A Tour of the Cell

CHAPTER 4

How has our knowledge of cells grown?

You can probably identify the blue blobs in this beautiful micrograph as the nuclei of the cells it depicts. But did you know that the brightly colored pink and green strands you also see form a cell's skeleton? These structures are part of a system of protein fibers called the cytoskeleton. Much like the way your skeleton provides support and also enables you to move, the cytoskeleton provides structural support to a cell and allows some cells to crawl and others to swim. But even stationary cells have movement: Many of their internal parts bustle about, often traveling on cytoskeletal "roads." Later in the chapter you will learn more about the cytoskeleton and how our knowledge of its structures and functions has grown. As you will see, our understanding of nature often goes hand in hand with the invention and refinement of instruments that extend our senses. This certainly applies to how cells were first discovered.

In 1665, Robert Hooke used a crude microscope to examine a piece of bark from an oak tree. Hooke compared the structures he saw to "little rooms"—*cellulae* in Latin—and the term *cell* stuck. His contemporary, Antoni van Leeuwenhoek, working with more refined lenses, examined numerous subjects, from blood and sperm to pond water. He produced drawings and enthusiastic descriptions of his discoveries, such as the tiny "animalcules, very prettily a-moving" he found in the scrapings from his teeth.

Since the days of Hooke and Leeuwenhoek, improved microscopes and techniques have vastly expanded our view of the cell. For example, fluorescently colored stains reveal the cytoskeleton in the cells pictured to the right. In this chapter, you will see many micrographs using such techniques, and they will often be paired with drawings that help emphasize specific details.

Neither drawings nor micrographs, however, allow you to see the dynamic nature of living cells. For that, you need to look through a microscope or view videos. As you study the images in this chapter, keep in mind that the parts of a cell are moving and interacting. Indeed, the phenomenon we call life emerges from the interactions of the many components of a cell.

BIG IDEAS

Introduction to the Cell

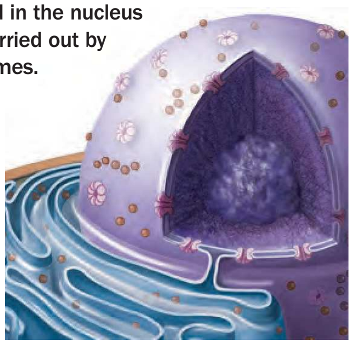
(4.1–4.4)

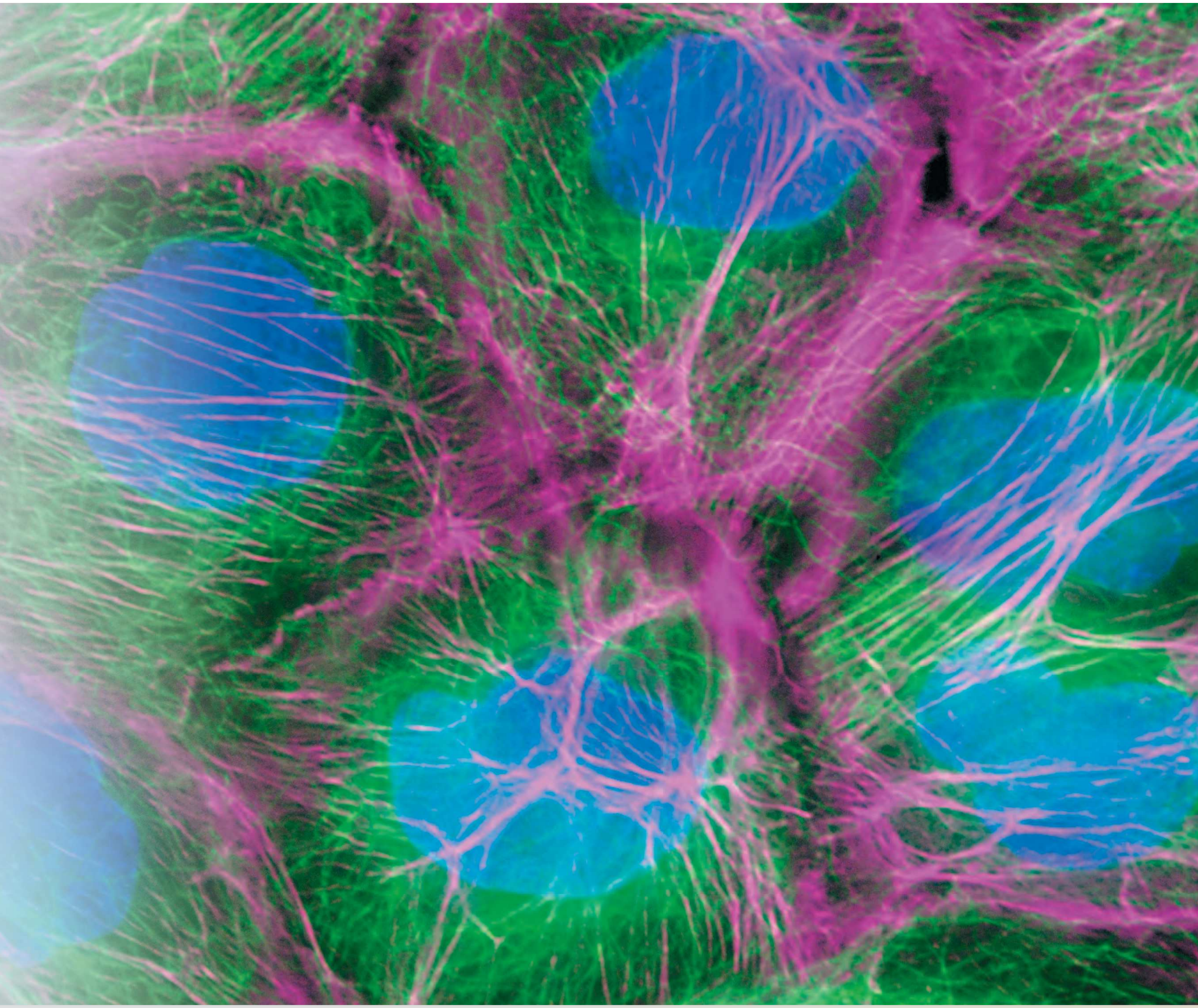
Microscopes reveal the structures of cells—the fundamental units of life.

