The Basic Unit of Life

6.1 Cell Study and Technology

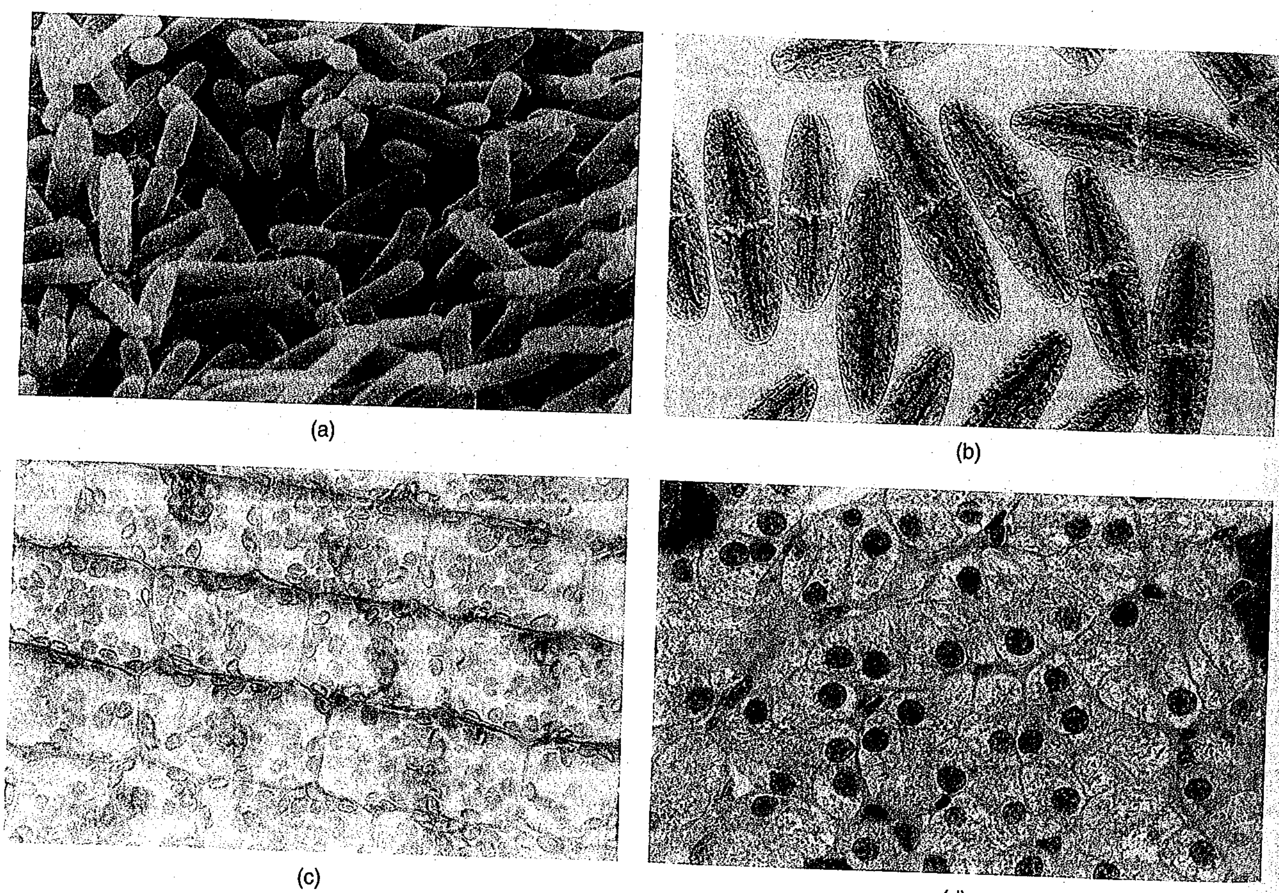
CHEMISTRY TIP

Samples for viewing with a light or electron microscope are often treated with dyes that selectively stain particular cell components. Which parts of a cell absorb these stains depend on chemical composition. Nonpolar stains, for example, make lipid droplets and cell membranes visible. Other stains bind strongly to proteins, starch, cellulose, or DNA.

Like all living things, you are composed of tiny parts called cells, trillions of them. Other animals, plants, and fungi also are made of many cells. There are many billions of organisms such as bacteria, yeasts, and algae that are single-celled. Whatever their size, all are organisms and are composed of cells—the basic units of life. Figure 6.1 shows a few of the great variety of cell types that make up organisms.

The idea that cells are the basic units of life began to take shape in the early 1800s, as many biologists contributed data and ideas that led to the **cell theory,** which can be stated in two parts.

1. Cells, or products made by cells, are the units of structure and function in organisms.
2. All cells come from preexisting cells.



