues, such as ligaments and tendons, contain the protein collagen, which is composed of tough fibers.

Peptides

Proteins are polymers with amino acid monomers. Figure 3.15 shows how two amino acids join by a dehydration reaction between the carboxyl group of one and the amino group of another. The resulting covalent bond between two amino acids is called a **peptide bond.** The atoms associated with the peptide bond share the electrons unevenly because oxygen is more electronegative than nitrogen. Therefore, the hydrogen attached to the nitrogen has a slightly positive charge, while the oxygen has a slightly negative charge:



The polarity of the peptide bond means that hydrogen bonding is possible between the —CO of one amino acid and the —NH of another amino acid in a polypeptide.

A **peptide** is two or more amino acids bonded together, and a **polypeptide** is a chain of many amino acids joined by peptide bonds. A protein may contain more than one polypeptide chain; therefore, you can see why a protein could have a very large number of amino acids. In 1953, Frederick Sanger developed a method to determine the sequence of amino acids in a polypeptide. Now that we know the sequences of thousands of polypeptides, it is clear that each polypeptide has its own normal sequence. This sequence influences the final three-dimensional shape of the protein. Proteins that have an abnormal sequence have the wrong shape and cannot function properly.

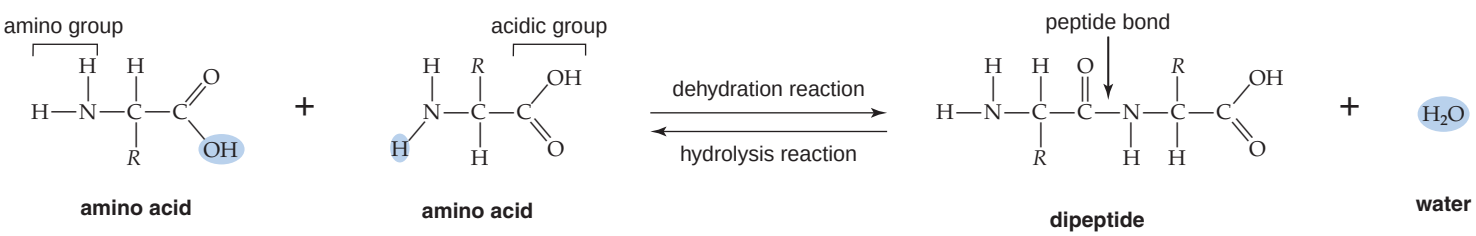
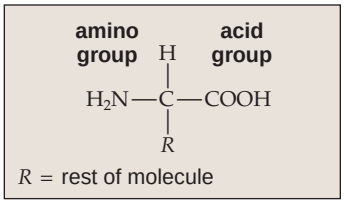


FIGURE 3.15 Synthesis and degradation of a peptide.

Following a dehydration reaction, a peptide bond joins two amino acids and a water molecule is released. Following a hydrolysis reaction, the bond is broken due to the addition of water.

Amino Acids: Protein Monomers

The name **amino acid** is appropriate because one of these groups is an —NH_2 (amino group) and another is a —COOH (an acid group). The third group is called an *R* group for an amino acid:



Note that the central carbon atom in an amino acid bonds to a hydrogen atom and also to three other groups of atoms, one of which is the *R* group (Fig. 3.15). Amino acids differ according to their particular *R* group, shaded in blue in Figure 3.16. The *R* groups range in complexity from a single hydrogen atom to a complicated ring compound. Some *R* groups are polar and some are not. Also, the amino acid cysteine has an *R* group that ends with an —SH group, which often serves to connect one chain of amino acids to another by a disulfide bond, —S—S—. Several other amino acids commonly found in cells are shown in Figure 3.16. Each protein has a definite sequence of amino acids, and this leads to levels of structure and a particular shape per protein.

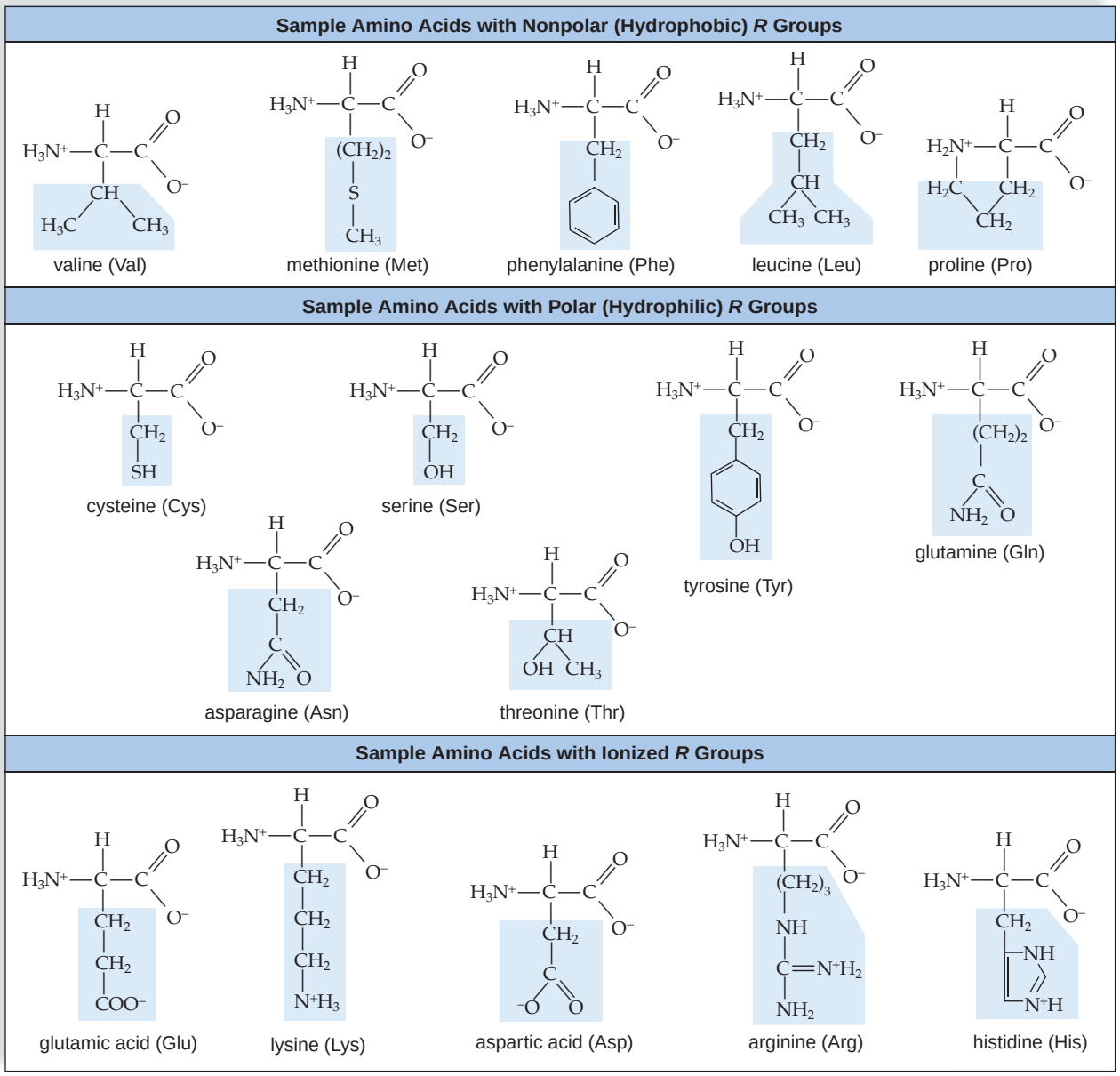


FIGURE 3.16 Amino acids.

Polypeptides contain 20 different kinds of amino acids, some of which are shown here. Amino acids differ by the particular *R* group (blue) attached to the central carbon. Some *R* groups are nonpolar and hydrophobic, some are polar and hydrophilic, and some are ionized and hydrophilic. The amino acids are shown in ionized form.

Shape of Proteins

A protein can have up to four levels of structure, but not all proteins have all four levels.

Primary Structure

The primary structure of one protein is its own particular sequence of amino acids. The following analogy can help you see that hundreds of thousands of different polypeptides can be built from just 20 amino acids: The English alphabet contains only 26 letters, but an almost infinite number of words can be constructed by varying the number and sequence of these few letters. In the same way, many different proteins can result by varying the number and sequence of just 20 amino acids.

Secondary Structure

The secondary structure of a protein occurs when the polypeptide coils or folds in a particular way (Fig. 3.17).

Linus Pauling and Robert Corey, who began studying the structure of amino acids in the late 1930s, concluded that a coiling they called an α (alpha) helix and a pleated sheet they called the β (beta) sheet were two basic patterns of amino acids within a polypeptide. The names came from the fact that the α helix was the first pattern they discovered, and the β sheet was the second pattern they discovered.

Hydrogen bonding often holds the secondary structure of a polypeptide in place. Hydrogen bonding between every fourth amino acid accounts for the spiral shape of the helix. In a β sheet, the polypeptide turns back upon itself,

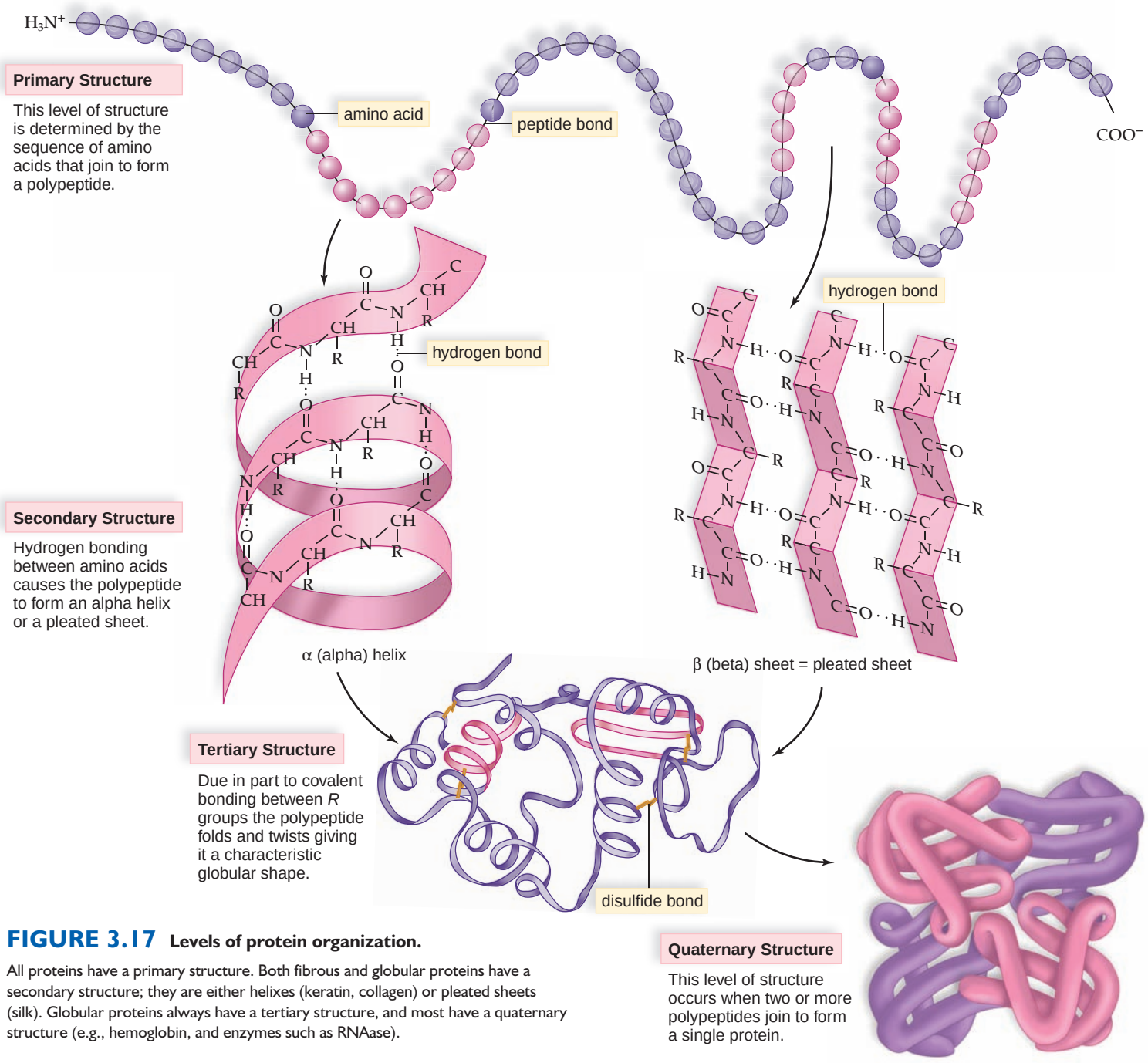


FIGURE 3.17 **Levels of protein organization.**

All proteins have a primary structure. Both fibrous and globular proteins have a secondary structure; they are either helixes (keratin, collagen) or pleated sheets (silk). Globular proteins always have a tertiary structure, and most have a quaternary structure (e.g., hemoglobin, and enzymes such as RNAase).

and hydrogen bonding occurs between extended lengths of the polypeptide. **Fibrous proteins,** which are structural proteins, exist as helices or pleated sheets that hydrogen-bond to each other. Examples are keratin, a protein in hair and silk, a protein that forms spider webs. Both of these proteins have only a secondary structure (Fig. 3.18).

Tertiary Structure

A tertiary structure is the folding that results in the final three-dimensional shape of a polypeptide. So-called **globular proteins,** which tend to ball up into rounded shapes, have a tertiary structure. Hydrogen bonds, ionic bonds, and covalent bonds between *R* groups all contribute to the tertiary structure of a polypeptide. Strong disulfide linkages in particular help maintain the tertiary shape. Hydrophobic *R* groups do not bond with other *R* groups, and they tend to collect in a common region where they are not exposed to water and can interact. Although hydrophobic interactions are not as strong as hydrogen bonds, they are important in creating and stabilizing the tertiary structure.

Enzymes are globular proteins. Enzymes work best at body temperature, and each one also has an optimal pH at which the rate of the reaction is highest. At this temperature and pH, the enzyme has its normal shape. A high temperature and change in pH can disrupt the interactions that maintain the shape of the enzyme. When a protein loses its natural shape, it is said to be **denatured.**

Quaternary Structure

Some proteins have a quaternary structure because they consist of more than one polypeptide. Hemoglobin is a much-studied globular protein that consists of four polypeptides, and therefore it has a quaternary structure. Each polypeptide in hemoglobin has a primary, secondary, and tertiary structure.

Protein-Folding Diseases

Proteins cannot function properly unless they fold into their correct shape. In recent years it has been shown that the cell contains **chaperone proteins,** which help new proteins fold into their normal shape. At first it seemed as if chaperone proteins ensured that proteins folded properly, but now it seems that they might correct any misfolding of a new protein. In any case, without fully functioning chaperone proteins, a cell's proteins may not be functional because they have misfolded. Several diseases in humans, such as cystic fibrosis and Alzheimer disease, are associated with misshapen proteins. The possibility exists that the diseases are due to missing or malfunctioning chaperone proteins.

Other diseases in humans are due to misfolded proteins, but the cause may be different. For years, investigators have been studying fatal brain diseases, known as TSEs,[1] that have no cure because no infective agent can be found. Mad cow disease is a well-known example of a TSE disease. Now it appears that TSE diseases could be due to misfolded proteins, called **prions,** that cause other proteins of the same type to fold the wrong way too. A possible relationship between prions and the functioning of chaperone proteins is now under investigation.

Check Your Progress 3.4

1. Which of the protein functions in animals is shared by plants (see page 48)?
2. What is the primary structure of a protein?
3. **a.** What does the peptide bond have to do with the secondary structure of a protein? **b.** What type of bonding maintains the tertiary structure of a protein?

[1] TSEs (transmissible spongiform encephalopathies)

a. b. c.

FIGURE 3.18 Fibrous proteins.

Fibrous proteins are structural proteins. **a.** Keratin—found, for example, in hair, horns, and hoofs—exemplifies fibrous proteins that are helical for most of their length. Keratin is a hydrogen-bonded triple helix. In this photo, Drew Barrymore has straight hair. **b.** In order to give her curly hair, water was used to disrupt the hydrogen bonds, and when the hair dried, new hydrogen bonding allowed it to take on the shape of a curler. A permanent-wave lotion induces new covalent bonds within the helix. **c.** Silk made by spiders and silkworms exemplifies fibrous proteins that are pleated sheets for most of their length. Hydrogen bonding between parts of the molecule occurs as the pleated sheet doubles back on itself.

3.5 Nucleic Acids

Nucleic acids are polymers of nucleotides with very specific functions in cells. **DNA (deoxyribonucleic acid)** is the genetic material that stores information regarding its own replication and the order in which amino acids are to be joined to make a protein. **RNA (ribonucleic acid)** is another type of nucleic acid. One type of RNA molecule called messenger RNA (mRNA) is an intermediary in the process of protein synthesis, conveying information from DNA regarding the amino acid sequence in a protein.

Some nucleotides have independent metabolic functions in cells. For example, some are components of **coenzymes,** nonprotein organic molecules that facilitate enzymatic reactions. **ATP (adenosine triphosphate)** is a nucleotide that supplies energy for synthetic reactions and for various other energy-requiring processes in cells.

Structure of DNA and RNA

Every **nucleotide** is a molecular complex of three types of molecules: phosphate (phosphoric acid), a pentose sugar, and a nitrogen-containing base (Fig. 3.19*a*). In DNA, the pentose sugar is deoxyribose, and in RNA the pentose sugar is ribose. A difference in the structure of these 5-carbon sugars accounts for their respective names because deoxyribose lacks an oxygen atom found in ribose (Fig. 3.19*b*).

There are four types of nucleotides in DNA and four types of nucleotides in RNA (Fig. 3.19*c*). The base of a nucleotide can be a pyrimidine with a single ring or a purine with a double ring. In DNA, the pyrimidine bases are cytosine and thymine; in RNA, the pyrimidine bases are cytosine and uracil. In both DNA and RNA, the purine bases are adenine or guanine. These molecules are called bases because their presence raises the pH of a solution.

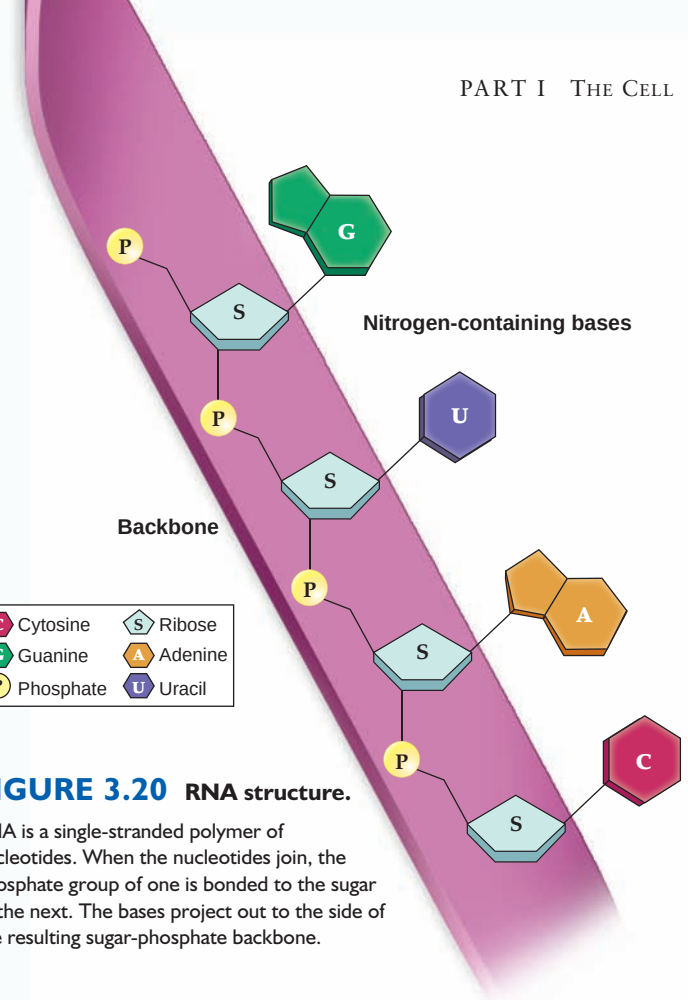


FIGURE 3.20 RNA structure.
RNA is a single-stranded polymer of nucleotides. When the nucleotides join, the phosphate group of one is bonded to the sugar of the next. The bases project out to the side of the resulting sugar-phosphate backbone.

