4 A Tour of the Cell

CHAPTER CONTENTS

WHAT DO YOU HAVE IN COMMON WITH A MUSHROOM? AT THE CELLULAR LEVEL, QUITE A LOT!

Why Cells Matter

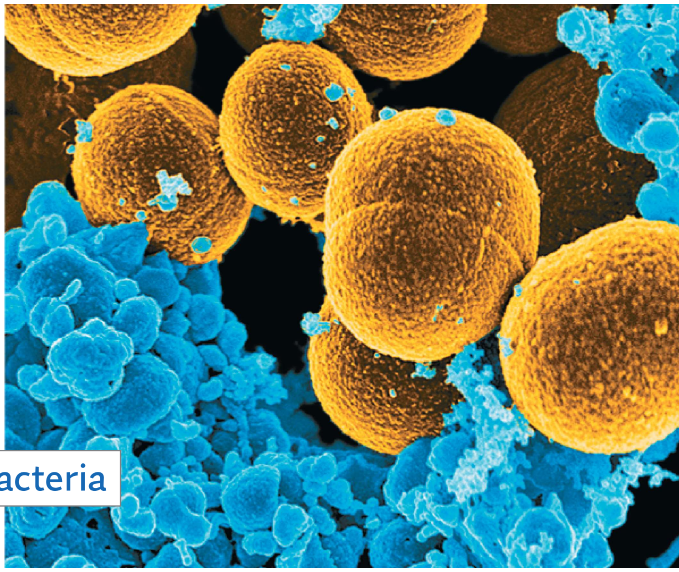
Life begins at the cellular level. Although microscopic, a cell contains complex machinery capable of supporting all of life's processes. Any study of biology can therefore benefit from an examination of cellular structures.

WITHOUT THE CYTOSKELETON, YOUR CELLS WOULD COLLAPSE IN ON THEMSELVES, MUCH LIKE A BUILDING COLLAPSES WHEN THE INFRASTRUCTURE FAILS.

ENJOY THAT BUZZ? THE CAFFEINE THAT GIVES COFFEE A KICK ALSO PROTECTS COFFEE PLANTS FROM HERBIVORES.

CHAPTER THREAD

Humans Versus Bacteria



Colorized SEM 20,000×

Staphylococcus aureus. These bacteria (yellow) are evading destruction by human white blood cells (blue).

BIOLOGY AND SOCIETY Humans Versus Bacteria

Antibiotics: Drugs That Target Bacterial Cells

Antibiotics—drugs that disable or kill infectious bacteria—are marvels of modern medicine. The first antibiotic to be discovered was penicillin in 1928. Before this time, even relatively minor infections could be deadly. After the development of penicillin, a revolution in human health rapidly followed. Fatality rates of many diseases (such as bacterial pneumonia and surgical infections) plummeted, saving millions of lives. In fact, human health care improved so quickly and so profoundly that some doctors in the early 1900s predicted the end of infectious diseases altogether. Unfortunately, this did not come to pass—see the Evolution Connection section in Chapter 13 for a discussion of why infectious diseases were not so easily defeated.

The goal of antibiotic treatment is to knock out invading bacteria while doing no damage to the human host. How does an antibiotic zero in on its bacterial target among trillions of human cells? Most antibiotics are so precise because they bind to structures found only in bacterial cells. For example, the common antibiotics erythromycin and streptomycin bind to the bacterial ribosome, a vital cellular structure responsible for producing proteins. The ribosomes of humans are different enough from those of bacteria that the antibiotics bind only to bacterial ribosomes, leaving human ribosomes unaffected. Ciprofloxacin (commonly referred to as Cipro) is an antibiotic that targets an enzyme bacteria need to maintain their chromosome structure. Your cells can survive just fine in the presence of Cipro because human chromosomes have a sufficiently different makeup from bacterial chromosomes. Other drugs, such as penicillin, ampicillin, and bacitracin, disrupt the synthesis of cell walls, a structure found in most bacteria that is absent from the cells of humans and other animals. As you'll learn in this chapter, researchers continue to exploit the unique structures of bacterial cells to design and discover new antibiotics.

This discussion of how various antibiotics target bacteria underscores the main point of this chapter: To understand how life works—whether in bacteria or in your own body—you first need to learn about cells. On the scale of biological organization, cells occupy a special place: They are the simplest objects that can be alive. Nothing smaller than a cell is capable of displaying all of life's properties. In this chapter, we'll explore the microscopic structure and function of cells. Along the way, we'll further consider how the ongoing battle between humans and infectious bacteria is affected by the cellular structures present on both sides.

The Microscopic World of Cells

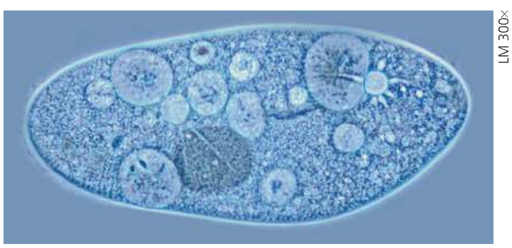
If you've ever gazed through a microscope, you've seen that every cell is a miniature marvel **(Figure 4.1)**. If the world's most sophisticated jumbo jet were reduced to microscopic size, its complexity would pale next to a living cell.

Organisms are either single-celled, such as most prokaryotes and protists, or multicellular, such as plants, animals, and most fungi. Your own body is a cooperative society of trillions of cells of many specialized types. As you read this page, muscle cells allow you to scan your eye across the words, while sensory cells in your eye gather information and send it to brain cells, which interpret the words. Everything you do—every action and every thought—is possible because of processes that occur at the cellular level.

Figure 4.2 shows the size range of cells compared with objects both larger and smaller. Most cells are between

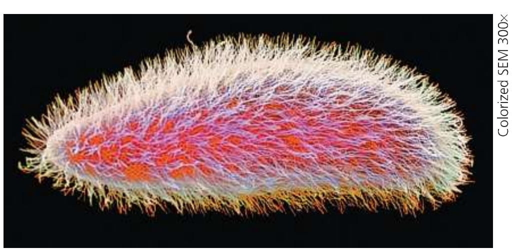
▼ **Figure 4.1 Types of micrographs.** Photographs taken with microscopes are called micrographs. Light microscopes can magnify up to about 1,000-fold. Electron microscopes use beams of electrons rather than light and can show objects about 100 times smaller than light microscopes.

Light Micrograph (LM)
(can be a view of a living or dead specimen)



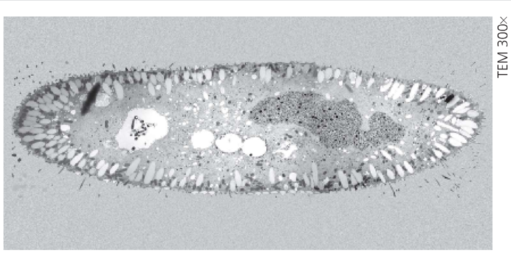
Light micrograph of a protist, *Paramecium*

Scanning Electron Micrograph (SEM)
(a view of surface features; specimens must be killed)



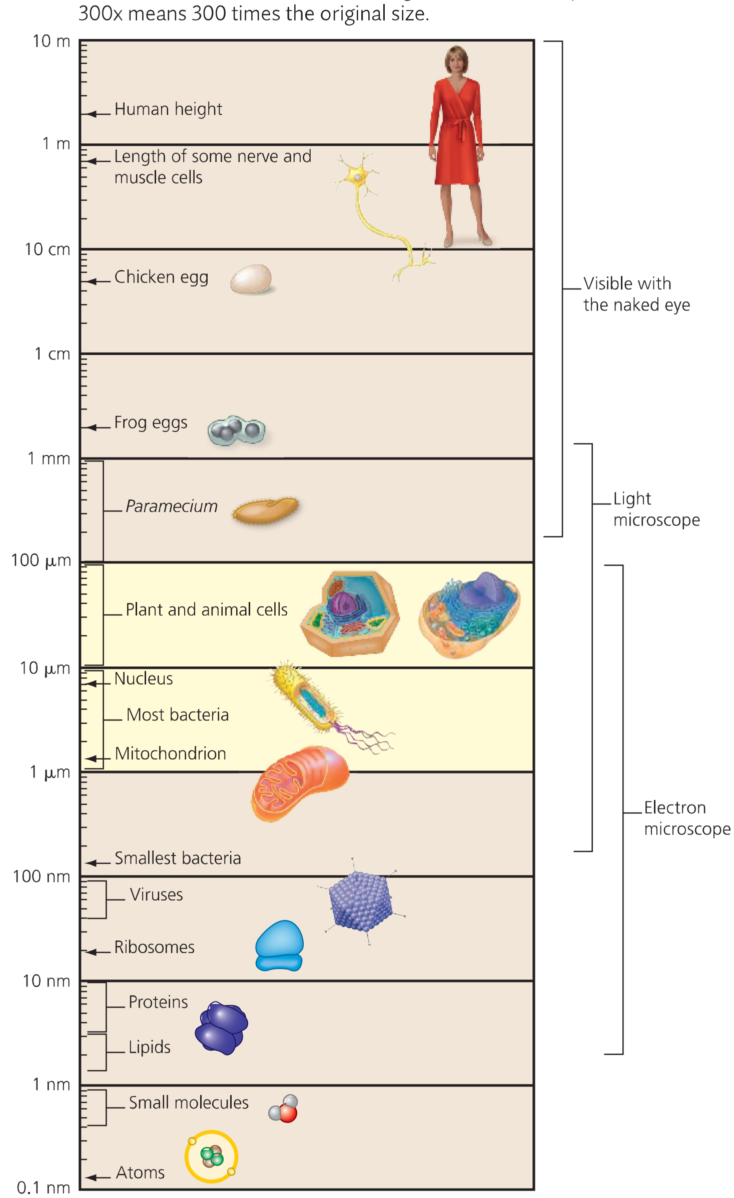
Scanning electron micrograph of *Paramecium*

Transmission Electron Micrograph (TEM)
(a view of internal structures; specimens must be killed)



Transmission electron micrograph of *Paramecium*

▼ **Figure 4.2 Size ranges.** Starting at the top of this scale with 10 m (10 meters) and going down, each measurement along the left side marks a tenfold decrease in size. Micrographs in this book have size notations (see Figure 4.1). For example, 300x means 300 times the original size.



See Appendix A for help in converting between measurements.

1 and 100 μm in diameter (yellow region of the figure) and are therefore visible only with a microscope. There are some interesting exceptions: An ostrich egg is a single cell about 6 inches across and weighing about 3 pounds, and nerve cells in giant squid can be more than 30 feet long!

How do new living cells arise? The **cell theory** states that all living things are composed of cells and that all cells come from earlier cells. So every cell in your body (and in every other living organism on Earth) was formed by division of a previously living cell. (That raises an obvious question: How did the first cell evolve? This fascinating topic is addressed in Chapter 15.) With that introduction, let's begin to explore the variety of cells found among life on Earth.