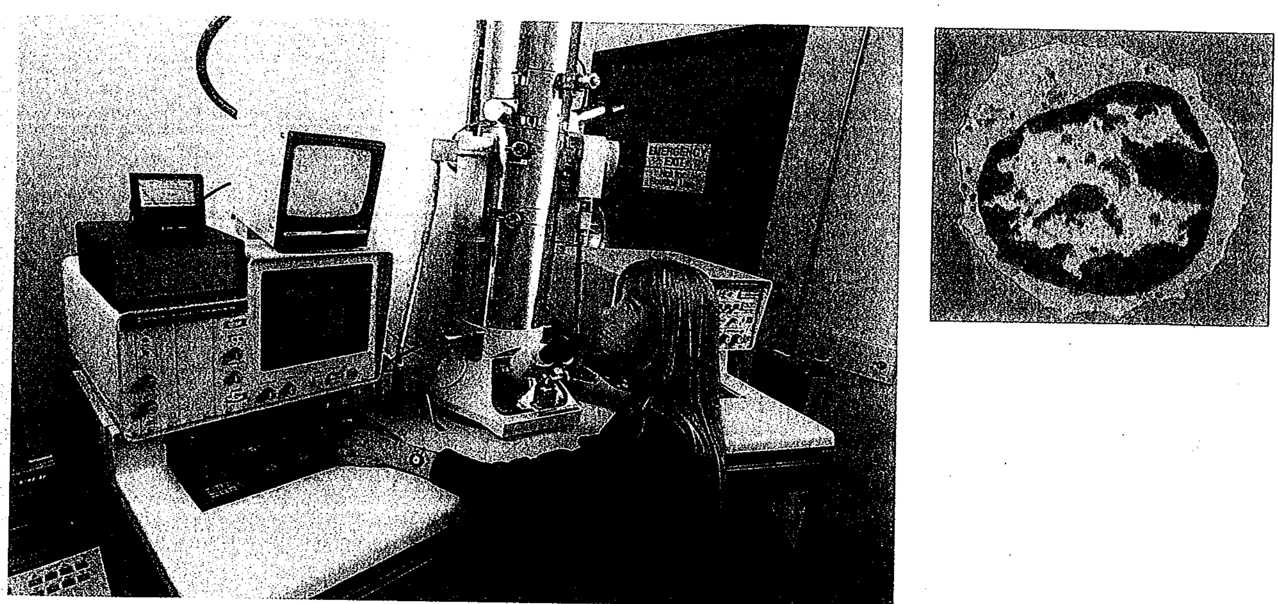
(a) (b) (c) (d)

FIGURE 6.1

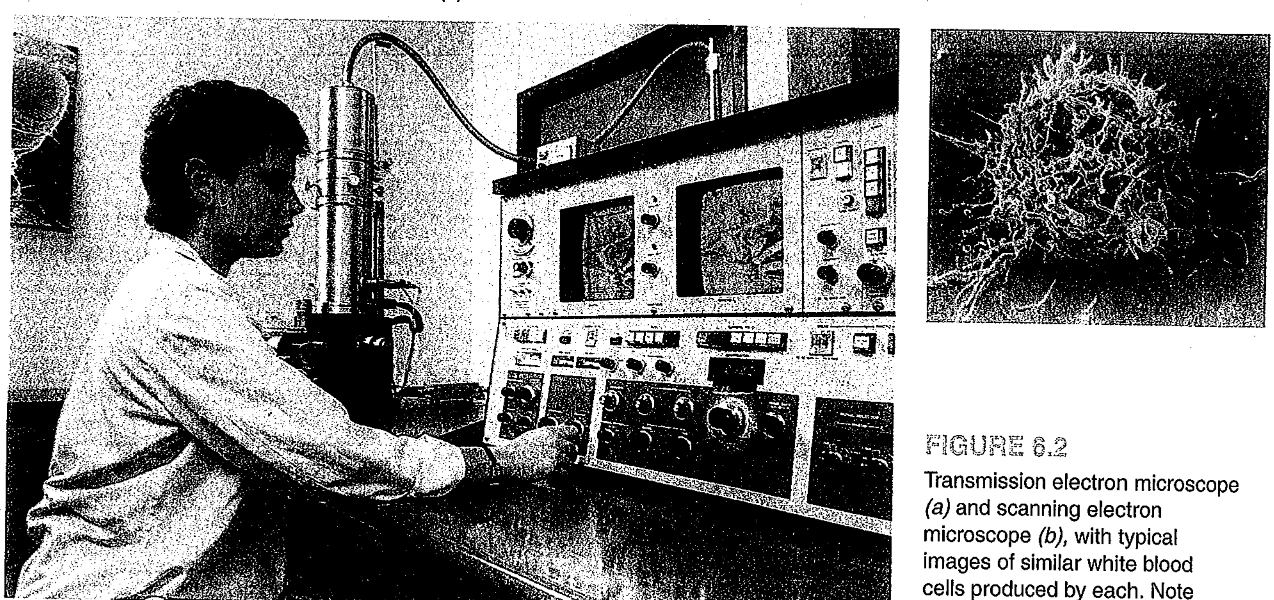
Examples of the variety of cells that make up all organisms (color added). Differences in cell structure and function account for many of the differences among living things. *a,* Unicellular (single-celled) bacteria, ×20,000; *b,* unicellular algae, ×150; *c,* photosynthetic cells in a leaf, ×200; *d,* cells from the liver of a salamander, ×400.

