Key Concepts

What all cells have in common

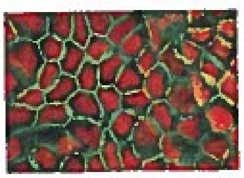
Each cell has a plasma membrane, a boundary between its interior and the outside environment. The interior consists of cytoplasm and an innermost region of DNA. **Sections 4.1, 4.2**

Microscopes

Microscopic analysis supports three generalizations of the cell theory: Each organism consists of one or more cells and their products, a cell has a capacity for independent life, and each new cell is descended from another cell. **Section 4.3**

Prokaryotic cells

Archaeans and bacteria are prokaryotic cells, which have few, if any, internal membrane-enclosed compartments. In general, they are the smallest and structurally the simplest cells. **Sections 4.4, 4.5**



Eukaryotic cells

Cells of protists, plants, fungi, and animals are eukaryotic; they have a nucleus and other membrane-enclosed compartments. They differ in internal parts and surface specializations. **Sections 4.6–4.12**

A look at the cytoskeleton

Diverse protein filaments reinforce a cell's shape and keep its parts organized. As some filaments lengthen and shorten, they move cell structures or the whole cell. **Section 4.13**

Links to Earlier Concepts

- Reflect on the overview of levels of organization in nature in Section 1.1. You will see how the properties of cell membranes emerge from the organization of lipids and proteins (3.4, 3.5).
- What you know about scientific theory (1.6) will help you understand how scientific thought led to the development of the cell theory. This chapter also offers examples of the effects of mutation, and how researchers use tracers (2.2).
- You will consider the cellular location of DNA (3.7) and the sites where carbohydrates (3.2, 3.3) are built and broken apart.
- You will also expand your understanding of the vital roles of proteins in cell functions (3.6), and see how a nucleotide helps control cell activities (3.7).

How would you vote? Some think the safest way to protect consumers from food poisoning is by exposing food to high-energy radiation, which kills bacteria. Others think we should tighten food safety standards instead. Would you choose irradiated food? See CengageNOW for details, then vote online.

4.1 The Cell Theory

- The cell theory, a foundation of modern biology, states that cells are the fundamental units of all life.
- Link to Theory 1.6

Measuring Cells

Do you ever think of yourself as being about 3/2000 of a kilometer (1/1000 miles) tall? Probably not, yet that is how we measure cells. Use the scale bars in Figure 4.2 like a ruler and you can see that the cells shown are a few micrometers "tall." One micrometer (μm) is one-thousandth of a millimeter, which is one-thousandth of a meter, which is one-thousandth of a kilometer (0.62 miles). The cells are bacteria. Bacteria are among the smallest and structurally simplest cells on Earth. The cells that make up your body are generally larger and more complex than bacteria.

Animalcules and Beasties

Nearly all cells are so small that they are invisible to the naked eye. No one even knew cells existed until after the first microscopes were invented, around the end of the sixteenth century.

The first microscopes were not very sophisticated. Dutch spectacle makers Hans and Zacharias Janssen discovered that objects appear greatly enlarged (magnified) when viewed through a series of lenses. The father and son team created the first compound microscope (one that uses multiple lenses) in the year 1590, when they mounted two glass lenses inside a tube.

Given the simplicity of their instruments, it is amazing that the pioneers in microscopy observed as much as they did. Antoni van Leeuwenhoek, a Dutch draper, had exceptional skill in constructing lenses and possibly the keenest vision. By the mid-1600s, he was spying on the microscopic world of rainwater, insects, fabric, sperm, feces—essentially any sample he could fit into his microscope (Figure 4.3*a*). He was fascinated by the tiny organisms he saw moving in many of his samples. For example, in scrapings of tartar from his teeth, Leeuwenhoek saw "many very small animalcules, the motions of which were very pleasing to behold." He (incorrectly) assumed that movement defined life, and (correctly) concluded that the moving "beasties" he saw were alive. Perhaps Leeuwenhoek was so pleased to behold his animalcules because he did not grasp the implications of what he was seeing: Our world, and our bodies, teem with microbial life.

Robert Hooke, a contemporary of Leeuwenhoek, added another lens that made the instrument easier to use. Many of the microscopes we use today are still based on his design. Hooke magnified a piece of thinly sliced cork from a mature tree and saw tiny compartments (Figure 4.3*b*). He named them cellulae—a Latin

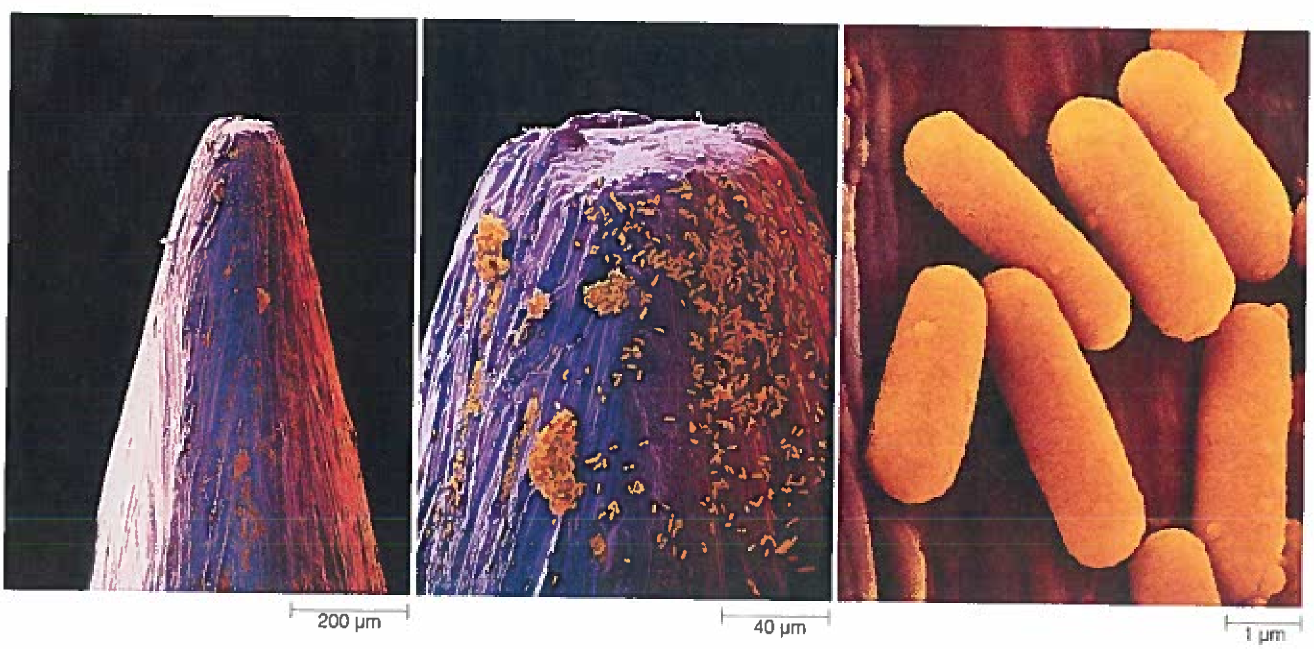
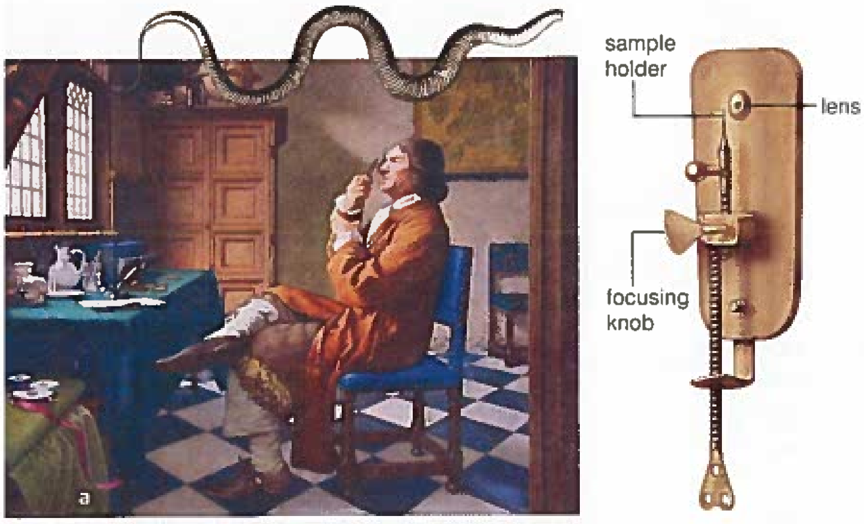


Figure 4.2 Rod-shaped bacterial cells on the tip of a household pin, shown at increasingly higher magnifications (enlargements). The "μm" is an abbreviation for micrometers, or 10^{-6} meters.
Figure It Out: About how big are these bacteria? Answer: About 1 μm wide, and 5 μm long



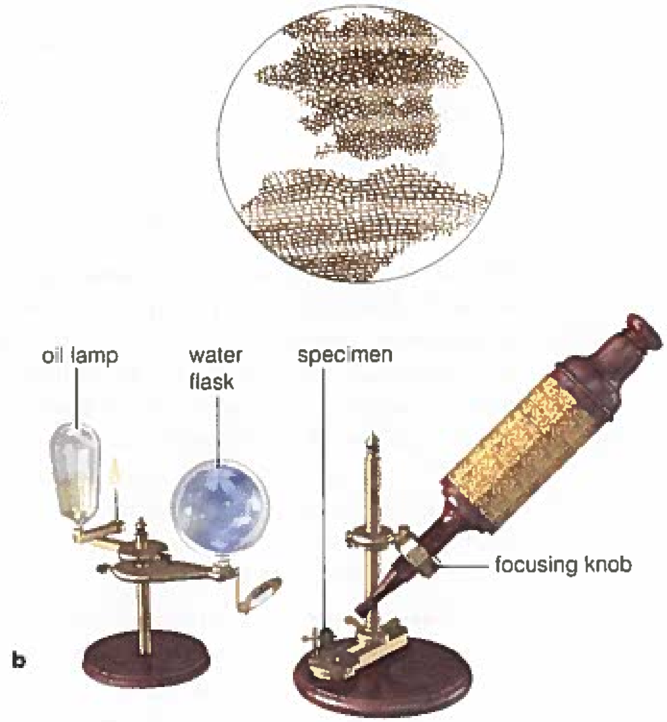


Figure 4.3 As microscopes improved, so did our understanding of cells. (**a**) A painting of Antoni van Leeuwenhoek with his microscope, which allowed him to view organisms too small to see with the naked eye. *Above*, Leeuwenhoek's sketch of a vinegar worm. (**b**) Robert Hooke's microscope and one of his sketches of cell walls from cork tissue.

word for the small chambers that monks lived in—and thus coined the term "cell." Actually they were dead plant cell walls, which is what cork consists of, but Hooke did not think of them as being dead because neither he nor anyone else knew cells could be alive. He observed cells "fill'd with juices" in green plant tissues but did not realize they were alive, either.

The Cell Theory Emerges

For nearly 200 years after their discovery, cells were thought to be part of a continuous membrane system in multicelled organisms, not separate entities. By the 1820s, vastly improved lenses brought cells into much sharper focus. Robert Brown, a botanist, was the first to identify a plant cell nucleus. Matthias Schleiden, another botanist, hypothesized that a plant cell is an independent living unit even when it is part of a plant. Schleiden compared notes with the zoologist Theodor Schwann, and both concluded that the tissues of animals as well as plants are composed of cells and their products. Together, the two scientists recognized that cells have a life of their own even when they are part of a multicelled body.

Another insight emerged from physiologist Rudolf Virchow, who studied how cells reproduce—that is, how they divide into descendant cells. Every cell, he realized, had descended from another living cell. These and many other observations yielded four generalizations that today constitute the **cell theory**:

1. Every living organism consists of one or more cells.
2. The cell is the structural and functional unit of all organisms. A cell is the smallest unit of life, individually alive even as part of a multicelled organism.
3. All living cells come from division of other, preexisting cells.
4. Cells contain hereditary material, which they pass to their offspring during division.

The cell theory, first articulated in 1839 by Schwann and Schleiden and later revised, remains a foundation of modern biology. It was not always so. The theory was a radical new interpretation of nature that underscored life's unity. As with every scientific theory, it has remained (and always will be) open to revision if new data do not support it.

Take-Home Message

What is the cell theory?

- All organisms consist of one or more cells.
- A cell is the smallest unit with the properties of life.
- Each new cell arises from division of another, preexisting cell.
- Each cell passes hereditary material to its offspring.

4.2 What Is a Cell?

- All cells have a plasma membrane and cytoplasm, and all start out life with DNA.
- Links to Lipid structure 3.4, DNA 3.7

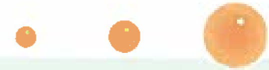
The Basics of Cell Structure

The **cell** is the smallest unit that shows the properties of life, which means it has a capacity for metabolism, homeostasis, growth, and reproduction. The interior of a **eukaryotic cell** is divided into various functional compartments, including a nucleus. **Prokaryotic cells** are usually smaller and simpler; none has a nucleus. Cells differ in size, shape, and activities. Yet, as Figure 4.4 suggests, all cells are similar in three respects. All cells start out life with a plasma membrane, a DNA-containing region, and cytoplasm:

1. A **plasma membrane** is the cell's outer membrane. It separates metabolic activities from events outside of the cell, but does not isolate the cell's interior. Water, carbon dioxide, and oxygen can cross it freely. Other substances cross only with the assistance of membrane proteins. Still others are kept out entirely.