The Nucleus and Ribosomes

(4.5–4.6)

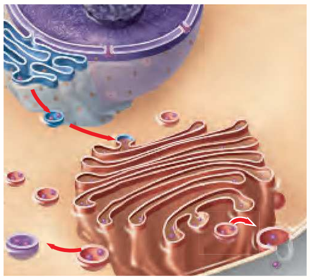
A cell's genetic instructions are housed in the nucleus and carried out by ribosomes.





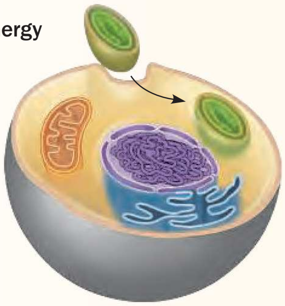
The Endomembrane System (4.7–4.12)

The endomembrane system participates in the manufacture, distribution, and breakdown of materials.



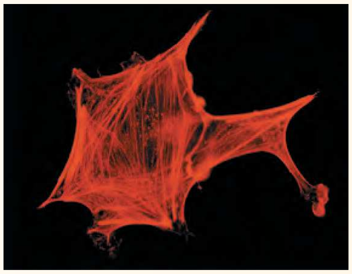
Energy-Converting Organelles (4.13–4.15)

Mitochondria in all eukaryotic cells and chloroplasts in plant cells function in energy processing.



The Cytoskeleton and Cell Surfaces (4.16–4.22)

The cytoskeleton and extracellular components provide support, motility, and functional connections.



Introduction to the Cell

4.1 Microscopes reveal the world of the cell

Before microscopes were first used in the 1600s, no one knew that living organisms were composed of the tiny units we call cells. The first microscopes were light microscopes, like the ones you may use in a biology laboratory. In a **light microscope (LM)**, visible light is passed through a specimen, such as a microorganism or a thin slice of animal or plant tissue, and then through glass lenses. The lenses bend the light in such a way that the image of the specimen is magnified as it is projected into your eye or a camera.

Magnification is the increase in an object's image size compared with its actual size. **Figure 4.1A** shows a micrograph of a single-celled organism called *Paramecium*. The notation "LM 230×" printed along the right edge tells you that this photograph was taken through a light microscope and that the image is 230 times the actual size of the organism. This *Paramecium* is about 0.33 millimeter (mm) in length. **Table 4.1** shows the most common units of length that biologists use.

An important factor in microscopy is resolution, a measure of the clarity of an image. Resolution is the ability to distinguish two nearby objects as separate. For example, what you see as a single star in the sky may be resolved as twin stars with a telescope. Each optical instrument—be it an eye, a telescope, or a microscope—has a limit to its resolution. The human eye can distinguish points as close together as 0.1 mm, about the size of a very fine grain of sand. A typical light microscope cannot resolve detail finer than about 0.2 micrometer (μm), about the size of the smallest bacterium. No matter how many times the image of such a small cell is magnified, the light microscope cannot resolve the details of its structure. Indeed, light microscopes can effectively magnify objects only about 1,000 times.

From the time that Hooke discovered cells in 1665 until the middle of the 1900s, biologists had only light microscopes for viewing cells. With these microscopes and various staining techniques to increase contrast between parts of cells, these early biologists discovered microorganisms, animal and plant cells, and even some structures within cells. By the mid-1800s, this accumulation of evidence led to the **cell theory**, which states that all living things are composed of cells and that all cells come from other cells.