Once the cell theory was established, scientists began to study cell structure and function in detail. At first, biologists who studied cells saw them as just tiny blobs of jelly. These early scientists had no idea of the complex and detailed structures of cells. Progress depended on the technology of improved microscopes, better techniques to prepare cells for observation, and studies of cell function. Even modern light microscopes cannot uncover all the detailed wonders of the cell—some of its structures are too small to see without the electron microscope, which was developed in the 1930s (see Appendix 6A, "Preparing Cells for Study").

Electron microscopes (Figure 6.2) reveal very tiny cell parts and even some large molecules down to 0.5 nm—a magnification of more than a million. (How does that compare with the magnification of the microscope



(a)



(b)

FIGURE 6.2

Transmission electron microscope *(a)* and scanning electron microscope *(b)*, with typical images of similar white blood cells produced by each. Note the differences in the images produced of the same subject.

CONNECTIONS
The cell theory reinforces the concepts of genetic continuity and a common evolutionary origin for life.

you use in biology class?) The major drawback of the electron microscope is that the steps needed to prepare samples for examination kill any living cells before they can be observed. Therefore, the movements and chemical reactions of living cells cannot be studied in this way. Sample preparation can also alter cell structures, so the electron microscope does not always show them as they are in life. Scanning tunneling microscopes can be more powerful than electron microscopes and do not require such harsh treatment of samples (see Biological Challenges, Section 1.12). Like scanning electron microscopes, however, these devices can reveal only surface features.

Cells differ in size but average 10 to 20 μm in diameter. The smaller cells of bacteria may be only 1 μm long. Figure 6.3 compares the sizes of cells and cell parts to the units of measurement biologists use. Because cells are so small, models and diagrams, such as those in this chapter, are used to represent ideas about cell structure and function.

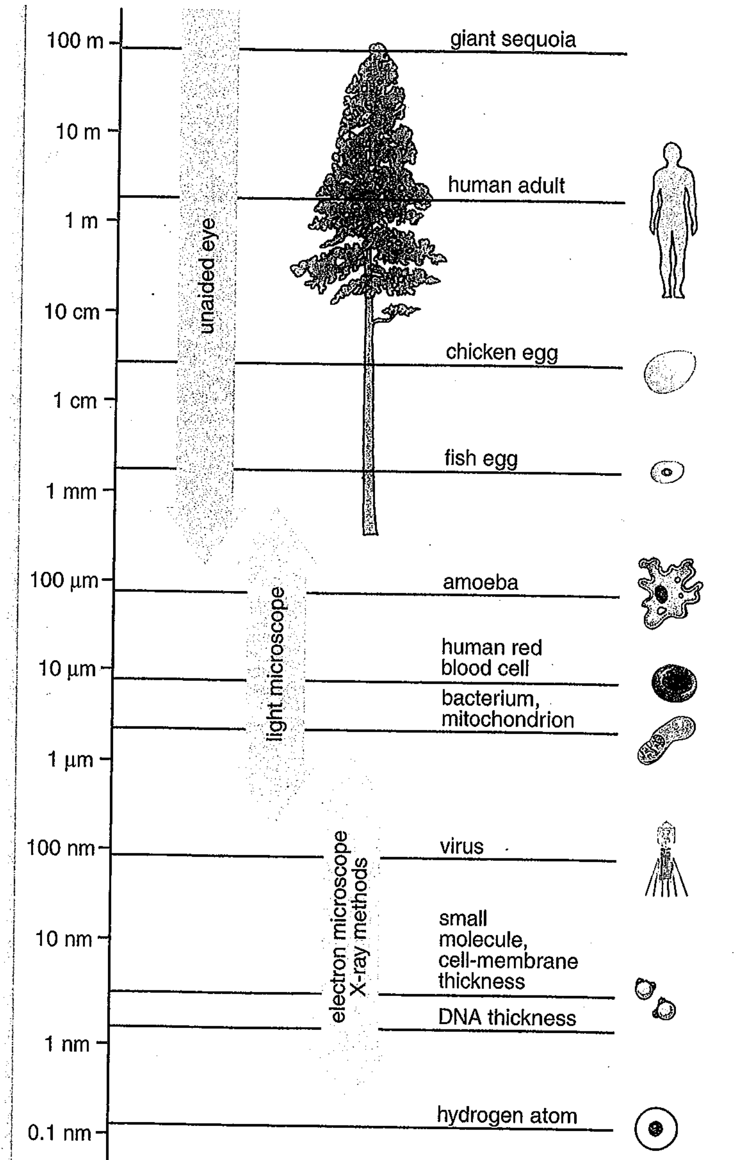
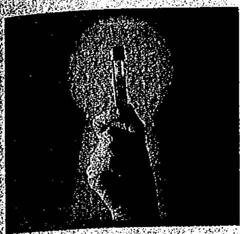


FIGURE 6.3

A comparison of sizes. Note that most cells are too small to be seen with the unaided eye. Each measurement (for example, 1 m, 10 cm) is one-tenth the size of the one above it.