Nucleotides join in a definite sequence by a series of dehydration reactions when DNA and RNA form. The polynucleotide is a linear molecule called a strand in which the backbone is made up of a series of sugar-phosphate-sugar-phosphate molecules. The bases project to one side of the backbone. Since the nucleotides occur in a definite order, so do the bases. RNA is single stranded (Fig. 3.20).

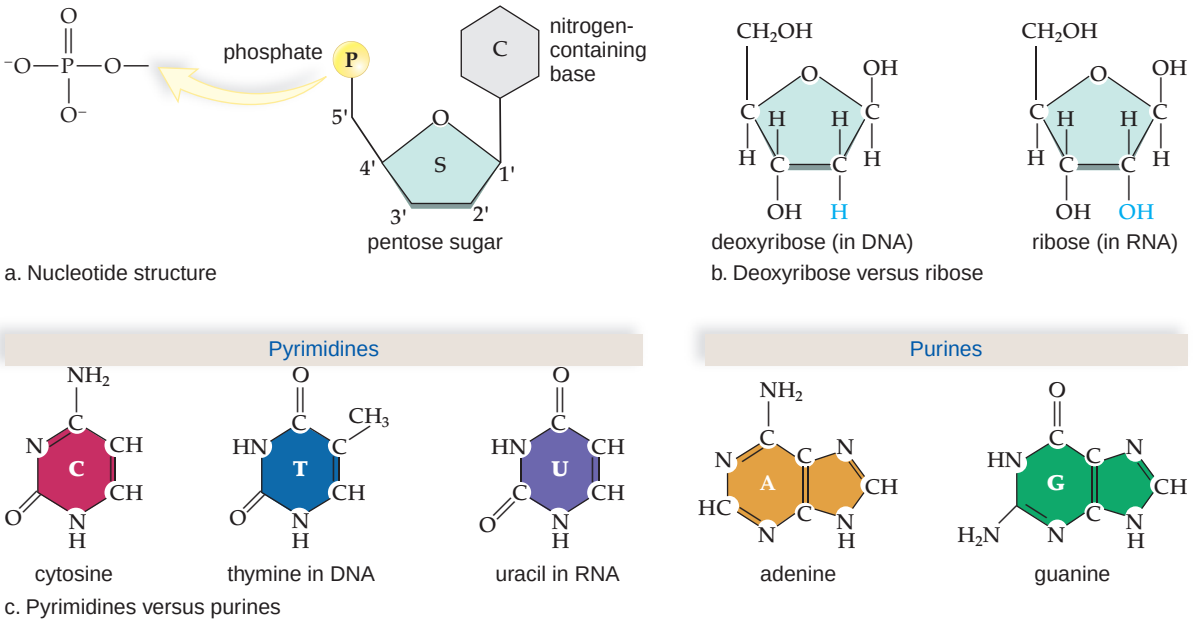
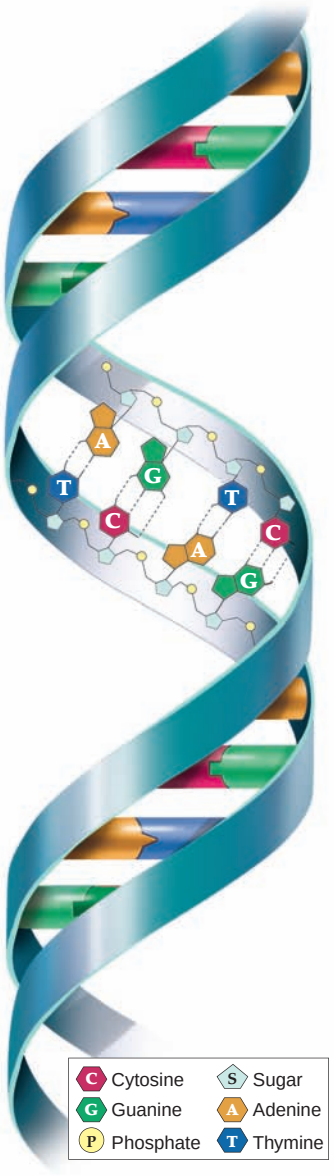


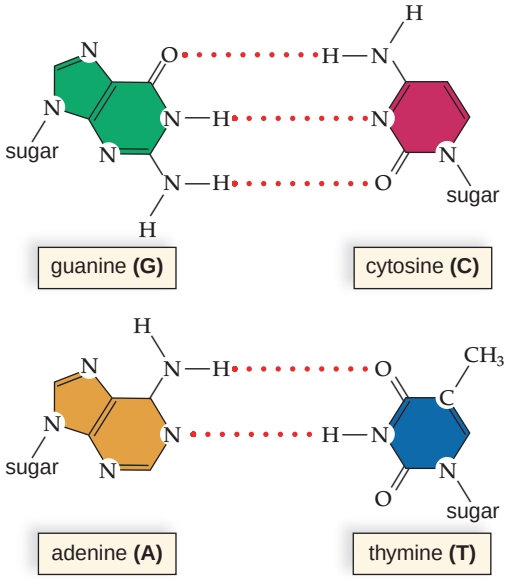
FIGURE 3.19 Nucleotides.

a. A nucleotide consists of a phosphate molecule, a pentose sugar, and a nitrogen-containing base. **b.** DNA contains the sugar deoxyribose, and RNA contains the sugar ribose. **c.** DNA contains the pyrimidines C and T and the purines A and G. RNA contains the pyrimidines C and U and the purines A and G.

a. Space-filling model



b. Double helix



c. Complementary base pairing

TABLE 3.3

DNA Structure Compared to RNA Structure

	DNA	*RNA*
Sugar	Deoxyribose	Ribose
Bases	Adenine, guanine, thymine, cytosine	Adenine, guanine, uracil, cytosine
Strands	Double stranded with base pairing	Single stranded
Helix	Yes	No

FIGURE 3.21 DNA structure.

a. Space-filling model of DNA. **b.** DNA is a double helix in which the two polynucleotide strands twist about each other. **c.** Hydrogen bonds (dotted lines) occur between the complementarily paired bases: C is always paired with G, and A is always paired with T.

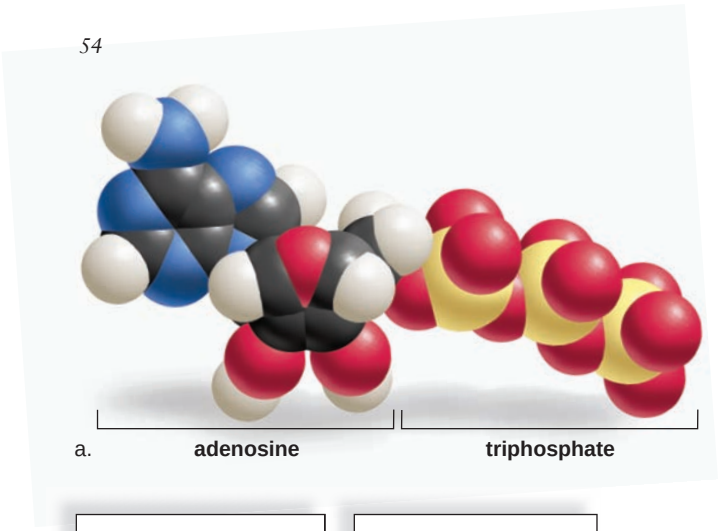
DNA is double stranded, with the two strands usually twisted about each other in the form of a double helix (Fig. 3.21*a, b*). The two strands are held together by hydrogen bonds between pyrimidine and purine bases. The bases can be in any order within a strand, but between strands, thymine (T) is always paired with adenine (A), and guanine (G) is always paired with cytosine (C). This is called **complementary base pairing.** Therefore, regardless of the order or the quantity of any particular base pair, the number of purine bases (A + G) always equals the number of pyrimidine bases (T + C) (Fig. 3.21*c*).

Table 3.3 summarizes the differences between DNA and RNA.

ATP (Adenosine Triphosphate)

ATP is a nucleotide in which **adenosine** is composed of adenine and ribose. Triphosphate stands for the three phosphate groups that are attached together and to ribose, the pentose sugar (Fig. 3.22).

ATP is a high-energy molecule because the last two phosphate bonds are unstable and are easily broken. In cells, the terminal phosphate bond is usually hydrolyzed to give the molecule **ADP (adenosine diphosphate)** and a phosphate molecule Ⓟ.



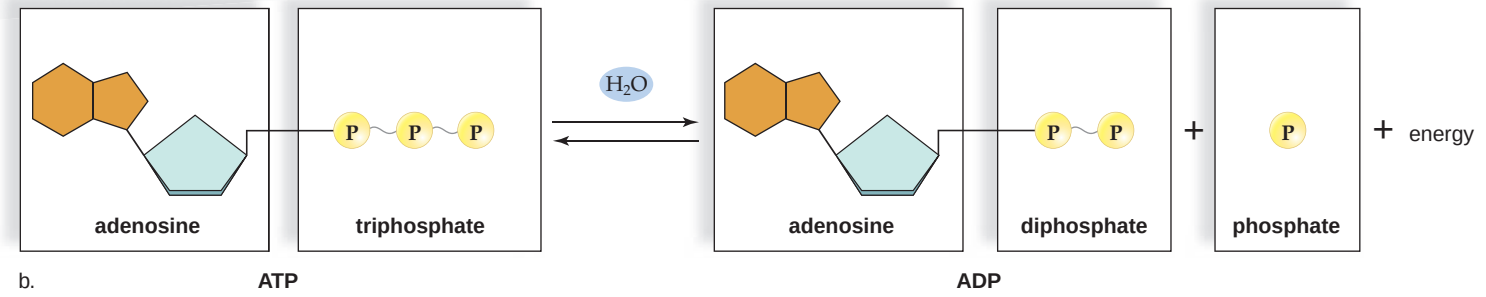


FIGURE 3.22 ATP.

ATP, the universal energy currency of cells, is composed of adenosine and three phosphate groups. **a.** Space-filling model of ATP. **b.** When cells require energy, ATP becomes ADP + Ⓟ, and energy is released. **c.** The breakdown of ATP provides the energy that an animal, such as a chipmunk, uses to acquire food and make more ATP.

The energy that is released by ATP breakdown is coupled to energy-requiring processes in cells. For example, the energy required for the synthesis of macromolecules, such as carbohydrates and proteins, is derived from ATP breakdown. ATP also supplies the energy for muscle contraction and nerve impulse conduction. Just as you spend money when you pay for a product or a service, cells "spend" ATP when they need something. Therefore, ATP is called the energy currency of cells.

Because energy is released when the last phosphate bond of ATP is hydrolyzed, it is sometimes called a high-energy bond, symbolized by a wavy line. But this terminology is misleading—the breakdown of ATP releases energy because the products of hydrolysis (ADP and Ⓟ) are more stable than the original reactant ATP. It is the entire molecule that releases energy, not a particular bond.

Check Your Progress 3.5

1. List the three components of a nucleotide.
2. What is complementary base pairing in and between nucleic acids?
3. What property of ATP makes it a carrier of energy?

Connecting the Concepts

What does the term *organic* mean? For some, organic means that food products have been grown without the use of chemicals or have been minimally processed. Biochemically speaking, organic refers to molecules containing carbon and hydrogen. In biology, organic also refers to living things or anything that has been alive in the past. Therefore, the food we eat and the wood we burn are organic substances. Fossil fuels (coal and oil) formed over 300 million years ago from plant and animal life that, by chance, did not fully decompose are also organic. When burned, they release carbon dioxide into the atmosphere just as we do when we breathe!

Although living things are very complex, certain biomolecules are simply polymers of small organic molecules. Simple sugars are the monomers of complex carbohydrates; amino acids are the monomers of proteins; nucleotides are the monomers of nucleic acids. Fats are composed of fatty acids and glycerol.

This system of forming macromolecules still allows for diversity. Monomers exist in modified forms and can combine in slightly different ways; therefore, a variety of macromolecules can come about. In cellulose, a plant product, glucose monomers are linked in a slightly different way than glucose monomers in glycogen, an animal product. One protein differs from another by the number and/or sequence of the same 20 amino acids.

There is no doubt that the chemistry of carbon is the chemistry of life. The groups of molecules discussed in this chapter, as well as other small molecules and ions, are assembled into structures that make up cells. As discussed in Chapter 4, each structure has a specific function necessary to the life of a cell.

summary

3.1 Organic Molecules

The chemistry of carbon accounts for the diversity of organic molecules found in living things. Carbon can bond with as many as four other atoms. It can also bond with itself to form both chains and rings. Differences in the carbon skeleton and attached functional groups cause organic molecules to have different chemical properties. The chemical properties of a molecule determine how it interacts with other molecules and the role the molecule plays in the cell. Some functional groups are hydrophobic and others are hydrophilic.

There are four classes of biomolecules in cells: carbohydrates, lipids, proteins, and nucleic acids (Table 3.4). Polysaccharides, the largest of the carbohydrates, are polymers of simple sugars called monosaccharides. The polypeptides of proteins are polymers of amino acids, and nucleic acids are polymers of nucleotides. Polymers are formed by the joining together of monomers. For each bond formed during a dehydration reaction, a molecule of water is removed, and for each bond broken during a hydrolysis reaction, a molecule of water is added.

3.2 Carbohydrates

Monosaccharides, disaccharides, and polysaccharides are all carbohydrates. Therefore, the term *carbohydrate* includes both the monomers (e.g., glucose) and the polymers (e.g., starch, glycogen, and cellulose). Glucose is the immediate energy source of cells. Polysaccharides such as starch, glycogen, and cellulose are polymers of glucose. Starch in plants and glycogen in animals are energy storage compounds, but cellulose in plants and chitin in crabs and related animals, as well as fungi, have structural roles. Chitin's monomer is glucose with an attached amino group.

3.3 Lipids

Lipids include a wide variety of compounds that are insoluble in water. Fats and oils, which allow long-term energy storage, contain one glycerol and three fatty acids. Both glycerol and fatty acids have polar groups, but fats and oils are nonpolar, and this accounts for their insolubility in water. Fats tend to contain saturated fatty acids, and oils tend to contain unsaturated fatty acids. Saturated fatty acids do not have carbon–carbon double bonds, but unsaturated fatty acids do have double bonds in their hydrocarbon chain. The double bond causes a kink in the molecule that accounts for the liquid nature of oils.

In a phospholipid, one of the fatty acids is replaced by a phosphate group. In the presence of water, phospholipids form a bilayer because the head of each molecule is hydrophilic and the tails are hydrophobic. Steroids have the same four-ring structure as cholesterol, but each differs by the groups attached to these rings. Waxes are composed of a fatty acid with a long hydrocarbon chain bonded to an alcohol, also with a long hydrocarbon chain.

TABLE 3.4

Organic Compounds in Cells

	Categories	*Elements*	*Examples*	*Functions*
Carbohydrates	Monosaccharides 6-carbon sugar 5-carbon sugar	C, H, O	 Glucose Deoxyribose, ribose	 Immediate energy source Found in DNA, RNA
	Disaccharides 12-carbon sugar	C, H, O	Sucrose	Transport sugar in plants
	Polysaccharides Polymer of glucose	C, H, O	Starch, glycogen, Cellulose	Energy storage in plants, animals Plant cell wall structure
Lipids	Triglycerides 1 glycerol + 3 fatty acids	C, H, O	Fats, oils	Long-term energy storage
	Phospholipids Like triglyceride except the head group contains phosphate	C, H, O, P	Lecithin	Plasma membrane phospholipid bilayer
	Steroids Backbone of 4 fused rings	C, H, O	Cholesterol Testosterone, estrogen	Plasma membrane component Sex hormones
	Waxes Fatty acid + alcohol	C, H, O	Cuticle Earwax	Protective covering in plants Protective wax in ears
Proteins	Polypeptides Polymer of amino acids	C, H, O, N, S	Enzymes Myosinand actin Insulin Hemoglobin Collagen	Speed cellular reactions Movement of muscle cells Hormonal control of blood sugar Transport of oxygen in blood Fibrous support of body parts
Nucleic Acids	Nucleic acids Polymer of nucleotides	C, H, O, N, P	DNA RNA	Genetic material Protein synthesis
	Nucleotides		ATP Coenzymes	Energy carrier Assist enzymes

3.4 Proteins

Proteins carry out many diverse functions in cells and organisms, including support, metabolism, transport, defense, regulation, and motion. Proteins contain polymers of amino acids.

A polypeptide is a long chain of amino acids joined by peptide bonds. There are 20 different amino acids in cells, and they differ only by their *R* groups. Presence or absence of polarity is an important aspect of the *R* groups. A polypeptide has up to four levels of structure: The primary level is the sequence of the amino acids, which varies between polypeptides; the secondary level contains α helices and β (pleated) sheets held in place by hydrogen bonding between amino acids along the polypeptide chain; and the tertiary level is the final folding of the polypeptide, which is held in place by bonding and hydrophobic interactions between *R* groups. Proteins that contain more than one polypeptide have a quaternary level of structure as well.

The shape of an enzyme is important to its function. Both high temperatures and a change in pH can cause proteins to denature and lose their shape.

3.5 Nucleic Acids

The nucleic acids DNA and RNA are polymers of nucleotides. Variety is possible because the nucleotides can be in any order. Each nucleotide has three components: a phosphate (phosphoric acid), a 5-carbon sugar, and a nitrogen-containing base.

DNA, which contains the sugar deoxyribose, is the genetic material that stores information for its own replication and for the order in which amino acids are to be sequenced in proteins. DNA, with the help of mRNA, specifies protein synthesis. DNA, which contains phosphate, the sugar deoxyribose, and nitrogen-containing bases, is a double-stranded helix in which A pairs with T and C pairs with G through hydrogen bonding. RNA, containing phosphate, the sugar ribose, and the bases A, U, C, and G, is single stranded.