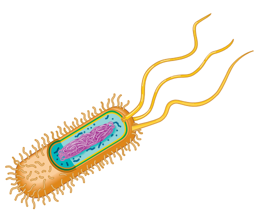
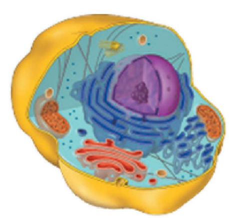
The Two Major Categories of Cells

The countless cells that exist on Earth can be divided into two basic types: prokaryotic cells and eukaryotic cells **(Table 4.1)**. Biologists classify all life into three major groups called **domains**. Organisms of the domains Bacteria and Archaea are composed of **prokaryotic cells** and are called prokaryotes. Organisms of the domain Eukarya—including protists, plants, fungi, and animals—are composed of **eukaryotic cells** and are called eukaryotes. Some (such as yeast) are microscopic, while others can be massive. Every organism you can see with your own eyes is a eukaryote.

All cells, whether prokaryotic or eukaryotic, have several features in common. They are all bounded by a barrier called a **plasma membrane**, which regulates the traffic of molecules between the cell and its surroundings. Inside all cells is a thick, jellylike fluid called the **cytosol**, in which cellular components are suspended. All cells have one or more **chromosomes** carrying genes made of DNA. And all cells have **ribosomes** that build proteins according to instructions from the genes. Because some structures are unique to bacteria, as mentioned in the Biology and Society section at the beginning of the chapter, some antibiotics—such as streptomycin—target prokaryotic ribosomes, crippling protein synthesis in the bacterial invaders but not in the eukaryotic host (you).

Although they have many similarities, prokaryotic and eukaryotic cells differ in several important ways. Fossil evidence shows that prokaryotes were the first life on Earth, appearing more than 3.5 billion years ago, and were Earth's sole inhabitants for over a billion years (see Figure 15.1). In contrast, the first eukaryotes did not appear until around 1.8 billion years ago. Prokaryotic cells are usually much smaller—about one-tenth the length of a typical eukaryotic cell—and are simpler in structure. Think of a prokaryotic cell as being like a

WHAT DO YOU HAVE IN COMMON WITH A MUSHROOM? AT THE CELLULAR LEVEL, QUITE A LOT!

Table 4.1	**Comparing Prokaryotic and Eukaryotic Cells**
Prokaryotic cells	Eukaryotic cells
	
First evolved approximately 3.5 billion years ago	First evolved approximately 2.1 billion years ago
Found in bacteria and archaea	Found in protists, plants, fungi, and animals
Smaller, simpler	Larger, more complex
Most have cell walls; some have capsules, fimbriae, and/or flagella.	Plant cells have cell walls; animal cells are surrounded by an extracellular matrix.
Have a plasma membrane	Have a plasma membrane
No membrane-bound organelles	Membrane-bound organelles (for example, nucleus, ER)
Have a nucleoid region containing a single circular chromosome	Have a nucleus containing one or more linear chromosomes
Have ribosomes	Have ribosomes

✅ **CHECKPOINT**

1. Name four structures found in both prokaryotic and eukaryotic cells.
2. How is the nucleoid region of a prokaryotic cell different from the nucleus of a eukaryotic cell?

■ Answers: **1.** plasma membrane, one or more chromosomes, cytosol, and ribosomes **2.** There is no membrane enclosing the prokaryotic nucleoid region.

bicycle, whereas a eukaryotic cell is like a sports utility vehicle. Both a bike and an SUV get you from place to place, but one is much smaller and contains many fewer parts than the other. Similarly, prokaryotic cells and eukaryotic cells perform similar functions, but prokaryotic cells are much smaller and less complex. The most significant structural difference between the two types of cells is that eukaryotic cells have **organelles** ("little organs"), membrane-enclosed structures that perform specific functions; prokaryotic cells do not have organelles. The most important organelle is the **nucleus**, which houses most of a eukaryotic cell's DNA. The nucleus is surrounded by a double membrane. A prokaryotic cell lacks a nucleus; its DNA is coiled into a "nucleus-like" region called the **nucleoid**, which is not partitioned from the rest of the cell by membranes.

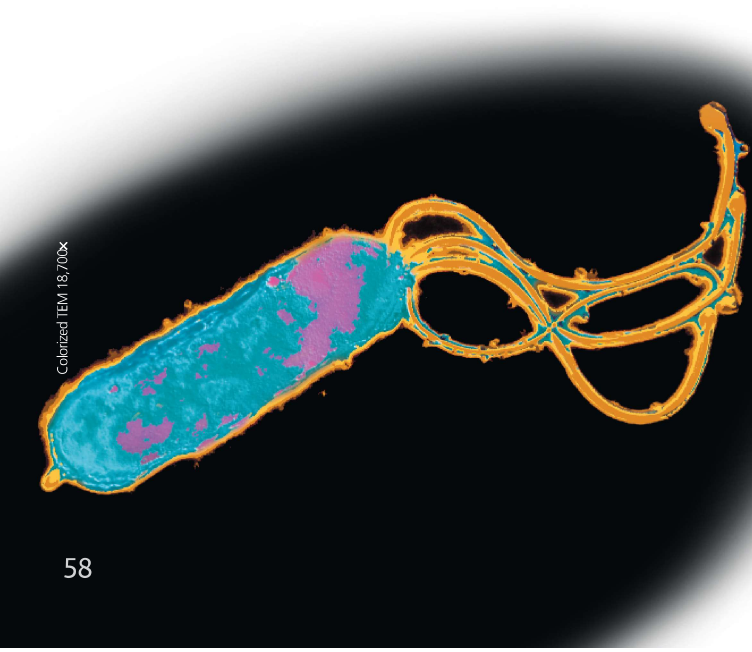
Consider this analogy: A eukaryotic cell is like an office building that is separated into cubicles. Within each cubicle, a specific function is performed, thus dividing the labor among many internal compartments. One cubicle may hold the accounting department, for example, while another is home to the sales force. The cubicle walls within eukaryotic cells are made from membranes that help maintain a unique chemical environment inside each cubicle. In contrast, the interior of a prokaryotic cell is like an open warehouse. The spaces for specific tasks within a prokaryotic warehouse are distinct, but they are not separated by physical barriers: Imagine desks for the sales and accounting departments arranged across an open floor.

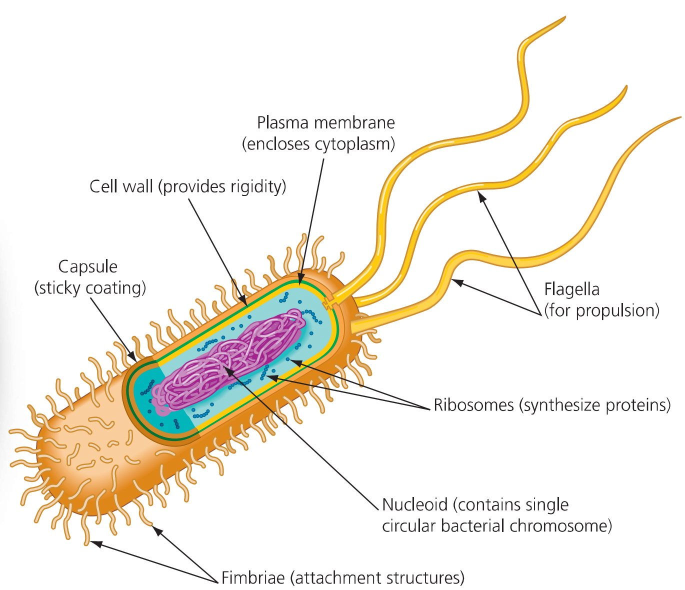
Figure 4.3 depicts an idealized prokaryotic cell and a micrograph of an actual bacterium. Surrounding the plasma membrane of most prokaryotic cells is a rigid cell wall, which protects the cell and helps maintain its shape. Recall from the Biology and Society section that bacterial cell walls are the targets of some antibiotics. In some prokaryotes, a sticky outer coat called a capsule surrounds the cell wall. Capsules provide protection and help prokaryotes stick to surfaces and to other cells in a colony. For example, capsules help bacteria in your mouth stick together to form harmful dental plaque. Prokaryotes can have short projections called fimbriae, which can also attach to surfaces. Many prokaryotic cells have flagella, long projections that propel them through their liquid environment. ✅

An Overview of Eukaryotic Cells

All eukaryotic cells—whether from animals, plants, protists, or fungi—are fundamentally similar to one another and quite different from prokaryotic cells. The key difference is that eukaryotic cells are partitioned by membranes into organelles. The membranes allow each organelle to maintain specific chemical conditions that favor the metabolic tasks performed there. **Figure 4.4** provides overviews of an idealized animal cell and plant cell. No real cell looks quite like these idealized cells because living cells have many more copies of most of the structures

▼ **Figure 4.3 A prokaryotic cell.** A micrograph of *Helicobacter pylori* (left), a bacterium that causes stomach ulcers, is shown alongside a drawing of an idealized prokaryotic cell (right).



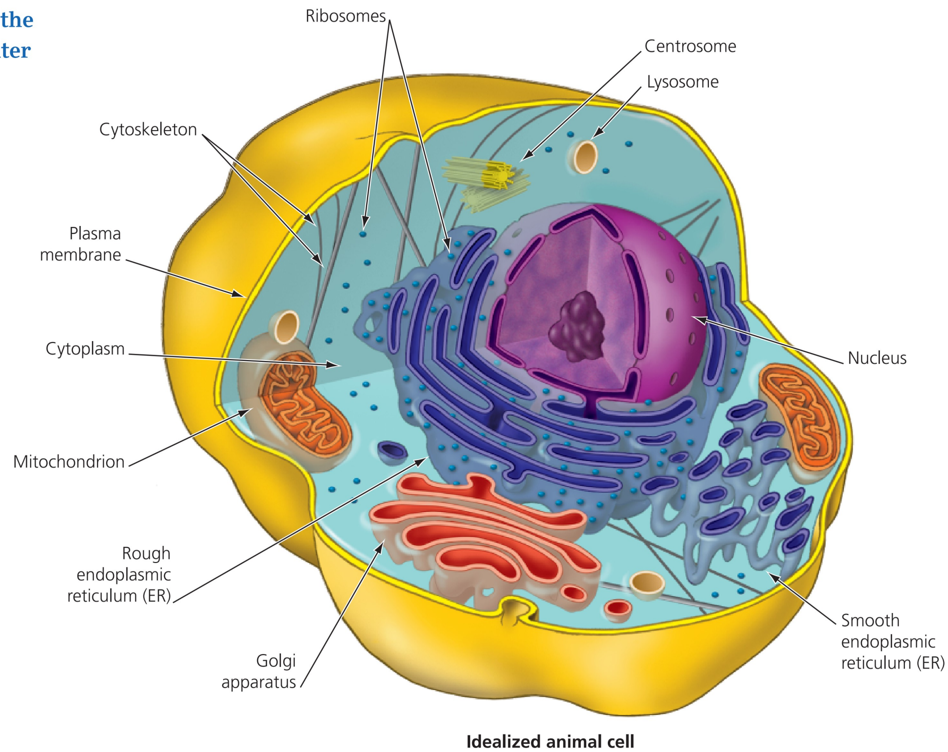


shown; each of your cells has hundreds of mitochondria and millions of ribosomes, for example.

The parts of a cell form an integrated team, with the properties of life emerging as a result of the team members working together. **A cell beautifully illustrates the theme of interactions: It is a living unit that is greater than the sum of its parts.** Throughout this chapter we'll use miniature versions of Figure 4.4 as road maps, highlighting the structure we're discussing. Notice that the structures are color-coded; we'll use this color scheme throughout the book.