2. All eukaryotic cells start life with a **nucleus**. This double-membraned sac holds a eukaryotic cell's DNA. The DNA inside prokaryotic cells is concentrated in a region of cytoplasm called the **nucleoid**.

3. **Cytoplasm** is a semifluid mixture of water, sugars, ions, and proteins between the plasma membrane and the region of DNA. Cell components are suspended in cytoplasm. For instance, **ribosomes**, structures on which proteins are built, are suspended in cytoplasm.



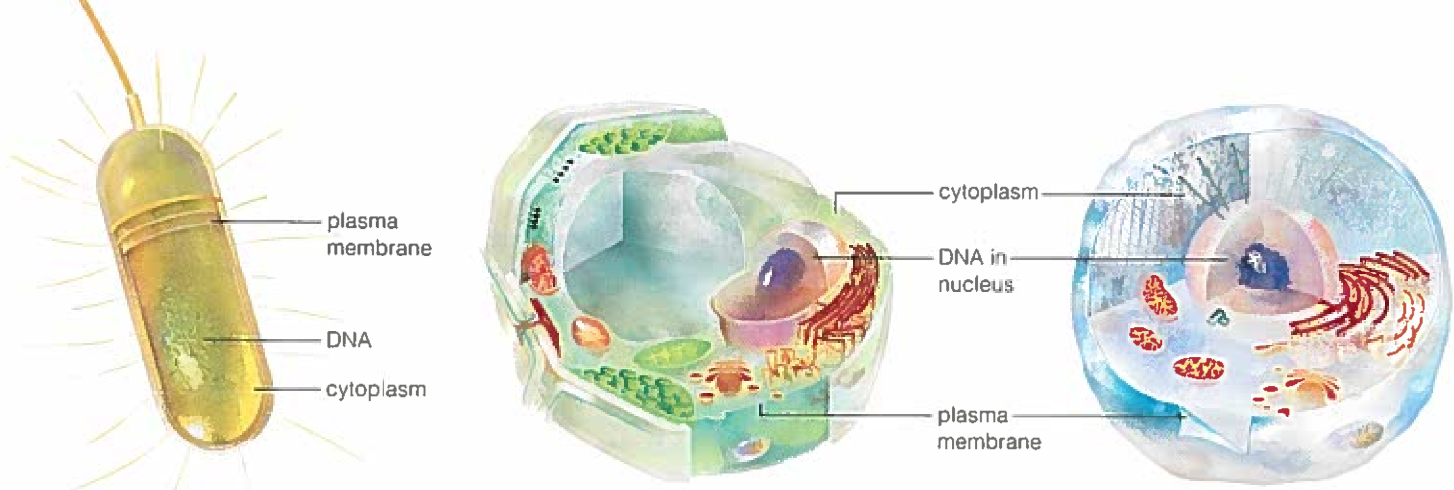
Diameter (cm)	2	3	6
Surface area (cm^2)	12.6	28.2	113
Volume (cm^3)	4.2	14.1	113
Surface-to-volume ratio	3:1	2:1	1:1

Figure 4.5 Animated Three examples of the surface-to-volume ratio. This physical relationship between increases in volume and surface area constrains cell size and shape.

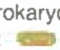
Are any cells big enough to be seen without the help of a microscope? A few. They include the "yolks" of bird eggs, cells in watermelon tissues, and the eggs of amphibians and fishes. These cells can be relatively large because they are not very metabolically active. Most of their volume simply acts as a warehouse.

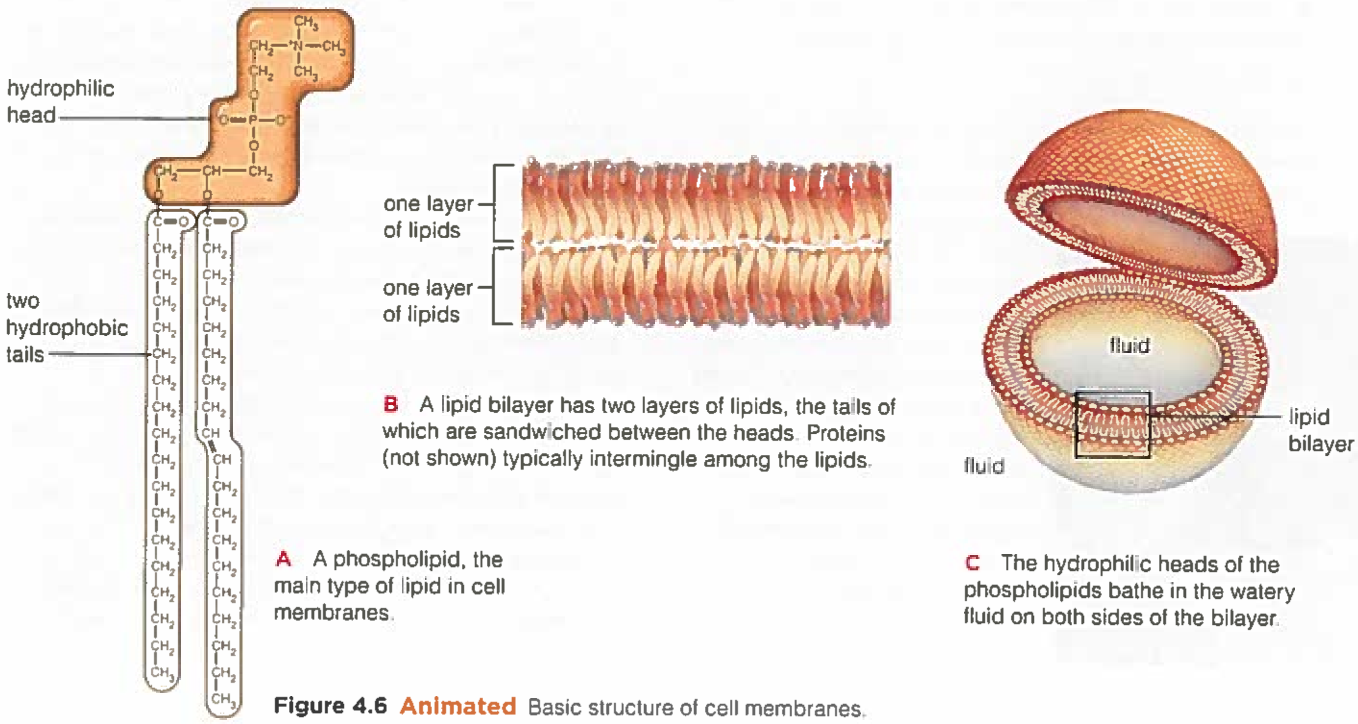
A physical relationship, the **surface-to-volume ratio,** strongly influences cell size and shape. By this ratio, an object's volume increases with the cube of its diameter, but its surface area increases only with the square. The ratio is important because the lipid bilayer can handle only so many exchanges between the cell's cytoplasm and the external environment.

Apply the surface-to-volume ratio to a round cell. As Figure 4.5 shows, when a cell expands in diameter during growth, its volume increases faster than its surface area does. Imagine that a round cell expands until it is four times its original diameter. The volume of the



a Bacterial cell (prokaryotic) **b** Plant cell (eukaryotic) **c** Animal cell (eukaryotic)

Figure 4.4 General organization of prokaryotic and eukaryotic cells. If the prokaryotic cell were drawn at the same scale as the other two cells, it would be about this big: 



A A phospholipid, the main type of lipid in cell membranes.

B A lipid bilayer has two layers of lipids, the tails of which are sandwiched between the heads. Proteins (not shown) typically intermingle among the lipids.

C The hydrophilic heads of the phospholipids bathe in the watery fluid on both sides of the bilayer.

Figure 4.6 **Animated** Basic structure of cell membranes.

cell has increased 64 times (4^3), but its surface area has increased only 16 times (4^2). Each unit of plasma membrane must now handle exchanges with four times as much cytoplasm. If a cell's circumference gets too big, the inward flow of nutrients and outward flow of wastes will not be fast enough to keep the cell alive.

A big, round cell would also have trouble moving substances through its cytoplasm. Molecules disperse by their own random motions, but they move only so quickly. Nutrients or wastes would not get distributed fast enough to keep up with a large, round, active cell's metabolism. That is why many cells are long and thin, or frilly surfaced with folds that increase surface area. The surface-to-volume ratio of such cells is enough to sustain their metabolism. The amount of raw materials that cross the plasma membrane, and the speed with which they are distributed through cytoplasm, satisfy the cell's needs. Wastes are also removed fast enough to keep the cell from getting poisoned.

Surface-to-volume constraints also affect the body plans of multicelled species. For example, small cells attach end to end in strandlike algae, so each interacts directly with its surroundings. Muscle cells in your thighs are as long as the muscle in which they occur, but each is thin, so it exchanges substances efficiently with fluids in the tissue surrounding it.

Preview of Cell Membranes

The structural foundation of all cell membranes is the **lipid bilayer**, a double layer of lipids organized so that their hydrophobic tails are sandwiched between their hydrophilic heads (Figure 4.6).

Phospholipids are the most abundant type of lipid in cell membranes. Many different proteins embedded in a bilayer or attached to one of its surfaces carry out membrane functions. For example, some proteins form channels through a bilayer; others pump substances across it. In addition to a plasma membrane, many cells also have internal membranes that form channels or enclose sacs. These membranous structures compartmentalize tasks such as building, modifying, and storing substances. Chapter 5 offers a closer look at membrane structure and function.

Take-Home Message

How are all cells alike?

- All cells start life with a plasma membrane, cytoplasm, and a region of DNA.
- A lipid bilayer forms the structural framework of all cell membranes.
- DNA of eukaryotic cells is enclosed by a nucleus. DNA of prokaryotic cells is concentrated in a region of cytoplasm called the nucleoid.

4.3 How Do We See Cells?

- We use different types of microscopes to study different aspects of organisms, from the smallest to the largest.
- Link to Tracers 2.2

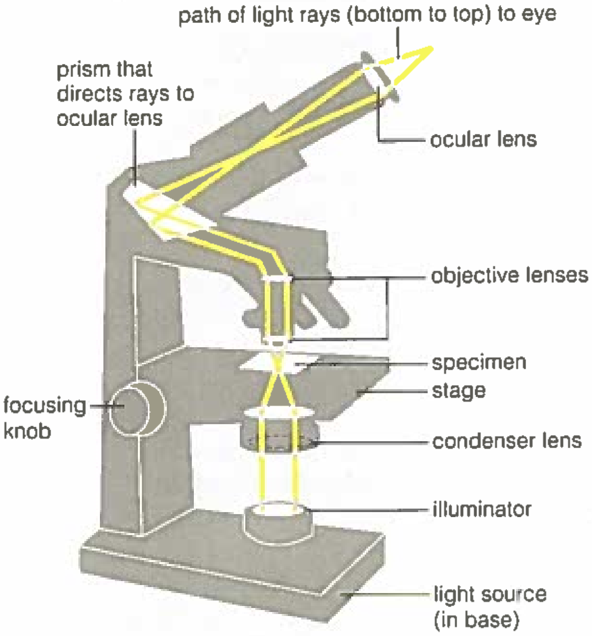
Modern Microscopes Like those early instruments mentioned in Section 4.1, many types of modern light microscopes still rely on visible light to illuminate objects. All light travels in waves, a property that allows us to focus light with glass lenses. Light microscopes use visible light to illuminate a cell or some other specimen (Figure 4.7*a*). Curved glass lenses bend the light and focus it as a magnified image of the specimen. Photographs of images enlarged with any microscope are called micrographs (Figure 4.8).

Phase-contrast microscopes shine light through specimens, but most cells are nearly transparent. Their internal details may not be visible unless they are first stained, or exposed to dyes that only some cell parts soak up. The parts that absorb the most dye appear darkest. The resulting increase in contrast (the difference between light and dark) allows us to see a greater range of detail (Figure 4.8*a*). Opaque samples are not stained; their surface details are revealed with reflected light microscopes (Figure 4.8*b*).

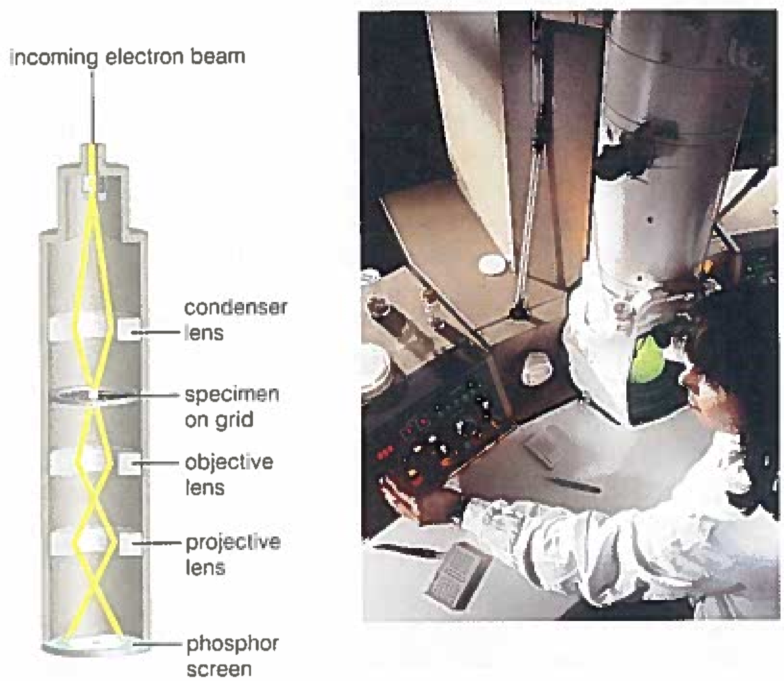
With a fluorescence microscope, a cell or a molecule is the light source; it fluoresces, or emits energy in the form of visible light, when a laser beam is focused on it. Some molecules, such as chlorophylls, fluoresce naturally (Figure 4.8*c*). More typically, researchers attach a light-emitting tracer to the cell or molecule of interest.