ATP, with its unstable phosphate bonds, is the energy currency of cells. Hydrolysis of ATP to ADP + Ⓟ releases energy, which is used by the cell to make a product or do any other type of metabolic work.

understanding the terms

adenosine 53
ADP (adenosine diphosphate) 53
amino acid 49
ATP (adenosine triphosphate) 52
biomolecule 38
carbohydrate 41
cellulose 43
chaperone protein 51
chitin 43
coenzyme 52
complementary base pairing 53
dehydration reaction 40
denatured 51
deoxyribose 41
disaccharide 41
DNA (deoxyribonucleic acid) 52
fat 44
fatty acid 44
fibrous protein 51
functional group 39
globular protein 51
glucose 41
glycerol 44
glycogen 42
hemoglobin 48
hexose 41
hydrolysis reaction 40
hydrophilic 39
hydrophobic 39
inorganic chemistry 38
isomer 39
lipid 44
monomer 40
monosaccharide 41
nucleic acid 52
nucleotide 52
oil 44
organic chemistry 38
organic molecule 38
pentose 41
peptide 48
peptide bond 48
peptidoglycan 43
phospholipid 46
polymer 40
polypeptide 48
polysaccharide 42
prion 51
protein 48
ribose 41
RNA (ribonucleic acid) 52
saturated fatty acid 44
starch 42
steroid 46
triglyceride 44
unsaturated fatty acid 44
wax 47

Match the terms to these definitions:

a. _____ Class of organic compounds that includes monosaccharides, disaccharides, and polysaccharides.
b. _____ Class of organic compounds that tend to be soluble in nonpolar solvents such as alcohol but insoluble in water.
c. _____ Biomolecule consisting of covalently bonded monomers.
d. _____ Molecules that have the same molecular formula but a different structure and, therefore, shape.
e. _____ Two or more amino acids joined together by covalent bonding.

reviewing this chapter

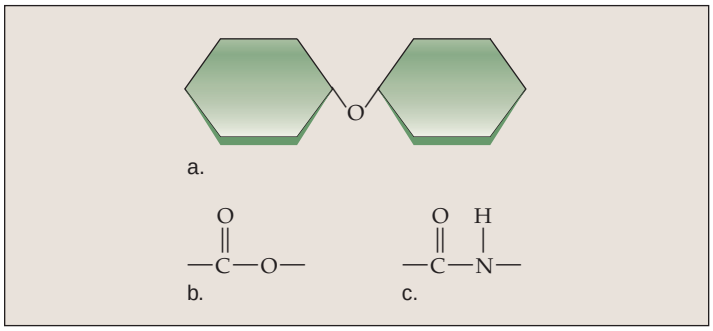
1. How do the chemical characteristics of carbon affect the structure of organic molecules? 38–39
2. Give examples of functional groups, and discuss the importance of these groups being hydrophobic or hydrophilic. 39
3. What biomolecules are monomers of the polymers studied in this chapter? How do monomers join to produce polymers, and how are polymers broken down to monomers? 40
4. Name several monosaccharides, disaccharides, and polysaccharides, and give a function of each. How are these molecules structurally distinguishable? 41–42
5. What is the difference between a saturated and an unsaturated fatty acid? Explain the structure of a fat molecule by stating its components and how they join together. 44–45
6. How does the structure of a phospholipid differ from that of a fat? How do phospholipids form a bilayer in the presence of water? 46
7. Describe the structure of a generalized steroid. How does one steroid differ from another? 46–47
8. Draw the structure of an amino acid and a peptide, pointing out the peptide bond. 48
9. Discuss the four possible levels of protein structure, and relate each level to particular bonding patterns. 50–51
10. How do nucleotides bond to form nucleic acids? State and explain several differences between the structure of DNA and that of RNA. 52–53
11. Discuss the structure and function of ATP. 53–54

testing yourself

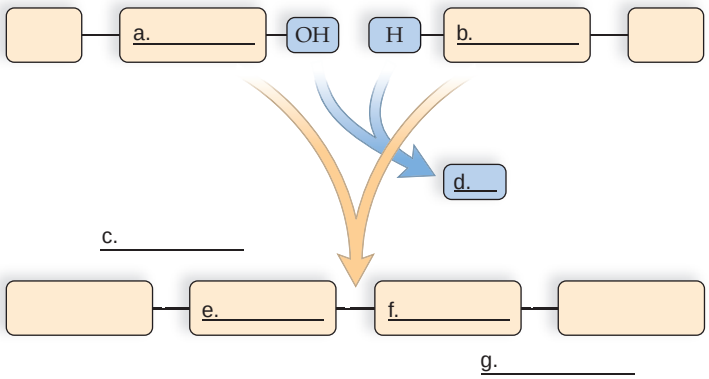
Choose the best answer for each question.

1. Which of these is not a characteristic of carbon?
   a. forms four covalent bonds
   b. bonds with other carbon atoms
   c. is sometimes ionic
   d. can form long chains
   e. sometimes shares two pairs of electrons with another atom
2. The functional group —COOH is
   a. acidic.
   b. basic.
   c. never ionized.
   d. found only in nucleotides.
   e. All of these are correct.

3. A hydrophilic group is
   a. attracted to water.
   b. a polar and/or ionized group.
   c. found at the end of fatty acids.
   d. the opposite of a hydrophobic group.
   e. All of these are correct.
4. Which of these is an example of a hydrolysis reaction?
   a. amino acid + amino acid ⟶ dipeptide + H_2O
   b. dipeptide + H_2O ⟶ amino acid + amino acid
   c. denaturation of a polypeptide
   d. Both a and b are correct.
   e. Both b and c are correct.
5. Which of these makes cellulose nondigestible in humans?
   a. a polymer of glucose subunits
   b. a fibrous protein
   c. the linkage between the glucose molecules
   d. the peptide linkage between the amino acid molecules
   e. The carboxyl groups ionize.
6. A fatty acid is unsaturated if it
   a. contains hydrogen.
   b. contains carbon–carbon double bonds.
   c. contains a carboxyl (acidic) group.
   d. bonds to glycogen.
   e. bonds to a nucleotide.
7. Which of these is not a lipid?
   a. steroid
   b. fat
   c. polysaccharide
   d. wax
   e. phospholipid
8. The difference between one amino acid and another is found in the
   a. amino group.
   b. carboxyl group.
   c. *R* group.
   d. peptide bond.
   e. carbon atoms.
9. The shape of a polypeptide is
   a. maintained by bonding between parts of the polypeptide.
   b. ultimately dependent on the primary structure.
   c. necessary to its function.
   d. All of these are correct.
10. Which of these illustrates a peptide bond?



11. Nucleotides
    a. contain a sugar, a nitrogen-containing base, and a phosphate group.
    b. are the monomers of fats and polysaccharides.
    c. join together by covalent bonding between the bases.
    d. are present in both DNA and RNA.
    e. Both a and d are correct.
12. ATP
    a. is an amino acid.
    b. has a helical structure.
    c. is a high-energy molecule that can break down to ADP and phosphate.
    d. provides enzymes for metabolism.
    e. is most energetic when in the ADP state.
13. Label the following diagram using the terms H_2O, monomer, hydrolysis reaction, dehydration reaction, and polymer. Terms can be used more than once and a term need not be used.



14. The monomer of a carbohydrate is
    a. an amino acid.
    b. a nucleic acid.
    c. a monosaccharide.
    d. a fatty acid.
15. The joining of two adjacent amino acids is called
    a. a peptide bond.
    b. a dehydration reaction.
    c. a covalent bond.
    d. All of these are correct.
16. The characteristic globular shape of a polypeptide is the
    a. primary structure.
    b. secondary structure.
    c. tertiary structure.
    d. quaternary structure.
17. The shape of a polypeptide
    a. is maintained by bonding between parts of the polypeptide.
    b. is ultimately dependent on the primary structure.
    c. involves hydrogen bonding.
    d. All of these are correct.
18. Which of the following pertains to an RNA nucleotide and not to a DNA nucleotide?
    a. contains the sugar ribose
    b. contains a nitrogen-containing base
    c. contains a phosphate molecule
    d. becomes bonded to other nucleotides following a dehydration reaction
19. Which is a carbohydrate?
    a. disaccharide
    b. amino acid
    c. dipeptide
    d. Both a and c are correct.

For questions 20–27, match the items to those in the key. Some answers are used more than once.

KEY:

a. carbohydrate
b. fats and oils
c. protein
d. nucleic acid

20. contains the bases adenine, guanine, cytosine, and thymine
21. the 6-carbon sugar, glucose
22. polymer of amino acids
23. glycerol and fatty acids
24. enzymes
25. long-term energy storage
26. genes
27. plant cell walls
28. muscle cells
29. butter
30. potato
31. Which of these does not apply to DNA?
    a. sequence of nucleotides
    b. sugar-phosphate backbone
    c. A-T and C-G
    d. sequence of amino acids
    e. Both a and c do not apply.
32. Which is a correct statement about carbohydrates?
    a. All polysaccharides serve as energy storage molecules.
    b. Glucose is broken down for immediate energy.
    c. Glucose is not a carbohydrate, only polysaccharides are.
    d. Starch, glycogen, and cellulose have different monomers.
    e. Both a and c are correct.
33. In phospholipids,
    a. heads are polar.
    b. tails are nonpolar.
    c. heads contain phosphate.
    d. All of these are correct.

For questions 34–38, match the items to those in the key.

KEY:

a. Most enzymes are globular.
b. DNA is a double helix.
c. Steroids differ by their attached groups.
d. The tails of a phospholipid can contain nonsaturated fatty acids.
e. Hydrogen bonding occurs between microfibrils of cellulose.

34. Strands held together by hydrogen bonding between strands.
35. Four fused rings plus functional groups.
36. Tertiary level of organization of a protein.
37. Provides added strength for plant cell wall.
38. Makes plasma membrane a fluid bilayer.

thinking scientifically

1. The seeds of temperate plants tend to contain unsaturated fatty acids, while the seeds of tropical plants tend to have saturated fatty acids. **a.** How would you test your hypothesis. **b.** Assuming your hypothesis is supported, give an explanation.
2. Chemical analysis reveals that an abnormal form of an enzyme contains a polar amino acid at the location where the normal form has a nonpolar amino acid. Formulate a testable hypothesis concerning the abnormal enzyme.

bioethical issue

Organic Pollutants

Organic compounds include the carbohydrates, proteins, lipids, and nucleic acids that make up our bodies. Modern industry also uses all sorts of organic compounds that are synthetically produced. Indeed, our modern way of life wouldn't be possible without synthetic organic compounds.

Pesticides, herbicides, disinfectants, plastics, and textiles contain organic substances that are termed pollutants when they enter the natural environment and cause harm to living things. Global use of pesticides has increased dramatically since the 1950s, and modern pesticides are ten times more toxic than those of the 1950s. The Centers for Disease Control and Prevention in Atlanta reports that 40% of children working in agricultural fields now show signs of pesticide poisoning. The U.S. Geological Survey estimates that 32 million people in urban areas and 10 million people in rural areas are using groundwater that contains organic pollutants. J. Charles Fox, an official of the Environmental Protection Agency, says that "over the life of a person, ingestion of these chemicals has been shown to have adverse health effects such as cancer, reproductive problems, and developmental effects."

At one time, people failed to realize that everything in the environment is connected to everything else. In other words, they didn't know that an organic chemical can wander far from the site of its entry into the environment and that eventually these chemicals can enter our own bodies and cause harm. Now that we are aware of this outcome, we have to decide as a society how to proceed. We might decide to do nothing if the percentage of people dying from exposure to organic pollutants is small. Or we might decide to regulate the use of industrial compounds more strictly than has been done in the past. We could also decide that we need better ways of purifying public and private water supplies so that they do not contain organic pollutants.

Biology website

The companion website for *Biology* provides a wealth of information organized and integrated by chapter. You will find practice tests, animations, videos, and much more that will complement your learning and understanding of general biology.

http://www.mhhe.com/maderbiology10

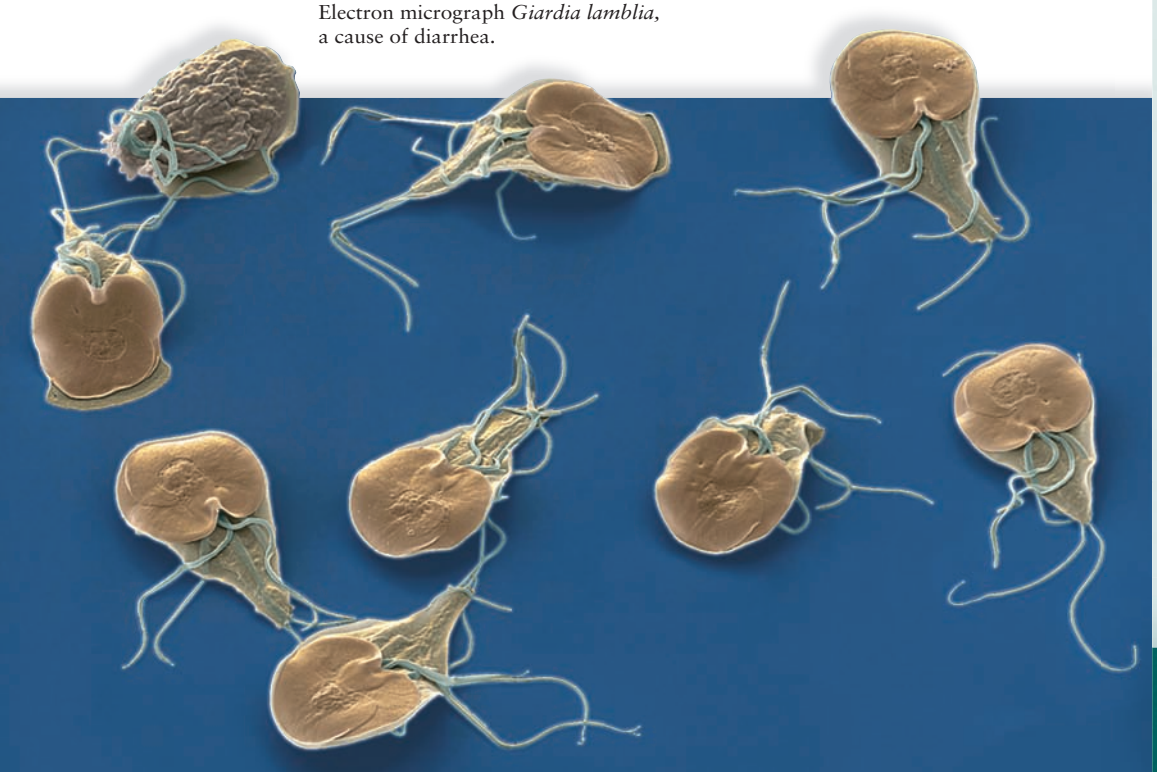
4

Cell Structure and Function

The Dutch shopkeeper Antoni van Leeuwenhoek (1632–1723) may have been the first person to see living cells. Using a microscope he built himself, he looked at everything possible, including his own stool. He wrote, "I have usually of a morning a well-formed stool. But, hitherto, I have had sometimes a looseness of bowels, so I went to stool some twice, thrice, or four times a day. My excrement being so thin, I was at diverse times constrained to examine it. Wherein I have sometimes seen animalcules a moving prettily. Their bodies were somewhat longer than broad, and the belly, which was flat-lie, furnished with sundry little paws. . . ."
November 9, 1681.

In this way, Antoni van Leeuwenhoek reported seeing the parasite Giardia lamblia *in his feces. Giardia are unicellular organisms, while humans are multicellular organisms. In this chapter, we will see that cells are the fundamental building blocks of organisms organized to carry out basic metabolic functions. We will concentrate on the generalized bacterial, animal, and plant cell, while still realizing that all cells are specialized in particular ways.*

Electron micrograph *Giardia lamblia*, a cause of diarrhea.



concepts

4.1 Cellular Level of Organization

Figure 4.1 illustrates that in our daily lives we observe whole organisms, but if it were possible to view them internally with a microscope, we would see their cellular nature. This became clear to microscopists during the 1830s.

In 1831, the English botanist Robert Brown described the nucleus of cells. In 1838, the German botanist Matthais Schleiden stated that all plants are composed of cells. A year later, the German zoologist Theodor Schwann declared that all animals are composed of cells. As a result of their work, the field of cytology (study of cells) began, and we can conclude that a **cell** is the smallest unit of living matter.

In the 1850s, the German physician Rudolph Virchow viewed the human body as a state in which each cell was a citizen. Today, we know that various illnesses of the body, such as diabetes and prostate cancer, are due to a malfunctioning of cells, rather than the organ itself. It also means that a cell is the basic unit of function as well as structure in organisms.

Virchow was the first to tell us that cells reproduce and "every cell comes from a preexisting cell." When unicellular organisms reproduce, a single cell divides, and when multicellular organisms grow, many cells divide. Cells are also involved in the sexual reproduction of multicellular organisms. In reality, there is a continuity of cells from generation to generation, even back to the very first cell (or cells) in the history of life. Due to countless investigations, which began with the work of Virchow, it is evident that cells are capable of self-reproduction.

The **cell theory** is based upon the work of Schleiden, Schwann, and Virchow. It states that:

1. all organisms are composed of cells,
2. cells are the basic units of structure and function in organisms, and
3. cells come only from preexisting cells because cells are self-reproducing.

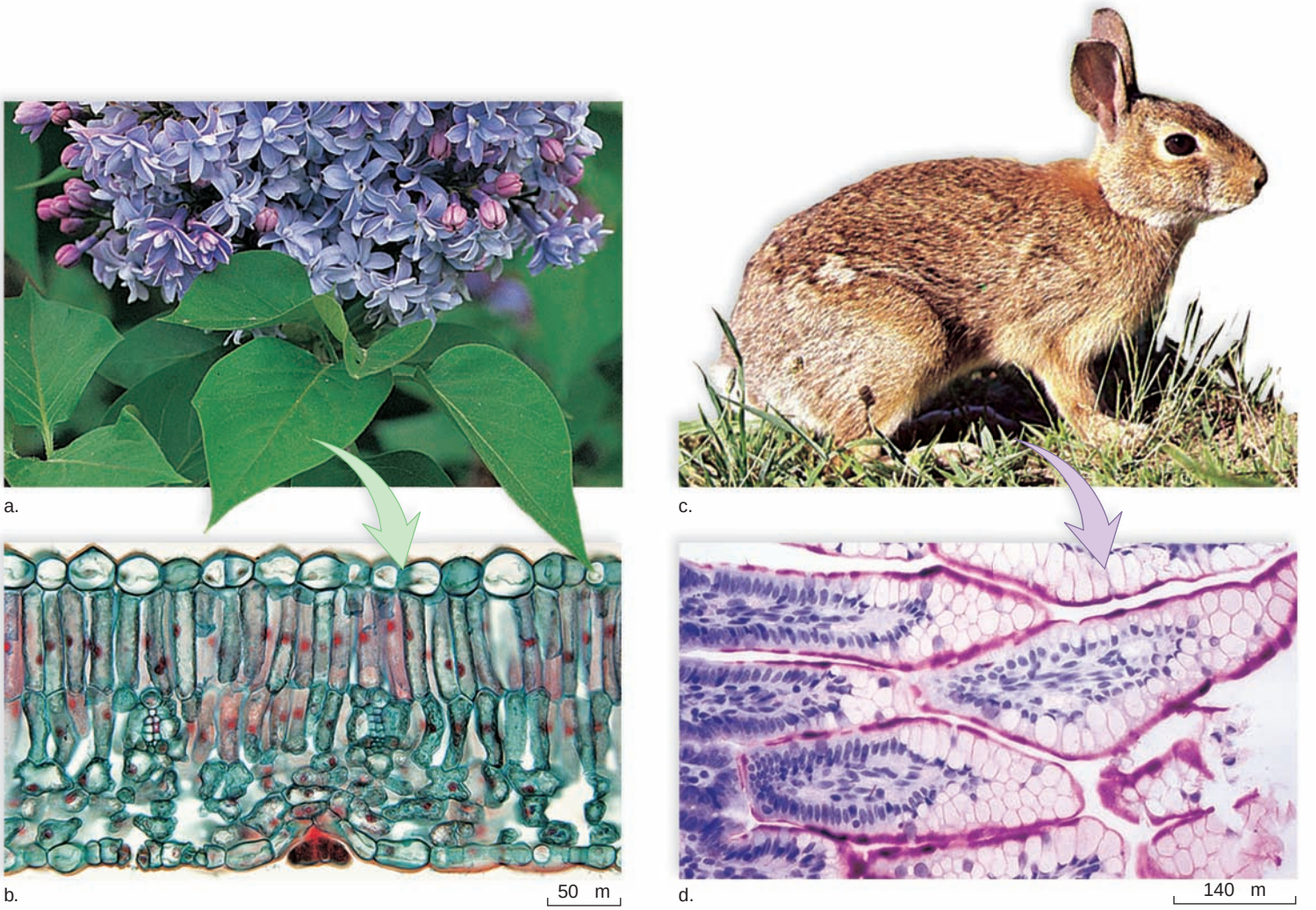


FIGURE 4.1 Organisms and cells.

All organisms, including plants and animals, are composed of cells. This is not readily apparent because a microscope is usually needed to see the cells. **a.** Lilac plant. **b.** Light micrograph of a cross section of a lilac leaf showing many individual cells. **c.** Rabbit. **d.** Light micrograph of a rabbit's intestinal lining showing that it, too, is composed of cells. The dark-staining bodies are nuclei.