The region of the cell outside the nucleus and within the plasma membrane is called the **cytoplasm**. (This term is also used to refer to the interior of a prokaryotic cell.) The cytoplasm of a eukaryotic cell consists of various organelles suspended in the liquid cytosol. As you can see in Figure 4.4, most organelles are found in both animal and plant cells. But you'll notice some important differences between these two types of cells. For example, plant cells have chloroplasts (where photosynthesis occurs), a cell wall (which provides stiffness to plant structures), and a central vacuole. In the rest of this section, we'll take a closer look at the architecture of eukaryotic cells, beginning with the plasma membrane. ✓

▼ **Figure 4.4 An idealized animal cell and plant cell.** For now, the labels on the drawings are just words, but these cellular components will come to life as we take a closer look at how each part of the cell functions.



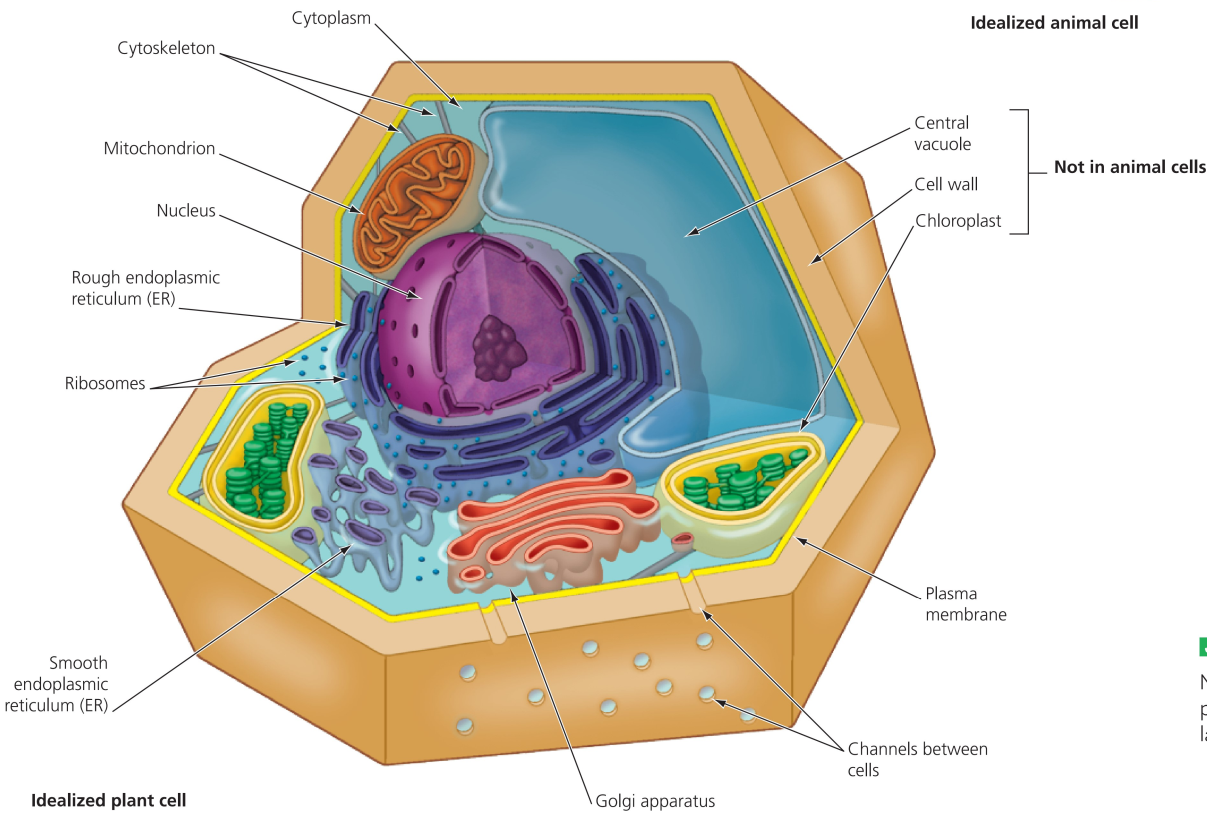


Figure Walkthrough
Mastering Biology
goo.gl/2bGkpo.qr

✓ CHECKPOINT

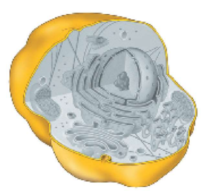
Name three structures in plant cells that animal cells lack.

■ Answer: chloroplasts, a central vacuole, and a cell wall

Membrane Structure

Before we enter the cell to explore the organelles, let's make a quick stop at the surface of this microscopic world: the plasma membrane. To help understand the plasma membrane (also called the cell membrane), imagine you want to create a new home in a rural area. You will probably want to start by fencing your property to protect it from the outside world. Similarly, the plasma membrane is the boundary that separates the living cell from its nonliving surroundings. The plasma membrane is a remarkable film, so thin that you would have to stack 8,000 of these membranes to equal the thickness of one piece of paper. Yet the plasma membrane can regulate the traffic of chemicals into and out of the cell. **As you'll see next, the plasma membrane illustrates the theme of the relationship between structure and function.** The composition of the plasma membrane relates to its job as a border guard, regulating the flow of materials into and out of the cell.

The Plasma Membrane



The plasma membrane and other membranes of the cell are composed mostly of **phospholipids**.

The structure of phospholipid molecules is well suited to their function 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." Phospholipids arrange themselves into a two-layer sheet called a **phospholipid bilayer**. As you can see in **Figure 4.5a**, the phospholipids' hydrophilic ("water-loving") heads are arranged to face outward, exposed to the aqueous solutions on both sides of a membrane. Their hydrophobic ("water-fearing") tails are arranged inward, mingling with each other and shielded from water. Suspended in the phospholipid bilayer of most membranes are proteins that help regulate traffic across the membrane. These proteins also perform other functions **(Figure 4.5b)**. (You'll learn more about membrane proteins in Chapter 5.)

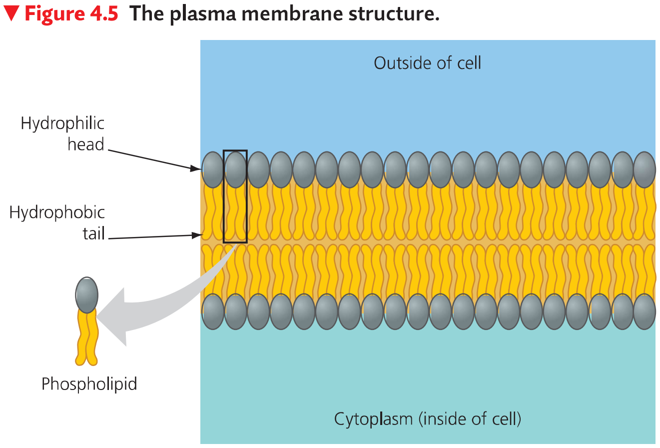
Membranes are not static sheets of molecules locked rigidly in place, however. In fact, the texture of a cellular membrane is similar to salad oil. The phospholipids and most of the proteins can therefore drift about within the membrane. Thus, a membrane is a **fluid mosaic**—fluid because the molecules can move freely past one another and mosaic because of the diversity of proteins that float like icebergs in the oily phospholipid sea. ✓

✓ **CHECKPOINT**

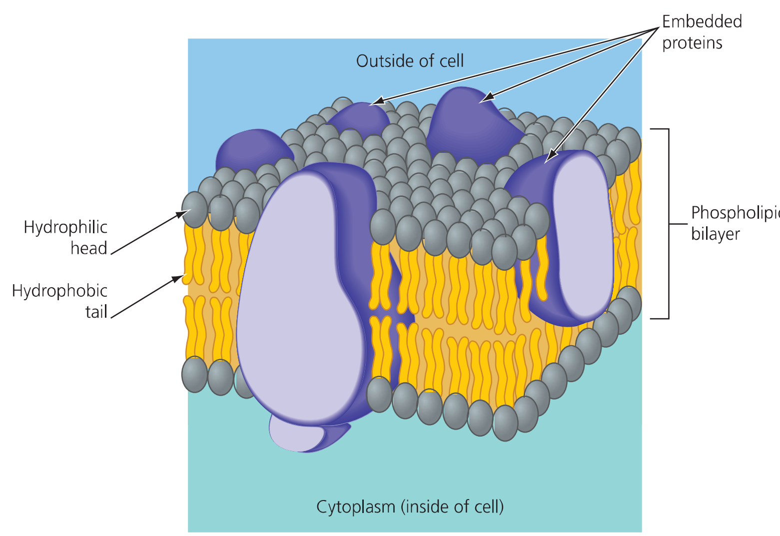
Why do phospholipids spontaneously form into a bilayer when placed in water?

■ *Answer: The bilayer structure shields the hydrophobic tails of the phospholipids from water while exposing the hydrophilic heads to water.*

▼ **Figure 4.5 The plasma membrane structure.**



(a) Phospholipid bilayer of membrane. In water, phospholipids arrange themselves into a bilayer. The symbol for a phospholipid used in this book looks like a lollipop with two wavy sticks. The "head" is the end with the phosphate group, and the two "tails" are chains of carbon and hydrogen. The bilayer arrangement keeps the heads exposed to water while keeping the tails in the oily interior of the membrane.



(b) Fluid mosaic model of membrane. Membrane proteins, like the phospholipids, have both hydrophilic and hydrophobic regions.

Cell Surfaces

Surrounding the plasma membrane of a plant cell is a cell wall made from cellulose fibers, which are long chains of polysaccharides (see Figure 3.9c). The walls protect the cells, maintain cell shape, and keep cells from absorbing so much water that they burst. Plant cells are connected to each other by channels that pass through the cell walls, joining the cytoplasm of each cell to that of its neighbors. These channels allow water and other small molecules to move between cells, integrating the activities of a tissue.

Animal cells lack a cell wall, but most animal cells secrete a sticky coat called the **extracellular matrix**. Fibers made of the protein collagen (also found in your skin, cartilage, bones, and tendons) hold cells together in tissues and can also have protective and supportive functions. In addition, the surfaces of most animal cells contain cell junctions, structures that connect cells together into tissues, allowing the cells to function in a coordinated way. Next, in the Process of Science section, we'll see how the outer surfaces of bacterial cells are exploited by a new antibiotic. ✅

✅ CHECKPOINT

What polysaccharide is the primary component of plant cell walls?

■ Answer: cellulose

THE PROCESS OF SCIENCE Humans Versus Bacteria

How Was the First 21st-Century Antibiotic Discovered?

BACKGROUND

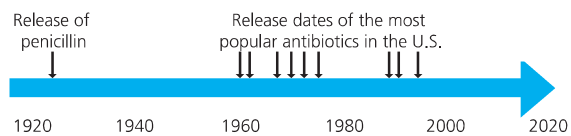
As discussed in the Biology and Society section, antibiotics are drugs that can treat infections by killing or slowing the growth of bacteria. Many antibiotics disrupt cellular structures that are found in bacteria but not in human cells, such as cell walls and bacterial chromosomes. Because human cells lack these structures, the antibiotics will not harm the human host. Like many scientific breakthroughs, antibiotics were not created by scientists in the lab, but rather were discovered to already exist in nature.