Biological Challenges

DISCOVERIES

The Cell Theory

In the 17th century, Robert Hooke used his microscope (Figure 6.4a) to examine thin slices of cork. Cork is harvested from the dead bark of certain oak trees. Magnified many times under the microscope, these cork shreds seemed to be composed of many little boxlike units. The boxes looked empty; Hooke could see right through them. The rows of boxes reminded Hooke of the little rooms in which monks lived, so he named them cells.

After Hooke published his observations, others saw that the living parts of plants are also made up of cells. But these cells were filled with fluid and various smaller structures. Robert Brown saw a dense object in many cells in 1831 and named it the nucleus. M. J. Schleiden, a botanist, advanced the idea that plants are made of cells that contain nuclei and cell fluid.

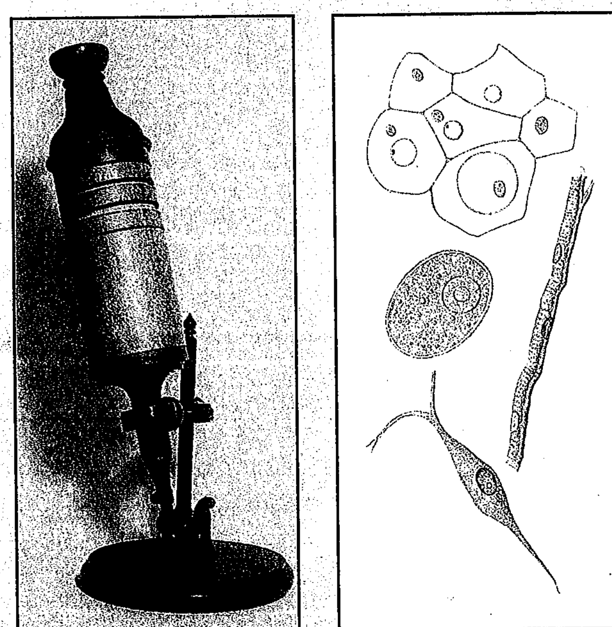
In 1839, Theodor Schwann used a microscope to examine parts of animals. Animals also seemed to be made up of small units (Figure 6.4b). Often these units looked like fluid-filled sacs. Each sac contained a nucleus. Schwann suggested that animals are also made of cells.

Thirty years after Hooke discovered cells, Anton van Leeuwenhoek observed microscopic organisms, or microorganisms. Water from ponds, rain barrels, and rivers revealed a wealth of tiny creatures. Soon after van Leeuwenhoek published his papers, many microbiologists were looking for living organisms in soil, spoiled food, and other places.

Eventually, the structure of microorganisms was compared with the structures of plants and animals. Many microorganisms did not seem to be composed of cells. Instead, they appeared to be about the size of one cell from a larger organism. The idea quickly took hold that they were unicellular (single-celled). Nuclei and other parts were discovered in many of these microorganisms. A large group of scientists began to think of the cell as the basic unit of life—either a complete organism or part of a multicellular organism.

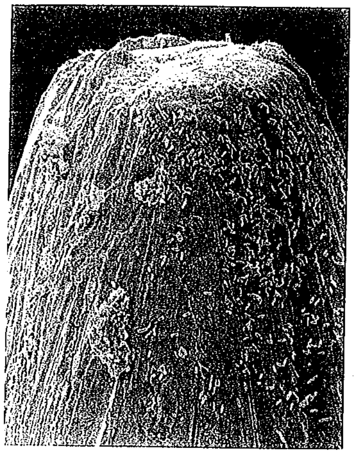
Cells were soon discovered in an increasing number of organisms. Numerous biologists observed cells dividing to produce more cells. A physician and biologist, Rudolf Virchow, saw in these events a principle—cells producing more cells through time. He stated the hypothesis simply: "All cells come from cells."

Today new technologies make possible extremely detailed studies of cell structure and function. New hypotheses about cell evolution are being investigated. The cell theory remains one of the unifying themes of biology.



(a) (b)

FIGURE 6.4
Early observations of cells. *a,* One of Robert Hooke's microscopes. *b,* The microscopic structure of small parts of animals as seen by Schwann: six cells from a fish *(top)*, an oval cell from the nervous system of a frog, a long cell from the muscle of an unborn pig, and a spindle-shaped cell, also from an unborn pig.



Prokaryotic cells. Prokaryotes are extremely small. Many bacteria are visible in this scanning electron micrograph (×290) of the point of a pin.