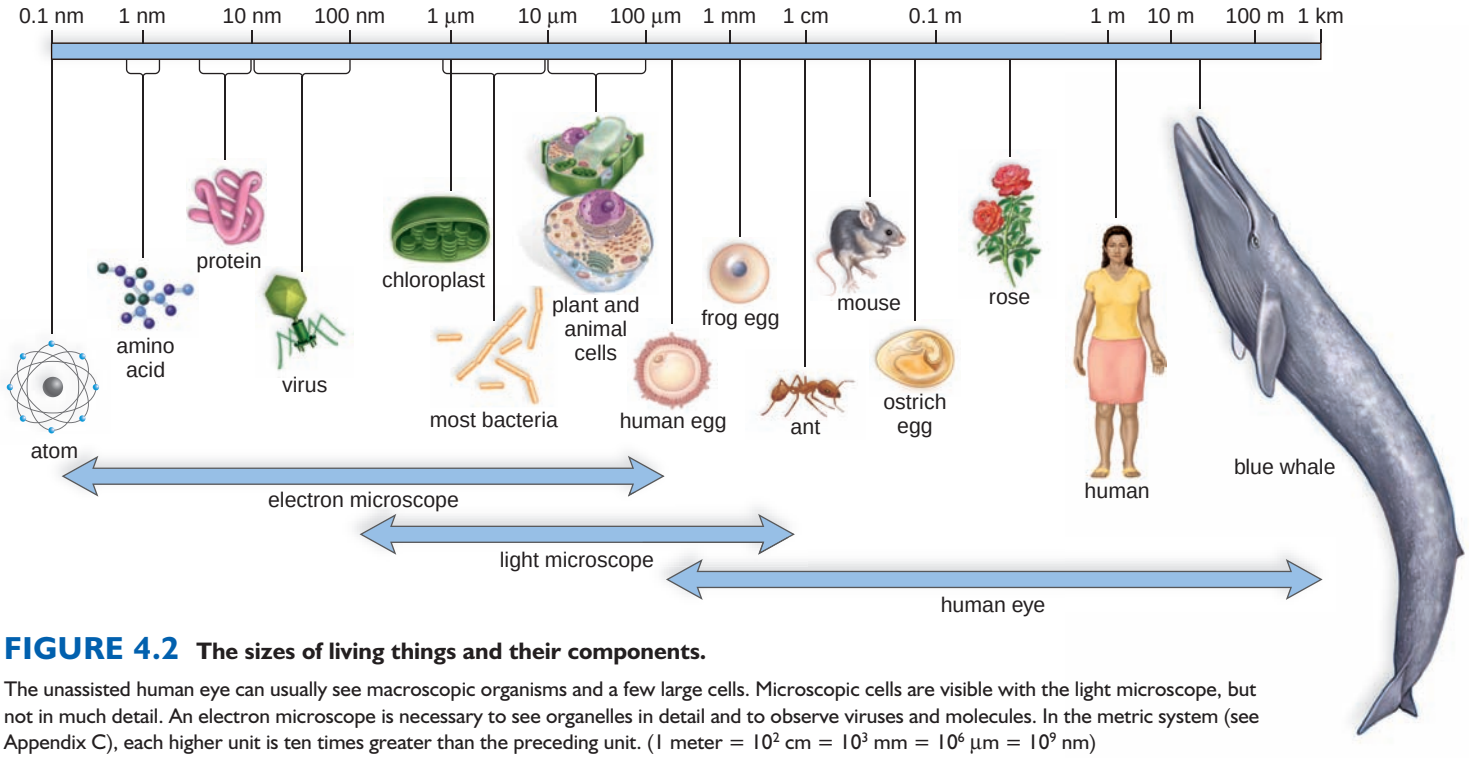


FIGURE 4.2 The sizes of living things and their components.

The unassisted human eye can usually see macroscopic organisms and a few large cells. Microscopic cells are visible with the light microscope, but not in much detail. An electron microscope is necessary to see organelles in detail and to observe viruses and molecules. In the metric system (see Appendix C), each higher unit is ten times greater than the preceding unit. (1 meter = 10^2 cm = 10^3 mm = 10^6 µm = 10^9 nm)

Cell Size

Cells are quite small. A frog's egg, at about 1 millimeter (mm) in diameter, is large enough to be seen by the human eye. But most cells are far smaller than 1 mm; some are even as small as 1 micrometer (µm)—one thousandth of a millimeter. Cell inclusions and macromolecules are smaller than a micrometer and are measured in terms of nanometers (nm). Figure 4.2 outlines the visual range of the eye, light microscope, and electron microscope, and the discussion of microscopy in the Science Focus on pages 62 and 63 explains why the electron microscope allows us to see so much more detail than the light microscope does.

Why are cells so small? To answer this question, consider that a cell needs a surface area large enough to allow adequate nutrients to enter and to rid itself of wastes. Small cells, not large cells, are likely to have an adequate surface area for exchanging wastes for nutrients. For example, Figure 4.3 visually demonstrates that cutting a large cube into smaller cubes provides a lot more surface area per volume. The calculations show that a 4-cm cube has a **surface-area-to-volume ratio** of only 1.5:1, whereas a 1-cm cube has a surface-area-to-volume ratio of 6:1.

A mental image might help you realize that a smaller cell has more surface area per volume than a large cell. Imagine a small room and a large room packed with people. The small room has only two doors and the large room has four doors. But in case of fire, the smaller room has the more favorable ratio of doors to people. Similarly, the small cell is more advantageous for the exchange of molecules because of its greater surface-area-to-volume ratio.

We would expect then that actively metabolizing cells would have to remain small. A chicken's egg is several centimeters in diameter, but the egg is not actively metabolizing. Once the egg is incubated and metabolic activity begins, the egg divides repeatedly without growth. Cell division restores the amount of surface area needed for adequate exchange of materials.

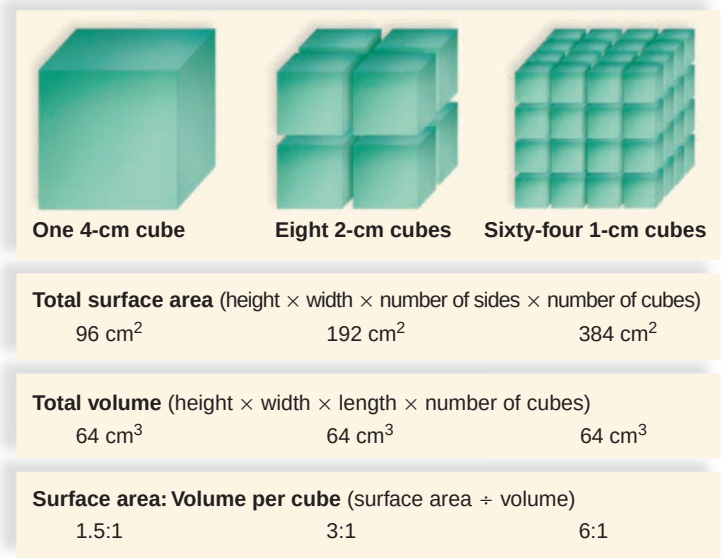


FIGURE 4.3 Surface-area-to-volume relationships.

As cell size decreases from 4 cm^3 to 1 cm^3, the surface-area-to-volume ratio increases.

Check Your Progress 4.1

1. Explain why a large surface-area-to-volume ratio is needed for the proper functioning of cells.

science focus

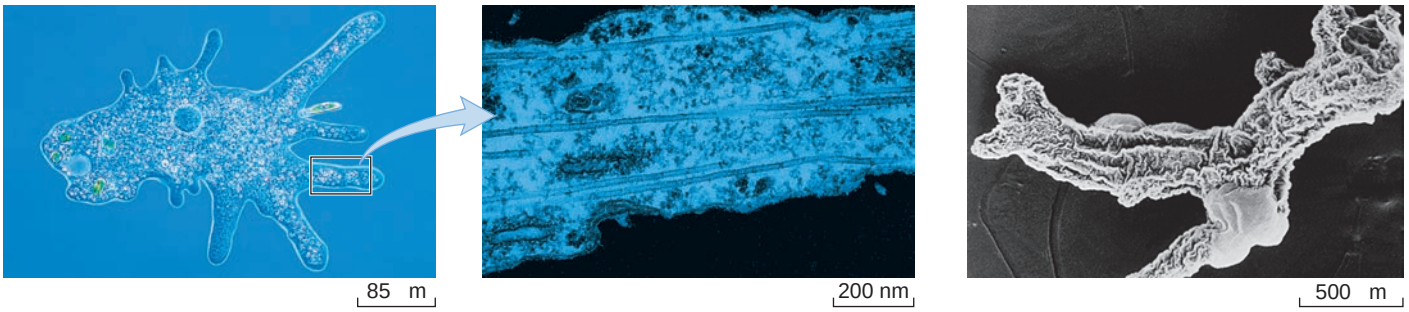
Microscopy Today

Cells were not discovered until the seventeenth century (when the microscope was invented). Since that time, various types of microscopes have been developed for the study of cells and their components.

In the *compound light microscope*, light rays passing through a specimen are brought into focus by a set of glass lenses, and the resulting image is then viewed by the human eye. In the *transmission electron microscope (TEM)*, electrons passing through a specimen are brought into focus by a set of electromagnetic lenses, and the resulting image is projected onto a fluorescent screen or photographic film. In the *scanning electron microscope (SEM)*, a narrow beam of electrons is scanned over the surface of the specimen, which is coated with a thin metal layer. The metal gives off secondary electrons that are collected by a detector to produce an image on a television screen. The SEM permits the development of three-dimensional images. Figure 4A shows these three types of microscopic images.

Magnification, Resolution, and Contrast

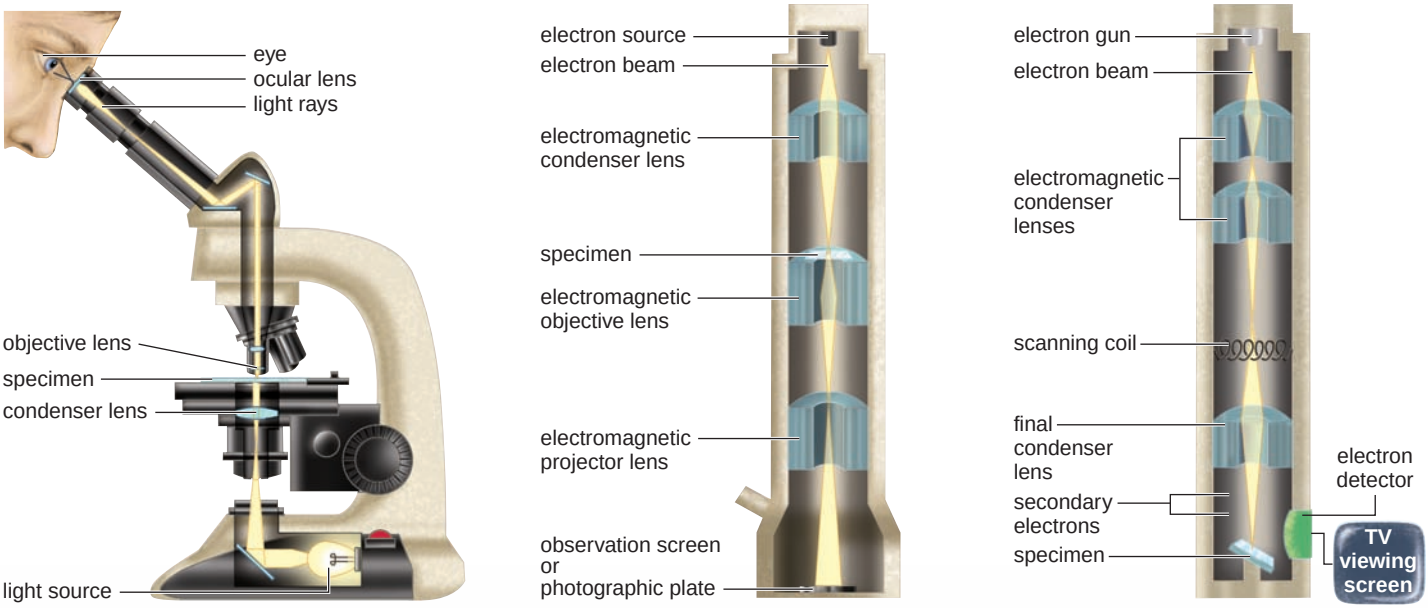
Magnification is the ratio between size of an image and its actual size. The electron microscope magnifies to a greater extent than does the compound light microscope. A light microscope can magnify objects about a thousand times, but an electron microscope can magnify them hundreds of thousands of times. The difference lies in the means of illumination. The path of light rays and electrons moving through



amoeba, light micrograph

pseudopod segment, transmission electron micrograph

amoeba, scanning electron micrograph



a. Compound light microscope

b. Transmission electron microscope

c. Scanning electron microscope

FIGURE 4A Diagram of microscopes with accompanying micrographs of *Amoeba proteus*.
a. *The compound light microscope and* ***(b)*** *the transmission electron microscope provide an internal view of an organism.* ***c.*** *The scanning electron microscope provides an external view of an organism.*

space is wavelike, but the wavelength of electrons is much shorter than the wavelength of light. This difference in wavelength accounts for the electron microscope's greater magnifying capability and its greater resolving power.

Resolution is the minimum distance between two objects that allows them to be seen as two separate objects. A microscope with poor resolution might enable a student to see only one cellular granule, while the microscope with the better resolution would show two granules next to each other. The greater the resolving power, the greater the detail eventually seen. If oil is placed between the sample and the objective lens of the compound light microscope, the resolving power is increased, and if ultraviolet light is used instead of visible light, it is also increased. But typically, a light microscope can resolve down to 0.2 μm, while the transmission electron microscope can resolve down to 0.0002 μm. If the resolving power of the average human eye is set at 1.0, then that of the typical compound light microscope is about 500, and that of the transmission electron microscope is 100,000 (Fig. 4A*b*).

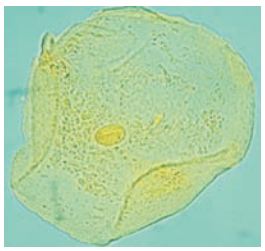
The ability to make out a particular object can depend on **contrast,** a difference in the shading of an object compared to its background. Contrast is often achieved by staining cells with colored dyes (light microscopy) or with electron-dense metals (electron microscopy). Another way to increase contrast is to use optical methods such as phase contrast and differential interference contrast (Fig. 4B). Then, too, fluorescent antibodies will attach to particular proteins in a cell to reveal their presence (see Fig. 4.18).

Illumination, Viewing, and Recording

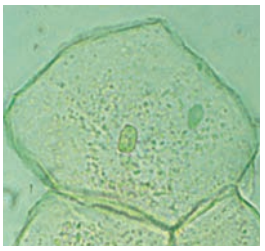
Light rays can be bent (refracted) and brought to focus as they pass through glass lenses, but electrons do not pass through glass. Electrons have a charge that allows them to be brought into focus by electromagnetic lenses. The human eye uses light to see an object but cannot use electrons for the same purpose. Therefore, electrons leaving the specimen in the electron microscope are directed toward a screen or a photographic plate that is sensitive to their presence. Humans can view the image on the screen or photograph.

A major advancement in illumination has been the introduction of *confocal microscopy,* which uses a laser beam scanned across the specimen to focus on a single shallow plane within the cell. The microscopist can "optically section" the specimen by focusing up and down, and a series of optical sections can be combined in a computer to create a three-dimensional image, which can be displayed and rotated on the computer screen.

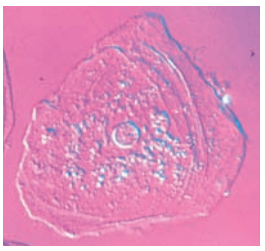
An image from a microscope may be recorded by replacing the human eye with a television camera. The television camera converts the light image into an electronic image, which can be entered into a computer. In *video-enhanced contrast microscopy,* the computer makes the darkest areas of the original image much darker and the lightest areas of the original much lighter. The result is a high-contrast image with deep blacks and bright whites. Even more contrast can be introduced by the computer if shades of gray are replaced by colors.



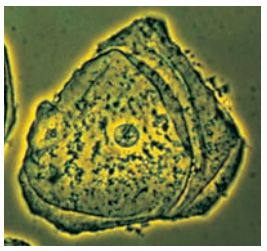
Bright-field. Light passing through the specimen is brought directly into focus. Usually, the low level of contrast within the specimen interferes with viewing all but its largest components.



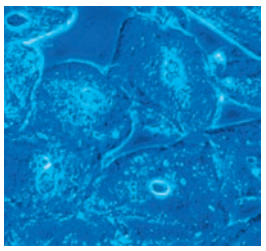
Bright-field (stained). Dyes are used to stain the specimen. Certain components take up the dye more than other components, and therefore contrast is enhanced.



Differential interference contrast. Optical methods are used to enhance density differences within the specimen so that certain regions appear brighter than others. This technique is used to view living cells, chromosomes, and organelle masses.



Phase contrast. Density differences in the specimen cause light rays to come out of "phase." The microscope enhances these phase differences so that some regions of the specimen appear brighter or darker than others. The technique is widely used to observe living cells and organelles.



Dark-field. Light is passed through the specimen at an oblique angle so that the objective lens receives only light diffracted and scattered by the object. This technique is used to view organelles, which appear quite bright against a dark field.

FIGURE 4B Photomicrographs of cheek cells.
Bright-field microscopy is the most common form used with a compound light microscope. Other types of microscopy include differential interference contrast, phase contrast, and dark-field.

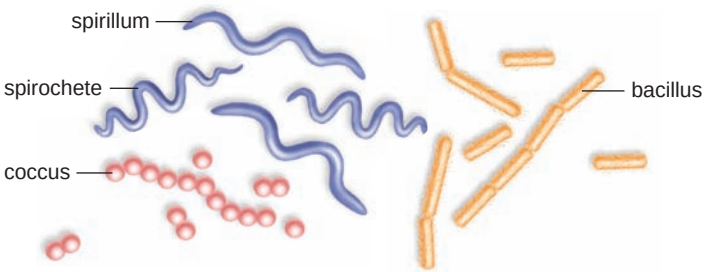
4.2 Prokaryotic Cells

Fundamentally, two different types of cells exist. **Prokaryotic cells** [Gk. *pro,* before, and *karyon,* kernel, nucleus] are so named because they lack a membrane-bounded nucleus. The other type of cell, called a **eukaryotic cell** [Gk. *eu,* true, and *karyon,* kernel, nucleus], has a nucleus (see Figs. 4.6 and 4.7). Prokaryotes are present in great numbers in the air, in bodies of water, in the soil, and they also live in and on other organisms. Although they are structurally less complicated than eukaryotes, their metabolic capabilities as a group far exceed those of eukaryotes. Prokaryotes are an extremely successful group of organisms whose evolutionary history dates back to the first cells on Earth.

Prokaryotic cells are divided into two types, largely based on DNA and RNA base sequence differences. The two groups of prokaryotes are so biochemically different that they have been placed in separate domains, called domain Bacteria and domain Archaea. Bacteria are well known because they cause some serious diseases, such as tuberculosis, anthrax, tetanus, throat infections, and gonorrhea. But many species of bacteria are important to the environment because they decompose the remains of dead organisms and contribute to ecological cycles. Bacteria also assist humans in still another way—we use them to manufacture all sorts of products, from industrial chemicals to foodstuffs and drugs. For example, today we know how to place human genes in bacteria so that they will produce human insulin, a necessary hormone for the treatment of diabetes.

The Structure of Prokaryotes

Prokaryotes are quite small; an average size is 1.1–1.5 µm wide and 2.0–6.0 µm long. While other prokaryote shapes have been identified, three basic shapes are most common:

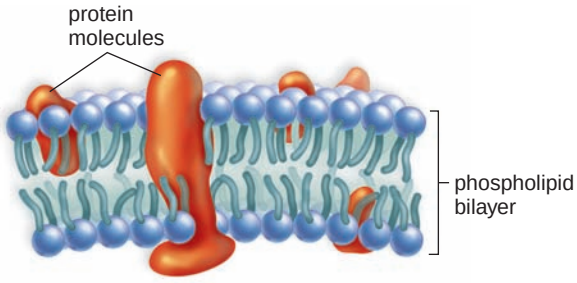


A rod-shaped bacterium is called a **bacillus,** while a spherical-shaped bacterium is a **coccus.** Both of these can occur as pairs or chains, and in addition, cocci can occur as clusters. Some long rods are twisted into spirals, in which case they are **spirilla** if they are rigid or **spirochetes** if they are flexible.