The wavelength of light—the distance from the peak of one wave to the peak behind it—limits the power of any light microscope. Why? Structures that are smaller than one-half of the wavelength of light are too small to scatter light waves, even after they have been stained. The smallest wavelength of visible light is about 400 nanometers. That is why structures that are smaller than about 200 nanometers across appear blurry under even the best light microscopes.

Other microscopes can reveal smaller details. For example, electron microscopes use electrons instead

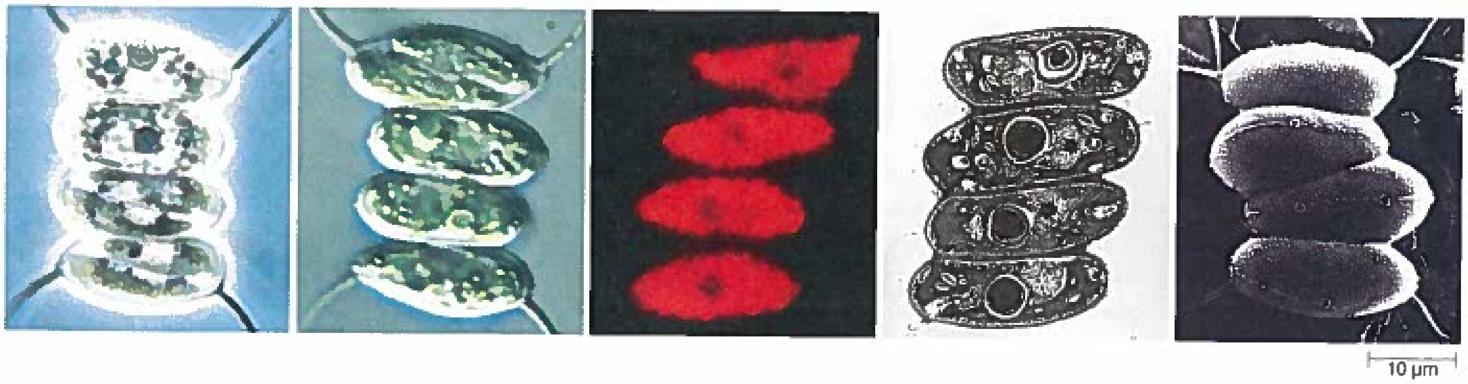


A A compound light microscope has more than one glass lens.



B Transmission electron microscope (TEM). Electrons passing through a thin slice of a specimen illuminate a fluorescent screen. Internal details of the specimen cast visible shadows, as in Figure 4.8*d*.

Figure 4.7 **Animated** Examples of microscopes.



a Light micrograph. A phase-contrast microscope yields high-contrast images of transparent specimens, such as cells.

b Light micrograph. A reflected light microscope captures light reflected from opaque specimens.

c Fluorescence micrograph. The chlorophyll molecules in these cells emitted red light (they fluoresced) naturally.

d A transmission electron micrograph reveals fantastically detailed images of internal structures.

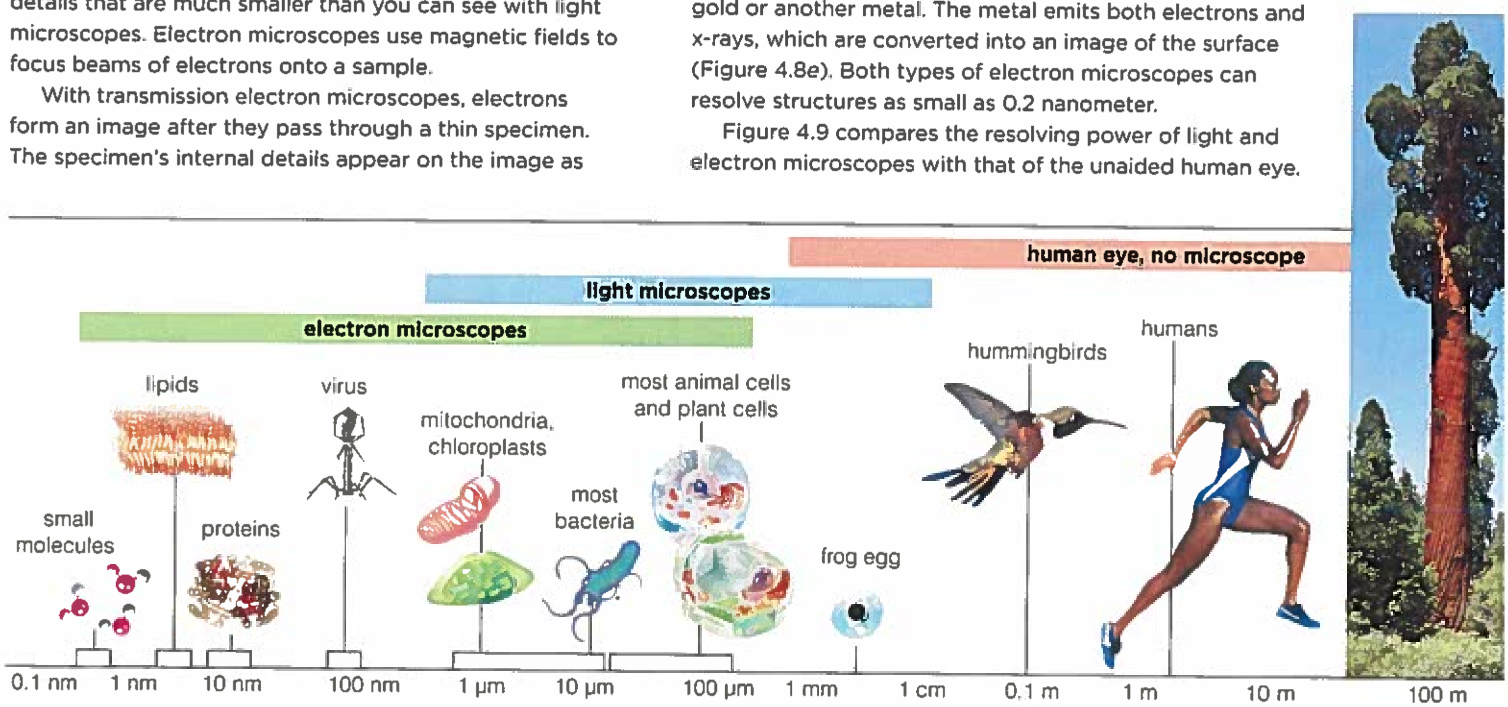
e A scanning electron micrograph shows surface details of cells and structures. Often, SEMs are artificially colored to highlight certain details.

Figure 4.8 Different microscopes can reveal different characteristics of the same aquatic organism—a green alga (*Scenedesmus*). Try estimating the size of one of these algal cells by using the scale bar.

of visible light to illuminate samples (Figure 4.7*b*). Because electrons travel in wavelengths that are much shorter than those of visible light, electron microscopes can resolve details that are much smaller than you can see with light microscopes. Electron microscopes use magnetic fields to focus beams of electrons onto a sample.

With transmission electron microscopes, electrons form an image after they pass through a thin specimen. The specimen's internal details appear on the image as shadows (Figure 4.8*d*). Scanning electron microscopes direct a beam of electrons back and forth across a surface of a specimen, which has been coated with a thin layer of gold or another metal. The metal emits both electrons and x-rays, which are converted into an image of the surface (Figure 4.8*e*). Both types of electron microscopes can resolve structures as small as 0.2 nanometer.

Figure 4.9 compares the resolving power of light and electron microscopes with that of the unaided human eye.



a

Figure 4.9 (**a**) Relative sizes of molecules, cells, and multicelled organisms. The diameter of most cells is in the range of 1 to 100 micrometers. Frog eggs, one of the exceptions, are 2.5 millimeters in diameter. The scale shown here is exponential, not linear; each unit of measure is ten times larger than the unit preceding it. (**b**) Units of measure. See also Appendix IX. **Figure It Out:** Which is smallest, a protein, a lipid, or a water molecule?

Answer: A water molecule

b

1 centimeter (cm)	=	1/100 meter, or 0.4 inch
1 millimeter (mm)	=	1/1000 meter, or 0.04 inch
1 micrometer (µm)	=	1/1,000,000 meter, or 0.00004 inch
1 nanometer (nm)	=	1/1,000,000,000 meter, or 0.00000004 inch

1 meter = 10^2 cm = 10^3 mm = 10^6 µm = 10^9 nm

4.4 Introducing Prokaryotic Cells

- Bacteria and archaea are the prokaryotes.
- Links to Polysaccharides 3.3, ATP 3.7

The word prokaryote means "before the nucleus," a reminder that the first prokaryotes evolved before the first eukaryotes. Prokaryotes are single-celled (Figure 4.10). As a group, they are the smallest and most metabolically diverse forms of life that we know about. Prokaryotes inhabit nearly all of Earth's environments, including some very hostile places.

Domains Bacteria and Archaea comprise all prokaryotes (Section 1.3). Cells of the two domains are alike in appearance and size, but differ in their structure and metabolic details (Figures 4.11 and 4.12). Some characteristics of archaeans indicate they are more closely related to eukaryotic cells than to bacteria. Chapter 21 revisits prokaryotes in more detail. Here we present an overview of their structure.

Most prokaryotic cells are not much wider than a micrometer. Rod-shaped species are a few micrometers long. None has a complex internal framework, but protein filaments under the plasma membrane impart shape to the cell. Such filaments also act as scaffolding for internal structures.

A rigid **cell wall** surrounds the plasma membrane of nearly all prokaryotes. Dissolved substances easily cross this permeable layer on the way to and from the plasma membrane. The cell wall of most bacteria consists of peptidoglycan, which is a polymer of cross-linked peptides and polysaccharides. The wall of most archaeans consists of proteins. Some types of eukaryotic cells (such as plant cells) also have a wall, but it is structurally different from a prokaryotic cell wall.

Sticky polysaccharides form a slime layer, or capsule, around the wall of many types of bacteria. The sticky capsule helps these cells adhere to many types of surfaces (such as spinach leaves and meat), and it also protects them from predators and toxins. A capsule can protect pathogenic (disease-causing) bacteria from host defenses.

Projecting past the wall of many prokaryotic cells are one or more **flagella** (singular, flagellum): slender cellular structures used for motion. A bacterial flagellum moves like a propeller that drives the cell through fluid habitats, such as a host's body fluids. It differs from a eukaryotic flagellum, which bends like a whip and has a distinctive internal structure.

Protein filaments called **pili** (singular, pilus) project from the surface of some bacterial species (Figure 4.12*a*). Pili help cells cling to or move across surfaces. One kind, a "sex" pilus, attaches to another bacterium and then shortens. The attached cell is reeled in, and genetic material is transferred from one cell to the other through the pilus.

The plasma membrane of all bacteria and archaeans selectively controls which substances move to and from the cytoplasm, as it does for eukaryotic cells. The plasma membrane bristles with transporters and receptors, and it also incorporates proteins that carry out important metabolic processes.

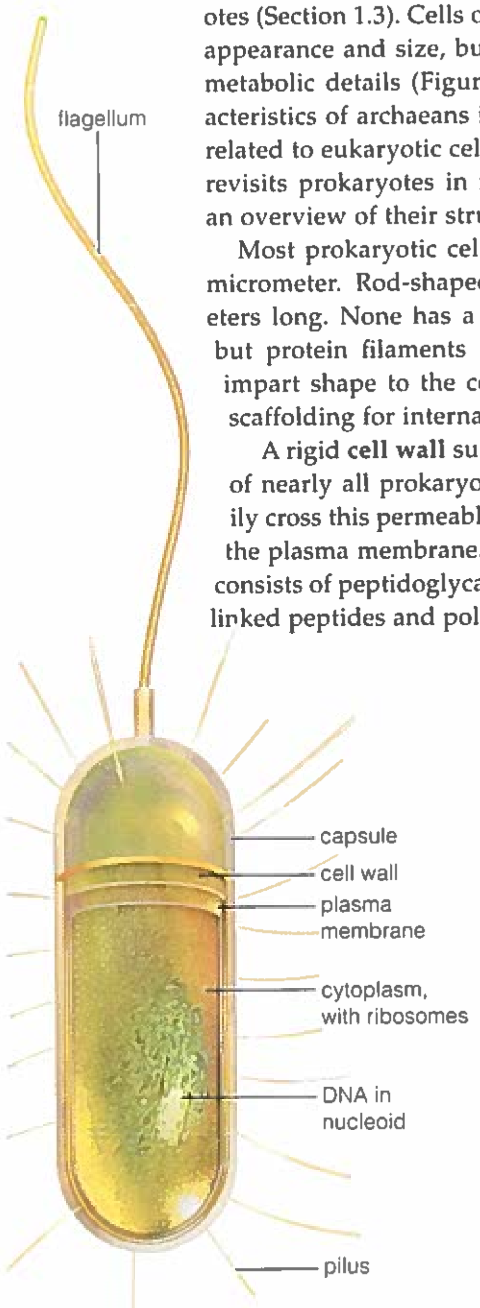
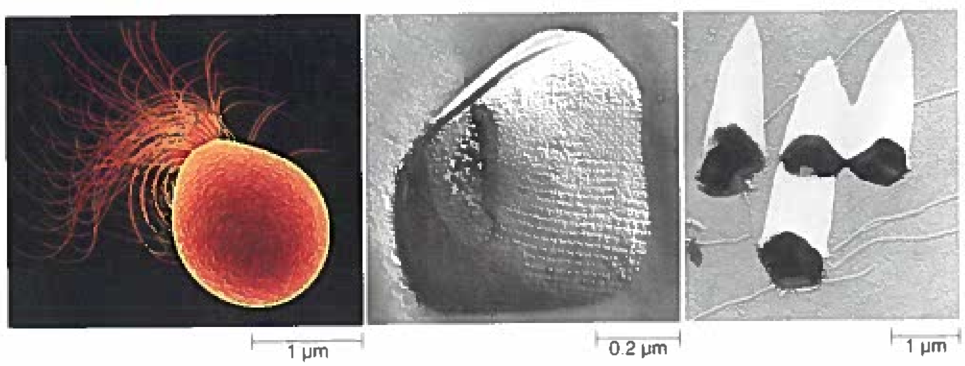


Figure 4.10 Animated Generalized body plan of a prokaryote.



a *Pyrococcus furiosus* was discovered in ocean sediments near an active volcano. It lives best at 100°C (212°F), and it makes a rare kind of enzyme that contains tungsten atoms.

b *Ferroglobus placidus* prefers superheated water spewing from the ocean floor. The unique composition of archaean lipid bilayers keeps these membranes intact at extreme heat and pH.

c *Metallosphaera prunae*, discovered in a smoking pile of ore at a uranium mine, prefers high temperatures and low pH. (*White shadows are an artifact of electron microscopy.*)

Figure 4.11 Some like it hot: many archaeans inhabit extreme environments. The cells in this example live without oxygen.