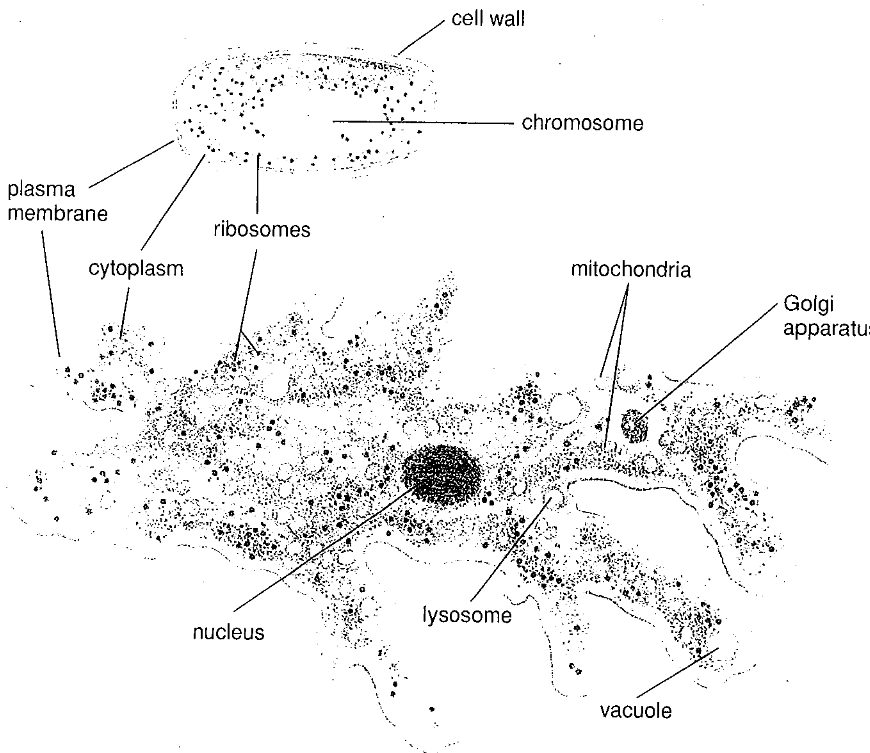
pro- = early or primitive (Greek)
eu- = good or true (Greek, Latin)
karyo- = nut or nucleus (Greek, Latin)

Eukaryotic cells have a fully formed nucleus. **Prokaryotic** cells are their evolutionary forerunners, with only a vaguely defined nuclear region.

Two Basic Types of Cells

Living cells can be separated into two groups, prokaryotes and eukaryotes, that differ in structure. This grouping is fundamental to the classification of organisms. Several types of strong evidence support the idea that the differences between prokaryotes and eukaryotes developed early in the history of life. These differences are essential to our understanding of the evolution of organisms. **Prokaryotes**—the bacteria—are the simplest living cells, and they are everywhere. They are common in soil, air, and water, and in or on every organism, including humans. Prokaryotic organisms are nearly always unicellular. Some prokaryotes inhabit extreme environments such as salt flats, hot springs such as those in Yellowstone National Park, and volcanic vents in the ocean floor. Others are so adaptable that you could find them almost anywhere on Earth. The smallest prokaryotes are only about 0.3 μm in diameter. Others are 1–5 μm across. Almost none are big enough to be seen without a microscope. Up to 700 million could fit side by side on the head of a thumbtack. Even the point of a pin can hold hundreds of bacteria (Figure 6.5.)

The cells of **eukaryotes** are larger (10–50 μm) and more complex than prokaryotes. These more complicated cells can form multicellular organisms: Plants, animals, and fungi are composed of eukaryotic cells.



A prokaryotic cell *(top)* and a eukaryotic cell *(bottom)*. Note the greater structural complexity of the eukaryotic cell (an amoeba) and its many membrane-enclosed parts, or organelles.

Unlike prokaryotes, eukaryotic cells have many parts, each with a specific function. This gives them the flexibility to develop into hundreds of specialized types that make up leaves, muscles, and other organs. Figure 6.6 compares a prokaryotic and a eukaryotic cell. You will learn about the structures shown in the diagram as you read this chapter.

Recall from Chapters 4 and 5 that prokaryotic cells lack mitochondria and chloroplasts. Eukaryotes contain many of these membrane-enclosed internal compartments. The most obvious difference between prokaryotes and eukaryotes is the **nucleus.** This membrane-enclosed structure contains the DNA of eukaryotic cells. Information encoded in this DNA directs the synthesis of the enzymes and other proteins that determine almost everything that happens in a living organism (see Figure 1.35 on page 47).

Check and Challenge

1. What is the cell theory?
2. In what ways does the study of cells depend on technology?
3. In centimeters, how long is your pencil? How does its size compare with that of a bacterium? of a eukaryotic cell?
4. Biologists have been able to keep isolated chloroplasts or mitochondria for a few hours or days. Can these structures be considered alive?
5. What is one advantage of using a light microscope rather than a more powerful electron microscope?

Cell Structure

6.3 Prokaryotic Cell Structure

The prokaryotes are bacteria. Most of them are unicellular but can associate in clusters, chains, and films. Nearly all prokaryotic cells have a rigid cell wall made of lipids, carbohydrates, and protein, but no cellulose. Figure 6.7 is a diagram of the structure of a prokaryote. Just inside the cell wall is a plasma membrane that encloses the cell. Prokaryotes have one chromosome made of a continuous, circular molecule of double-stranded DNA. The chromosome is attached to the plasma membrane in an area of the cell known as the nuclear region, or **nucleoid.** In addition, bacteria usually contain one or more smaller circular DNA molecules called **plasmids.** These extrachromosomal elements contain a few genes and are also attached to the plasma membrane. The part of the plasma membrane attached to the chromosome may contain enzymes that aid in making a copy of the chromosome before the cell reproduces by dividing in two.