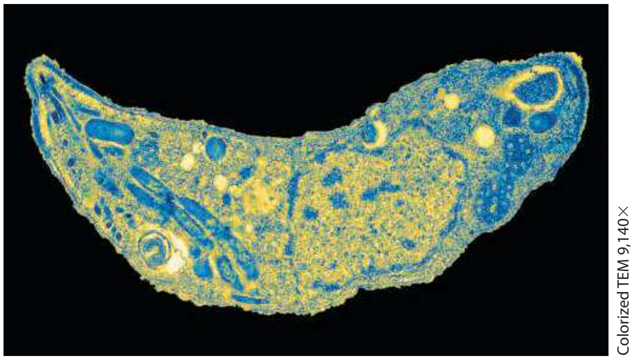
Our knowledge of cell structure took a giant leap forward as biologists began using the electron microscope in the 1950s. Instead of using light, an **electron microscope (EM)** focuses a beam of electrons through a specimen or onto its surface. Electron microscopes can distinguish biological structures as small as about 2 nanometers (nm), a 100-fold improvement over the light microscope. This high resolution has enabled biologists to explore cell ultrastructure, the complex internal anatomy of a cell. **Figures 4.1B** and **4.1C** show images produced by two kinds of electron microscopes.

TABLE 4.1 Metric Measurement Equivalents

1 meter (m) = 100 cm = 1,000 mm = 39.4 inches
1 centimeter (cm) = 10^{-2} m (0.01 or 1/100 m) = 0.4 inch
1 millimeter (mm) = 10^{-3} m (0.001 or 1/1,000 m)
1 micrometer (μm) = 10^{-6} m (0.000001 m) = 10^{-3} mm
1 nanometer (nm) = 10^{-9} m = 10^{-3} μm

▲ **Figure 4.1A** Light micrograph of the unicellular organism *Paramecium*

▲ **Figure 4.1B** Scanning electron micrograph of *Paramecium*



▲ **Figure 4.1C** Transmission electron micrograph of *Toxoplasma* (This parasite of cats can be transmitted to humans, causing the disease toxoplasmosis.)

TRY THIS Describe a major difference between the *Paramecium* in Figure 4.1B and the *Toxoplasma* in this figure. (Hint: Compare the notations along the right sides of the micrographs.)

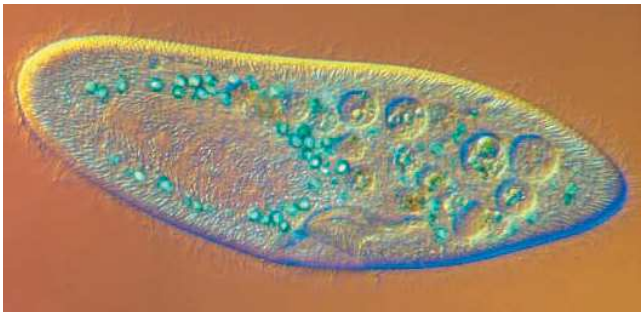
Biologists use the **scanning electron microscope (SEM)** to study the detailed architecture of cell surfaces. The SEM uses an electron beam to scan the surface of a cell or other sample, which is usually coated with a thin film of gold. The beam excites electrons on the surface, and these electrons are then detected by a device that translates their pattern into an image projected onto a video screen. The scanning electron micrograph in Figure 4.1B highlights the numerous cilia on *Paramecium*, projections it uses for movement. Notice the indentation, called the oral groove, through which food enters the cell. As you can see, the SEM produces images that look three-dimensional.

The **transmission electron microscope (TEM)** is used to study the details of internal cell structure. The TEM aims an electron beam through a very thin section of a specimen, just as a light microscope aims a beam of light through a specimen. The section is stained with atoms of heavy metals, which attach to certain cellular structures more than others. Electrons are scattered by these more dense parts, and the image is created by the pattern of transmitted electrons. Instead of using glass lenses, both the SEM and TEM use electromagnets as lenses to bend the paths of the electrons, magnifying and focusing the image onto a monitor. The transmission electron micrograph in Figure 4.1C shows internal details of a single-celled organism called *Toxoplasma*. SEMs and TEMs are initially black and white but are often artificially colorized, as they are here, to highlight or clarify structural features.

Electron microscopes have truly revolutionized the study of cells and their structures. Nonetheless, they have not replaced the light microscope: Electron microscopes cannot be used to study living specimens because the methods used to prepare the specimen kill the cells. For a biologist studying a living process, such as the movement of *Paramecium*, a light microscope equipped with a video camera is more suitable than either an SEM or a TEM.