Figure 4.12 Bacteria. (**a**) Protein filaments, or pili, anchor bacterial cells to one another and to surfaces. Here, *Salmonella typhimurium* cells (*red*) use their pili to invade a culture of human cells. (**b**) Ball-shaped *Nostoc* cells stick together in a sheath of their own secretions. *Nostoc* are photosynthetic cyanobacteria. Other types of bacteria are shaped like rods or corkscrews.

For example, the plasma membrane of photosynthetic bacteria has arrays of proteins that capture light energy and convert it to the chemical energy of ATP (Section 3.7). The ATP is then used to build sugars. Similar metabolic processes occur in eukaryotes, but they take place at specialized internal membranes, not the plasma membrane.

The cytoplasm of prokaryotes contains thousands of ribosomes, structures upon which polypeptides are assembled. A prokaryotic cell's single chromosome, a circular DNA molecule, is located in an irregularly shaped region called the nucleoid. Most nucleoids are not enclosed by a membrane. Many prokaryotes also have plasmids in the cytoplasm. These small circles of DNA carry a few genes (units of inheritance) that can confer advantages, such as resistance to antibiotics.

One more intriguing point: There is evidence that all protists, plants, fungi, and animals evolved from a few ancient types of prokaryotes. For example, part of the plasma membrane of cyanobacteria folds into the cytoplasm. Pigments and other molecules that carry out photosynthesis are embedded in the membrane, just as they are in the inner membrane of chloroplasts—structures specialized for photosynthesis in eukaryotic cells. Section 20.4 returns to this topic.

Take-Home Message

What do all prokaryotic cells have in common?

- All prokaryotes are single-celled organisms with no nucleus. These organisms inhabit nearly all regions of the biosphere.
- Bacteria and archaeans are the only prokaryotes. Most kinds have a cell wall around their plasma membrane.
- Prokaryotes have a relatively simple structure, but they are a diverse group of organisms.

4.5 Microbial Mobs

- Although prokaryotes are all single-celled, few live alone.
- Link to Glycoproteins 3.5

Bacterial cells often live so close together that an entire community shares a layer of secreted polysaccharides and glycoproteins. Such communal living arrangements, in which single-celled organisms live in a shared mass of slime, are called **biofilms**. In nature, a biofilm typically consists of multiple species, all entangled in their own mingled secretions. It may include bacteria, algae, fungi, protists, and archaeans. Such associations allow cells living in a fluid to linger in a particular spot rather than be swept away by currents.

The microbial inhabitants of a biofilm benefit each other. Rigid or netlike secretions of some species serve as permanent scaffolding for others. Species that break down toxic chemicals allow more sensitive ones to thrive in polluted habitats that they could not withstand on their own. Waste products of some serve as raw materials for others.

Like a bustling metropolitan city, a biofilm organizes itself into "neighborhoods," each with a distinct microenvironment that stems from its location within the biofilm and the particular species that inhabit it (Figure 4.13). For example, cells that reside near the middle of a biofilm are very crowded and do not divide often. Those at the edges divide repeatedly, expanding the biofilm.

The formation and continuation of a biofilm is not random. Free-living cells sense the presence of other cells. Those that encounter a biofilm with favorable conditions switch their metabolism to support a more sedentary, communal lifestyle, and join in. Flagella disassemble, and sex pili form. If conditions become less favorable, the cells can revert to a free-living mode and swim away to find more hospitable accommodations.

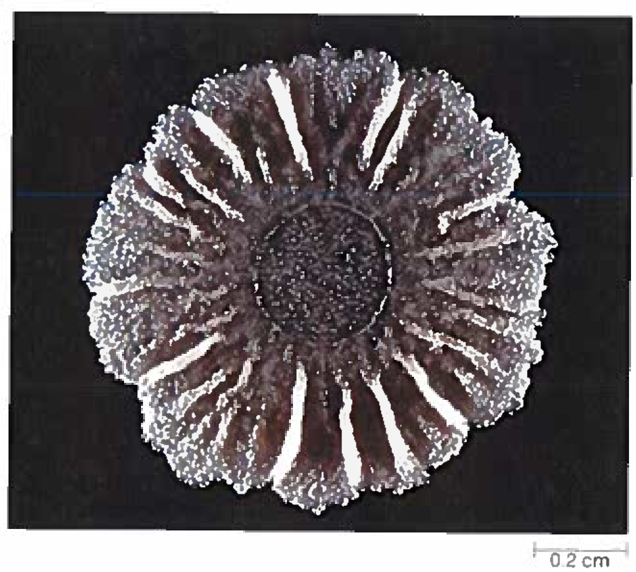


Figure 4.13 Biofilms. A single species of bacteria, *Bacillus subtilis*, formed this biofilm. Note the distinct regions.

4.6 Introducing Eukaryotic Cells

- Eukaryotic cells carry out much of their metabolism inside organelles enclosed by membranes.

All eukaryotic cells start out life with a nucleus. *Eu–* means true; and *karyon*, meaning kernel, refers to the nucleus. A nucleus is a type of **organelle**: a structure that carries out a specialized function inside a cell. Many organelles, particularly those in eukaryotic cells, are bounded by membranes. Like all cell membranes, those around organelles control the types and amounts of substances that cross them. Such control maintains a special internal environment that allows an organelle to carry out its particular function. That function may be isolating a toxic or sensitive substance from the rest of the cell, transporting some substance through the cytoplasm, maintaining fluid balance, or providing a favorable environment for a reaction that could not occur in the cytoplasm. For example, a mitochondrion makes ATP after concentrating hydrogen ions inside its membrane system.

Much as interactions among organ systems keep an animal body running, interactions among organelles keep a cell running. Substances shuttle from one kind of organelle to another, and to and from the plasma membrane. Some metabolic pathways take place in a series of different organelles.

Table 4.1 lists common components of eukaryotic cells. These cells all start out life with certain kinds of organelles such as a nucleus and ribosomes. They also have a cytoskeleton, a dynamic "skeleton" of proteins (*cyto–* means cell). Specialized cells contain additional kinds of organelles and structures. Figure 4.14 shows two typical eukaryotic cells.

Table 4.1 Organelles of Eukaryotic Cells

Name	Function
Organelles with membranes	
Nucleus	Protecting, controlling access to DNA
Endoplasmic reticulum (ER)	Routing, modifying new polypeptide chains; synthesizing lipids; other tasks
Golgi body	Modifying new polypeptide chains; sorting, shipping proteins and lipids
Vesicles	Transporting, storing, or digesting substances in a cell; other functions
Mitochondrion	Making ATP by sugar breakdown
Chloroplast	Making sugars in plants, some protists
Lysosome	Intracellular digestion
Peroxisome	Inactivating toxins
Vacuole	Storage
Organelles without membranes	
Ribosomes	Assembling polypeptide chains
Centriole	Anchor for cytoskeleton

Take-Home Message

What do all eukaryotic cells have in common?

- Eukaryotic cells start life with a nucleus and other membrane-enclosed organelles (structures that carry out specific tasks).

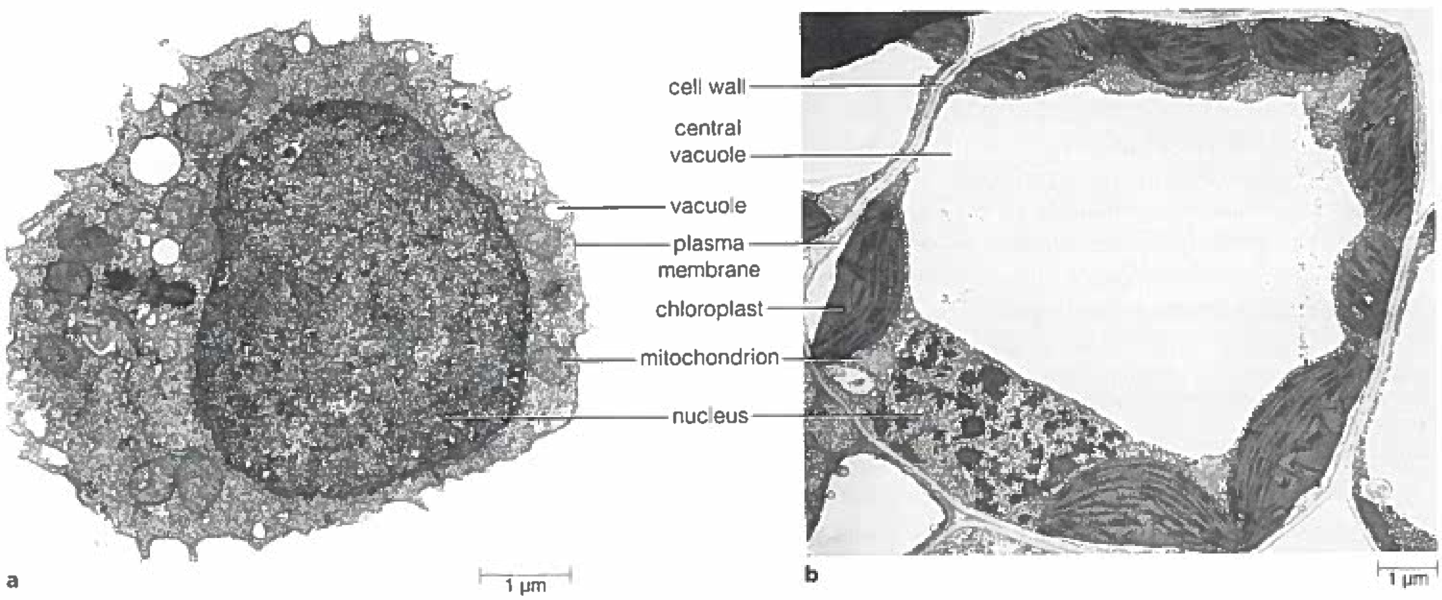
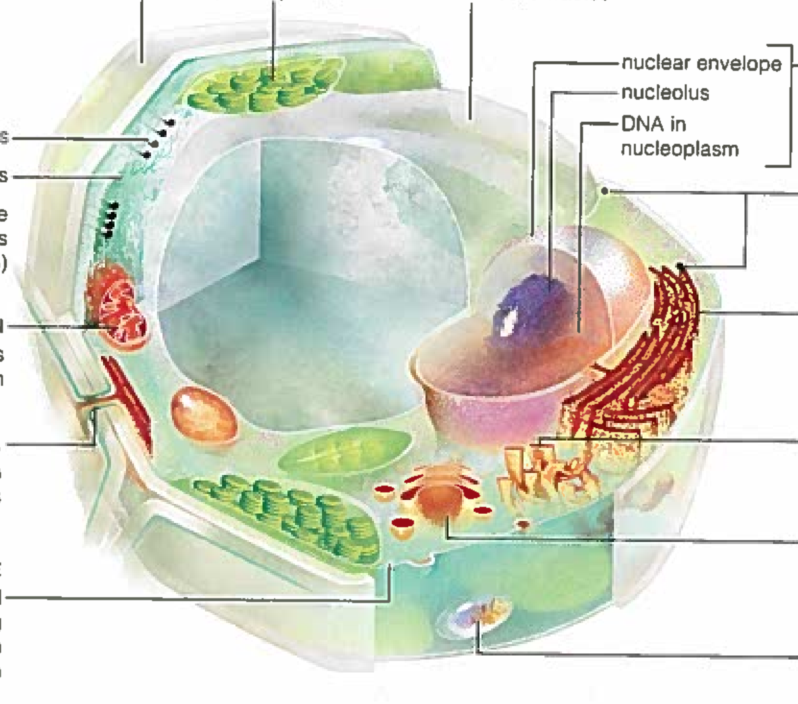
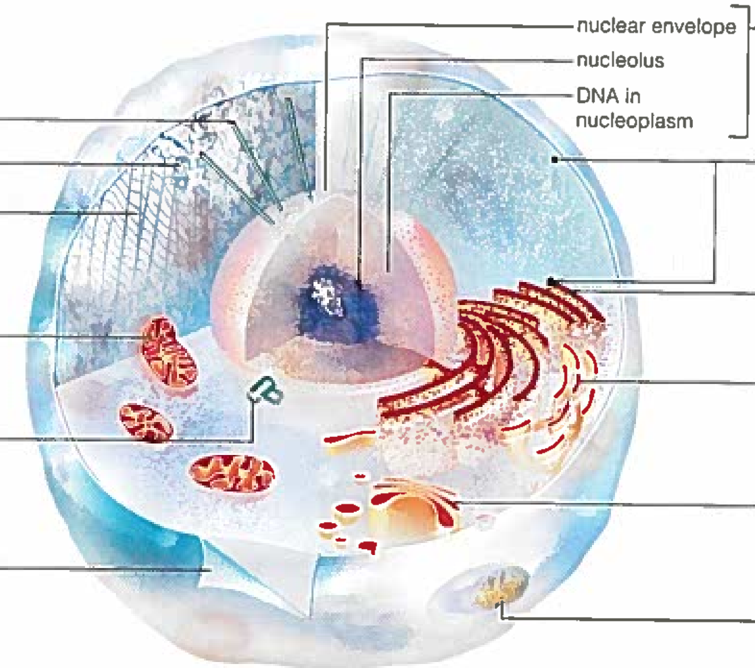


Figure 4.14 Transmission electron micrographs of eukaryotic cells. **(a)** Human white blood cell. **(b)** Photosynthetic cell from a blade of timothy grass.