Figure 4.4 shows the generalized structure of a bacterium. This means that not all bacteria have all the structures depicted, and some have more than one of each. Also, for the sake of discussion, we will divide the organization of bacteria into the cell envelope, the cytoplasm, and the appendages.

Cell Envelope

In bacteria, the **cell envelope** includes the plasma membrane, the cell wall, and the glycocalyx. The **plasma membrane** is a phospholipid bilayer with embedded proteins:



The plasma membrane has the important function of regulating the entrance and exit of substances into and out of the cytoplasm. After all, the cytoplasm has a normal composition that needs to be maintained.

In prokaryotes, the plasma membrane can form internal pouches called mesosomes. **Mesosomes** most likely increase the internal surface area for the attachment of enzymes that are carrying on metabolic activities.

The **cell wall,** when present, maintains the shape of the cell, even if the cytoplasm should happen to take up an abundance of water. You may recall that the cell wall of a plant cell is strengthened by the presence of cellulose, while the cell wall of a bacterium contains peptidoglycan, a complex molecule containing a unique amino disaccharide and peptide fragments.

The **glycocalyx** is a layer of polysaccharides lying outside the cell wall in some bacteria. When the layer is well organized and not easily washed off, it is called a **capsule.** A slime layer, on the other hand, is not well organized and is easily removed. The glycocalyx aids against drying out and helps bacteria resist a host's immune system. It also helps bacteria attach to almost any surface.

Cytoplasm

The **cytoplasm** is a semifluid solution composed of water and inorganic and organic molecules encased by a plasma membrane. Among the organic molecules are a variety of enzymes, which speed the many types of chemical reactions involved in metabolism.

The DNA of a prokaryote is found in a chromosome that coils up and is located in a region called the **nucleoid.** Many bacteria also have an extrachromosomal piece of circular DNA called a **plasmid.** Plasmids are routinely used in biotechnology laboratories as vectors to transport DNA into a bacterium—even human DNA can be put into a bacterium by using a plasmid as a vector. This technology is important in the production of new medicines.

The many proteins specified for by bacterial DNA are synthesized on tiny particles called **ribosomes.** A bacterial cell contains thousands of ribosomes that are smaller than eukaryotic ribosomes. However, bacterial ribosomes still

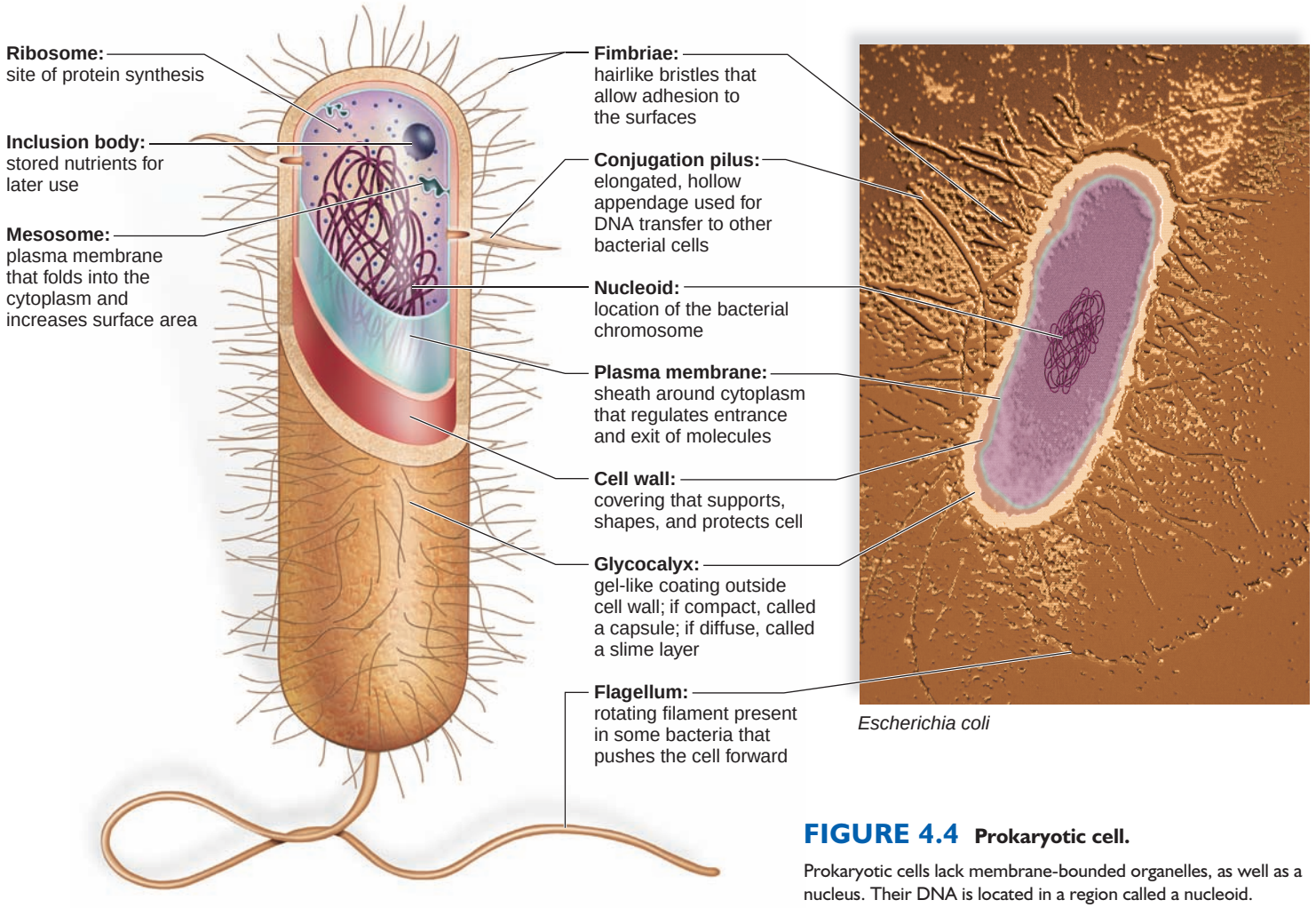


FIGURE 4.4 Prokaryotic cell.

Prokaryotic cells lack membrane-bounded organelles, as well as a nucleus. Their DNA is located in a region called a nucleoid.

contain RNA and protein in two subunits, as do eukaryotic ribosomes. The **inclusion bodies** found in the cytoplasm are stored granules of various substances. Some are nutrients that can be broken down when needed.

Most bacteria metabolize in the same manner as animals, but the **cyanobacteria** are bacteria that photosynthesize in the same manner as plants. These organisms live in water, in ditches, on buildings, and on the bark of trees. Their cytoplasm contains extensive internal membranes called **thylakoids** [Gk. *thylakon*, small sac], where chlorophyll and other pigments absorb solar energy for the production of carbohydrates. Cyanobacteria are called the blue-green bacteria because some have a pigment that adds a shade of blue to the cell, in addition to the green color of chlorophyll. The cyanobacteria release oxygen as a side product of photosynthesis, and perhaps ancestral cyanobacteria were the first types of organisms on Earth to do so. The addition of oxygen changed the composition of the Earth's atmosphere.

Appendages

The appendages of a bacterium, namely the flagella, fimbriae, and conjugation pili, are made of protein. Motile bacteria can propel themselves in water by the means of appendages called **flagella** (usually 20 nm in diameter and 1–70 nm long). The bacterial flagellum has a filament, a hook, and a basal body. The basal body is a series of rings anchored in the cell wall and membrane. The hook rotates 360° within the basal body, and this motion propels bacteria—the bacterial flagellum does not move back and forth like a whip. Sometimes flagella occur only at the two ends of a cell, and sometimes they are dispersed randomly over the surface. The number and location of flagella can be used to help distinguish different types of bacteria.

Fimbriae are small, bristlelike fibers that sprout from the cell surface. They are not involved in locomotion; instead, fimbriae attach bacteria to a surface. **Conjugation pili** are rigid tubular structures used by bacteria to pass DNA from cell to cell. Bacteria reproduce asexually by binary fission, but they can exchange DNA by way of the conjugation pili. They can also take up DNA from the external medium or by way of viruses.

Check Your Progress 4.2

1. What is the major distinction between a prokaryotic cell and a eukaryotic cell?
2. Which of the structures shown in Figure 4.4 pertain to the cell envelope, the cytoplasm, and the appendages?

4.3 Introducing Eukaryotic Cells

Eukaryotic cells, like prokaryotic cells, have a plasma membrane that separates the contents of the cell from the environment and regulates the passage of molecules into and out of the cytoplasm. The plasma membrane is a phospholipid bilayer with embedded proteins. It has been suggested by some scientists that the nucleus evolved as the result of the invagination of the plasma membrane (Fig. 4.5).

Origin of the Eukaryotic Cell

While Figure 4.5 suggests that the nucleus evolved as a result of plasma membrane invagination, the **endosymbiotic theory** says that mitochondria and chloroplasts, the two energy-related organelles, arose when a large eukaryotic cell engulfed independent prokaryotes. This explains why they are bounded by a double membrane and contain their own genetic material separate from that of the nucleus. We will be mentioning this theory again when the structure and function of mitochondria and chloroplasts are discussed in more detail later in the chapter. Figures 4.6 and 4.7 can represent the fully evolved animal and plant cell, but they are generalized cells. A specialized cell, as opposed to a generalized cell, does not contain all the structures depicted and may have more copies of any particular organelle. A generalized cell is useful for study purposes, but the body of a plant or animal is made up of specialized cells.

Structure of Eukaryotic Cell

Some eukaryotic cells, notably plant cells and those of fungi and many protists, have a cell wall in addition to a plasma membrane. A plant cell wall contains cellulose fibrils and, therefore, has a different composition from the bacterial cell wall.

As shown in Figures 4.6 and 4.7, eukaryotic cells are compartmentalized—they have compartments. The compartments of a eukaryotic cell, typically called **organelles,** are membranous. The nucleus is a compartment that houses the genetic material within eukaryotic chromosomes. The nucleus communicates with ribosomes in the cytoplasm, and the organelles of the endomembrane system—notably the endoplasmic reticulum and the Golgi apparatus—communicate with one another. Because each organelle has its own particular set of enzymes it produces its own products, and the products move from one organelle to the other. The products are carried between organelles by little transport **vesicles,** membranous sacs that enclose the molecules and keep them separate from the cytoplasm. For example, the endoplasmic reticulum communicates with the Golgi apparatus by means of transport vesicles. Communication with the energy-related organelles—mitochondria and chloroplasts—is less obvious but it does occur because they are capable of importing particular molecules from the cytoplasm. An animal cell has only mitochondria, while a plant cell has both mitochondria and chloroplasts.

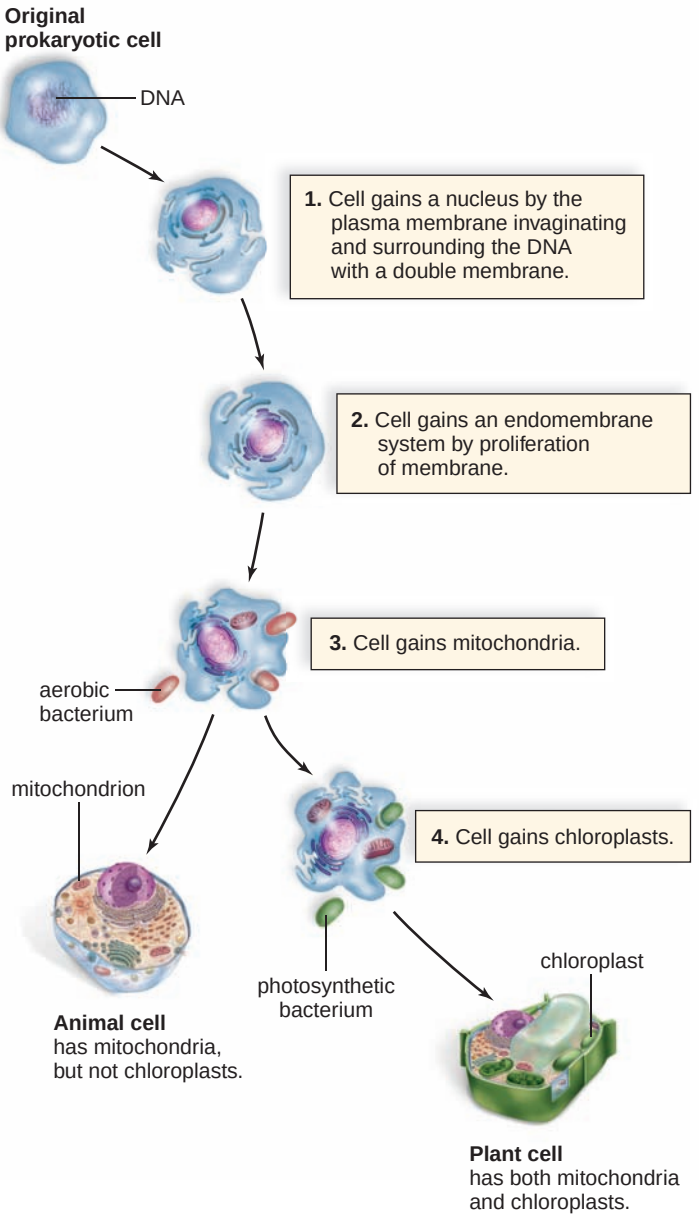


FIGURE 4.5 Origin of organelles.

Invagination of the plasma membrane could have created the nuclear envelope and an endomembrane system that involves several organelles. The endosymbiotic theory states that mitochondria and chloroplasts were independent prokaryotes that took up residence in a eukaryotic cell. Mitochondria carry on cellular respiration, and chloroplasts carry on photosynthesis. Endosymbiosis was a first step toward the origin of the plant and animal cell during the evolutionary history of life.

Each membranous organelle has a specific structure and function. This is possible because all the molecules necessary to specificity can be concentrated inside an organelle. The internal membrane of organelles provides a large surface for the attachment of enzymes. Having organelles also means that cells can become specialized by the presence or absence of particular organelles. The final result has been the complexity we associate with an organism that has

science focus

Separating the Contents of Cells

Modern microscopy can be counted on to reveal the structure and distribution of organelles in a cell. But how do researchers separate the different types of organelles from a cell so that they can determine their function? Suppose, for example, you wanted to study the function of ribosomes. How would you acquire some ribosomes? First, researchers remove cells from an organism or cell culture and place them in a sugar or salt solution. Then they fractionate (break open) the cells in a tube.

A process called *differential centrifugation* allows researchers to separate the parts of a cell by size and density. A centrifuge works like the spin cycle of a washing machine. Only when the centrifuge spins do cell components come out of suspension and form a sediment. The faster the centrifuge spins, the smaller the components that settle out.

Figure 4C shows that the slowest spin cycle separates out the nuclei, and then progressively faster cycles separate out ever smaller components. In between spins, the fluid portion of the previous cycle must be poured into another test tube. Why? If you didn't start with a fresh tube, all the different cell parts would pile up in the sediment of one tube.

By using different concentrations of salt solutions and different centrifuge speeds, researchers can obtain essentially pure preparations of almost any cell component. Biochemical analysis and manipulation then allow them to determine the functions of that cell component.

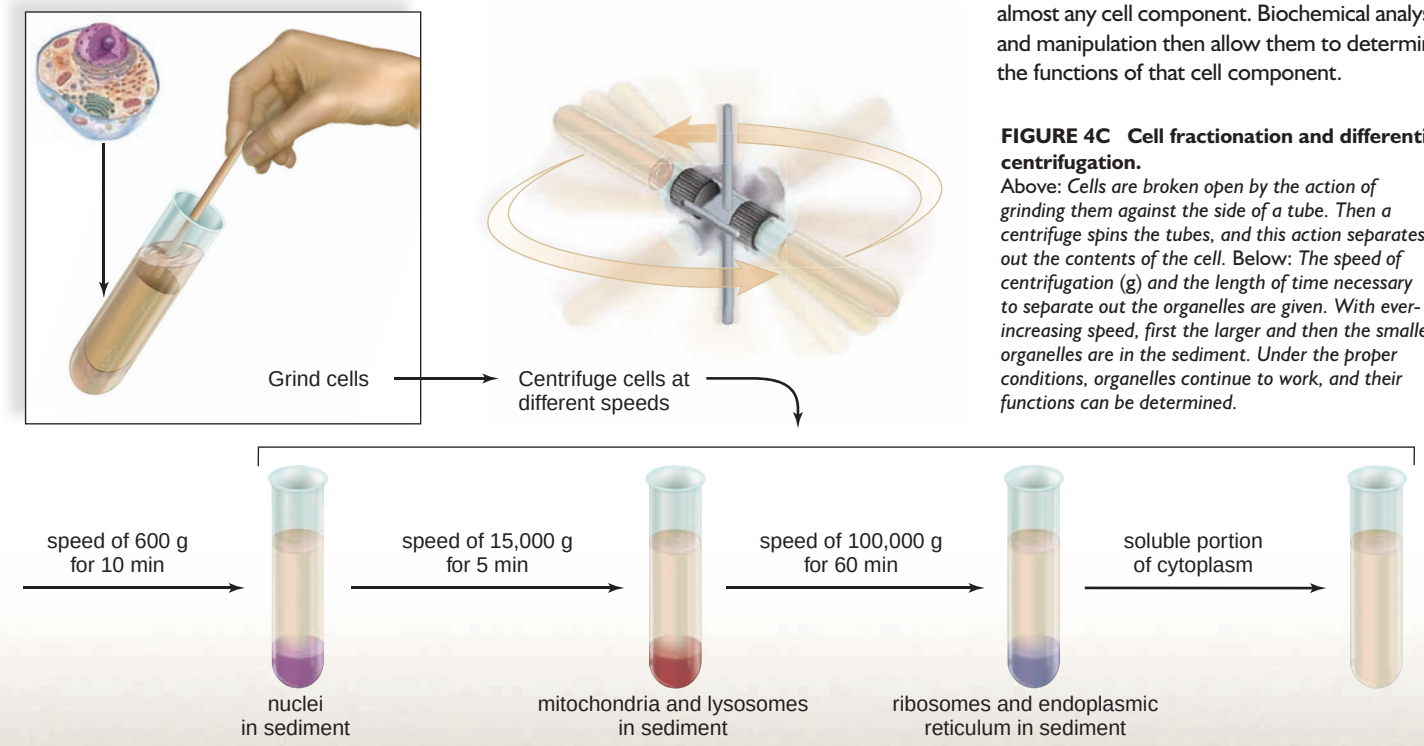


FIGURE 4C Cell fractionation and differential centrifugation.
Above: *Cells are broken open by the action of grinding them against the side of a tube. Then a centrifuge spins the tubes, and this action separates out the contents of the cell.* Below: *The speed of centrifugation (g) and the length of time necessary to separate out the organelles are given. With ever-increasing speed, first the larger and then the smaller organelles are in the sediment. Under the proper conditions, organelles continue to work, and their functions can be determined.*

different tissues arranged in organs, each with a particular structure and function. The Science Focus above describes the process by which investigators were able to discover the structure and function of various organelles.

The **cytoskeleton** is a lattice of protein fibers that maintains the shape of the cell and assists in the movement of organelles. The protein fibers serve as tracks for the transport vesicles that are taking molecules from one organelle to another. In other words, the tracks direct and speed them on their way. The manner in which vesicles and other types of organelles move along these tracks will be discussed in more detail later in the chapter. Without a cytoskeleton, a eukaryotic cell would not have an efficient means of moving organelles and their products within the cell and possibly could not exist.