Most of the antibiotics prescribed today were developed decades ago **(Figure 4.6a)**. Penicillin, for example, was first discovered in 1928, amoxicillin in 1972 and ciprofloxacin in 1987. As populations of bacteria are exposed to antibiotics, natural selection will favor those that can survive and reproduce. Thus, many early antibiotics have been rendered ineffective by the evolution of antibiotic resistance.

To combat the growing problem of antibiotic resistance, medical researchers are constantly trying to produce new antibiotics. Although some (such as ciprofloxacin) are human-made, most classes of antibiotics were discovered in the natural world. Penicillin and ampicillin, for example, are produced by fungi and bacteria (respectively) that grow naturally in soil.

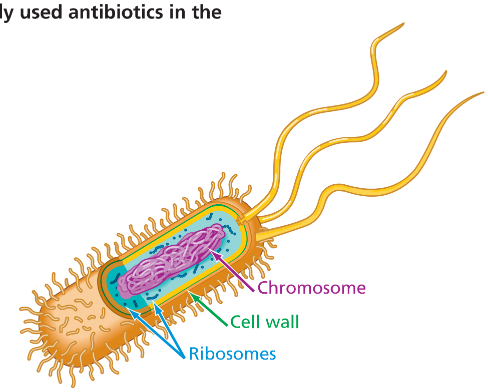
METHOD

One of the newest natural antibiotics to be discovered is a molecule called teixobactin. What may be most interesting is how it was discovered. Soil samples from a grass field in Maine were placed in plastic devices with many tiny compartments. The soil was diluted so each compartment contained a single bacterium, thereby allowing different species of bacteria to be grown simultaneously. The devices were then buried in the original soil **(Figure 4.6b)**. Membranes allowed nutrients into each compartment while keeping other bacteria species out. After being grown into colonies, the bacteria in each compartment were tested for the ability to kill the bacteria *Staphylococcus aureus,* which causes deadly MRSA (methicillin-resistant *S. aureus*) infections and tuberculosis.



(a) Release dates of the most widely used antibiotics in the United States

(b) A device used to grow potentially helpful species of bacteria in soil



(c) Bacterial structures commonly targeted by antibiotics

◀ **Figure 4.6 The search for new antibiotics.** The quest for drugs that target harmful bacteria is an ongoing effort.

RESULTS

When the researchers analyzed the soil samples, they observed that the bacterium most effective in killing *S. aureus* was a previously undiscovered species named *Eleftheria terrae*. They found that this bacterium produced teixobactin, which inhibits production of bacterial cell walls, leading to the destruction of the bacterial cell **(Figure 4.6c)**.

After the discovery of teixobactin in 2015, researchers expected that it will take several years until this new antibiotic can be tested against *S. aureus* in human clinical trials. If proven successful, it will be a good illustration of how a knowledge of cellular structures, combined with new technologies, can benefit human health.

Thinking Like a Scientist

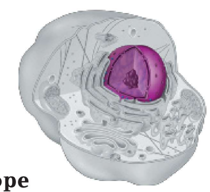
In what way does the history of antibiotic discovery promote efforts to conserve natural habitats?

For the answer, see Appendix D.

The Nucleus and Ribosomes: Genetic Control of the Cell

If you think of the cell as a factory, then the nucleus is its control center. Here, the master plans are stored, orders are given, changes are made in response to external signals, and the process of making new factories is initiated. The factory supervisors are the genes, the inherited DNA molecules that direct almost all the business of the cell. Each gene is a stretch of DNA that stores the information necessary to produce a particular protein. Proteins can be likened to workers on the factory floor because they do most of the actual work of the cell.

The Nucleus



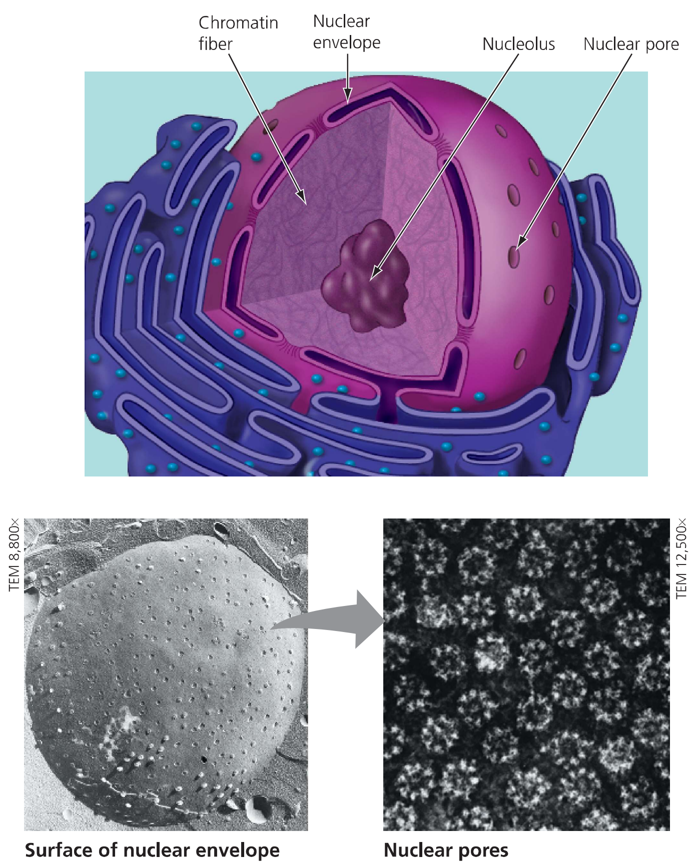
The nucleus is separated from the cytoplasm by a double membrane called the **nuclear envelope** **(Figure 4.7)**. Each membrane of the nuclear envelope is similar in structure to the plasma membrane: a phospholipid bilayer with associated proteins. Pores in the envelope allow certain materials to pass between the nucleus and the surrounding cytoplasm. Within the nucleus, long DNA molecules and associated proteins form fibers called **chromatin**. Each long chromatin fiber constitutes one chromosome **(Figure 4.8)**. The number of chromosomes in a cell depends on the species. For example, each human body cell has 46 chromosomes, whereas rice cells have 24 and dog cells have 78 (see Figure 8.2 for more examples). The **nucleolus** (shown in Figure 4.7), a prominent structure within the nucleus, is the site where the components of ribosomes are made. We'll examine ribosomes next. ✓

✓ **CHECKPOINT**

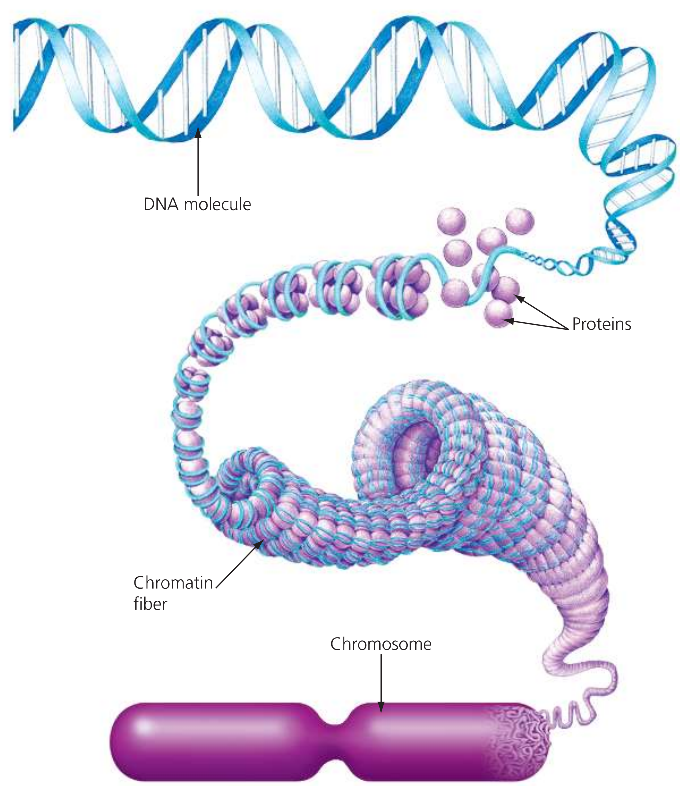
What is the relationship between chromosomes, chromatin, and DNA?

■ Answer: Chromosomes are made of chromatin, which is a combination of DNA and proteins.

▼ **Figure 4.7** **The nucleus.**

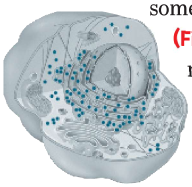


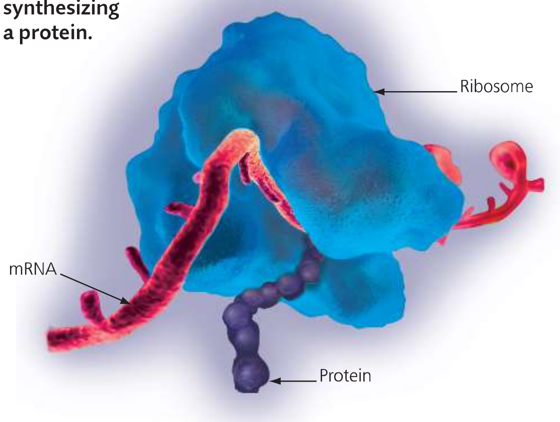
▼ **Figure 4.8** **The relationship between DNA, chromatin, and a chromosome.**



Ribosomes

The small blue dots in the cells in Figure 4.4 and outside the nucleus in Figure 4.7 represent the ribosomes. Ribosomes are responsible for protein synthesis **(Figure 4.9)**. In eukaryotic cells, the components of ribosomes are made in the nucleus and then transported through the pores of the nuclear envelope into the cytoplasm. It is in the cytoplasm that the ribosomes assemble and begin their work. Some ribosomes are suspended in the cytosol, making proteins that remain within the fluid of the cell. Other ribosomes are attached to the outside of the nucleus or an organelle called the endoplasmic reticulum (or ER) **(Figure 4.10)**, making proteins that are incorporated into membranes or secreted by the cell. Free and bound ribosomes are structurally identical, and ribosomes can switch locations, moving between the endoplasmic reticulum and the cytosol. Cells that make a lot of proteins have many ribosomes. For example, each cell in your pancreas that produces digestive enzymes may contain a few million ribosomes.





▶ Figure 4.9 A computer model of a ribosome in the process of synthesizing a protein.

▼ Figure 4.10 ER-bound ribosomes.