4.7 Visual Summary of Eukaryotic Cell Components



a Typical plant cell components.



b Typical animal cell components.

Figure 4.15 Animated Organelles and structures typical of (**a**) plant cells and (**b**) animal cells.

4.8 The Nucleus

- The nucleus keeps eukaryotic DNA away from potentially damaging reactions in the cytoplasm.
- The nuclear envelope controls when DNA is accessed.

The nucleus contains all of a eukaryotic cell's DNA. A molecule of DNA is big to begin with, and the nucleus of most kinds of eukaryotic cells has many of them. If you could tease out all of the DNA molecules from the nucleus of a single human cell, unravel them, and stretch them out end to end, you would have a line of DNA about 2 meters (6–1/2 feet) long. That is a lot of DNA for one microscopic nucleus.

The nucleus serves two important functions. First, it keeps a cell's genetic material—its one and only copy of DNA—safe and sound. Isolated in its own compartment, DNA stays separated from the bustling activity of the cytoplasm, and from metabolic reactions that might damage it.

Second, a nuclear membrane controls the passage of molecules between the nucleus and the cytoplasm. For example, cells access their DNA when they make RNA and proteins, so the various molecules involved in this process must pass into the nucleus and out of it. The nuclear membrane allows only certain molecules to cross it, at certain times and in certain amounts. This control is another measure of safety for the DNA, and it is also a way for the cell to regulate the amount of RNA and proteins it makes.

Table 4.2 Components of the Nucleus

Nuclear envelope	Pore-riddled double membrane that controls which substances enter and leave the nucleus
Nucleoplasm	Semifluid interior portion of the nucleus
Nucleolus	Rounded mass of proteins and copies of genes for ribosomal RNA used to construct ribosomal subunits
Chromatin	Total collection of all DNA molecules and associated proteins in the nucleus; all of the cell's chromosomes
Chromosome	One DNA molecule and many proteins associated with it

Figure 4.16 shows the components of the nucleus. Table 4.2 lists their functions. Let's zoom in on the individual components.

The Nuclear Envelope

The membrane of a nucleus, or **nuclear envelope**, consists of two lipid bilayers folded together as a single membrane. As Figure 4.16 shows, the outer bilayer of the membrane is continuous with the membrane of

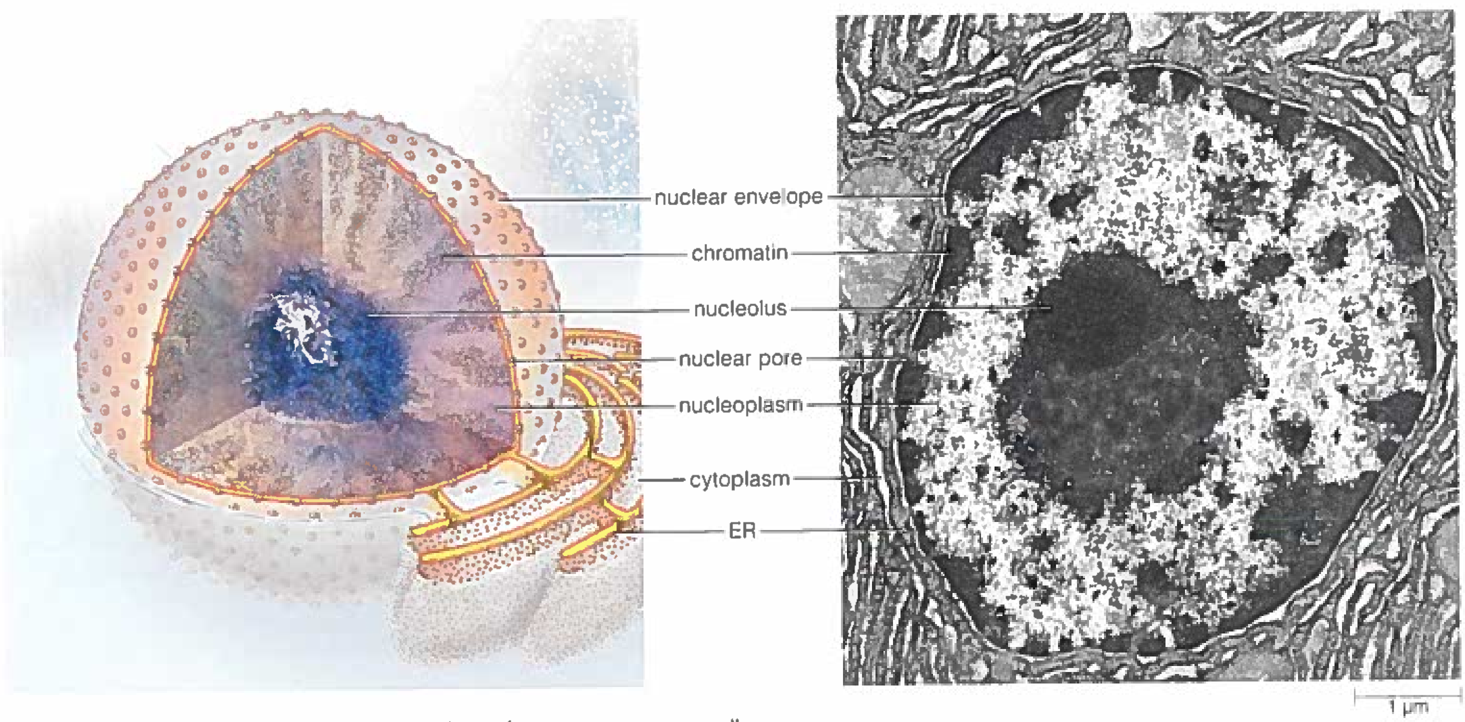


Figure 4.16 The nucleus. TEM at *right*, nucleus of a mouse pancreas cell.

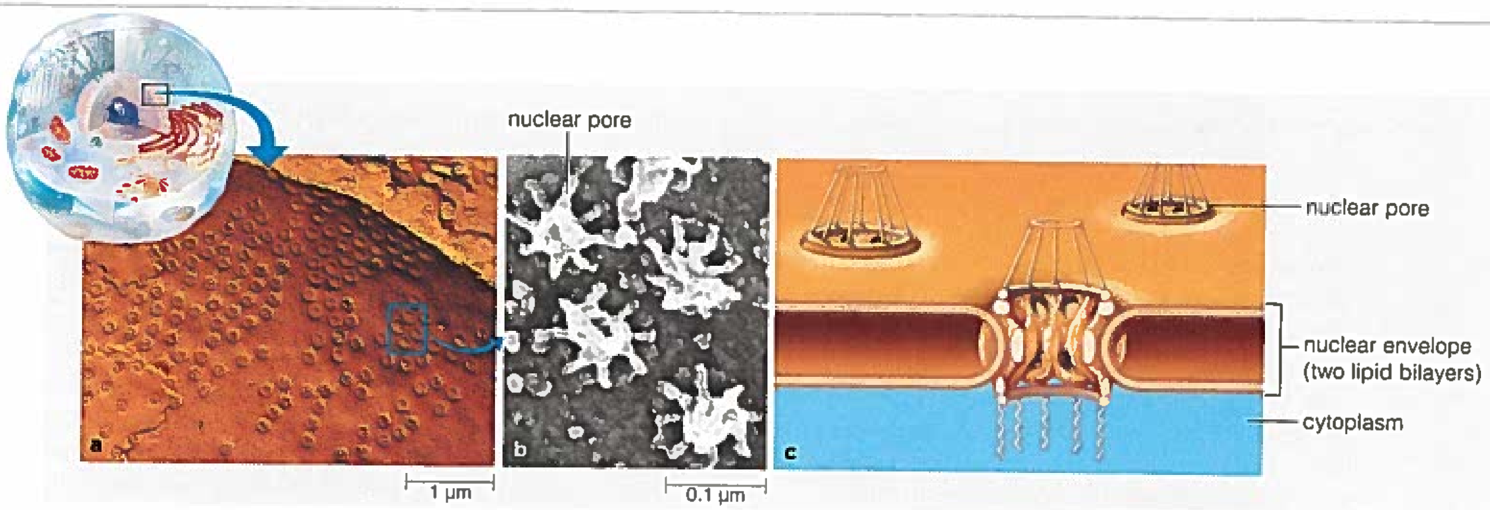


Figure 4.17 **Animated** Structure of the nuclear envelope. (**a**) The outer surface of a nuclear envelope was split apart, revealing the pores that span the two lipid bilayers. (**b**) Each nuclear pore is an organized cluster of membrane proteins that selectively allows certain substances to cross it on their way into and out of the nucleus. (**c**) Sketch of the nuclear envelope's structure.

another organelle, the ER. (We will discuss the ER in the next section.)

Different kinds of membrane proteins are embedded in the two lipid bilayers. Some are receptors and transporters; others aggregate into tiny pores that span the membrane (Figure 4.17). These molecules and structures work as a system to transport various molecules across the nuclear membrane. As with all membranes, water and gases cross nuclear membranes freely. All other substances can cross only through transporters and nuclear pores, both of which are selective about which molecules they allow through.

Fibrous proteins that attach to the inner surface of the nuclear envelope anchor DNA molecules and keep them organized. During cell division, these proteins help the cell parcel out the DNA into its offspring.

The Nucleolus

The nuclear envelope encloses **nucleoplasm**, a viscous fluid similar to cytoplasm. The nucleus also contains at least one **nucleolus** (plural, nucleoli), a dense, irregularly shaped region where subunits of ribosomes are assembled from proteins and RNA. The subunits pass through nuclear pores into the cytoplasm, where they join and become active in protein synthesis.

The Chromosomes

Chromatin is the name for all of the DNA, together with its associated proteins, in the nucleus. The genetic material of a eukaryotic cell is distributed among a specific number of DNA molecules. That number is characteristic of the type of organism and the type of cell, but it varies widely among species. For instance, the nucleus of a normal oak tree cell contains 12 DNA molecules; a human body cell, 46; and a king crab cell, 208. Each molecule of DNA, together with its many attached proteins, is called a **chromosome.**

Chromosomes change in appearance over the lifetime of a cell. When a cell is not dividing, its chromatin can appear grainy (as in Figure 4.16). Just before a cell divides, the DNA in each chromosome is copied, or duplicated. Then, during cell division, the chromosomes condense. As they do, they become visible in micrographs. The chromosomes first appear threadlike, then rodlike:

one chromosome (one unduplicated DNA molecule) | one chromosome (one duplicated DNA molecule, partially condensed) | one chromosome (one duplicated DNA molecule, completely condensed)

In later chapters, we will look in more detail at the dynamic structure and the function of chromosomes.

Take-Home Message

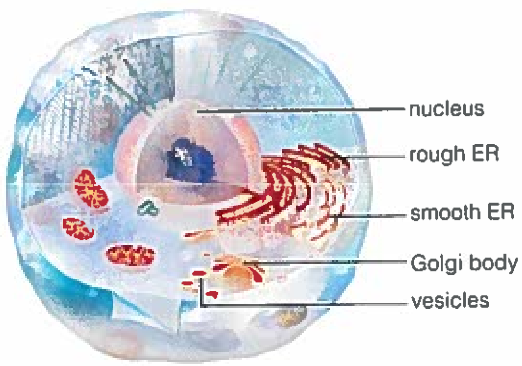
What is the function of the cell nucleus?

- A nucleus protects and controls access to a eukaryotic cell's genetic material—its chromosomes.
- The nuclear envelope is a double lipid bilayer. Proteins embedded in it control the passage of molecules between the nucleus and the cytoplasm.

4.9 The Endomembrane System

- The endomembrane system is a set of organelles that makes, modifies, and transports proteins and lipids.
- Links to Lipids 3.4, Proteins 3.5

The **endomembrane system** is a series of interacting organelles between the nucleus and the plasma membrane (Figure 4.18). Its main function is to make lipids, enzymes, and proteins for secretion or insertion into cell membranes. It also destroys toxins, recycles wastes, and has other specialized functions. The system's components vary among different types of cells, but here we present the most common ones.