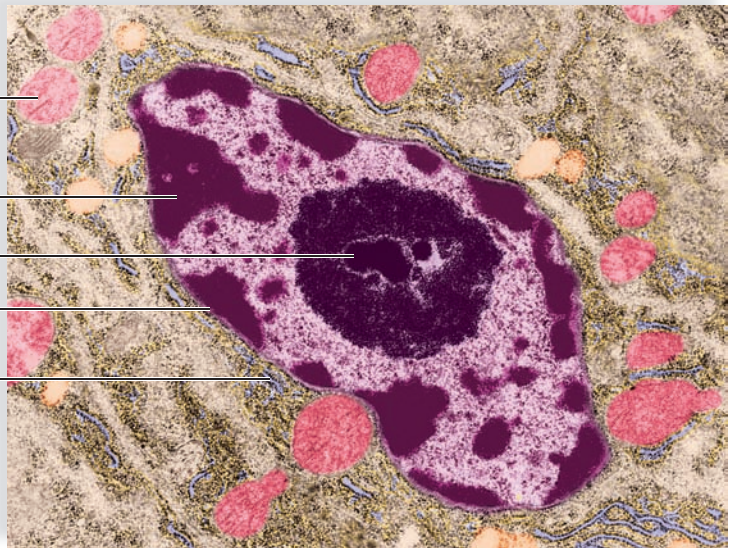
Check Your Progress 4.3

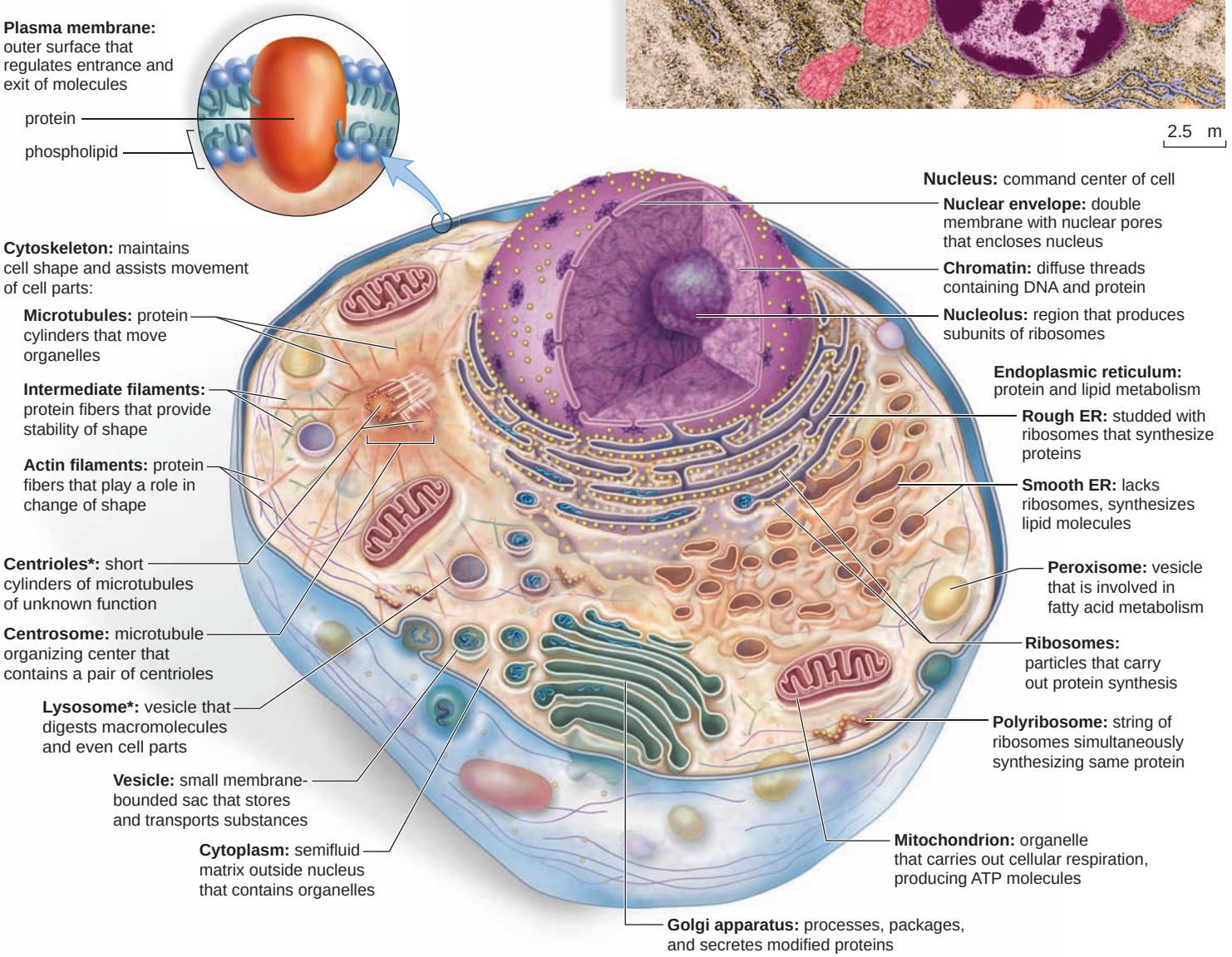
1. Name three benefits of compartmentalization found in cells.
2. How did the energy-related organelles arise?

FIGURE 4.6

Animal cell anatomy.

Micrograph of an insect cell (*above*) and drawing of a generalized animal cell (*below*).





*not in plant cells

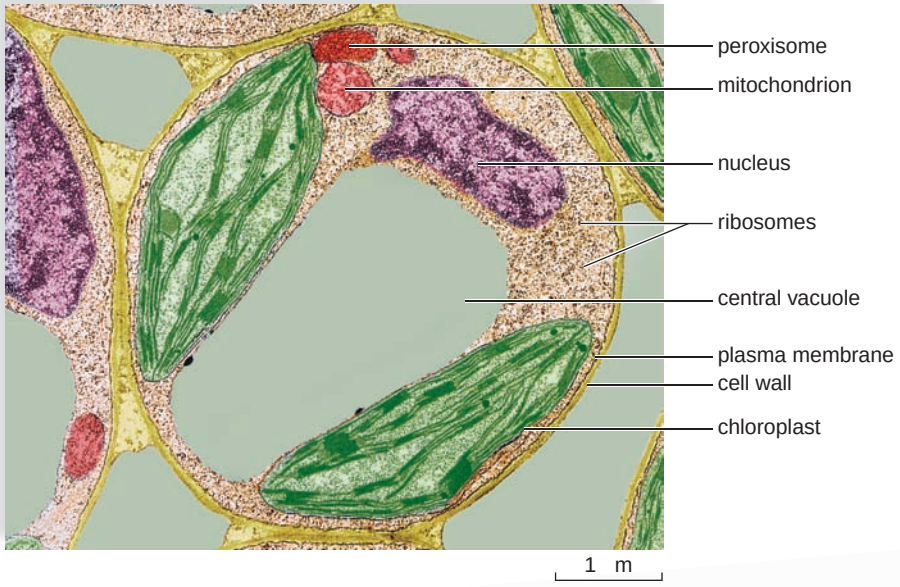


FIGURE 4.7

Plant cell anatomy.

False-colored micrograph of a young plant cell (*above*) and drawing of a generalized plant cell (*below*).

Nucleus: command center of cell

Nuclear envelope: double membrane with nuclear pores that encloses nucleus

Nucleolus: produces subunits of ribosomes

Chromatin: diffuse threads containing DNA and protein

Nuclear pore: permits passage of proteins into nucleus and ribosomal subunits out of nucleus

Ribosomes: carry out protein synthesis

Centrosome: microtubule organizing center (lacks centrioles)

Endoplasmic reticulum: protein and lipid metabolism

Rough ER: studded with ribosomes that synthesize proteins

Smooth ER: lacks ribosomes, synthesizes lipid molecules

Peroxisome: vesicle that is involved in fatty acid metabolism

Golgi apparatus: processes, packages, and secretes modified proteins

Cytoplasm: semifluid matrix outside nucleus that contains organelles

Central vacuole*: large, fluid-filled sac that stores metabolites and helps maintain turgor pressure

Cell wall of adjacent cell

Middle lamella: cements together the primary cell walls of adjacent plant cells

Chloroplast*: carries out photosynthesis, producing sugars

Granum*: a stack of chlorophyll-containing thylakoids in a chloroplast

Mitochondrion: organelle that carries out cellular respiration, producing ATP molecules

Microtubules: protein cylinders that aid movement of organelles

Actin filaments: protein fibers that play a role in movement of cell and organelles

Plasma membrane: surrounds cytoplasm, and regulates entrance and exit of molecules

Cell wall*: outer surface that shapes, supports, and protects cell

*not in animal cells

4.4 The Nucleus and Ribosomes

The nucleus is essential to the life of a cell. It contains the genetic information that is passed on from cell to cell and from generation to generation. The ribosomes use this information to carry out protein synthesis.

The Nucleus

The nucleus, which has a diameter of about 5 µm, is a prominent structure in the eukaryotic cell (Fig. 4.8). It generally appears as an oval structure located near the center of most cells. Some cells, such as skeletal muscle cells, can have more than one nucleus. The nucleus contains **chromatin** [Gk. *chroma,* color, and *teino,* stretch] in a semifluid matrix called the **nucleoplasm.** Chromatin looks grainy, but actually it is a network of strands that condenses and undergoes coiling into rodlike structures called **chromosomes** [Gk. *chroma,* color, and *soma,* body], just before the cell divides. All the cells of an individual contain the same number of chromosomes, and the mechanics of nuclear division ensure that each daughter cell receives the normal number of chromosomes, except for the egg and sperm, which usually have half this number. This alone suggested to early investigators that the chromosomes are the carriers of genetic information and that the nucleus is the command center of the cell.

Chromatin, and therefore chromosomes, contains DNA, protein, and some RNA (ribonucleic acid). **Genes,** composed of DNA, are units of heredity located on the chromosomes.

Three types of RNA are produced in the nucleus: *ribosomal RNA (rRNA), messenger RNA (mRNA),* and *transfer RNA (tRNA).* Ribosomal RNA is produced in the **nucleolus,** a dark region of chromatin where rRNA joins with proteins to form the subunits of ribosomes. Ribosomes are small bodies in the cytoplasm where protein synthesis occurs. Messenger RNA acts as an intermediary for DNA, which specifies the sequence of amino acids in a protein. Transfer RNA participates in the assembly of amino acids during protein synthesis. The proteins of a cell determine its structure and functions.

The nucleus is separated from the cytoplasm by a double membrane known as the **nuclear envelope.** Even so, the nucleus communicates with the cytoplasm. The nuclear envelope has **nuclear pores** of sufficient size (100 nm) to per-

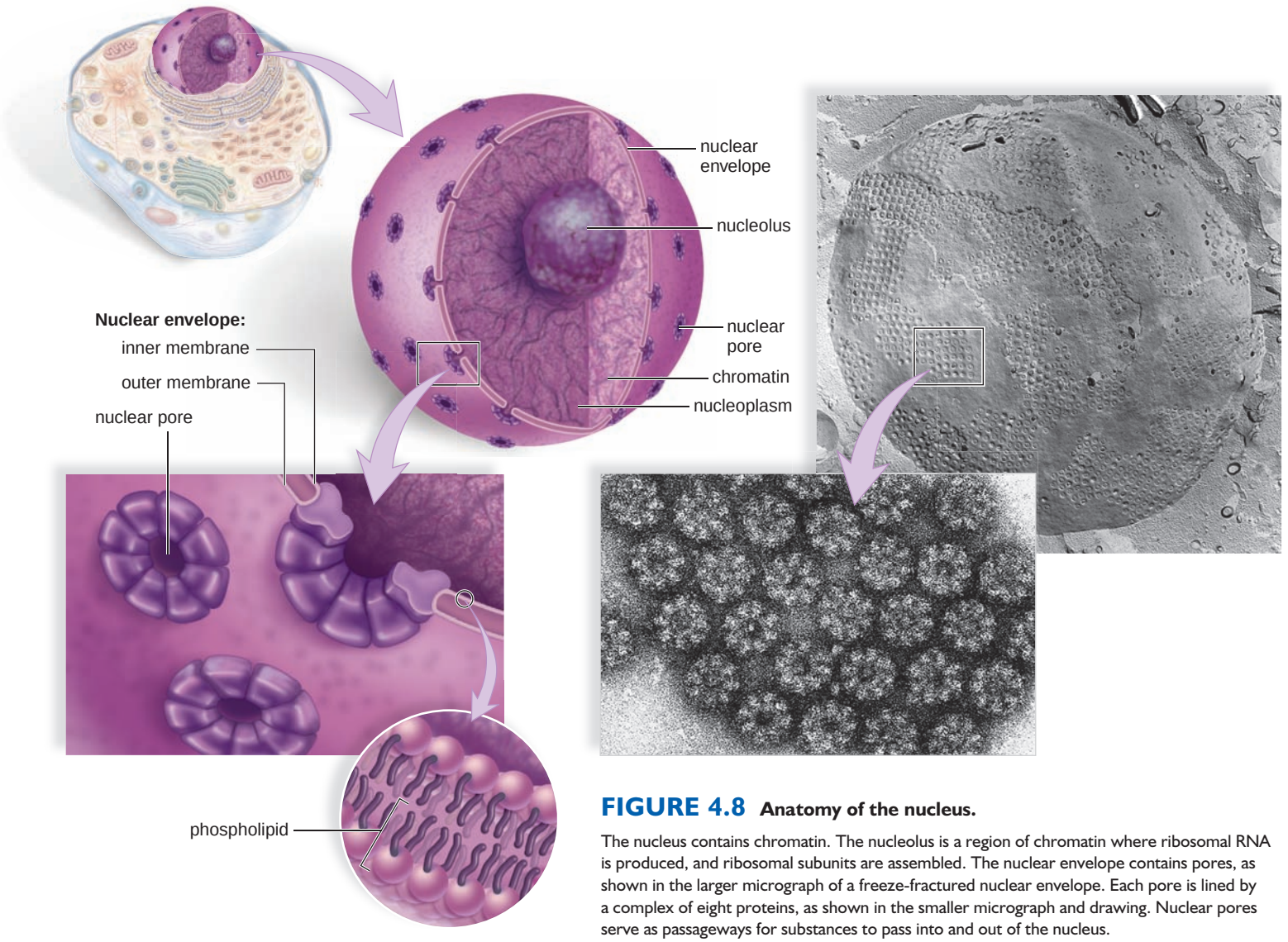


FIGURE 4.8 Anatomy of the nucleus.

The nucleus contains chromatin. The nucleolus is a region of chromatin where ribosomal RNA is produced, and ribosomal subunits are assembled. The nuclear envelope contains pores, as shown in the larger micrograph of a freeze-fractured nuclear envelope. Each pore is lined by a complex of eight proteins, as shown in the smaller micrograph and drawing. Nuclear pores serve as passageways for substances to pass into and out of the nucleus.

mit the passage of ribosomal subunits and mRNA out of the nucleus into the cytoplasm and the passage of proteins from the cytoplasm into the nucleus. High-power electron micrographs show that nonmembranous components associated with the pores form a nuclear pore complex.

Ribosomes

Ribosomes are particles where protein synthesis occurs. In eukaryotes, ribosomes are 20 nm by 30 nm, and in prokaryotes they are slightly smaller. In both types of cells, ribosomes are composed of two subunits, one large and one small. Each subunit has its own mix of proteins and rRNA. The number of ribosomes in a cell varies depending on its functions. For example, pancreatic cells and those of other glands have many ribosomes because they produce secretions that contain proteins.

In eukaryotic cells, some ribosomes occur freely within the cytoplasm, either singly or in groups called **polyribosomes,** and others are attached to the endoplasmic reticulum (ER), a membranous system of flattened saccules (small sacs) and tubules, which is discussed more fully on the next page. Ribosomes receive mRNA from the nucleus, and this mRNA carries a coded message from DNA indicating the correct sequence of amino acids in a particular protein. Proteins synthesized by cytoplasmic ribosomes are used in the cytoplasm, and those synthesized by attached ribosomes end up in the ER.

What causes a ribosome to bind to the endoplasmic reticulum? Binding occurs only if the protein being synthesized by a ribosome begins with a sequence of amino acids called a **signal peptide.** The signal peptide binds a particle (signal recognition particle, SRP), which then binds to a receptor on the ER. Once the protein enters the ER, an enzyme cleaves off the signal peptide, and the protein ends up within the lumen (interior) of the ER, where it folds into its final shape (Fig. 4.9).

Check Your Progress 4.4

1. List the components of the nucleus and give a function for each.
2. Where are ribosomes found in the cell, and what do they do?

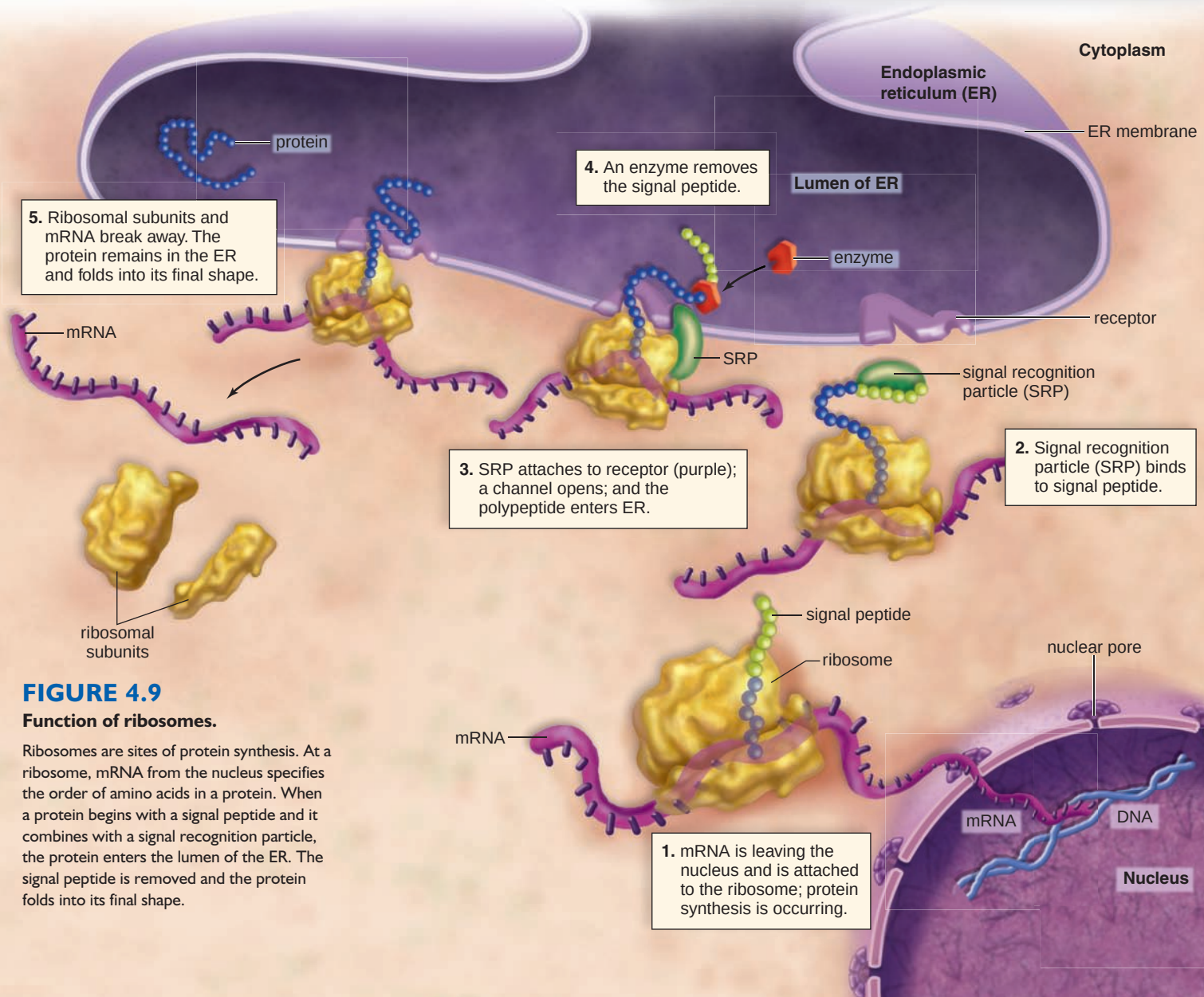


FIGURE 4.9

Function of ribosomes.