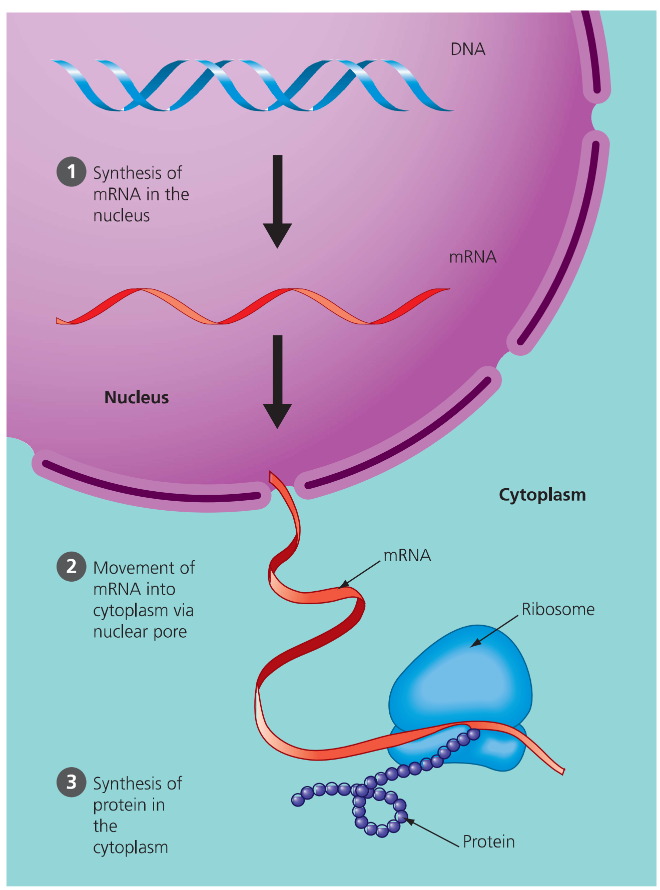
How DNA Directs Protein Production

Like a company executive, the DNA doesn't actually do any of the work of the cell. Instead, the DNA executive issues orders that result in work being done by the protein workers. **Figure 4.11** shows the sequence of events during protein production in a eukaryotic cell (with the DNA and other structures being shown disproportionately large in relation to the nucleus). ❶ DNA transfers its coded information to a molecule called messenger RNA (mRNA). Like a middle manager, the mRNA molecule carries the order to "build this type of protein." ❷ The mRNA exits the nucleus through pores in the nuclear envelope and travels to the cytoplasm, where it binds to a ribosome. ❸ The ribosome moves along the mRNA, translating the genetic message into a protein with a specific amino acid sequence. (You'll learn how the message is translated in Chapter 10.) In this way, information carried by the DNA can direct the work of the entire cell without the DNA ever leaving the protective confines of the nucleus. **The pathway from DNA to RNA to protein, involving several organelles, illustrates the importance of the flow of information within living cells.** ✓

✓ CHECKPOINT

1. What is the function of ribosomes?
2. What is the role of mRNA in making a protein?

■ Answers: **1.** *protein synthesis* **2.** *A molecule of mRNA carries the genetic message from a gene (DNA) to ribosomes that translate it into protein.*

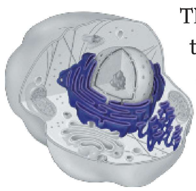


◀ Figure 4.11 DNA → RNA → protein. Inherited genes in the nucleus control protein production and hence the activities of the cell.

The Endomembrane System: Manufacturing and Distributing Cellular Products

Like an office partitioned into cubicles, the cytoplasm of a eukaryotic cell is partitioned by organelle membranes (see Figure 4.4). Some organelles are physically connected, like two cubicles that share a door. Other organelles are linked by **vesicles**, sacs made of membrane that transfer membrane segments between organelles, like a mail cart delivering packages from one department to another. Together, these organelles form the **endomembrane system**. This system includes the nuclear envelope, the endoplasmic reticulum, the Golgi apparatus, lysosomes, and vacuoles.

The Endoplasmic Reticulum

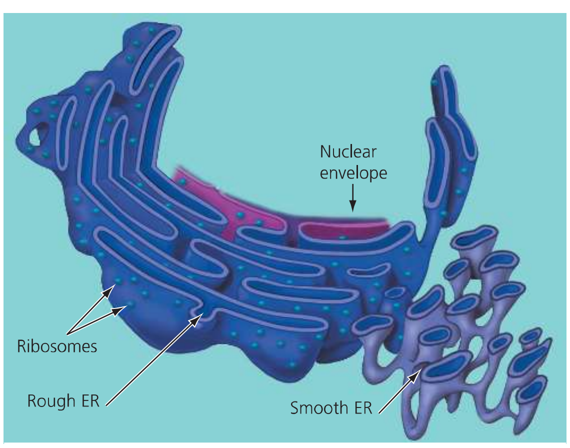


The **endoplasmic reticulum (ER)** is one of the main manufacturing facilities within a cell. It produces an enormous variety of molecules. Connected to the nuclear envelope, the ER forms an extensive labyrinth of tubes and sacs running throughout the cytoplasm **(Figure 4.12)**. A membrane separates the internal ER compartment from the cytosol. There are two components that make up the ER: rough ER and smooth ER. These two types of ER are physically connected but differ in structure and function.

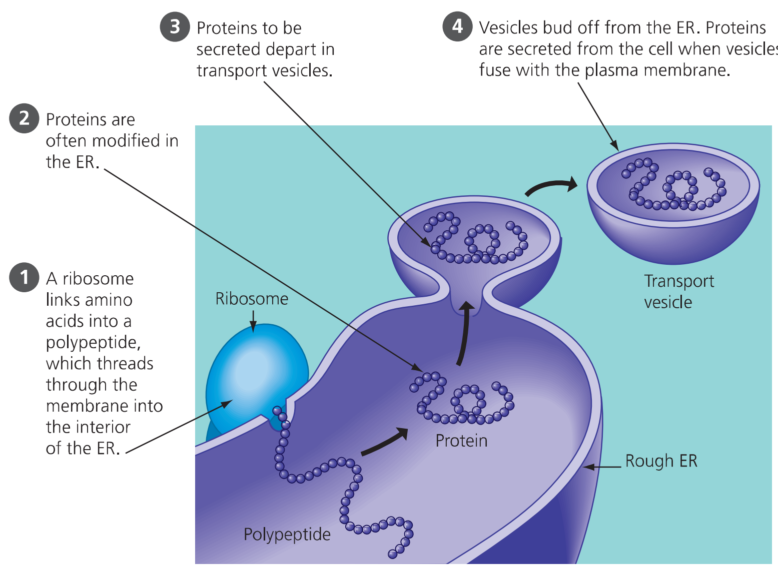
Rough ER

The "rough" in **rough ER** refers to ribosomes that stud the outside of its membrane. One of the functions of rough ER is to make phospholipids that are inserted into the ER membrane. In this way, the ER membrane grows, and portions of it can bubble off and be transferred to other parts of the cell. The ribosomes attached to the rough ER produce proteins that will be inserted into the growing ER membrane, transported to other organelles, and eventually exported. Cells that secrete a lot of protein—such as the cells of your salivary glands, which secrete enzymes into your mouth—are especially rich in rough ER. As shown in **Figure 4.13**, (1) some products manufactured by rough ER are (2) chemically modified and then (3) packaged into transport vesicles that are (4) dispatched to other locations in the cell.

▼ **Figure 4.12 The endoplasmic reticulum (ER).** In this drawing, the flattened sacs of rough ER and the tubes of smooth ER are connected. Notice that the ER is also connected to the nuclear envelope (the nucleus has been omitted from the illustration for clarity).



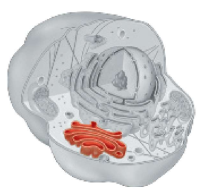
▼ **Figure 4.13 How rough ER manufactures and packages secretory proteins.**



Smooth ER

The "smooth" in **smooth ER** refers to the fact that this organelle lacks the ribosomes that populate the surface of rough ER (see Figure 4.13). A diversity of enzymes built into the smooth ER membrane enables this organelle to perform many functions. One is the synthesis of lipids, including steroids (see Figure 3.14). For example, the cells in ovaries or testes that produce the steroid sex hormones are enriched with smooth ER. In liver cells, enzymes of the smooth ER detoxify circulating drugs such as barbiturates, amphetamines, and some antibiotics (which is why antibiotics don't remain in the bloodstream for long after you stop taking them). As liver cells are exposed to a drug, the amounts of smooth ER and its detoxifying enzymes increase. This can strengthen the body's tolerance of the drug, meaning that higher doses will be required in the future to achieve the desired effect. The growth of smooth ER in response to one drug can also increase tolerance of other drugs. For example, abusing sleeping pills may make other useful drugs less effective by accelerating their breakdown in the liver.

The Golgi Apparatus



Working in close partnership with the ER, the **Golgi apparatus**, an organelle named for its discoverer (Italian scientist Camillo Golgi), receives, refines, stores, and distributes chemical products of the cell **(Figure 4.14)**. You can think of the Golgi apparatus as a detailing facility that receives shipments of newly manufactured goods (proteins), puts on finishing touches, stores the completed goods, and then ships them out when needed.

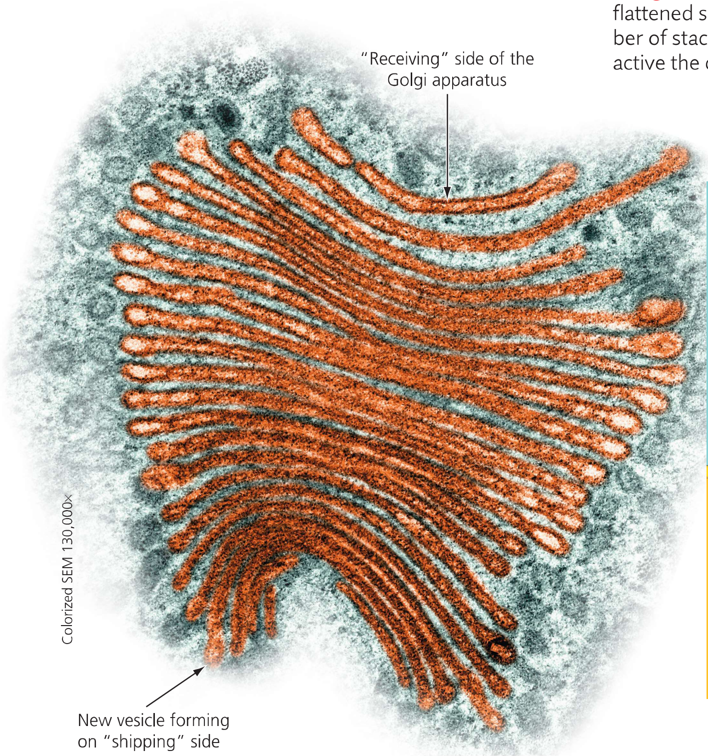
Products made in the ER reach the Golgi apparatus in transport vesicles. The Golgi apparatus consists of a stack of membrane plates, looking much like a pile of pita bread. ❶ One side of a Golgi stack serves as a receiving dock for vesicles from the ER. ❷ Proteins within a vesicle are usually modified by enzymes during their transit from the receiving to the shipping side of the Golgi apparatus. For example, molecular identification tags may be added that serve to mark and sort protein molecules into different batches for different destinations. ❸ The shipping side of a Golgi stack is a depot from which finished products can be carried in transport vesicles to other organelles or to the plasma membrane. Vesicles that bind with the plasma membrane transfer proteins to it or secrete finished products to the outside of the cell. ✅

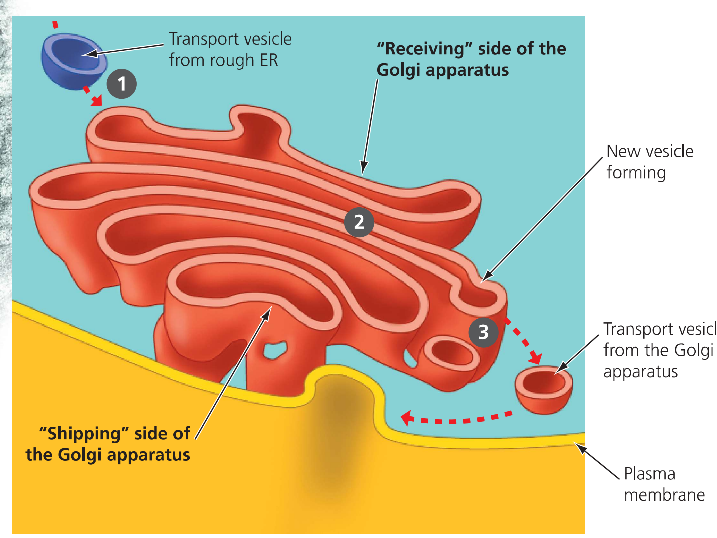
✅ **CHECKPOINT**

1. What makes rough ER rough?
2. What is the relationship between the Golgi apparatus and the ER in a protein-secreting cell?