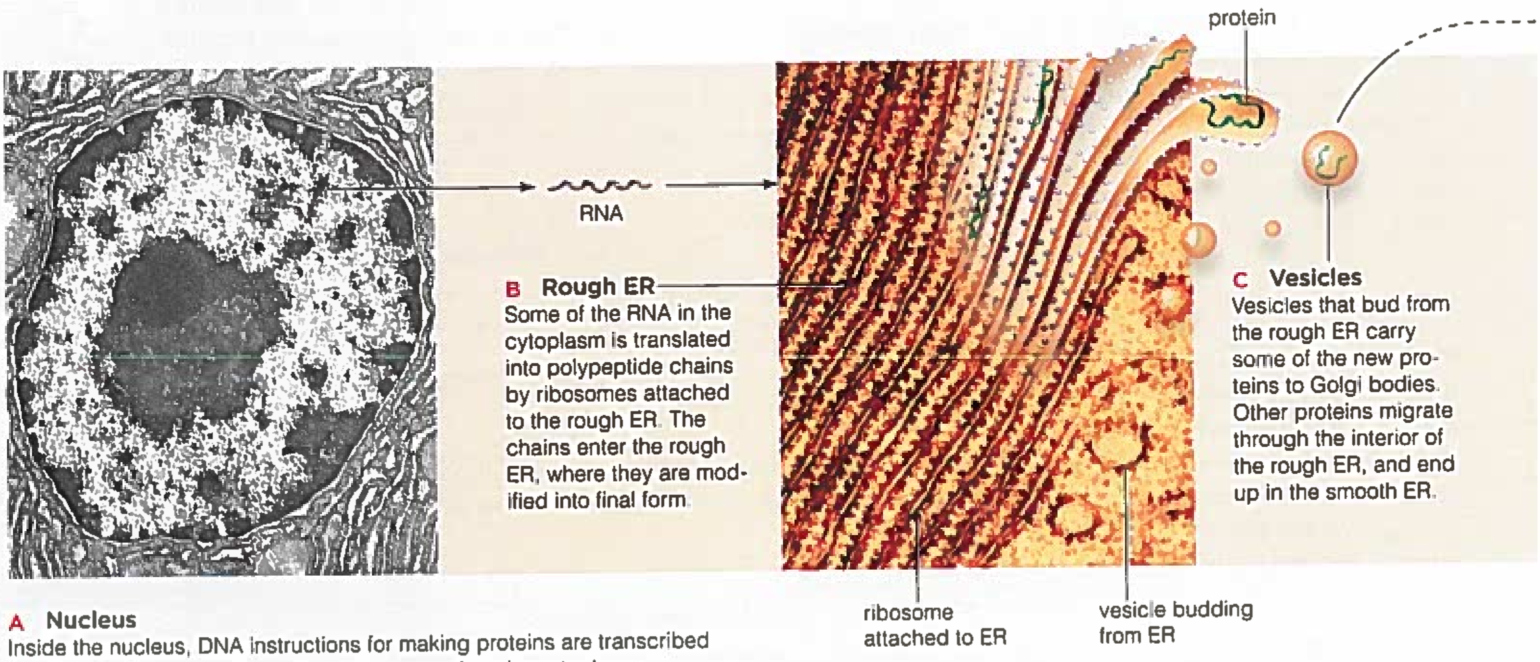


The Endoplasmic Reticulum

Endoplasmic reticulum, or ER, is an extension of the nuclear envelope. It forms a continuous compartment that folds over and over into flattened sacs and tubes. Two kinds of ER are named for their appearance in electron micrographs. Many thousands of ribosomes attach to the outer surface of rough ER (Figure 4.18*b*). The ribosomes synthesize polypeptide chains, which extrude into the interior of the ER. Inside the ER, the proteins fold and take on their tertiary structure. Some of the proteins become part of the ER membrane itself; others are carried to different destinations in the cell.

Cells that make, store, and secrete a lot of proteins have a lot of rough ER. For example, ER-rich gland cells in the pancreas (an organ) make and secrete enzymes that help digest food in the small intestine.

Smooth ER has no ribosomes, so it does not make proteins (Figure 4.18*d*). Some of the polypeptides made in the rough ER end up in the smooth ER, as enzymes. These enzymes make most of the cell's membrane lipids. They also break down carbohydrates, fatty acids, and some drugs and poisons. In skeletal muscle cells, a special type of smooth ER called sarcoplasmic reticulum stores calcium ions and has a role in contraction.



B Rough ER Some of the RNA in the cytoplasm is translated into polypeptide chains by ribosomes attached to the rough ER. The chains enter the rough ER, where they are modified into final form.

C Vesicles Vesicles that bud from the rough ER carry some of the new proteins to Golgi bodies. Other proteins migrate through the interior of the rough ER, and end up in the smooth ER.

A Nucleus Inside the nucleus, DNA instructions for making proteins are transcribed into RNA, which moves through nuclear pores into the cytoplasm.

Figure 4.18 Animated Endomembrane system, where lipids and many proteins are built, then transported to cellular destinations or to the plasma membrane. Chapter 14 describes transcription and translation.

Vesicles

Vesicles are small, membrane-enclosed, saclike organelles. They form in great numbers, and in a variety of types, either on their own or by budding from other organelles or the plasma membrane.

Many types of vesicles transport substances from one organelle to another, or to and from the plasma membrane (Figure 4.18*c*–*f*). Other kinds have different roles. For example, **peroxisomes** contain enzymes that digest fatty acids and amino acids. These vesicles form and divide on their own. Peroxisomes have a variety of functions, such as inactivating hydrogen peroxide, a toxic by-product of fatty acid breakdown. Enzymes in the peroxisomes convert hydrogen peroxide to water and oxygen, or they use it in reactions that break down alcohol and other toxins. Drink alcohol, and the peroxisomes in your liver and kidney cells degrade nearly half of it.

Plant and animal cells contain **vacuoles**. Although these vesicles appear empty under a microscope, they serve an important function. Vacuoles are like trash cans; they isolate and dispose of waste, debris, or toxic materials. A central vacuole, described in Section 4.11, helps a plant cell maintain its shape and size.

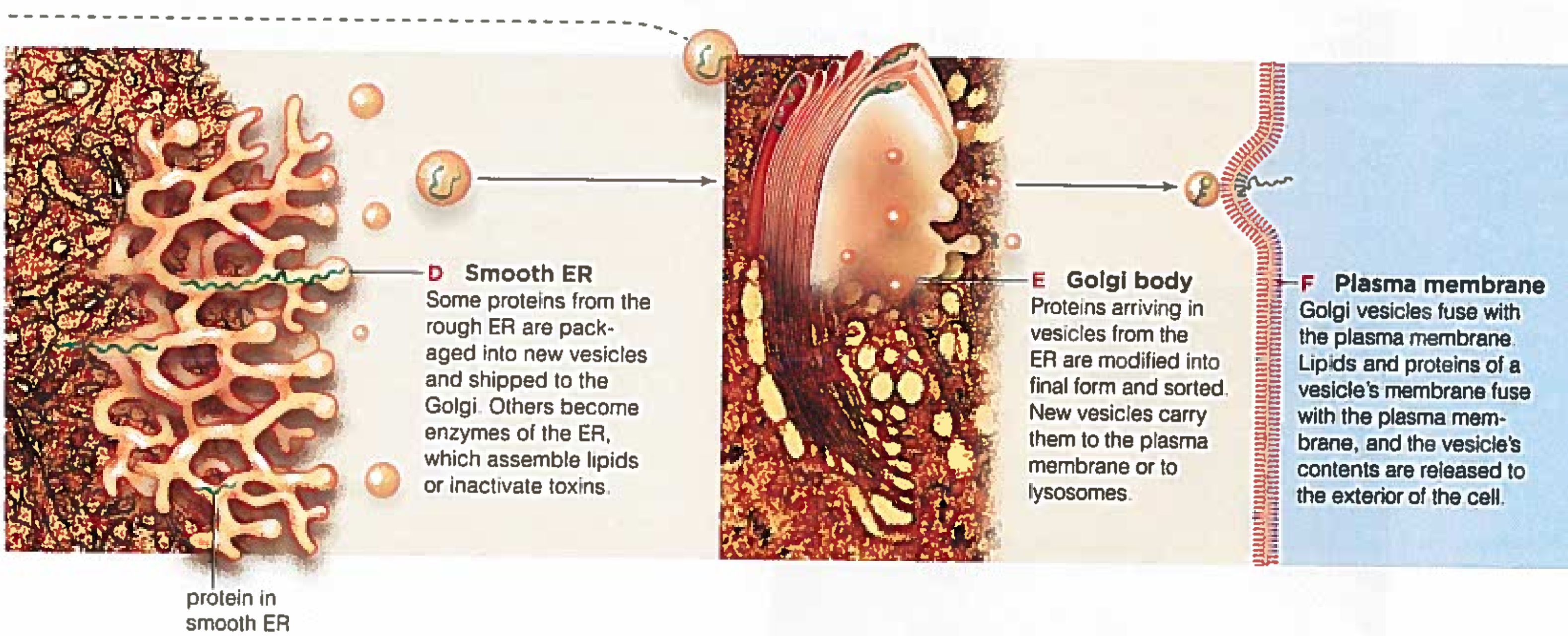
Golgi Bodies

Many vesicles fuse with and empty their contents into a **Golgi body**. This organelle has a folded membrane that typically looks like a stack of pancakes (Figure 4.18*e*). Enzymes in a Golgi body put finishing touches on polypeptide chains and lipids that have been delivered from the ER. They attach phosphate groups or sugars, and cleave certain polypeptide chains. The finished products—membrane proteins, proteins for secretion, and enzymes—are sorted and packaged into new vesicles that carry them to the plasma membrane or to lysosomes. **Lysosomes** are vesicles that contain powerful digestive enzymes. They fuse with vacuoles carrying particles or molecules for disposal, such as worn-out cell components. Lysosomal enzymes empty into the other vesicles and digest their contents into bits.

Take-Home Message

What is the endomembrane system?

- The endomembrane system includes rough and smooth endoplasmic reticulum, vesicles, and Golgi bodies.
- This series of organelles works together mainly to synthesize and modify cell membrane proteins and lipids.



4.10 Lysosome Malfunction

- When lysosomes do not work properly, some cellular materials are not properly recycled, with devastating results.
- Link to Mutations 1.4

Lysosomes serve as waste disposal and recycling centers. Enzymes inside them break large molecules into smaller subunits that the cell can use as building material or eliminate. Different kinds of molecules are broken down by different lysosomal enzymes.

In some people, a genetic mutation causes a deficiency or malfunction in one of the lysosomal enzymes. As a result, molecules that would normally get broken down accumulate instead. The result can be deadly.

For example, cells continually make, use, and break down gangliosides, a kind of lipid. This lipid turnover is especially brisk during early development. In Tay-Sachs disease, the enzyme responsible for ganglioside breakdown misfolds and is destroyed. Most commonly, affected infants seem normal for the first few months. Symptoms begin to appear as gangliosides accumulate to higher and higher levels inside their nerve cells. Within three to six months the child becomes irritable, listless, and may have seizures. Blindness, deafness, and paralysis follow. Affected children usually die by age five (Figure 4.19).

The mutation that causes Tay-Sachs is most prevalent in Jews of Eastern European descent. Cajuns and French Canadians also have a higher than average incidence, but Tay-Sachs occurs in all populations. The mutation can be detected in prospective parents by genetic screening, and in a fetus by prenatal diagnosis.

Researchers continue to explore options for treatment. Potential therapies involve blocking ganglioside synthesis, using gene therapy to deliver a normal version of the missing enzyme to the brain, or infusing normal blood cells from umbilical cords. All treatments are still considered experimental, and Tay-Sachs is still incurable.

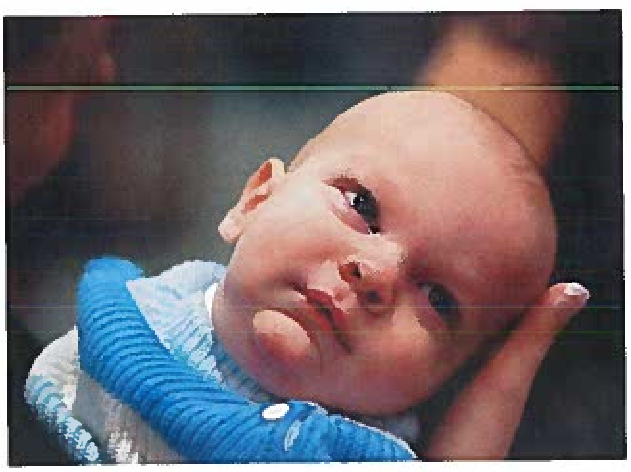


Figure 4.19 Conner Hopf was diagnosed with Tay-Sachs disease at age 7-1/2 months. He died at 22 months.

4.11 Other Organelles

- Eukaryotic cells make most of their ATP in mitochondria.
- Organelles called plastids function in storage and photosynthesis in plants and some types of algae.
- Links to Metabolism 3.2, ATP 3.7

Mitochondria

The **mitochondrion** (plural, mitochondria) is a type of organelle that specializes in making ATP (Figure 4.20). Aerobic respiration, an oxygen-requiring series of reactions that proceeds inside mitochondria, can extract more energy from organic compounds than any other metabolic pathway. With each breath, you are taking in oxygen mainly for the mitochondria in your trillions of aerobically-respiring cells.