ETYMOLOGY

nucleus = kernel or core (Latin)
-oid = similar (Greek, Latin)

Early observers thought of the nucleus as the cell's "core." A bacterial cell's **nucleoid** is similar to a nucleus but lacks a selectively permeable nuclear membrane.

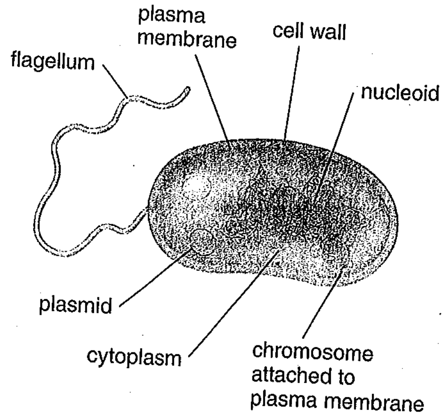


FIGURE 6.7

The structure of a prokaryotic cell. Electron micrographs revealed the details of the structure.

ETYMOLOGY

flagrum = whip (Latin)
-elle = little (Latin)

Flagella look like tiny whips, but bacterial flagella do not whip back and forth; they rotate like propellers.

Most bacteria have one of three shapes—rod, sphere, or corkscrew (Figure 6.8). Some have **flagella** (singular: flagellum), long, whiplike extensions made of protein that rotate like propellers, enabling cells to swim through water or the body fluids of larger organisms. These swimming bacteria can sense substances in their environment. They swim toward food and away from harmful substances such as strong acids.

Prokaryotes are extremely diverse in their metabolism. Many of their metabolic processes, such as glycolysis, are similar to those of eukaryotes, but others are unique. For example, all ecosystems include many types of bacterial decomposers that help recycle nutrients such as carbon, nitrogen, and sulfur compounds. Some of the reactions these prokaryotes perform provide them with free energy or fixed carbon and nitrogen, as you learned in Chapters 4 and 5. These reactions also recycle nutrients that would otherwise remain unavailable in wastes and dead organisms. This function of prokaryotes is essential to other members of their ecosystems.

(a) (b) (c)

FIGURE 6.8

The three most common shapes of bacterial cells. *a,* Cocci (spheres), ×45,000; *b,* bacilli (rods), ×31,000; and *c,* spirochetes (corkscrews), ×700. Note the flagella in *b.*

Many prokaryotes are autotrophs. They are important primary producers in lakes and oceans. Other bacteria are useful as the source of antibiotics and other compounds that are difficult to make artificially. Although some bacteria can cause human diseases such as strep throat, rheumatic fever, and skin infections, most are beneficial. Bacteria that live in your intestines help digest your food and provide you with certain vitamins. Other bacteria are used in manufacturing fermented foods, such as cheese and yogurt, and life-saving drugs.

CONNECTIONS

The great diversity and adaptability of bacteria reflect the power of natural selection to produce organisms that are adapted to diverse habitats.

6.4 Eukaryotic Cell Structure

Eukaryotic cells are divided into small functional parts called **organelles**. This is an important difference from prokaryotes. Any part of a eukaryotic cell that has its own structure and function can be considered an organelle. Thousands of chemical reactions occur constantly in eukaryotic cells. Many of those reactions are not compatible, yet they can occur at the same time because membranes that surround many organelles divide the cell into compartments. The concentration of a substance may be very different in different compartments. Different reactions may produce a substance in one organelle and consume it in another. For example, a membrane separates the genes, which are made of DNA, from the rest of the cell. This separation protects the DNA from enzymes that might break it down. The selectively permeable membrane also helps the cell control which of its genes are expressed at any time. Thus compartmentation makes eukaryotic cells more efficient by separating specific processes and enabling a division of labor within the cell. Figure 6.9 shows the major organelles of most eukaryotic cells. Refer to this figure and locate the organelles as you read the descriptions that follow.

ETYMOLOGY

organ = functional part (Latin, Greek)
-elle = little (Latin)

A cell's **organelles** are its "little organs."

A plasma membrane (Figure 6.9a) encloses the contents of both eukaryotic cells and prokaryotic cells. The structure of cell membranes is described in detail in Section 3.2. The plasma membrane of plant and fungal cells and some unicellular eukaryotes is surrounded by a rigid structure, the **cell wall** (Figure 6.9f). The wall is composed of stiff fibers of cellulose and other complex carbohydrates (Figure 6.10). This enables it to support and protect the cell. Animal cells lack a rigid cell wall. The cell wall is the most consistent difference between plant and animal cells.

The most noticeable organelle in a eukaryotic cell usually is its nucleus (Figures 6.9b and 6.11). The nucleus is a cell's genetic control center because it contains the chromosomes. Looking for a nucleus is the most reliable way to decide whether a cell is a prokaryote or a eukaryote. A double layer of membranes forms the nuclear envelope, or nuclear membrane, that surrounds the chromosomes. Each eukaryotic chromosome consists of a single long DNA molecule wrapped around a series of protein "spools." One or more drops of concentrated RNA are usually visible in the nucleus. These bodies are called **nucleoli** (singular: nucleolus). The nucleoli are the sites where types of RNA that will become part of the cell's protein-synthesizing machinery are synthesized.