■ Answers: **1.** ribosomes attached to the membrane **2.** The Golgi apparatus receives proteins from the ER through vesicles, processes the proteins, and then dispatches them in vesicles.

▼ **Figure 4.14 The Golgi apparatus.** The Golgi apparatus consists of flattened sacs arranged something like a stack of pita bread. The number of stacks in a cell (from a few to hundreds) correlates with how active the cell is in secreting proteins.





Lysosomes

A **lysosome** is a membrane-enclosed sac of digestive enzymes. The enzymes and membranes of lysosomes are made by rough ER and processed in the Golgi apparatus. The lysosome provides a compartment where digestive enzymes can safely break down large molecules without unleashing the digestive enzymes on the cell itself.

Lysosomes perform several digestive functions. Many single-celled protists engulf nutrients into tiny cytoplasmic sacs called food vacuoles. Lysosomes fuse with the food vacuoles, exposing the food to digestive enzymes **(Figure 4.15a)**. Small molecules that result from this digestion, such as amino acids, leave the lysosome and nourish the cell. Lysosomes also help destroy harmful bacteria. For example, your white blood cells ingest bacteria into vacuoles, and lysosomal enzymes that are emptied into these vacuoles rupture the bacterial cell walls. In addition, without harming the cell, a lysosome can engulf and digest parts of another organelle, recycling it by making its molecules available for the construction of new organelles **(Figure 4.15b and c)**. With the help of lysosomes, a cell can thereby continually renew itself. Lysosomes also have sculpting functions in embryonic development. For example, lysosomes release enzymes that digest webbing between developing fingers in an early human embryo.

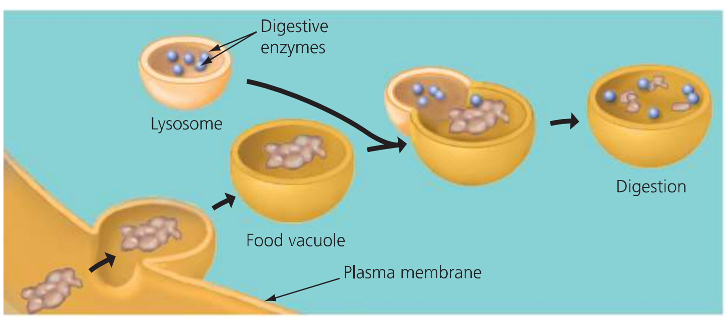
The importance of lysosomes to cell function and human health is made clear by hereditary disorders called lysosomal storage diseases. A person with such a disease is missing one or more of the digestive enzymes normally found within lysosomes. The abnormal lysosomes become filled with indigestible substances, and this eventually interferes with other cellular functions. Most of these diseases are fatal in early childhood. In Tay-Sachs disease, for example, lysosomes lack a lipid-digesting enzyme. As a result, nerve cells die as they accumulate excess lipids, ravaging the nervous system. Fortunately, lysosomal storage diseases are rare. ✓

✓ CHECKPOINT

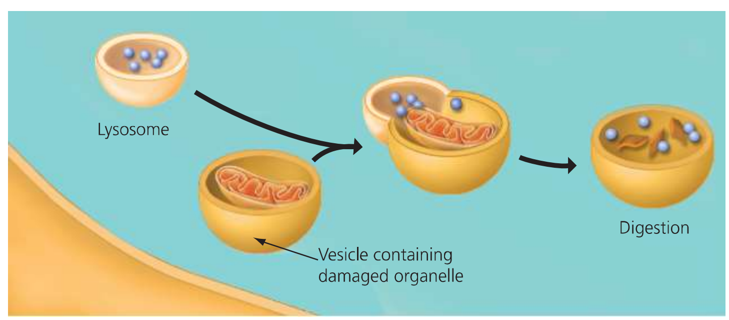
How can defective lysosomes result in excess accumulation of a particular chemical compound in a cell?

■ *Answer: If the lysosomes lack an enzyme needed to break down the compound, the cell will accumulate an excess of that compound.*

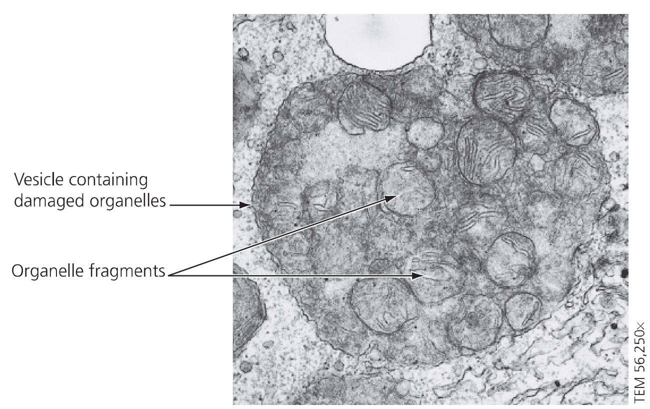
▼ Figure 4.15 **Two functions of lysosomes.**



(a) A lysosome digesting food



(b) A lysosome breaking down the molecules of damaged organelles



(c) Electron micrograph of lysosome recycling damaged organelles.

Vacuoles

Vacuoles are large vesicles with a variety of functions. For example, Figure 4.15a shows a food vacuole budding from the plasma membrane. Certain freshwater protists have contractile vacuoles that pump out excess water that flows into the cell **(Figure 4.16a)**.

Another type of vacuole is a **central vacuole**, a versatile compartment that can account for more than half the volume of a mature plant cell **(Figure 4.16b)**. A central vacuole stores organic nutrients, such as proteins stockpiled in the vacuoles of seed cells. It also contributes to plant growth by absorbing water and causing cells to expand. In the cells of flower petals, central vacuoles may contain pigments that attract pollinating insects. Central vacuoles may also contain poisons that protect against plant-eating animals. Some important crop plants produce and store large amounts of toxic chemicals—harmful to animals that might graze on the plant but useful to us—such as tobacco plants (which store nicotine) and coffee and tea plants (which store caffeine).

THE CAFFEINE THAT GIVES COFFEE A KICK PROTECTS COFFEE PLANTS FROM HERBIVORES.

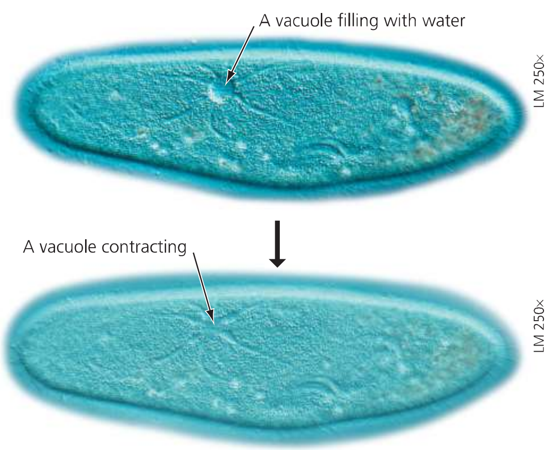
Now that we've explored the organelles of the endomembrane system, **Figure 4.17** reviews how they are related. A product made in one part of the endomembrane system may exit the cell or become part of another organelle without crossing a membrane. Also, membrane made by the ER can become part of the plasma membrane through the fusion of a transport vesicle. So even the plasma membrane is related to the endomembrane system. ✅

✅ CHECKPOINT

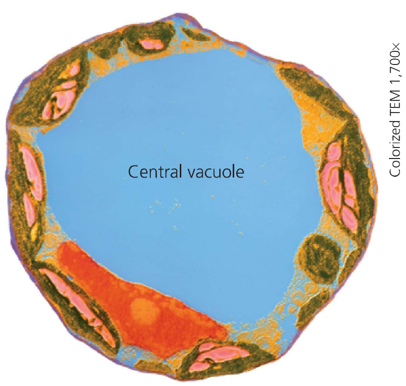
Place the following cellular structures in the order they would be used in the production and secretion of a protein: Golgi apparatus, nucleus, plasma membrane, ribosome, transport vesicle.

Answer: nucleus, ribosome, transport vesicle, Golgi apparatus, plasma membrane

▼ **Figure 4.16 Two types of vacuoles.**

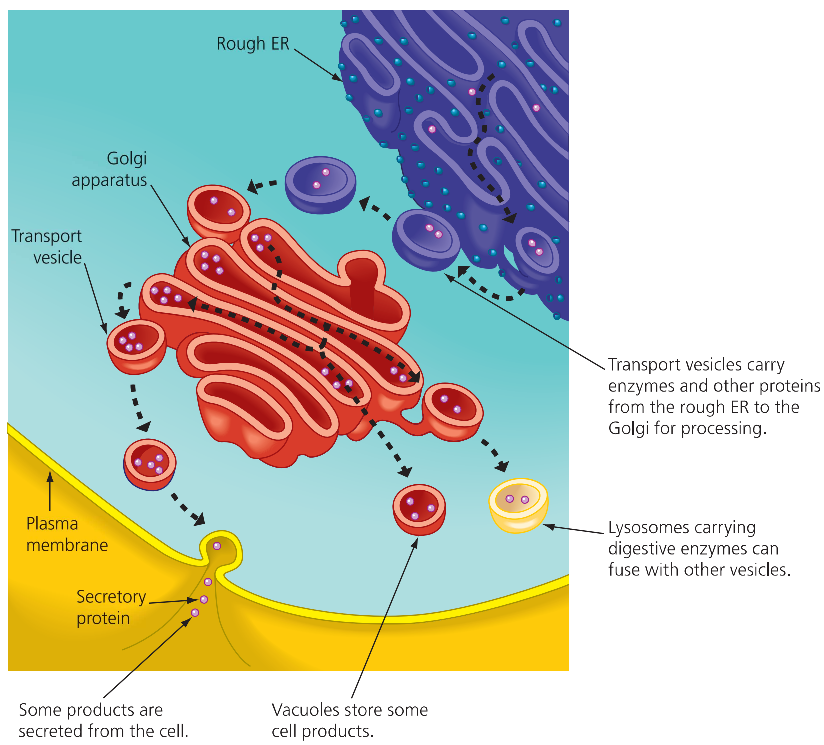


(a) Contractile vacuole in *Paramecium*. A contractile vacuole fills with water and then contracts to pump the water out of the cell.



(b) Central vacuole in a plant cell. The central vacuole (colorized blue in this micrograph) is often the largest organelle in a mature plant cell.