Typical mitochondria are between 1 and 4 micrometers in length; a few are as long as 10 micrometers. Some are branched. These organelles can change shape, split in two, and fuse together.

A mitochondrion has two membranes, one highly folded inside the other. This arrangement creates two compartments. Aerobic respiration causes hydrogen ions to accumulate between the two membranes. The buildup causes the ions to flow across the inner membrane, through the interior of membrane transport proteins. That flow drives the formation of ATP.

Nearly all eukaryotic cells have mitochondria, but prokaryotes do not (they make ATP in their cell walls and cytoplasm). The number of mitochondria varies by the type of cell and by the type of organism. For example, a single-celled yeast (a type of fungus) might have only one mitochondrion; a human skeletal muscle cell may have a thousand or more. Cells that have a very high demand for energy tend to have a profusion of mitochondria.

Mitochondria resemble bacteria, in size, form, and biochemistry. They have their own DNA, which is similar to bacterial DNA. They divide independently of the cell, and have their own ribosomes. Such clues led to a theory that mitochondria evolved from aerobic bacteria that took up permanent residence inside a host cell. By the theory of endosymbiosis, one cell was engulfed by another cell, or entered it as a parasite, but escaped digestion. That cell kept its plasma membrane intact and reproduced inside its host. In time, the cell's descendants became permanent residents that offered their hosts the benefit of extra ATP. Structures and functions once required for independent life were no longer needed and were lost over time. Later descendants evolved into mitochondria. We will explore evidence for the theory of endosymbiosis in Section 20.4.

Plastids

Plastids are membrane-enclosed organelles that function in photosynthesis or storage in plants and algal cells. Chloroplasts, chromoplasts, and amyloplasts are common types of plastids.

Photosynthetic cells of plants and many protists contain **chloroplasts**, organelles that are specialized for photosynthesis. Most chloroplasts have an oval or disk shape. Two outer membranes enclose a semifluid interior called the stroma (Figure 4.21). The stroma contains enzymes and the chloroplast's own DNA. Inside the stroma, a third, highly folded membrane forms a single compartment. The folds resemble stacks of flattened disks; the stacks are called grana (singular, granum). Photosynthesis takes place at this membrane, which is called the thylakoid membrane.

The thylakoid membrane incorporates many pigments and other proteins. The most abundant of the pigments are chlorophylls, which appear green. By the process of photosynthesis, the pigments and other molecules harness the energy in sunlight to drive the synthesis of ATP and the coenzyme NADPH. The ATP and NADPH are then used inside the stroma to build carbohydrates from carbon dioxide and water. We will describe the process of photosynthesis in more detail in Chapter 7.

In many ways, chloroplasts resemble photosynthetic bacteria, and like mitochondria they may have evolved by endosymbiosis.

Chromoplasts make and store pigments other than chlorophylls. They have an abundance of carotenoids, a pigment that colors many flowers, leaves, fruits, and roots red or orange. For example, as a tomato ripens, its green chloroplasts are converted to red chromoplasts, and the color of the fruit changes.

Amyloplasts are unpigmented plastids that typically store starch grains. They are notably abundant in cells of stems, tubers (underground stems), and seeds. Starch-packed amyloplasts are dense; in some plant cells, they function as gravity-sensing organelles.

The Central Vacuole

Amino acids, sugars, ions, wastes, and toxins accumulate in the water-filled interior of a plant cell's **central vacuole**. Fluid pressure in the central vacuole keeps plant cells—and structures such as stems and leaves—firm. Typically, the central vacuole takes up 50 to 90 percent of the cell's interior, with cytoplasm confined to a narrow zone in between this large organelle and the plasma membrane. Figure 4.14*b* has an example.

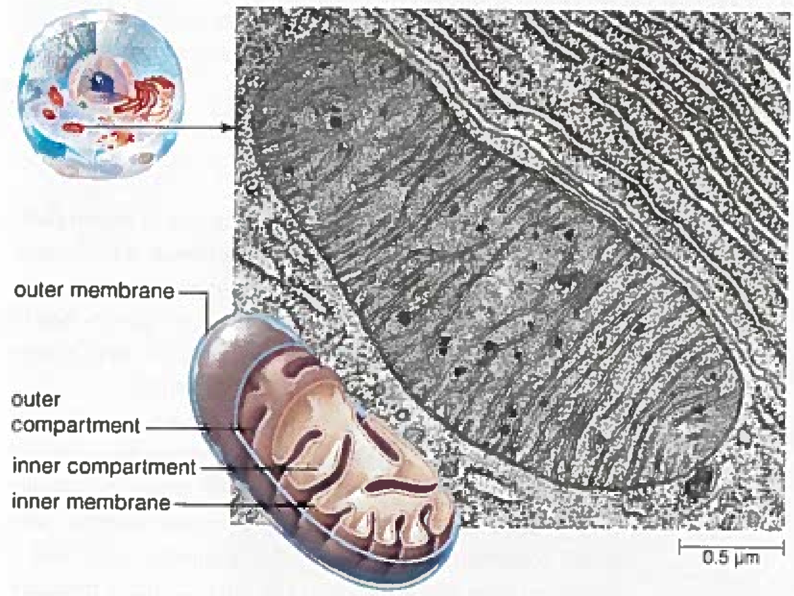


Figure 4.20 Sketch and transmission electron micrograph of a mitochondrion. This organelle specializes in producing large quantities of ATP.

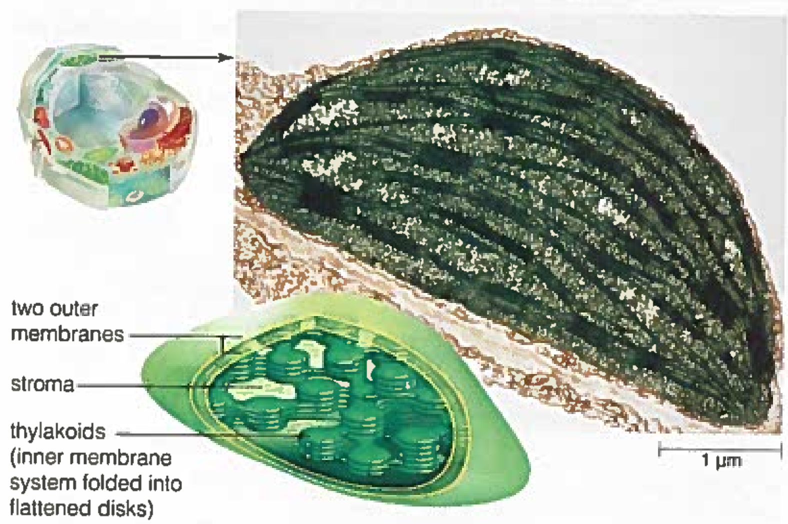


Figure 4.21 **Animated** The chloroplast, a defining character of photosynthetic eukaryotic cells. *Right*, transmission electron micrograph of a chloroplast from a tobacco leaf (*Nicotiana tabacum*). The lighter patches are nucleoids where DNA is stored.

Take-Home Message

What are some other specialized organelles of eukaryotes?

- Mitochondria are eukaryotic organelles that produce ATP from organic compounds in reactions that require oxygen.
- Chloroplasts are plastids that carry out photosynthesis.
- Fluid pressure in a central vacuole keeps plant cells firm.

4.12 Cell Surface Specializations

- A wall or other protective covering often intervenes between a cell's plasma membrane and the surroundings.
- Link to Tissue 1.1

Eukaryotic Cell Walls

Like most prokaryotic cells, many types of eukaryotic cells have a cell wall around the plasma membrane. The wall is a porous structure that protects, supports, and imparts shape to the cell. Water and solutes easily cross it on the way to and from the plasma membrane. Cells could not live without such exchanges.

Animal cells do not have walls, but plant cells and many protist and fungal cells do. For example, a young plant cell secretes pectin and other polysaccharides onto the outer surface of its plasma membrane. The sticky coating is shared between adjacent cells, and it cements them together. Each cell then forms a **primary wall** by secreting strands of cellulose into the coating. Some of the coating remains as the middle lamella, a sticky layer in between the primary walls of abutting plant cells (Figure 4.22*a*,*b*).

Being thin and pliable, the primary wall allows the growing plant cell to enlarge. Plant cells with only a thin primary wall can change shape as they develop. At maturity, cells in some plant tissues stop enlarging and begin to secrete material onto the primary wall's inner surface. These deposits form a firm **secondary wall**, of the sort shown in Figure 4.22*b*. One of the materials deposited is **lignin**, a complex polymer of alcohols that makes up as much as 25 percent of the secondary wall of cells in older stems and roots. Lignified plant parts are stronger, more waterproof, and less susceptible to plant-attacking organisms than younger tissues.

A **cuticle** is a protective body covering made of cell secretions. In plants, a semitransparent cuticle helps protect exposed surfaces of soft parts and limits water loss on hot, dry days (Figure 4.23).

Matrixes Between Cells

Most cells of multicelled organisms are surrounded and organized by **extracellular matrix** (ECM). This nonliving, complex mixture of fibrous proteins and polysaccharides is secreted by cells, and varies with the type of tissue. It supports and anchors cells, separates tissues, and functions in cell signaling.

Primary cell walls are a type of extracellular matrix, which in plants is mostly cellulose. The extracellular matrix of fungi is mainly chitin (Section 3.3). In most

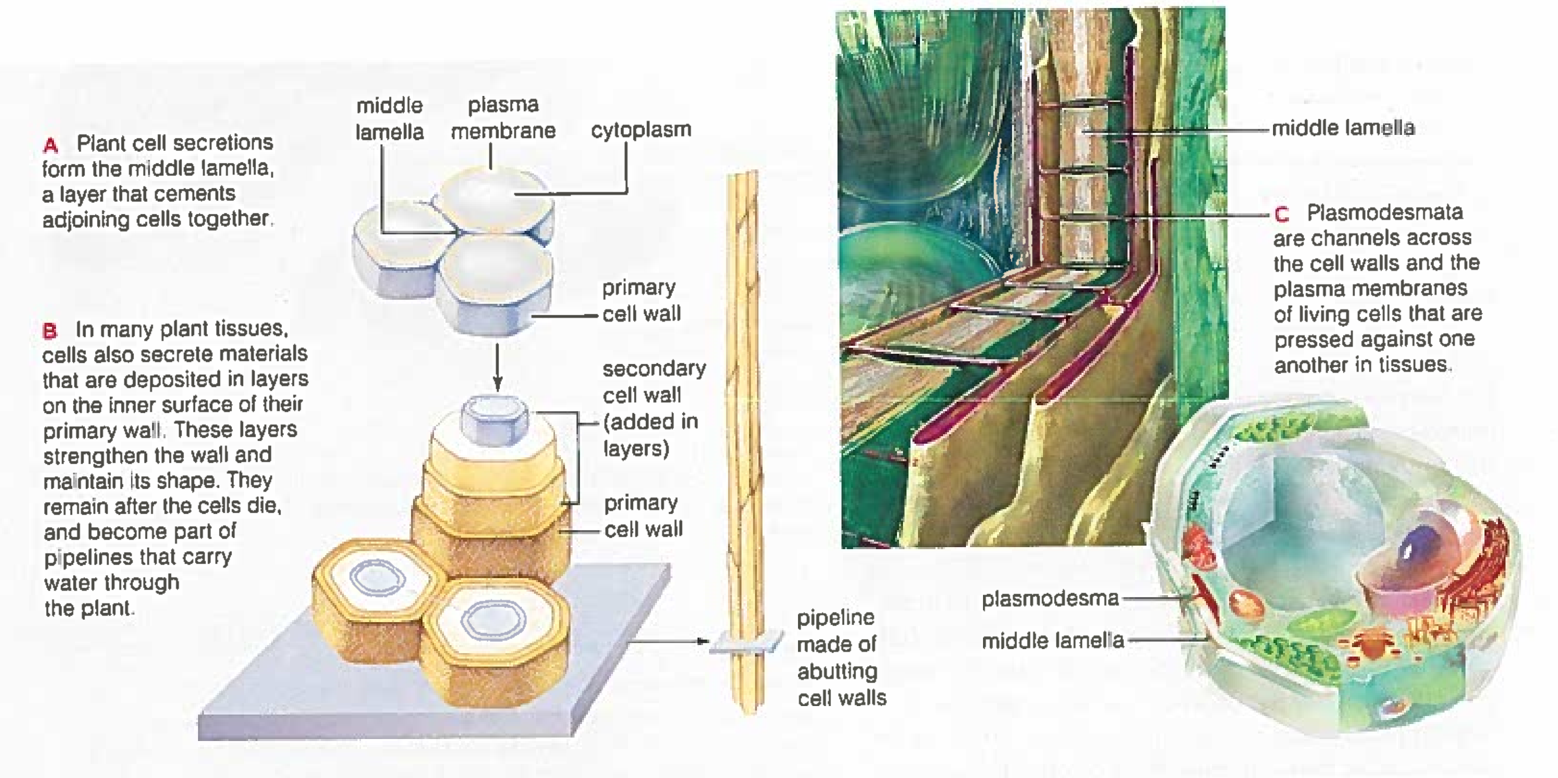


Figure 4.22 **Animated** Some characteristics of plant cell walls.