There are different types of light microscopy, and major technical advances in the past several decades have greatly expanded our ability to visualize cells. **Figure 4.1D** shows *Paramecium* as seen using differential interference contrast microscopy. This optical technique amplifies differences in density so that the structures in living cells appear almost three-dimensional. Other techniques use fluorescent stains that selectively bind to various cellular molecules (see the chapter introduction).

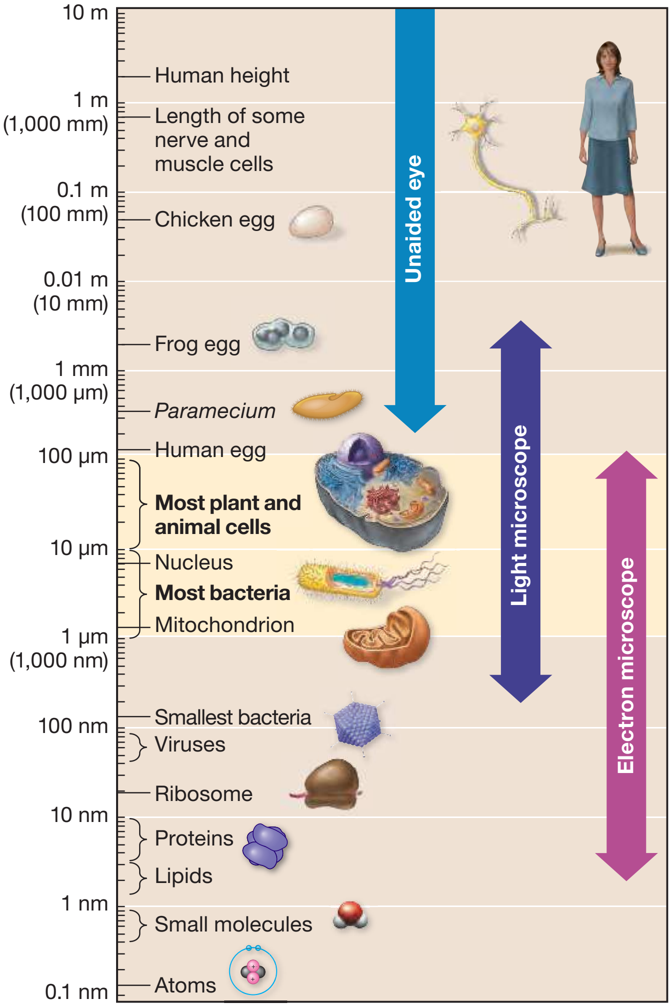
You will see many beautiful and illuminating examples of microscopy in this textbook. But even with the magnification shown beside each micrograph, it is often hard to imagine just how small cells are. **Figure 4.1E** shows the size range of cells compared with objects both larger and smaller and the optical instrument that allows us to view them. Notice that the scale along the left side of the figure is logarithmic to accommodate the range of sizes shown. Starting at the top with 10 meters (m), each reference measurement marks a tenfold decrease in length. Most cells are between 1 and 100 µm in diameter (yellow region of the figure) and are therefore visible only with a microscope. Certain bacteria are as small as 0.2 µm and can barely be seen with a light microscope, whereas chicken eggs are large enough to be seen with the unaided eye. A single nerve cell running from the base of your spinal cord to your big toe may be 1 m in length, although it is so thin you would still need a microscope to see it. In the next module, we explore why cells are so small.



▲ **Figure 4.1D** **Differential interference contrast micrograph of *Paramecium***

? Which type of microscope would you use to study (a) the changes in shape of a living human white blood cell; (b) the finest details of surface texture of a human hair; (c) the detailed structure of an organelle in a liver cell?

■ (a) Light microscope; (b) scanning electron microscope; (c) transmission electron microscope



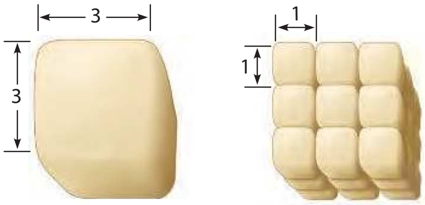
▲ **Figure 4.1E** **The size range of cells and related objects**

4.2 The small size of cells relates to the need to exchange materials across the plasma membrane

As you saw in Figure 4.1E, most cells are microscopic. Are there advantages to being so small? The logistics of carrying out a cell's functions appear to set both lower and upper limits on cell size. At minimum, a cell must be large enough to house enough DNA, protein molecules, and structures to survive and reproduce. But why aren't most cells as large as chicken eggs? The maximum size of a cell is influenced by geometry—the need to have a surface area large enough to service the volume of a cell. Active cells have a huge amount of traffic across their outer surface. A chicken egg cell isn't very active, but once a chick embryo starts to develop, the egg is divided into many microscopic cells, each bounded by a membrane that allows the essential flow of oxygen, nutrients, and wastes across its surface.