Try Investigation 6A Cell Structure.

Within the plasma membrane, but outside the nucleus, is the cellular material, or cytoplasm. The cytoplasm was once thought to be mostly a

ETYMOLOGY

cyto- = cell (Greek)
sol = solution (Latin)

The **cytosol** is the solution within a cell.

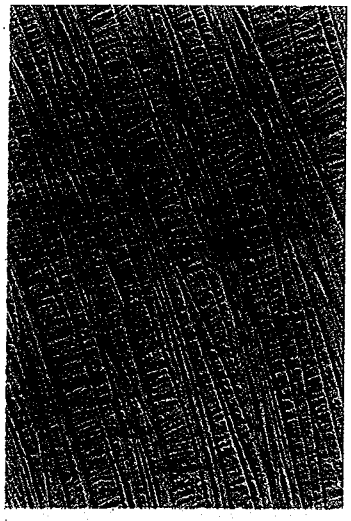


FIGURE 6.10
Cellulose fibers in the cell wall of an algal cell (×18,000). Overlapping layers of these fibers and other materials make the cell wall rigid.

ETYMOLOGY

endo- = inside (Greek)
-plasm = a form (cell) (Greek, Latin)
reticulum = net (Latin)

The **endoplasmic reticulum** forms a network within the cell.

simple solution of salts and organic compounds in water. The organelles were said to float in this solution, also known as the **cytosol**. The protein-rich, semifluid material in the cell that surrounds and bathes the organelles is still sometimes called the cytosol (Figure 6.9j). The cytoplasm includes the cytosol and the organelles.

More recently, our model of the cytosol has changed from a simple solution to a more organized system. A network of several types of very fine protein fibers helps to shape the cell and organize the cytoplasm. Changes in this protein scaffolding also enable some cells to move or change shape. This system is known as the **cytoskeleton** (Figures 6.9c and 6.12). It includes hollow microtubules (25 nm thick), solid but flexible strands called microfilaments (5 nm thick), and connecting intermediate filaments (10 nm thick). The cytoskeleton may hold organelles in place or move them around. Much of the water in a eukaryotic cell may be loosely bound to the cytoskeleton or to various other proteins and solutes. This binding of water makes the cytosol more like an organized gel, in which many components have a specific place, and less like a simple solution.

Scattered throughout the cytoplasm of both eukaryotes and prokaryotes are many small bodies composed of RNA and protein, called **ribosomes**. Ribosomes catalyze the synthesis of a cell's proteins. In eukaryotes, some ribosomes are attached to a system of membranes called the **endoplasmic reticulum**, or ER (Figures 6.9h and 6.13). The ER membranes form tubes and channels throughout the cytoplasm. This system connects many of the organelles in the cell. In electron micrographs, the ER resembles wrapping paper, folded back on itself, running through the cell. Proteins that are synthesized at the ribosomes attached to the ER pass directly into the ER as they are formed. They are transported through the ER to their final destinations in the cell. The ER also carries other substances to places in the cell where they are needed.

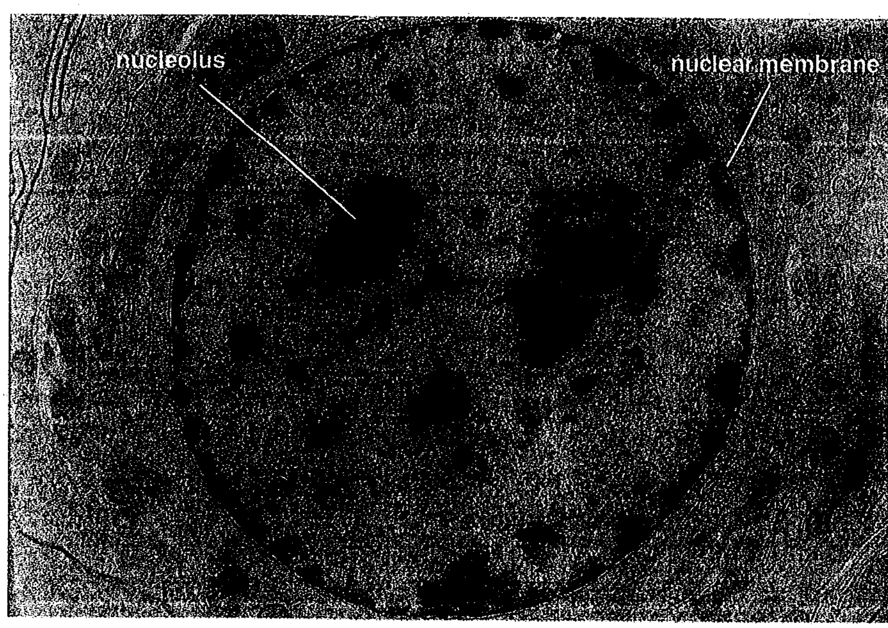


FIGURE 6.11
Transmission electron micrograph of the nucleus of a human liver cell, ×16,000. Note the double membrane that makes up the nuclear envelope. The large, dark, round body is the nucleolus.