Ribosomes are sites of protein synthesis. At a ribosome, mRNA from the nucleus specifies the order of amino acids in a protein. When a protein begins with a signal peptide and it combines with a signal recognition particle, the protein enters the lumen of the ER. The signal peptide is removed and the protein folds into its final shape.

4.5 The Endomembrane System

The **endomembrane system** consists of the nuclear envelope, the membranes of the endoplasmic reticulum, the Golgi apparatus, and several types of vesicles. This system compartmentalizes the cell so that particular enzymatic reactions are restricted to specific regions. The vesicles transport molecules from one part of the system to another.

Endoplasmic Reticulum

The **endoplasmic reticulum (ER)** [Gk. *endon,* within; *plasma,* something molded; L. *reticulum,* net], consisting of a complicated system of membranous channels and saccules (flattened vesicles), is physically continuous with the nuclear envelope (Fig. 4.10). The ER consists of rough ER and smooth ER, which have a different structure and functions. Only **rough ER** is studded with ribosomes on the side of the membrane that faces the cytoplasm, and because of this, rough ER has the capacity to produce proteins. Inside its lumen, rough ER contains enzymes that can add carbohydrate (sugar) chains to proteins, and then these proteins are called glycoproteins. While in the ER, proteins fold and take on their final three-dimensional shape.

Smooth ER, which is continuous with rough ER, does not have attached ribosomes. Certain organs contain an abundance of smooth ER and its function depends on the organ. In some organs, smooth ER is associated with the production of lipids. For example, in the testes, smooth ER produces testosterone, a steroid hormone. In the liver, smooth ER helps detoxify drugs. The smooth ER of the liver increases in quantity when a person consumes alcohol or takes barbiturates on a regular basis. Regardless of a difference in their functions, both rough and smooth ER form vesicles that transport molecules to other parts of the cell, notably the Golgi apparatus.

The Golgi Apparatus

The **Golgi apparatus** is named for Camillo Golgi, who discovered its presence in cells in 1898. The Golgi apparatus typically consists of a stack of three to twenty slightly curved, flattened saccules whose appearance can be compared to a stack of pancakes (Fig. 4.11). In animal cells, one side of the stack (the cis or inner face) is directed toward the ER, and the other side of the stack (the trans or outer face) is directed toward the plasma membrane. Vesicles can frequently be seen at the edges of the saccules.

Protein-filled vesicles that bud from the rough ER and lipid-filled vesicles that bud from the smooth ER are received by the Golgi apparatus at its inner face. Thereafter, the apparatus alters these substances as they move through its saccules. For example, the Golgi apparatus contains enzymes that modify the carbohydrate chains first attached to proteins in the rough ER. It can change one sugar for another sugar. In some cases, the modified carbohydrate chain serves as a signal molecule that determines the protein's final destination in the cell.

The Golgi apparatus sorts the modified molecules and packages them into vesicles that depart from the outer face. In animal cells, some of these vesicles are lysosomes, which are discussed next. Other vesicles may return to the ER or proceed to the plasma membrane, where they become part of the membrane as they discharge their contents during **secretion.** Secretion is termed exocytosis because the substance exits the cytoplasm.

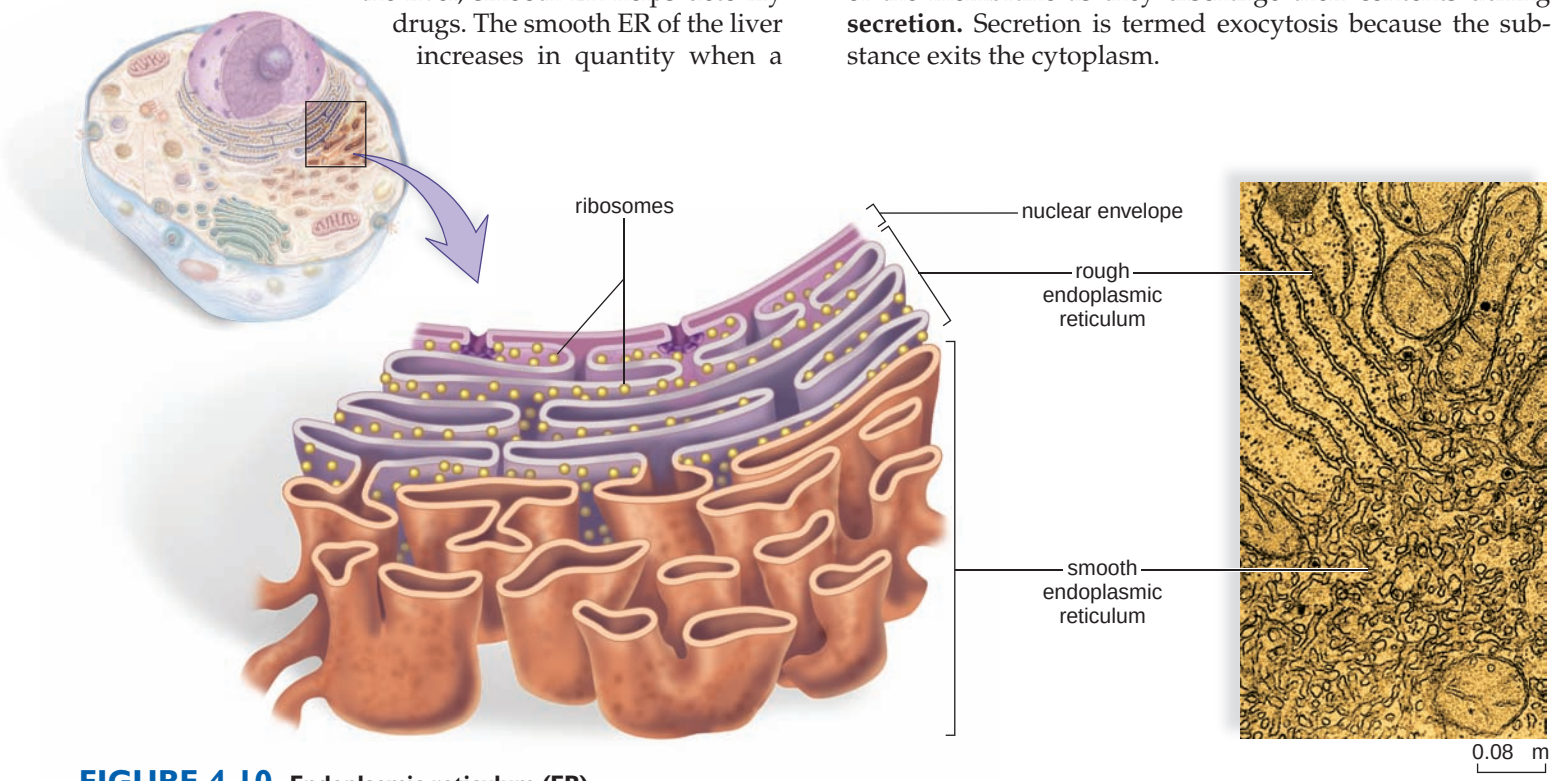


FIGURE 4.10 **Endoplasmic reticulum (ER).**

Ribosomes are present on rough ER, which consists of flattened saccules, but not on smooth ER, which is more tubular. Proteins are synthesized by rough ER, which can also attach carbohydrate chains to proteins after they enter its lumen, as described in Figure 4.9. Smooth ER is involved in lipid synthesis, detoxification reactions, and several other possible functions.

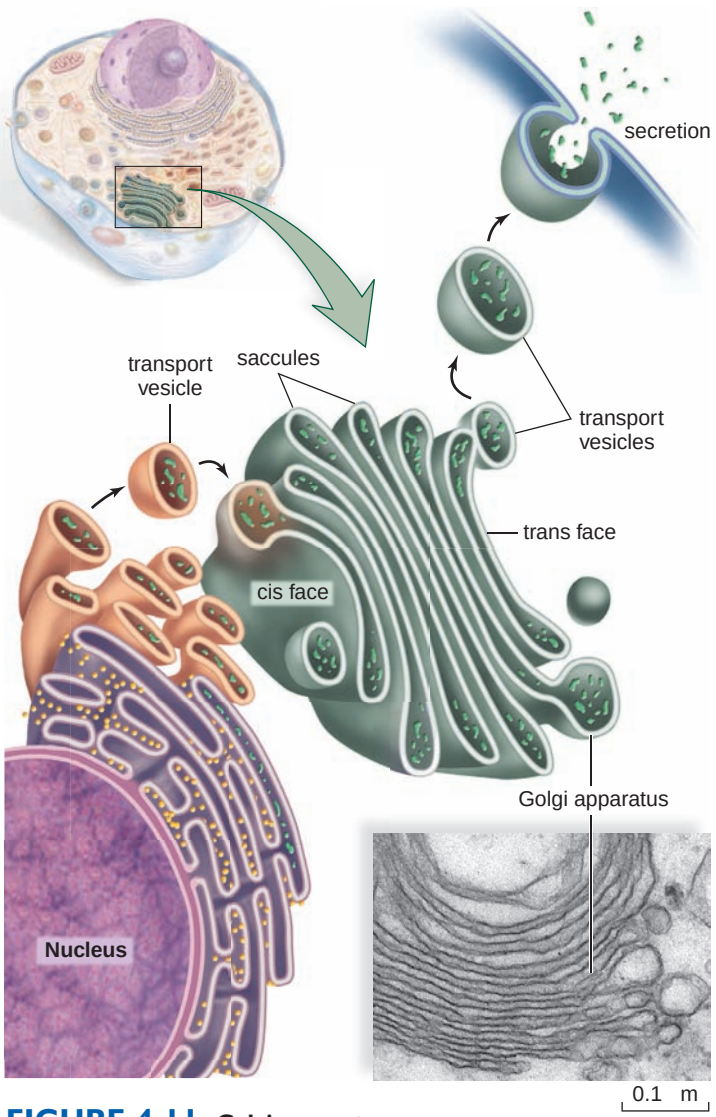


FIGURE 4.11 Golgi apparatus.

The Golgi apparatus is a stack of flattened, curved saccules. It processes proteins and lipids and packages them in transport vesicles that distribute these molecules to various locations.

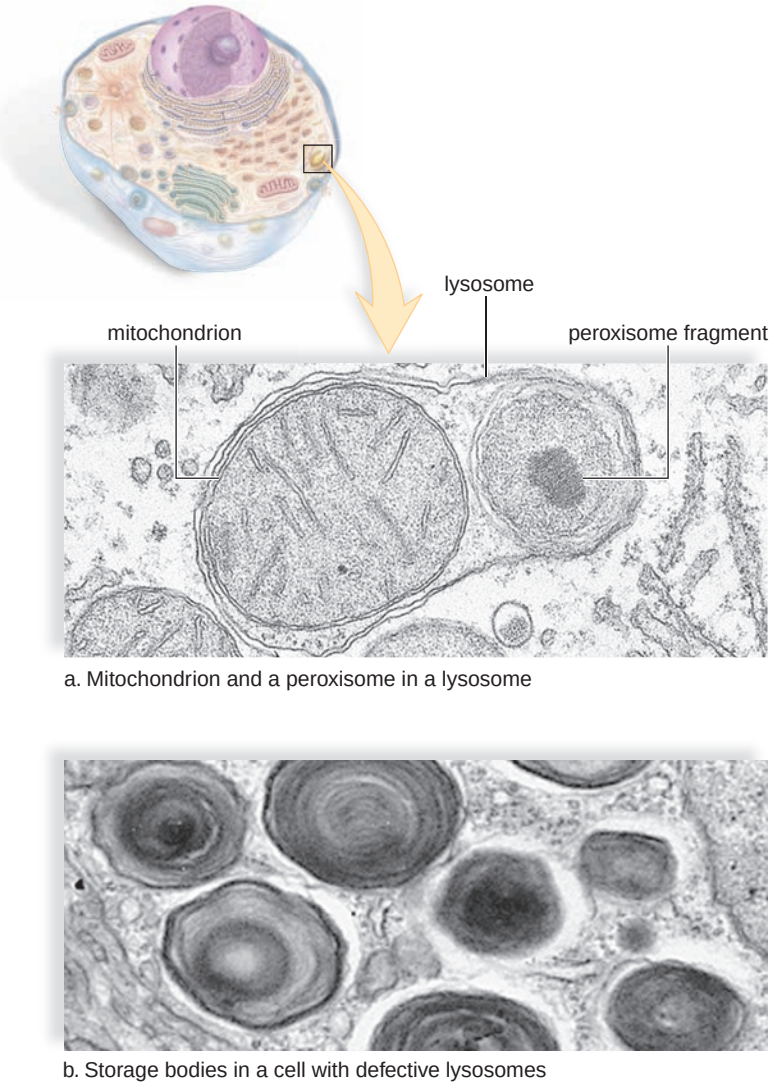


FIGURE 4.12 Lysosomes.

a. Lysosomes, which bud off the Golgi apparatus in cells, are filled with hydrolytic enzymes that digest molecules and parts of the cell. Here a lysosome digests a worn mitochondrion and a peroxisome. **b.** The nerve cells of a person with Tay-Sachs disease are filled with membranous cytoplasmic bodies storing a fat that lysosomes are unable to digest.

Lysosomes

Lysosomes [Gk. *lyo,* loose, and *soma,* body] are membrane-bounded vesicles produced by the Golgi apparatus. They have a very low pH and store powerful hydrolytic-digestive enzymes in an inactive state. Lysosomes assist in digesting material taken into the cell, and they destroy nonfunctional organelles and portions of cytoplasm (Fig. 4.12).

Materials can be brought into a cell by vesicle or vacuole formation at the plasma membrane. When a lysosome fuses with either, the lysosomal enzymes are activated and digest the material into simpler subunits that then enter the cytoplasm. Some white blood cells defend the body by engulfing bacteria that are then enclosed within vacuoles. When lysosomes fuse with these vacuoles, the bacteria are digested. Sometimes a small amount of residue is left and then it is ejected from the cell at the plasma membrane

A number of human lysosomal storage diseases are due to a missing lysosomal enzyme. In Tay-Sachs disease, the missing enzyme digests a fatty substance that helps insulate nerve cells and increases their efficiency. The fatty substance accumulates in so many storage bodies that nerve cells die off. Affected individuals appear normal at birth but begin to develop neurological problems at four to six months of age. Eventually, the child suffers cerebral degeneration, slow paralysis, blindness, and loss of motor function. Children with Tay-Sachs disease live only about three to four years. In the future, it may be possible to provide the missing enzyme and, in that way, prevent lysosomal storage diseases.

Endomembrane System Summary

We have seen that the endomembrane system is a series of membranous organelles that work together and communicate by means of transport vesicles. The endoplasmic reticulum (ER) and the Golgi apparatus are essentially flattened saccules, and lysosomes are specialized vesicles.

Figure 4.13 shows how the components of the endomembrane system work together. Proteins produced in rough ER and lipids produced in smooth ER are carried in transport vesicles to the Golgi apparatus, where they are further modified before being packaged in vesicles that leave the Golgi. Using signaling sequences, the Golgi apparatus sorts proteins and packages them into vesicles that transport them to various cellular destinations. Secretory vesicles take the proteins to the plasma membrane, where they exit the cell when the vesicles fuse with the membrane. This is called secretion by exocytosis. For example, secretion into ducts occurs when the mammary glands produce milk or the pancreas produces digestive enzymes.

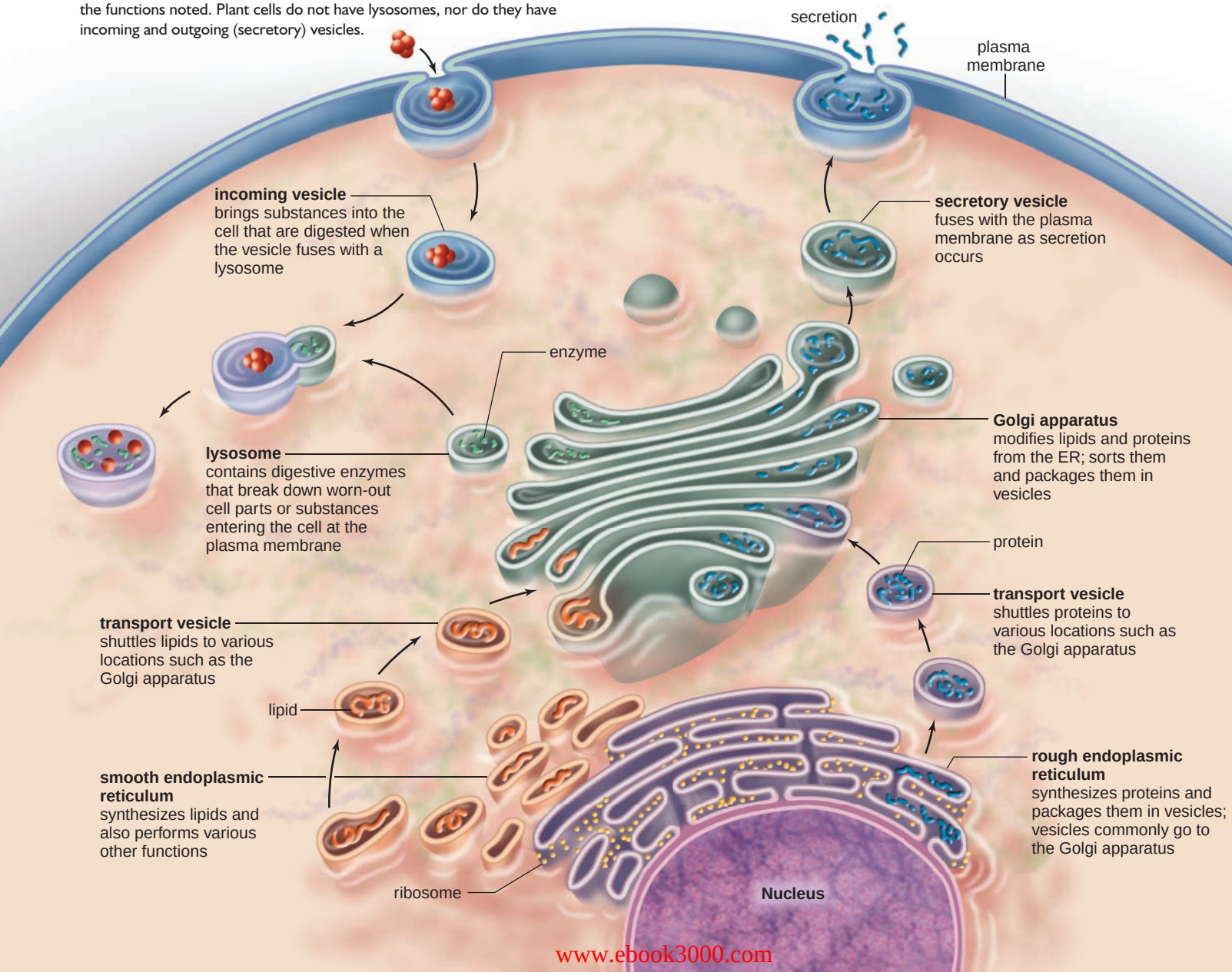
In animal cells, the Golgi apparatus also produces specialized vesicles called lysosomes that contain stored hydrolytic enzymes. Lysosomes fuse with incoming vesicles from the plasma membrane and digest macromolecules and/or even debris brought into a certain cell. White blood cells are well known for engulfing pathogens (e.g., disease-causing viruses and bacteria) that are then broken down in lysosomes.

Check Your Progress 4.5

1. Contrast the structure and functions of rough endoplasmic reticulum with those of smooth endoplasmic reticulum.
2. Describe the relationship between the components of the endomembrane system.

FIGURE 4.13 Endomembrane system.

The organelles in the endomembrane system work together to carry out the functions noted. Plant cells do not have lysosomes, nor do they have incoming and outgoing (secretory) vesicles.



4.6 Other Vesicles and Vacuoles

Peroxisomes and the vacuoles of cells do not communicate with the organelles of the endomembrane system, and therefore are not part of it.