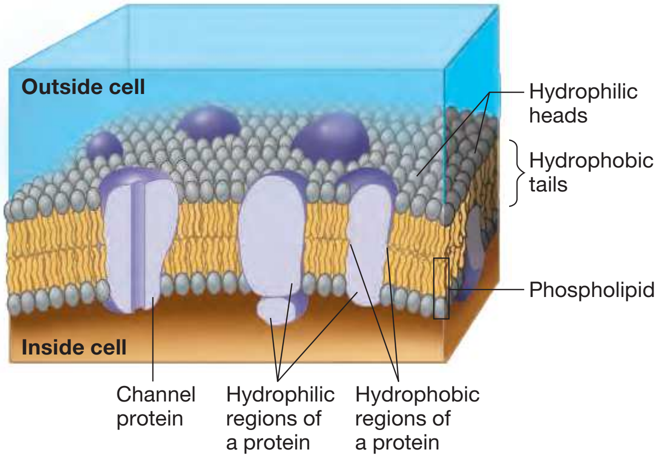
Surface-to-Volume Ratio Large cells have more surface area than small cells, but they have a much smaller surface area relative to their volume than small cells. **Figure 4.2A** illustrates this by comparing 1 large cube to 27 small ones. Using arbitrary units of measurement, the total volume is the same in both cases: 27 units^3 (height × width × length). The total surface areas, however, are quite different. A cube has six sides; thus, its surface area is six times the area of each side (height × width). The surface area of the large cube is 54 units^2, while the total surface area of all 27 cubes is 162 units^2 ($27 \times 6 \times 1 \times 1$), three times greater than the surface area of the large cube. Thus, the combined smaller cubes have a much greater surface-to-volume ratio than the large cube. How about those neurons that extend from the base of your spine to your toes? Very thin, elongated shapes also provide a large surface area relative to a cell's volume.

The Plasma Membrane So what is a cell's surface like? And how does it control the traffic of molecules across it? The **plasma membrane**, also referred to as the cell membrane, forms a flexible boundary between the living cell and its surroundings. For a structure that separates life from nonlife, this membrane is amazingly thin. It would take a stack of more than 8,000 plasma membranes to equal the thickness of this page. And, as you have come to expect with all things biological, the structure of the plasma membrane correlates with its function.



Total volume	27 units^3	27 units^3
Total surface area	54 units^2	162 units^2
Surface-to-volume ratio	2	6

▲ **Figure 4.2A** Effect of cell size on surface area and volume



▲ **Figure 4.2B** The structure of a plasma membrane

Phospholipid molecules are well suited to their role as a major constituent of biological membranes. Each phospholipid is composed of two distinct regions—a head with a negatively charged phosphate group and two nonpolar fatty acid tails (see Module 3.10). Phospholipids group together to form a two-layer sheet called a phospholipid bilayer. As you can see in **Figure 4.2B**, the phospholipids' hydrophilic (water-loving) heads face outward, exposed to the aqueous solutions on both sides of a membrane. Their hydrophobic (water-fearing) tails point inward, mingling together and shielded from water. Embedded in this lipid bilayer are diverse proteins, floating like icebergs in a phospholipid sea. The regions of the proteins within the center of the membrane are hydrophobic; the exterior sections exposed to water are hydrophilic.

Illustrating our theme of **STRUCTURE AND FUNCTION**, the properties of the phospholipid bilayer and the proteins suspended in it relate to the plasma membrane's job as a traffic cop, regulating the flow of material into and out of the cell. Nonpolar molecules, such as O_2 and CO_2, can easily move across the membrane's hydrophobic interior. Some of the membrane's proteins form channels (tunnels) that shield ions and polar molecules as they pass through the hydrophobic center of the membrane. Still other proteins serve as pumps, using energy to actively transport molecules into or out of the cell.

We will return to the structure and function of biological membranes later (see Chapter 5). In the next module, we consider other features common to all cells and take a closer look at the prokaryotic cells found in two of the three major groups of organisms.

? **To convince yourself that a small cell has a greater surface area relative to volume than a large cell, compare the surface-to-volume ratios of the large cube and one of the small cubes in Figure 4.2A.**

■ Large cube: 54/27 = 2; small cube: 6/1 = 6 (surface area is 1 × 1 × 6 sides = 6 units^2; volume is 1 × 1 × 1 unit^3)

4.3 Prokaryotic cells are structurally simpler than eukaryotic cells

Cells are of two distinct types: prokaryotic and eukaryotic. **Prokaryotic cells** were the first to evolve and were Earth's sole inhabitants for more than 1.5 billion years. Evidence indicates that **eukaryotic cells** evolved from some of these ancestral cells about 1.8 billion years ago. Biologists recognize three domains or major groups of organisms. The microorganisms placed in domains Bacteria and Archaea consist of prokaryotic cells. These organisms are known as prokaryotes. All other forms of life are placed in domain Eukarya. They are composed of eukaryotic cells and are referred to as eukaryotes.