▼ **Figure 4.17 Review of the endomembrane system.** The dashed arrows show some of the pathways of cell product distribution and membrane migration through transport vesicles.



Chloroplasts and Mitochondria: Providing Cellular Energy

One of the central themes of biology is the transformation of energy: how it enters living systems, is converted from one form to another, and is eventually given off as heat. To follow this flow of energy, we must consider the cellular power stations: chloroplasts and mitochondria.

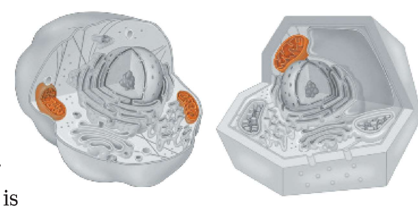
Chloroplasts

Most of the living world runs on energy from photosynthesis, the conversion of light energy from the sun to the chemical energy of sugar molecules.

Chloroplasts are the photosynthetic organelles of plants and algae.

A chloroplast is divided into compartments by membranes, **(Figure 4.18)**. The innermost compartment holds a thick fluid called stroma, which contains DNA, ribosomes, and enzymes. A network of sacs called thylakoids is suspended in the stroma. The sacs are often stacked like poker chips; each stack is called a granum (plural, *grana*). The grana are solar power packs, converting light energy to chemical energy (as detailed in Chapter 7).

Mitochondria



Mitochondria (singular, *mitochondrion*) are the organelles in which cellular respiration takes place; during cellular respiration, energy is harvested from sugars and transformed into another form of chemical energy called ATP (adenosine triphosphate). Cells use molecules of ATP as a direct energy source. Mitochondria are found in almost all eukaryotic cells, including those of plants and animals.

A mitochondrion is enclosed by two membranes, separated by a narrow space. The inner membrane encloses a thick fluid called the mitochondrial matrix **(Figure 4.19)**. The inner membrane has many infoldings called cristae. The cristae create a large surface area in which many molecules that function in cellular respiration are embedded, maximizing ATP output. (You'll learn more about how mitochondria work in Chapter 6.)

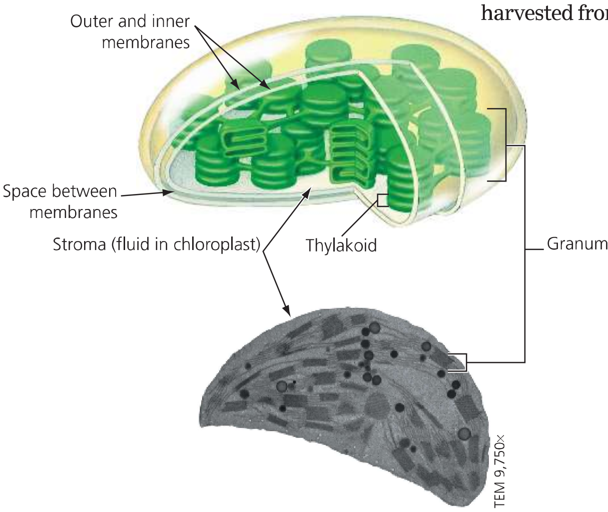
Besides providing cellular energy, mitochondria and chloroplasts share another feature: They contain their own DNA that encodes some proteins made by their own ribosomes. Each chloroplast and mitochondrion contains a single circular DNA chromosome that resembles a prokaryotic chromosome. In fact, mitochondria and chloroplasts can grow and pinch in two, reproducing themselves as many prokaryotes do. This and other evidence indicate that they evolved from ancient free-living prokaryotes that established residence within other, larger host prokaryotes. This phenomenon, where one species lives inside a host species, is a special type of symbiosis (see Chapter 16). Over time, mitochondria and chloroplasts became increasingly interdependent with the host prokaryote, eventually evolving into a single organism with inseparable parts. **The DNA found within mitochondria and chloroplasts likely includes remnants of this ancient evolutionary event.** ✓

✓ CHECKPOINT

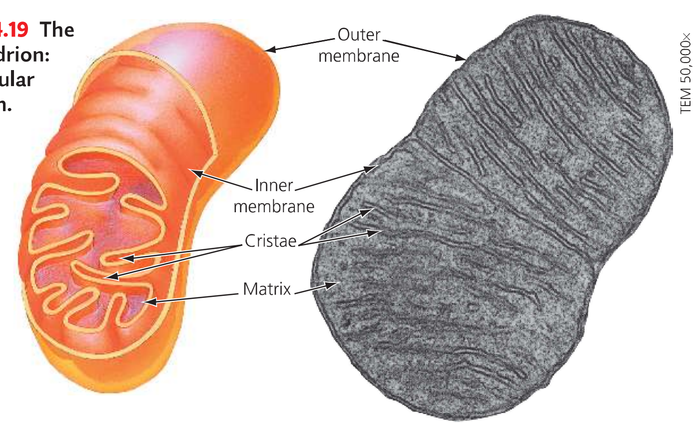
1. What does photosynthesis accomplish?
2. What is cellular respiration?
3. Explain what is wrong with the following statement: "Plant cells have chloroplasts, and animal cells have mitochondria."

■ Answers: **1.** the conversion of light energy to chemical energy stored in food molecules **2.** a process that converts the chemical energy of sugars and other food molecules to chemical energy in the form of ATP **3.** It implies that plant cells do not have mitochondria, when in fact they do.

▼ Figure 4.18 The chloroplast: site of photosynthesis.

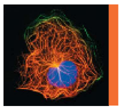


► Figure 4.19 The mitochondrion: site of cellular respiration.



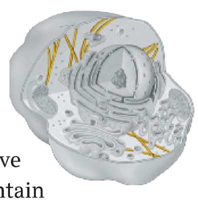
The Cytoskeleton: Cell Shape and Movement

If someone asked you to describe a house, you would most likely mention the various rooms and their locations. You probably would not think to mention the foundation and beams that support the house. Yet these structures perform an extremely important function. Similarly, cells have an infrastructure called the **cytoskeleton**, a network of protein fibers extending throughout the cytoplasm. The cytoskeleton serves as both skeleton and "muscles" for the cell, functioning in support and movement.



WITHOUT THE CYTOSKELETON, YOUR CELLS WOULD COLLAPSE IN ON THEMSELVES.

Maintaining Cell Shape



One function of the cytoskeleton is to give mechanical support to the cell and maintain its shape. This is especially important for animal cells, which lack rigid cell walls. The cytoskeleton contains several types of fibers made from different types of protein. One important type of fiber forms **microtubules**, hollow tubes of protein **(Figure 4.20a)**. The other kinds of cytoskeletal fibers, called intermediate filaments and microfilaments, are thinner and solid.

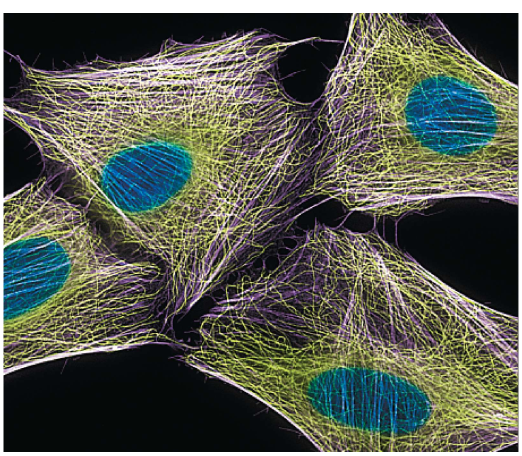
Just as the bony skeleton of your body helps fix the positions of your organs, the cytoskeleton provides anchorage and reinforcement for many organelles in a cell. For instance, the nucleus is held in place by a "cage" of cytoskeletal filaments. Other organelles use the cytoskeleton for movement. For example, a lysosome might reach a food vacuole by gliding along a microtubule track. Microtubules growing from a region called a centrosome guide the movement of chromosomes when cells divide (by means of the mitotic spindle—see Chapter 8). Microfilaments are also involved in cell movements. Different filaments composed of different kinds of proteins contract, resulting in the crawling movement of the protist *Amoeba* **(Figure 4.20b)** and movement of some of our white blood cells. ✓

✓ CHECKPOINT

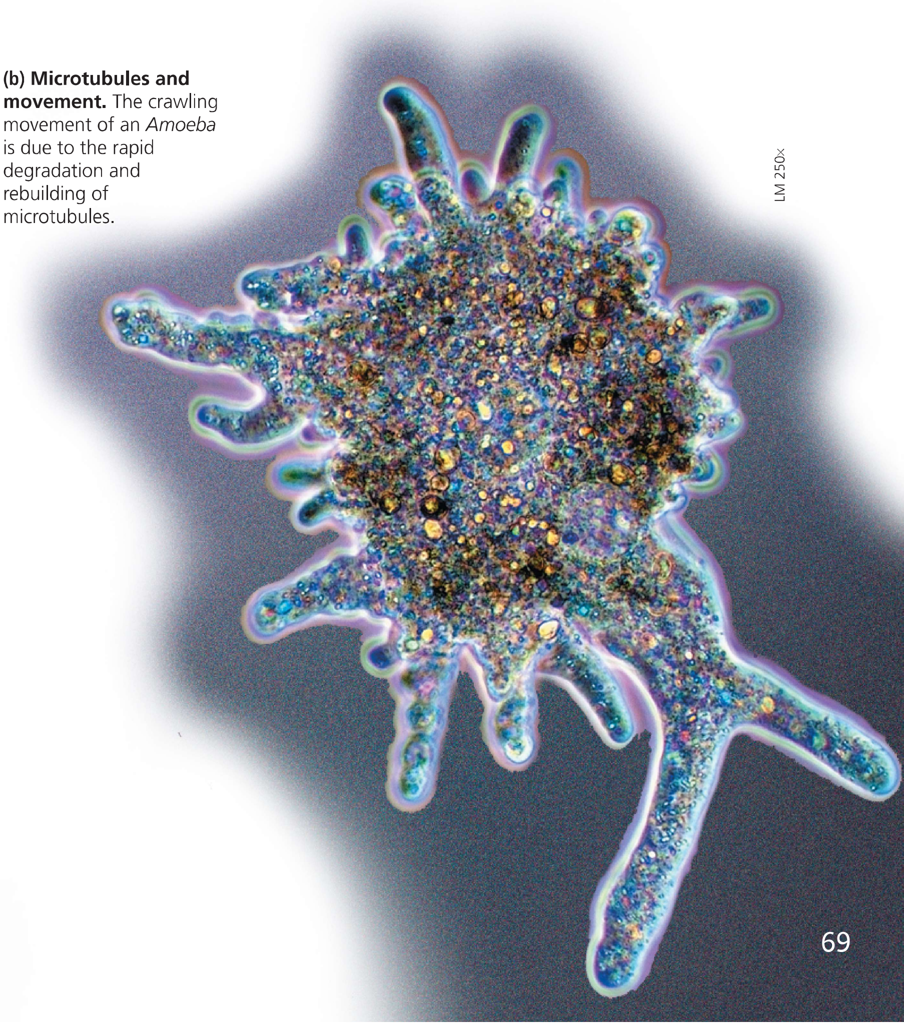
From which important class of biological molecules are the microtubules of the cytoskeleton made?

■ Answer: protein

▼ Figure 4.20 **The cytoskeleton.**



(a) Microtubules in the cytoskeleton. In this micrograph of animal cells, the cytoskeleton microtubules are labeled with a fluorescent yellow dye.