Peroxisomes

Peroxisomes, similar to lysosomes, are membrane-bounded vesicles that enclose enzymes. However, the enzymes in peroxisomes are synthesized by free ribosomes and transported into a peroxisome from the cytoplasm. All peroxisomes contain enzymes whose actions result in hydrogen peroxide (H_2O_2):

$$RH_2 + O_2 \longrightarrow R + H_2O_2$$

Hydrogen peroxide, a toxic molecule, is immediately broken down to water and oxygen by another peroxisomal enzyme called catalase. When hydrogen peroxide is applied to a wound, bubbling occurs as catalase breaks it down.

Peroxisomes are metabolic assistants to the other organelles. They have varied functions but are especially prevalent in cells that are synthesizing and breaking down lipids. In the liver, some peroxisomes produce bile salts from cholesterol, and others break down fats. In a 1992 movie, *Lorenzo's Oil,* the peroxisomes in a boy's cells lack a membrane protein needed to import a specific enzyme and/or long chain fatty acids from the cytoplasm. As a result, long chain fatty acids accumulate in his brain, and he suffers neurological damage. This disorder is known as adrenoleukodystrophy.

Plant cells also have peroxisomes (Fig. 4.14). In germinating seeds, they oxidize fatty acids into molecules that can be converted to sugars needed by the growing plant. In leaves, peroxisomes can carry out a reaction that is opposite to photosynthesis—the reaction uses up oxygen and releases carbon dioxide.

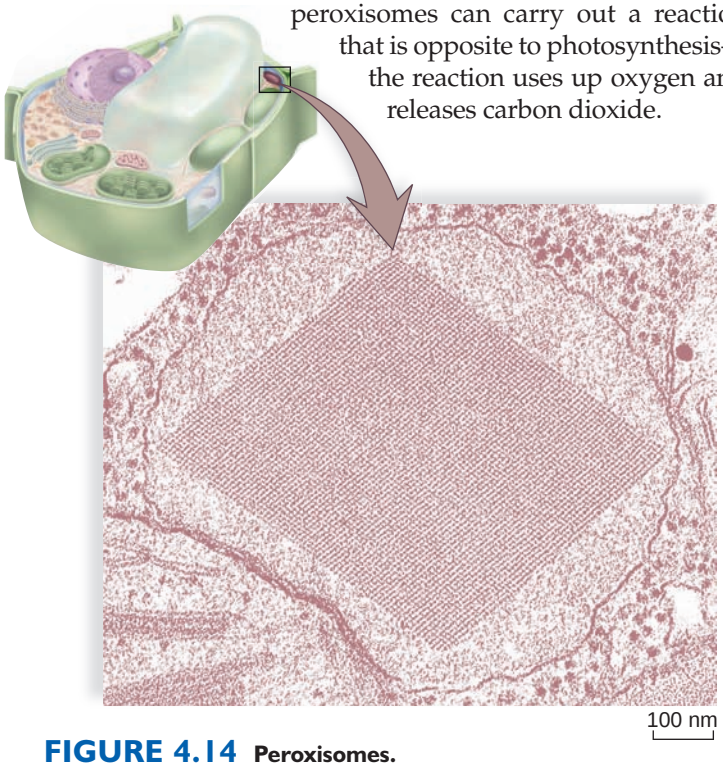


FIGURE 4.14 Peroxisomes.

Peroxisomes contain one or more enzymes that can oxidize various organic substances. Peroxisomes also contain the enzyme catalase, which breaks down hydrogen peroxide (H_2O_2), which builds up after organic substances are oxidized.

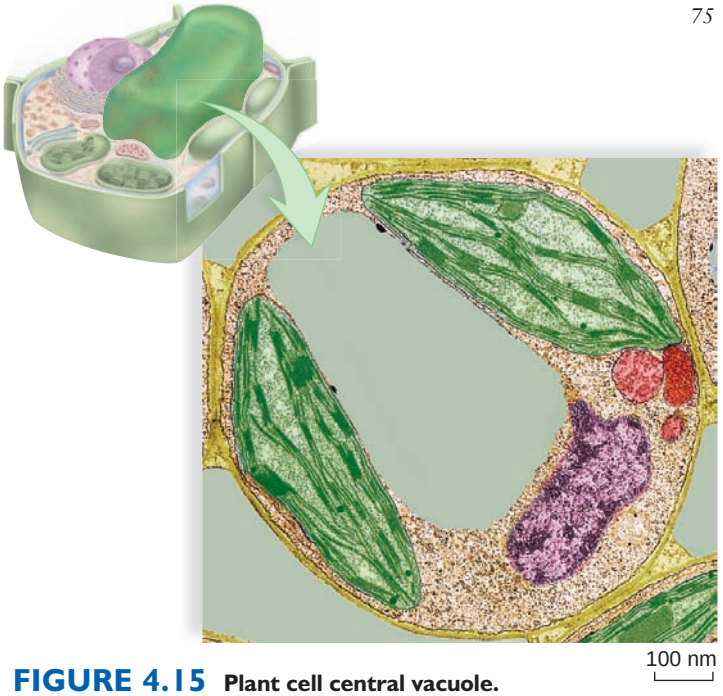


FIGURE 4.15 Plant cell central vacuole.

The large central vacuole of plant cells has numerous functions, from storing molecules to helping the cell increase in size.

Vacuoles

Like vesicles, **vacuoles** are membranous sacs, but vacuoles are larger than vesicles. The vacuoles of some protists are quite specialized including contractile vacuoles for ridding the cell of excess water and digestive vacuoles for breaking down nutrients. Vacuoles usually store substances. Few animal cells contain vacuoles, but fat cells contain a very large lipid-engorged vacuole that takes up nearly two-thirds of the volume of the cell!

Plant vacuoles contain not only water, sugars, and salts but also water-soluble pigments and toxic molecules. The pigments are responsible for many of the red, blue, or purple colors of flowers and some leaves. The toxic substances help protect a land plant from herbivorous animals.

Plant Cell Central Vacuole

Typically, plant cells have a large **central vacuole** that may take up to 90% of the volume of the cell. The vacuole is filled with a watery fluid called cell sap that gives added support to the cell (Fig. 4.15). The central vacuole maintains hydrostatic pressure or turgor pressure in plant cells. A plant cell can rapidly increase in size by enlarging its vacuole. Eventually, a plant cell also produces more cytoplasm.

The central vacuole functions in storage of both nutrients and waste products. Metabolic waste products are pumped across the vacuole membrane and stored permanently in the central vacuole. As organelles age and become nonfunctional, they fuse with the vacuole, where digestive enzymes break them down. This is a function carried out by lysosomes in animal cells.

Check Your Progress 4.6

1. How is a peroxisome like, and how is it different from, a lysosome?
2. How is the plant cell central vacuole like, and how is it different from, a lysosome?

4.7 The Energy-Related Organelles

Life is possible only because a constant input of energy maintains the structure of cells. Chloroplasts and mitochondria are the two eukaryotic membranous organelles that specialize in converting energy to a form that can be used by the cell.

During photosynthesis, **chloroplasts** [Gk. *chloros,* green, and *plastos,* formed, molded], use solar energy to synthesize carbohydrates, which serve as organic nutrient molecules for plants and all living things on Earth. *Photosynthesis* can be represented by this equation:

$$\text{solar energy} + \text{carbon dioxide} + \text{water} \rightarrow \text{carbohydrate} + \text{oxygen}$$

Plants, algae, and cyanobacteria are capable of carrying on photosynthesis in this manner, but only plants and algae have chloroplasts because they are eukaryotes.

Cellular respiration is the process by which carbohydrate-derived products are broken down in **mitochondria** (sing., mitochondrion) to produce ATP (adenosine triphosphate). *Cellular respiration* can be represented by this equation:

$$\text{carbohydrate} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

Here the word *energy* stands for ATP molecules. When a cell needs energy, ATP supplies it. The energy of ATP is used for synthetic reactions, active transport, and all energy-requiring processes in cells.

Chloroplasts

Some algal cells have only one chloroplast, while some plant cells have as many as a hundred. Chloroplasts can be quite large, being twice as wide and as much as five times the length of a mitochondrion. Chloroplasts have a three-membrane system (Fig. 4.16). They are bounded by a double membrane, which includes an outer membrane and an inner membrane. The double membrane encloses the semifluid **stroma,** which contains enzymes and **thylakoids,** disklike sacs formed from a third chloroplast membrane. A stack of thylakoids is a **granum.** The lumens of the thylakoids are believed to form a large internal compartment called the thylakoid space. Chlorophyll and the other pigments that capture solar energy are located in the thylakoid membrane, and the enzymes that synthesize carbohydrates are located outside the thylakoid in the fluid of the stroma.

The endosymbiotic theory says that chloroplasts are derived from a photosynthetic bacterium that was engulfed by a eukaryotic cell. This certainly explains why a chloroplast is bounded by a double membrane—one membrane is derived from the vesicle that brought the prokaryote into the cell, while the inner membrane is derived from the prokaryote. The endosymbiotic theory is also supported by the finding that chloroplasts have their own prokaryotic-type chromosome and ribosomes, and they produce some of their own enzymes even today!

Other Types of Plastids

A chloroplast is a type of plastid. **Plastids** are plant organelles that are surrounded by a double membrane and having varied functions. **Chromoplasts** contain pigments that result in a yellow, orange, or red color. Chromoplasts are responsible for the color of autumn leaves, fruits, carrots, and some flowers. **Leucoplasts** are generally colorless plastids that synthesize and store starches and oils. A microscopic examination of potato tissue yields a number of leucoplasts.

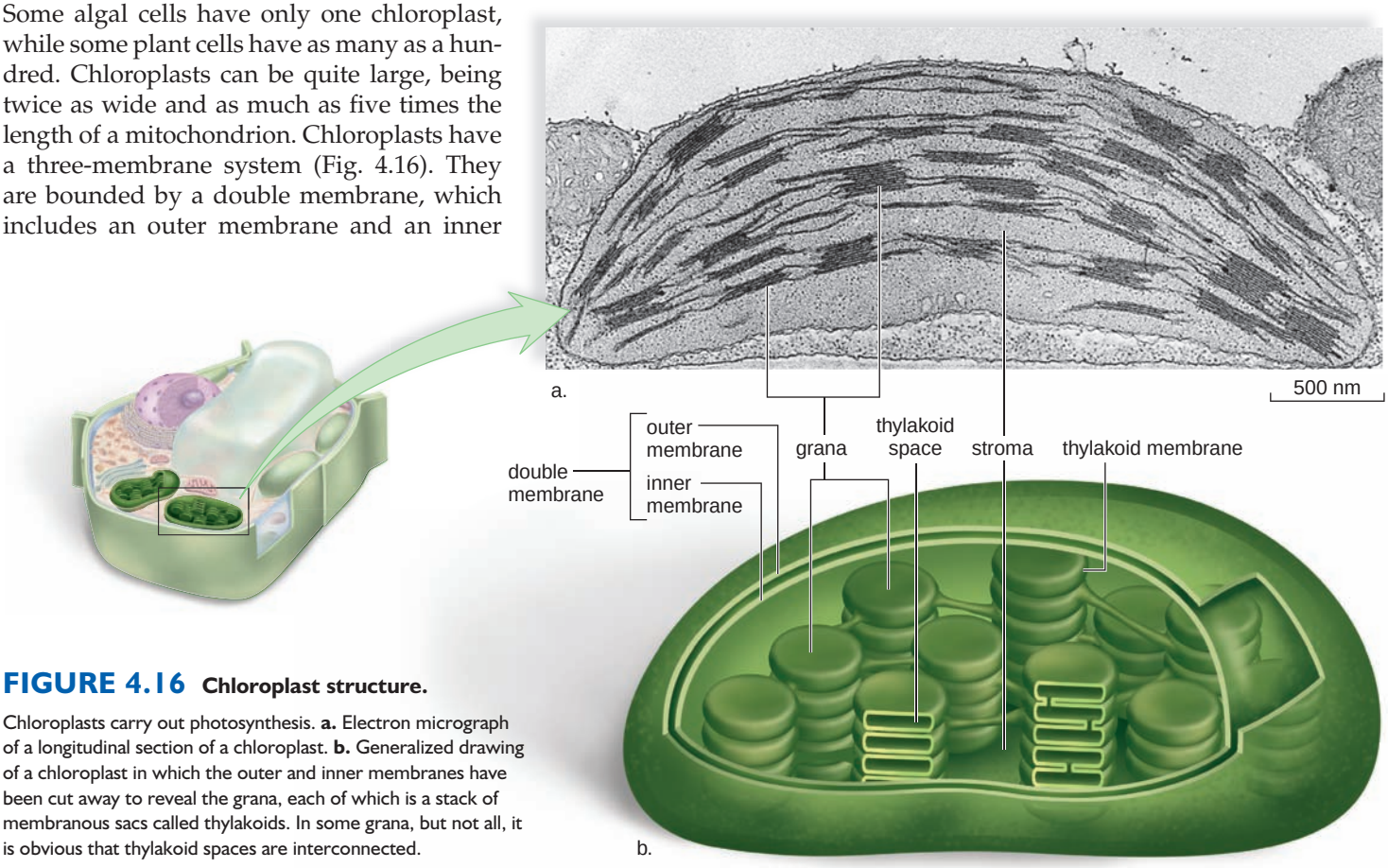


FIGURE 4.16 Chloroplast structure.

Chloroplasts carry out photosynthesis. **a.** Electron micrograph of a longitudinal section of a chloroplast. **b.** Generalized drawing of a chloroplast in which the outer and inner membranes have been cut away to reveal the grana, each of which is a stack of membranous sacs called thylakoids. In some grana, but not all, it is obvious that thylakoid spaces are interconnected.

Mitochondria

Nearly all eukaryotic cells, and certainly all plant and algal cells in addition to animal cells, contain mitochondria. Even though mitochondria are smaller than chloroplasts, they can usually be seen when using a light microscope. The number of mitochondria can vary in cells depending on their activities. Some cells, such as liver cells, may have as many as 1,000 mitochondria. We think of mitochondria as having a shape like that shown in Figure 4.17, but actually they often change shape to be longer and thinner or shorter and broader. Mitochondria can form long, moving chains, or they can remain fixed in one location—typically where energy is most needed. For example, they are packed between the contractile elements of cardiac cells and wrapped around the interior of a sperm's flagellum. Fat cells contain few mitochondria—they function in fat storage, which does not require energy.

Mitochondria have two membranes, the outer membrane and the inner membrane. The inner membrane is highly convoluted into **cristae** that project into the matrix. These cristae increase the surface area of the inner membrane so much that in a liver cell they account for about one-third the total membrane in the cell. The inner membrane encloses a semifluid **matrix,** which contains mitochondrial DNA and ribosomes. Again, the presence of a double membrane and mitochondrial genes is consistent with the endosymbiotic theory regarding the origin of mitochondria, which was illustrated in Figure 4.5.

Mitochondria are often called the powerhouses of the cell because they produce most of the ATP utilized by the cell. The procedure described in the Science Focus on page 67 allowed investigators to separate the inner membrane, the outer membrane, and the matrix from each other. Then they discovered that the matrix is a highly concentrated mixture of enzymes that break down carbohydrates and other nutrient molecules. These reactions supply the chemical energy that permits a chain of proteins on the inner membrane to create the conditions that allow ATP synthesis to take place. The entire process, which also involves the cytoplasm, is called cellular respiration because oxygen is used and carbon dioxide is given off, as shown on the previous page.

Mitochondrial Diseases

So far, more than 40 different mitochondrial diseases that affect the brain, muscles, kidneys, heart, liver, eyes, ears, or pancreas have been identified. The common factor among these genetic diseases is that the patient's mitochondria are unable to completely metabolize organic molecules to produce ATP. As a result, toxins accumulate inside the mitochondria and the body. The toxins can be free radicals (substances that readily form harmful compounds when they react with other molecules), and these compounds damage mitochondria over time. In the United States, between 1,000 and 4,000 children per year are born with a mitochondrial disease. In addition, it is possible that many diseases of aging are due to malfunctioning mitochondria.

Check Your Progress 4.7

1. Compare and contrast the structure and function of chloroplasts with those of mitochondria.

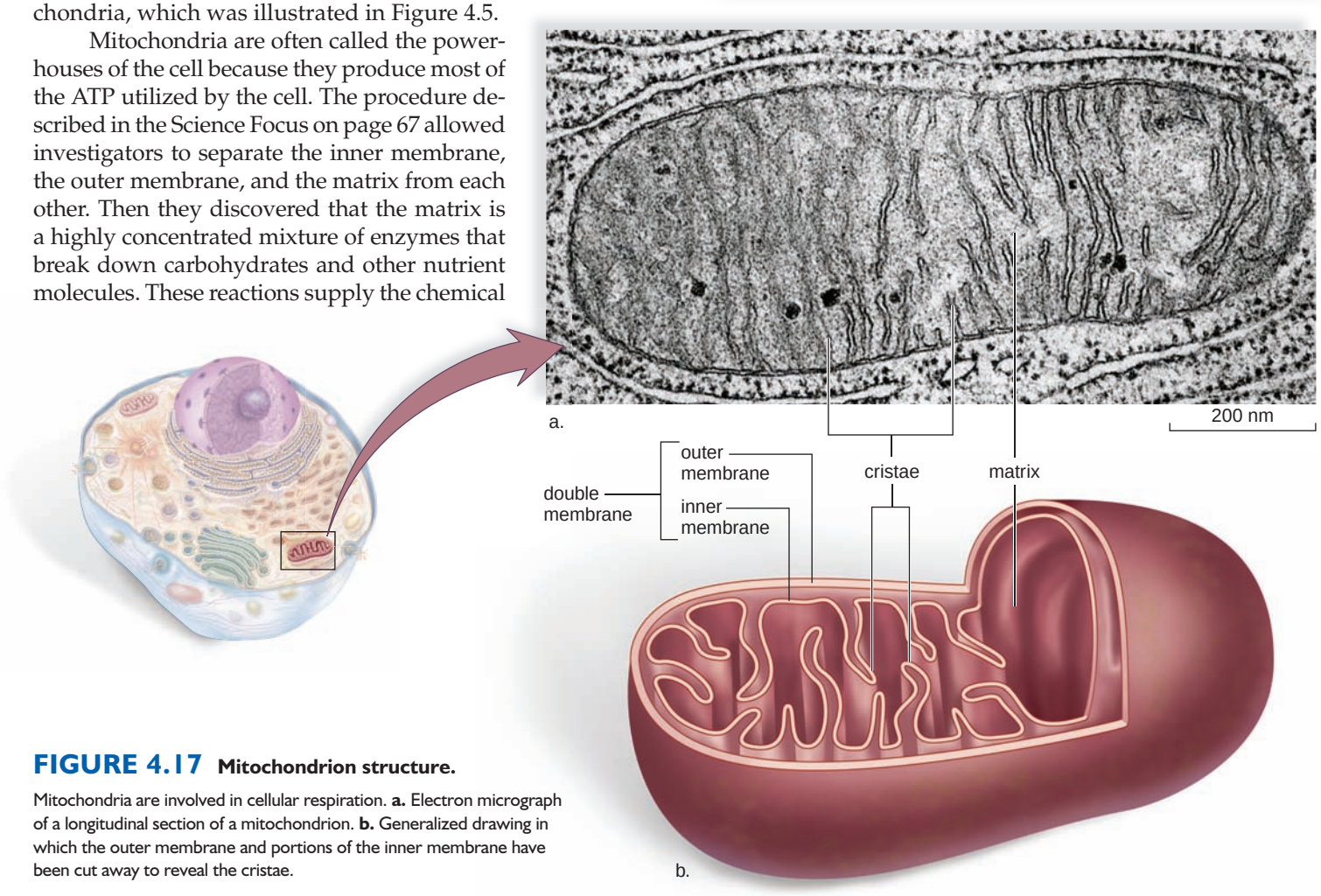


FIGURE 4.17 Mitochondrion structure.

Mitochondria are involved in cellular respiration. **a.** Electron micrograph of a longitudinal section of a mitochondrion. **b.** Generalized drawing in which the outer membrane and portions of the inner membrane have been cut away to reveal the cristae.