Eukaryotic cells are distinguished by having a membrane-enclosed nucleus, which houses most of their DNA, and many membrane-enclosed organelles that perform specific functions. Prokaryotic cells are smaller and simpler in structure.

Both types of cells, however, share certain basic features. In addition to being bounded by a plasma membrane, the interior of all cells is filled with a thick, jellylike fluid called **cytosol**, in which cellular components are suspended. All cells have one or more **chromosomes**, which carry genes made of DNA. They also contain **ribosomes**, tiny structures that make proteins according to instructions from the genes. The inside of both types of cells is called the **cytoplasm**. However, in eukaryotic cells, this term refers only to the region between the nucleus and the plasma membrane.

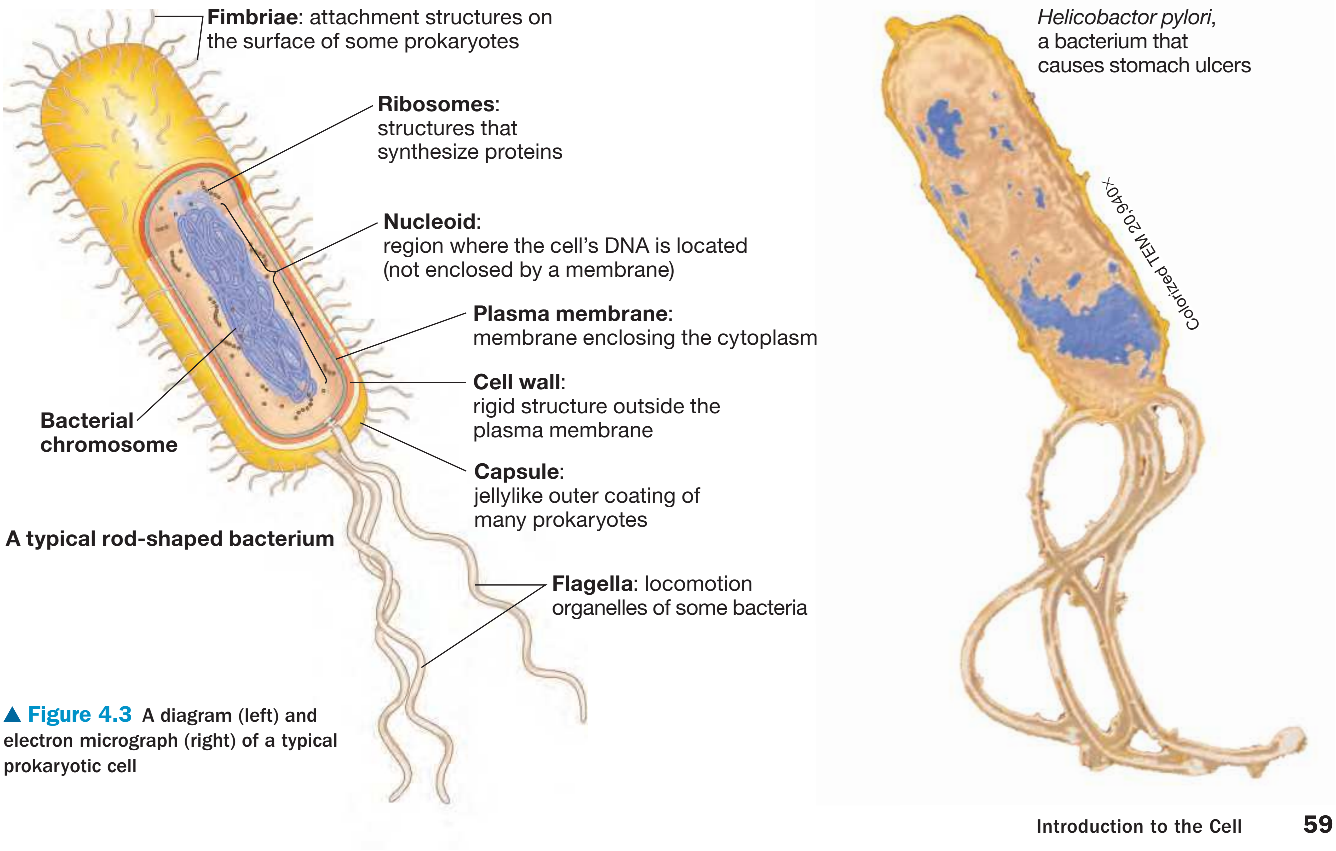
Figure 4.3 explores the structure of a generalized prokaryotic cell. Notice that the DNA is coiled into a region called the **nucleoid** ("nucleus-like"), but no membrane surrounds the DNA. The ribosomes of prokaryotes are smaller and differ somewhat from those of eukaryotes. These molecular differences are the basis for the action of some antibiotics, which specifically target prokaryotic ribosomes. Thus, protein synthesis can be blocked for the bacterium that's invaded you, but not for you, the eukaryote who is taking the drug.