(b) Microtubules and movement. The crawling movement of an *Amoeba* is due to the rapid degradation and rebuilding of microtubules.

Flagella and Cilia

In some eukaryotic cells, microtubules are arranged into structures called flagella and cilia, extensions from a cell that aid in movement. Eukaryotic **flagella** (singular, *flagellum*) propel cells with an undulating, whiplike motion. They often occur singly, such as in human sperm cells **(Figure 4.21a)**, but may also appear in groups on the outer surface of protists. **Cilia** (singular, *cilium*) are generally shorter and more numerous than flagella and move in a coordinated back-and-forth motion, like the rhythmic oars of a rowing team. Both cilia and flagella propel various protists through water. For example, *Paramecium* cilia are visible in the SEM in Figure 4.1. Though different in length, number per cell, and beating pattern, cilia and flagella have the same basic architecture.

Some cilia extend from nonmoving cells that are part of a tissue layer, moving fluid over the tissue's surface. For example, cilia lining your windpipe clean your respiratory system by sweeping mucus with trapped debris out of your lungs **(Figure 4.21b)**. Tobacco smoke can paralyze these cilia, interfering with the normal cleansing mechanisms and allowing more toxin-laden smoke particles to reach the lungs. Frequent coughing—common in heavy smokers—then becomes the body's attempt to cleanse the respiratory system.

Because human sperm rely on flagella for movement, it's easy to understand why problems with flagella can lead to male infertility. Interestingly, some men with a type of hereditary sterility also suffer from respiratory problems. Because of a defect in the structure of their flagella and cilia, the sperm of men afflicted with this disorder cannot swim normally within the female reproductive tract to fertilize an egg (causing sterility), and their cilia do not sweep mucus out of their lungs (causing recurrent respiratory infections). ✓

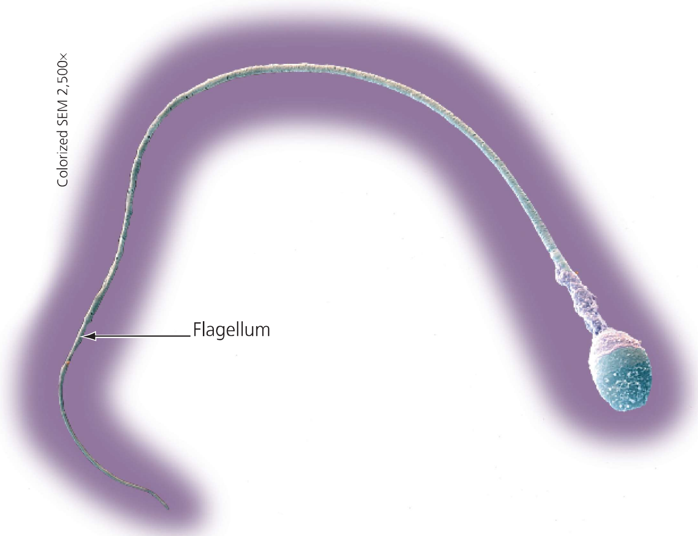
✓ CHECKPOINT

Compare and contrast cilia and flagella.

■ Answer: *Cilia and flagella have the same basic structure, are made from microtubules, and aid in movement. Cilia are short and numerous and move back and forth. Flagella are longer, often occurring singly, and they undulate.*

▼ Figure 4.21 Examples of flagella and cilia.

Colorized SEM 2,500×



(a) Flagellum of a human sperm cell. A eukaryotic flagellum undulates in a whiplike motion, driving a cell such as this sperm cell through its fluid environment.

Colorized SEM 3,000×

(b) Cilia lining the respiratory tract. The cilia lining your respiratory tract sweep mucus with trapped debris out of your lungs. This helps keep your airway clear and prevents infections.

EVOLUTION CONNECTION | Humans Versus Bacteria

The Evolution of Bacterial Resistance in Humans

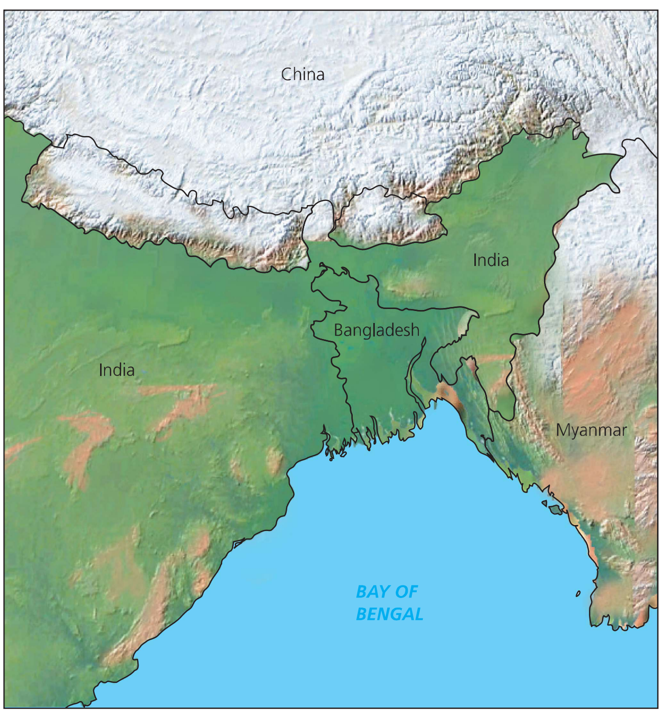
Individuals with variations that make them better suited for the local environment will survive and reproduce more often (on average) than those who lack such variations. When the advantageous variations have a genetic basis, the offspring of individuals with the variations will more often also have the favorable adaptions, giving them a survival and reproductive advantage. In this way, repeated over many generations, natural selection promotes evolution of the population.

Within a human population, the presence of a disease can provide a new basis for measuring those people who are best suited for survival in the local environment. For example, a recent evolutionary study examined people living in Bangladesh. This population has been exposed to the disease cholera—caused by an infectious bacterium—for millennia **(Figure 4.22)**. After cholera bacteria enter a victim's digestive tract (usually through contaminated drinking water), the bacteria produce a toxin that binds to intestinal cells. There, the toxin alters proteins in the plasma membrane, causing the cells to excrete fluid. The resulting diarrhea, which spreads the bacteria by shedding it back into the environment, can cause severe dehydration and death if untreated.

Because Bangladeshis have lived for so long in an environment that teems with cholera bacteria, one might expect that natural selection would favor those individuals who have some resistance to the bacteria. Indeed, recent studies of people from Bangladesh revealed mutations in several genes that appear to confer an increased resistance to cholera. Researchers discovered one mutation in a gene that encodes for the plasma membrane proteins that are the targets of the cholera bacteria. Although the mechanism is not yet understood, these genes appear to offer a survival advantage by making the proteins more resistant to attack by the cholera toxin. Because such genes offer a survival advantage within this population, they have slowly spread through the Bangladeshi population over the past 30,000 years. In other words, the Bangladeshi population is evolving increased resistance to cholera.

In addition to providing insight into the recent evolutionary past, data from this study reveal potential ways that humans might thwart the cholera bacterium. Perhaps pharmaceutical companies can exploit the proteins produced by the identified mutations to create a new generation of antibiotics. If so, this will represent another way that biologists have applied lessons learned from our understanding of evolution to improve human health. It also reminds us that we humans, like all life on Earth, are shaped by evolution due to changes in our environment, including the presence of infectious microorganisms that live around us.

▼ **Figure 4.22** ***Vibrio cholerae*, the cause of the deadly disease cholera.** Some people living in Bangladesh have evolved resistance to this bacterium.

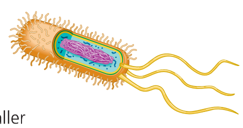
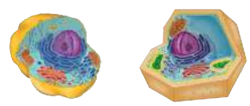


Chapter Review

SUMMARY OF KEY CONCEPTS

The Microscopic World of Cells

The Two Major Categories of Cells

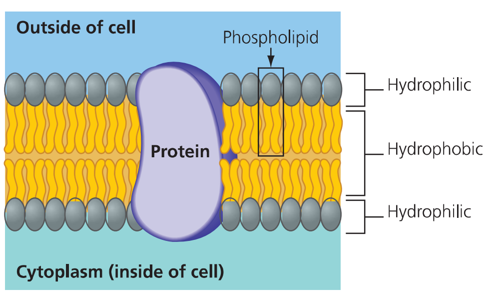
CATEGORIES OF CELLS	
Prokaryotic Cells	**Eukaryotic Cells**
	
• Smaller • Simpler • Lack membrane-bound organelles • Found in bacteria and archaea	• Larger • More complex • Have membrane-bound organelles • Found in protists, plants, fungi, animals

An Overview of Eukaryotic Cells

Membranes partition eukaryotic cells into functional compartments. The largest organelle is usually the nucleus. Other organelles are located in the cytoplasm, the region outside the nucleus and within the plasma membrane.

Membrane Structure

The Plasma Membrane



Cell Surfaces

The walls that encase plant cells support plants against the pull of gravity and also prevent cells from absorbing too much water. Animal cells are coated by a sticky extracellular matrix.

The Nucleus and Ribosomes: Genetic Control of the Cell

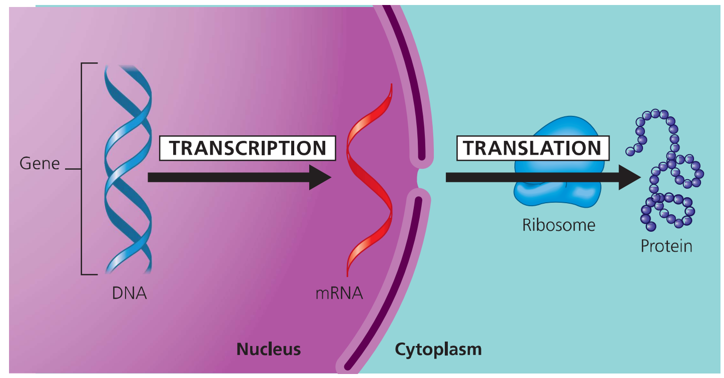
The Nucleus

An envelope consisting of two membranes encloses the nucleus. Within the nucleus, DNA and proteins make up chromatin fibers; each very long fiber is a single chromosome. The nucleus also contains the nucleolus, which produces components of ribosomes.

Ribosomes

Ribosomes produce proteins in the cytoplasm using messages produced by the DNA.

How DNA Directs Protein Production



The Endomembrane System: Manufacturing and Distributing Cellular Products

The Endoplasmic Reticulum

The ER consists of membrane-enclosed tubes and sacs within the cytoplasm. Rough ER, named because of the ribosomes attached to its surface, makes membrane and secretory proteins. The functions of smooth ER include lipid synthesis and detoxification.

The Golgi Apparatus

The Golgi apparatus refines certain ER products and packages them in transport vesicles targeted for other organelles or export from the cell.

Lysosomes

Lysosomes, sacs containing digestive enzymes, aid digestion and recycling within the cell.

Vacuoles

Vacuoles include the contractile vacuoles that expel water from certain freshwater protists and the large, multifunctional central vacuoles of plant cells.

Chloroplasts and Mitochondria: Providing Cellular Energy

Chloroplasts and Mitochondria