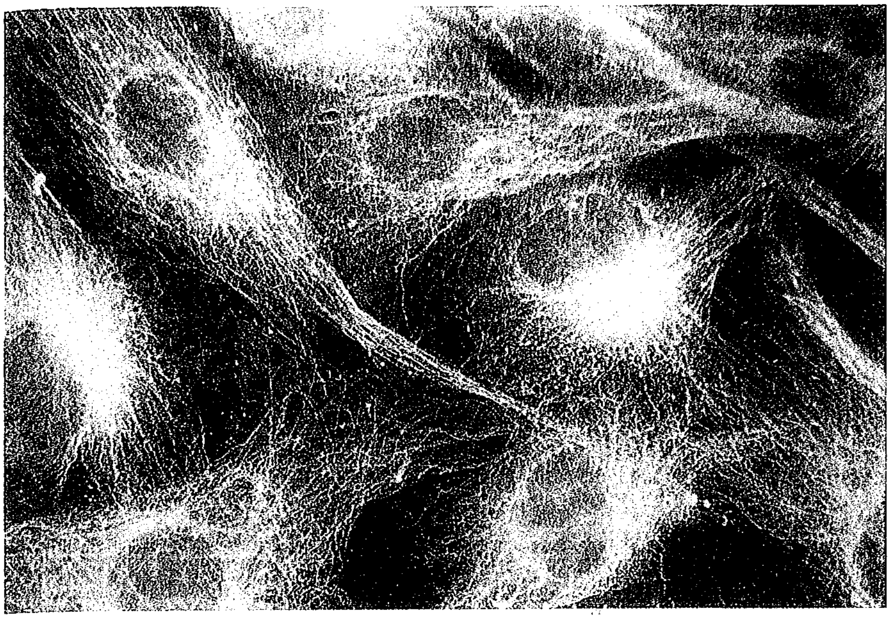


FIGURE 6.12

The cytoskeleton. Scanning electron micrograph image of the cytoskeletal protein network in hamster kidney cells, ×800. This internal protein network gives the cell shape and participates in cell movement.

Many substances that are exported from the cell pass through the ER to the **Golgi apparatus** (Figures 6.9i and 6.14). This organelle consists of a series of membranous sacs that look like a stack of pancakes. As material passes through these compartments, it is packaged in spherical, membrane-enclosed **vesicles** that appear to pinch off of the Golgi membranes. The vesicles can fuse with the plasma membrane, releasing their contents outside of the cell. Some vesicles deliver their contents to other organelles. Proteins synthesized on the ribosomes of the rough ER may be modified in the Golgi apparatus before they are released. For example, specific sugars are attached to some proteins before they are released from the cell. This system enables cells to release large polymers such as proteins and polysaccharides. These large molecules can then become part of an external

ETYMOLOGY

-icle = small (Latin)

A **vesicle** is a small "vessel," or container.

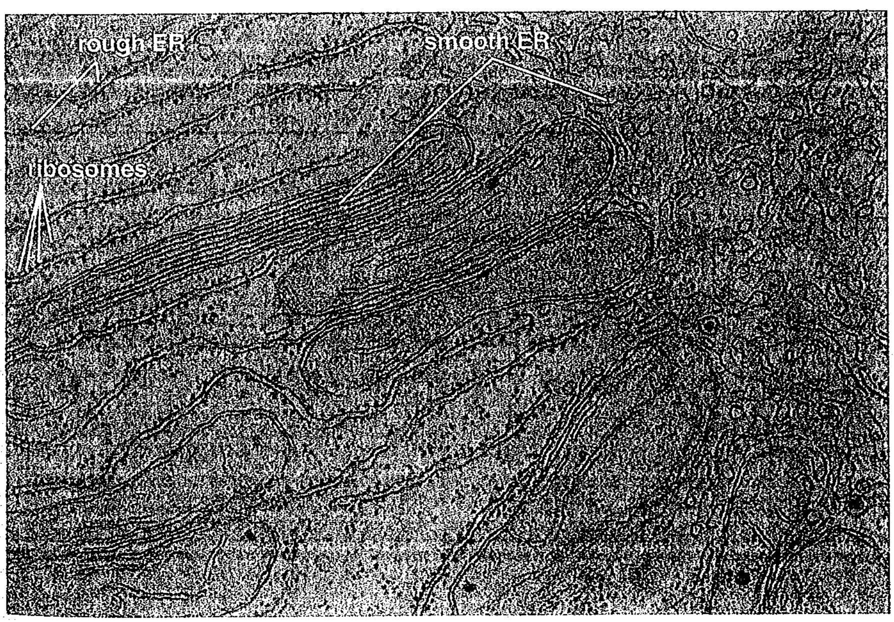


FIGURE 6.13

Transmission electron micrograph of endoplasmic reticulum in a rat liver cell (×23,600). Note rough ER, with ribosomes, and smooth ER without ribosomes. The ER carries newly made proteins to their destinations in or out of the cell.