Outside the plasma membrane of most prokaryotes is a fairly rigid, chemically complex cell wall. The wall protects the cell and helps maintain its shape. Some antibiotics, such as penicillin, prevent the formation of these protective walls. Again, because your cells don't have such walls, these antibiotics can kill invading bacteria without harming your cells. Certain prokaryotes have a sticky outer coat called a capsule around the cell wall, helping to glue the cells to surfaces or to other cells in a colony. In addition to capsules, some prokaryotes have surface projections. Short projections help attach prokaryotes to each other or their substrate. Longer projections called **flagella** (singular, *flagellum*) propel a cell through its liquid environment.

It takes an electron microscope to see the internal details of any cell, and this is especially true of prokaryotic cells. Notice that the TEM of the bacterium in Figure 4.3 has a magnification of 20,940×. Most prokaryotic cells are about one-tenth the size of a typical eukaryotic cell. (Prokaryotes will be described in more detail in Chapter 16.) Eukaryotic cells are the main focus of this chapter, so we turn to these next.

? **List three features that are common to prokaryotic and eukaryotic cells. List three features that differ.**

■ Both types of cells have plasma membranes, chromosomes containing DNA, and ribosomes. Prokaryotic cells are smaller, do not have a nucleus or other membrane-enclosed organelles, and have somewhat different ribosomes.



▲ **Figure 4.3** A diagram (left) and electron micrograph (right) of a typical prokaryotic cell

4.4 Eukaryotic cells are partitioned into functional compartments

All eukaryotic cells—whether from protists (a diverse group of mostly unicellular organisms), fungi, animals, or plants—are fundamentally similar to one another and profoundly different from prokaryotic cells. Let's look at an animal cell and a plant cell as representatives of the eukaryotes.

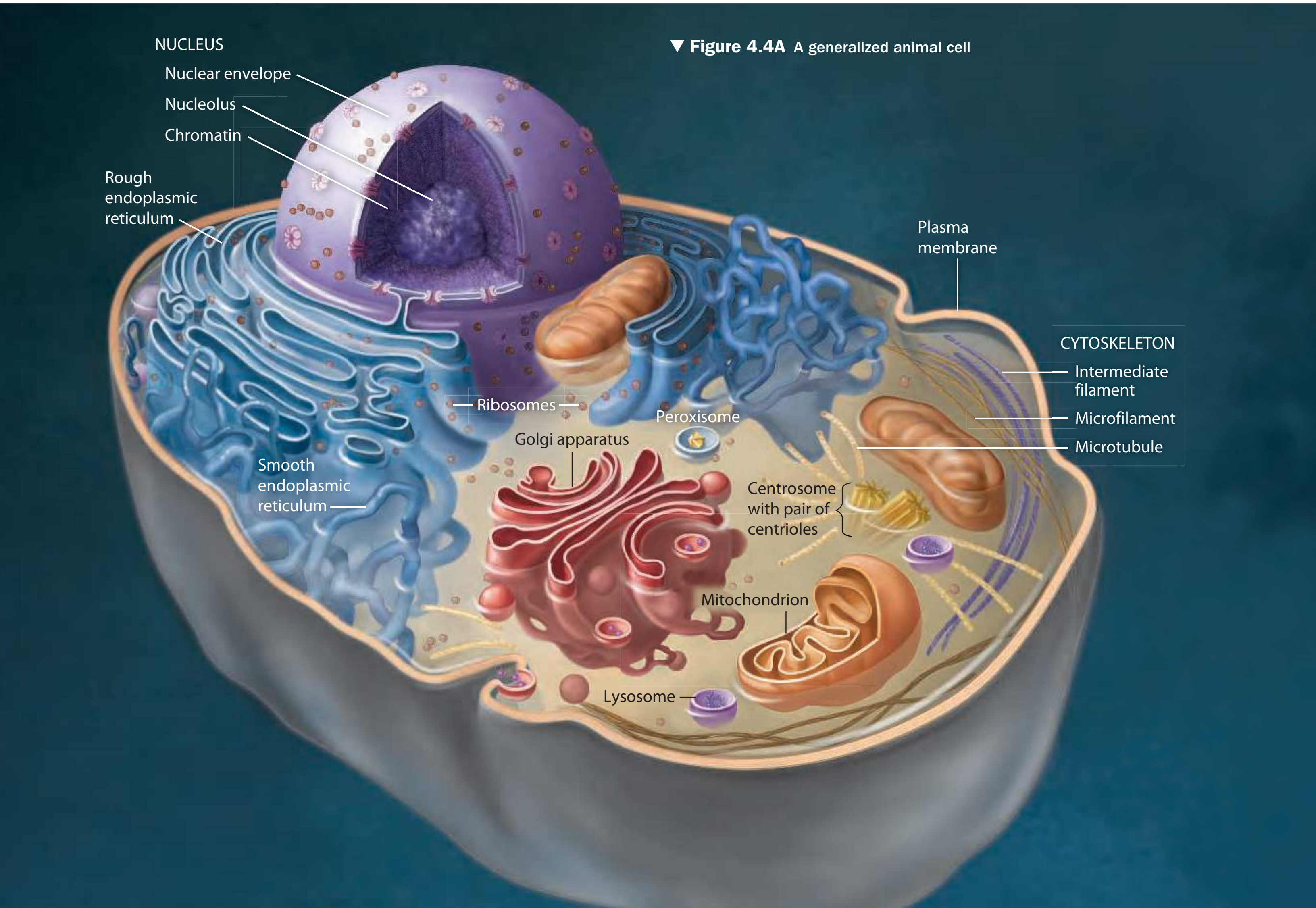
Figure 4.4A is a diagram of a generalized animal cell, and **Figure 4.4B** shows a generalized plant cell. We color-code the various structures in the diagrams for easier identification, and you will see miniature versions of these cells to orient you during our in-depth tour in the rest of the chapter. But no cells would look exactly like these. For one thing, cells have multiple copies of all of these structures (except for the nucleus). Your cells have hundreds of mitochondria and millions of ribosomes. A plant cell may have 30 chloroplasts packed inside. Cells also have different shapes and relative proportions of cell parts, depending on their specialized functions.

The most obvious hallmark of a eukaryotic cell is its nucleus. But it also contains various other **organelles** ("little organs"), which perform specific tasks. Just as the cell itself is wrapped in a membrane made of phospholipids and proteins that perform various functions, each organelle is bounded by a membrane with a lipid and protein composition that suits its function.

The organelles and other structures of eukaryotic cells can be organized into four basic functional groups: (1) The nucleus and ribosomes carry out the genetic control of the cell. (2) Organelles involved in the manufacture, distribution, and breakdown of molecules include the endoplasmic reticulum, Golgi apparatus, lysosomes, vacuoles, and peroxisomes. (3) Mitochondria in all cells and chloroplasts in plant cells function in energy processing. (4) Structural support, movement, and communication between cells are the functions of the cytoskeleton, plasma membrane, and plant cell wall. The cellular components identified in these two figures will be examined in detail in the modules that follow.

In essence, the internal membranes of a eukaryotic cell partition it into functional compartments in which many

▼ **Figure 4.4A** A generalized animal cell



of its chemical activities—collectively called **cellular metabolism**—take place. In fact, various enzymes essential for metabolic processes are built into the membranes of organelles. The fluid-filled spaces within such compartments are locations where specific chemical conditions are maintained. These conditions vary among organelles and favor the metabolic processes occurring in each. For example, while a part of the endoplasmic reticulum is engaged in making hormones, neighboring peroxisomes may be detoxifying harmful compounds and making hydrogen peroxide (H_2O_2) as a poisonous by-product of their activities. But because the H_2O_2 is confined within the peroxisomes, where it is converted to H_2O by resident enzymes, the rest of the cell is protected.

Except for lysosomes and centrosomes, the organelles and other structures of animal cells are found in plant cells. Also, although some animal cells have flagella or cilia (not shown in Figure 4.4A), among plants, only the sperm cells of a few species have flagella.

A plant cell (Figure 4.4B) also has some structures that an animal cell lacks. For example, a plant cell has a rigid, rather thick cell wall. Chemically different from prokaryotic cell walls, plant cell walls contain the polysaccharide cellulose. Plasmodesmata (singular, plasmodesma) are cytoplasmic channels through cell walls that connect adjacent cells. An important organelle found in plant cells is the chloroplast, where photosynthesis occurs. Unique to plant cells is a large central vacuole, a compartment that stores water and a variety of chemicals.

Eukaryotic cells contain nonmembranous structures as well. The cytoskeleton, which you were introduced to in the chapter introduction, is composed of different types of protein fibers that extend throughout the cell. And ribosomes are found in the cytosol as well as attached to certain membranes.

After you preview these cell diagrams, let's move to the first stop on our detailed tour of the eukaryotic cell—the nucleus.

? Identify the structures in the plant cell that are not present in the animal cell.

■ Chloroplasts, central vacuole, cell wall, and plasmodesmata

▼ Figure 4.4B A generalized plant cell