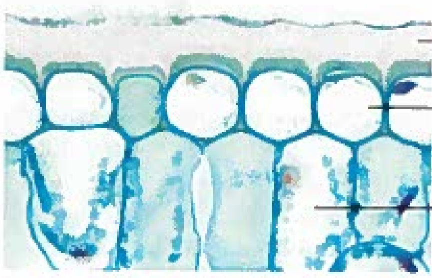


Figure 4.23 A plant cuticle is a waxy, waterproof covering secreted by living cells.

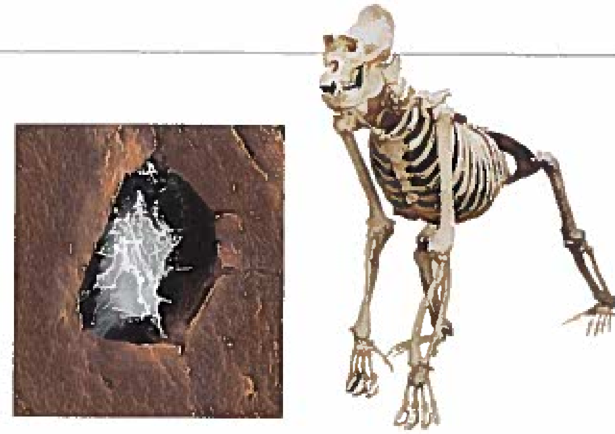


Figure 4.24 A living cell surrounded by hardened bone tissue, the main structural material in the skeleton of most vertebrates.

animals, extracellular matrix consists of various kinds of carbohydrates and proteins; it is the basis of tissue organization, and it provides structural support. For example, bone is mostly extracellular matrix (Figure 4.24). Bone ECM is mostly collagen, a fibrous protein, and it is hardened by mineral deposits.

Cell Junctions

A cell that is surrounded by a wall or other secretions is not isolated; it can still interact with other cells and with the surroundings. In multicelled species, such interaction occurs by way of **cell junctions**, which are structures that connect a cell to other cells and to the environment. Cells send and receive ions, molecules or signals through some junctions. Other kinds help cells recognize and stick to each other and to extracellular matrix.

In plants, channels called plasmodesmata (singular, plasmodesma) extend across the primary wall of two adjoining cells, connecting the cytoplasm of the cells (Figure 4.22*c*). Substances such as water, ions, nutrients, and signalling molecules can flow quickly from cell to cell through plasmodesmata.

Three types of cell-to-cell junctions are common in most animal tissues: tight junctions, adhering junctions, and gap junctions (Figure 4.25). Tight junctions link cells that line the surfaces and internal cavities of animals. These junctions seal the cells together tightly, so fluid cannot pass between them. Those in your gastrointestinal tract prevent gastric fluid from leaking out of your stomach and damaging your internal tissues. Adhering junctions anchor cells to each other and to extracellular matrix; they strengthen contractile tissues such as heart muscle. Gap junctions are open channels that connect the cytoplasm of adjoining cells; they are similar to plasmodesmata in plants. Gap junctions allow entire regions of cells to respond to a single stimulus. For example, in heart muscle, a signal to contract passes instantly from cell to cell through gap junctions, so all cells contract as a unit.

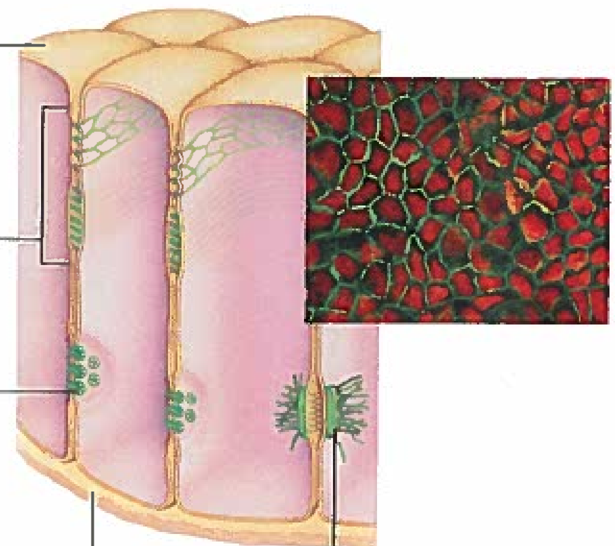


Figure 4.25 Animated Cell junctions in animal tissues. In the micrograph, a continuous array of tight junctions (*green*) seals the abutting surfaces of kidney cell membranes. DNA, which fills each cell's nucleus, appears *red*.

Take-Home Message

What structures form on the outside of eukaryotic cells?

- Cells of many protists, nearly all fungi, and all plants, have a porous wall around the plasma membrane. Animal cells do not have walls.
- Plant cell secretions form a waxy cuticle that helps protect the exposed surfaces of soft plant parts.
- Cell secretions form extracellular matrixes between cells in many tissues.
- Cells make structural and functional connections with one another and with extracellular matrix in tissues.

4.13 The Dynamic Cytoskeleton

- Eukaryotic cells have an extensive and dynamic internal framework called a cytoskeleton.
- Links to Protein structure and function 3.5, 3.6

In between the nucleus and plasma membrane of all eukaryotic cells is a **cytoskeleton**—an interconnected system of many protein filaments. Parts of the system reinforce, organize, and move cell structures, and often the whole cell. Some are permanent; others form only at certain times. Figure 4.26 shows the main types.

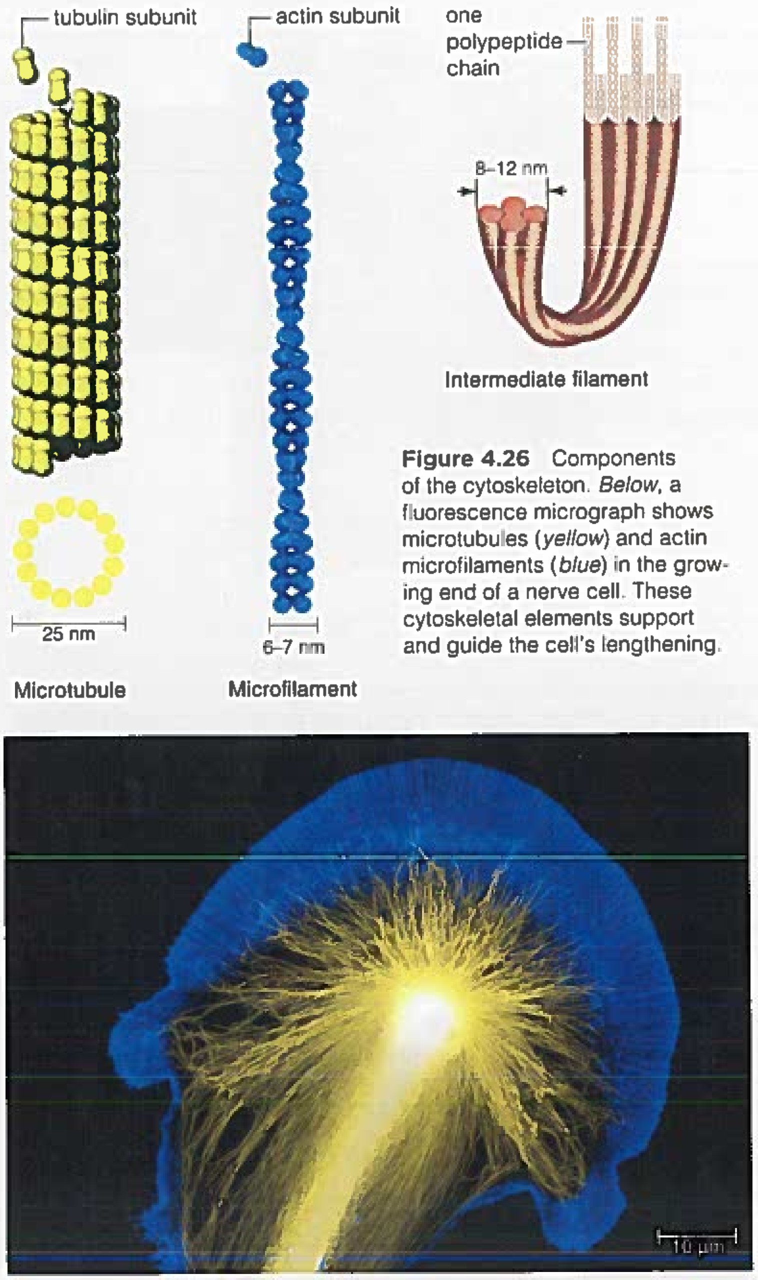


Figure 4.26 Components of the cytoskeleton. *Below*, a fluorescence micrograph shows microtubules (*yellow*) and actin microfilaments (*blue*) in the growing end of a nerve cell. These cytoskeletal elements support and guide the cell's lengthening.

Microtubules are long, hollow cylinders that consist of subunits of the protein tubulin. They form a dynamic scaffolding for many cellular processes, rapidly assembling when they are needed, disassembling when they are not. For example, some of the microtubules that assemble before a eukaryotic cell divides separate the cell's duplicated chromosomes, then disassemble. As another example, microtubules that form in the growing end of a young nerve cell support and guide its lengthening in a particular direction.

Microfilaments are fibers that consist primarily of subunits of the globular protein actin. They strengthen or change the shape of eukaryotic cells. Crosslinked, bundled, or gel-like arrays of them make up the **cell cortex**, a reinforcing mesh under the plasma membrane. Actin microfilaments that form at the edge of a cell drag or extend it in a certain direction (Figure 4.26). In muscle cells, microfilaments of myosin and actin interact to bring about contraction.

Intermediate filaments are the most stable parts of a cell's cytoskeleton. They strengthen and maintain cell and tissue structures. For example, some intermediate filaments called lamins form a layer that structurally supports the inner surface of the nuclear envelope.

All eukaryotic cells have similar microtubules and microfilaments. Despite the uniformity, both kinds of elements play diverse roles. How? They interact with accessory proteins, such as the **motor proteins** that can move cell parts in a sustained direction when they are repeatedly energized by ATP.

A cell is like a train station during a busy holiday, with molecules being transported through its interior. Microtubules and microfilaments are like dynamically assembled train tracks. Motor proteins are the freight engines that move along those tracks (Figure 4.27).

Some motor proteins move chromosomes. Others slide one microtubule over another. Some chug along tracks in nerve cells that extend from your spine to your toes. Many engines are organized in series, each moving some vesicle partway along the track before giving it up to the next in line. In plant cells, kinesins drag chloroplasts away from light that is too intense, or toward a light source under low-light conditions.

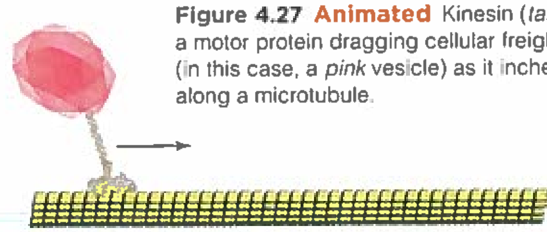


Figure 4.27 Animated Kinesin (*tan*), a motor protein dragging cellular freight (in this case, a *pink* vesicle) as it inches along a microtubule.

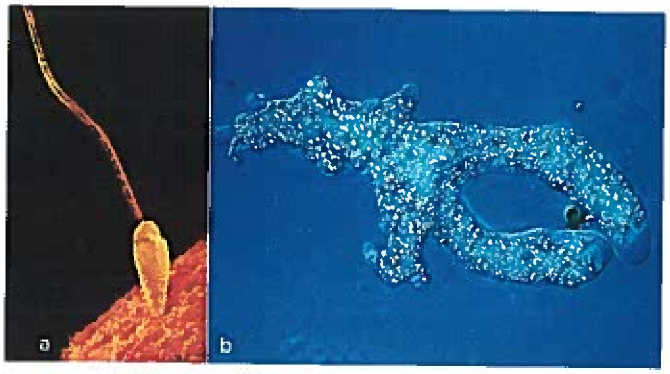


Figure 4.28 (**a**) Flagellum of a human sperm, which is about to penetrate an egg. (**b**) A predatory amoeba (*Chaos carolinense*) extending two pseudopods around its hapless meal: a single-celled green alga (*Pandorina*).

Cilia, Flagella, and False Feet

Organized arrays of microtubules occur in **eukaryotic flagella** (singular, flagellum) and **cilia** (cilium), which are whiplike structures that propel cells such as sperm through fluid (Figure 4.28*a*). Flagella tend to be longer and less profuse than cilia. The coordinated beating of cilia propels motile cells through fluid, and stirs fluid around stationary cells. For example, the coordinated motion of cilia on the thousands of cells lining your airways sweeps particles away from your lungs.

A special array of microtubules extends lengthwise through a flagellum or cilium. This 9+2 array consists of nine pairs of microtubules ringing another pair in the center (Figure 4.29). Protein spokes and links stabilize the array. The microtubules grow from a barrel-shaped organelle called the **centriole**, which remains below the finished array as a basal body.

Amoebas and other types of eukaryotic cells form **pseudopods**, or "false feet" (Figure 4.28*b*). As these temporary, irregular lobes bulge outward, they move the cell and engulf a target such as prey. Elongating microfilaments force the lobe to advance in a steady direction. Motor proteins that are attached to the microfilaments drag the plasma membrane along with them.

Take-Home Message

What is a cytoskeleton?

- A cytoskeleton of protein filaments is the basis of eukaryotic cell shape, internal structure, and movement.
- Microtubules organize the cell and help move its parts. Networks of microfilaments reinforce the cell surface. Intermediate filaments strengthen cells and tissues, and maintain their shape.
- When energized by ATP, motor proteins move along tracks of microtubules and microfilaments. As part of cilia, flagella, and pseudopods, they can move the whole cell.

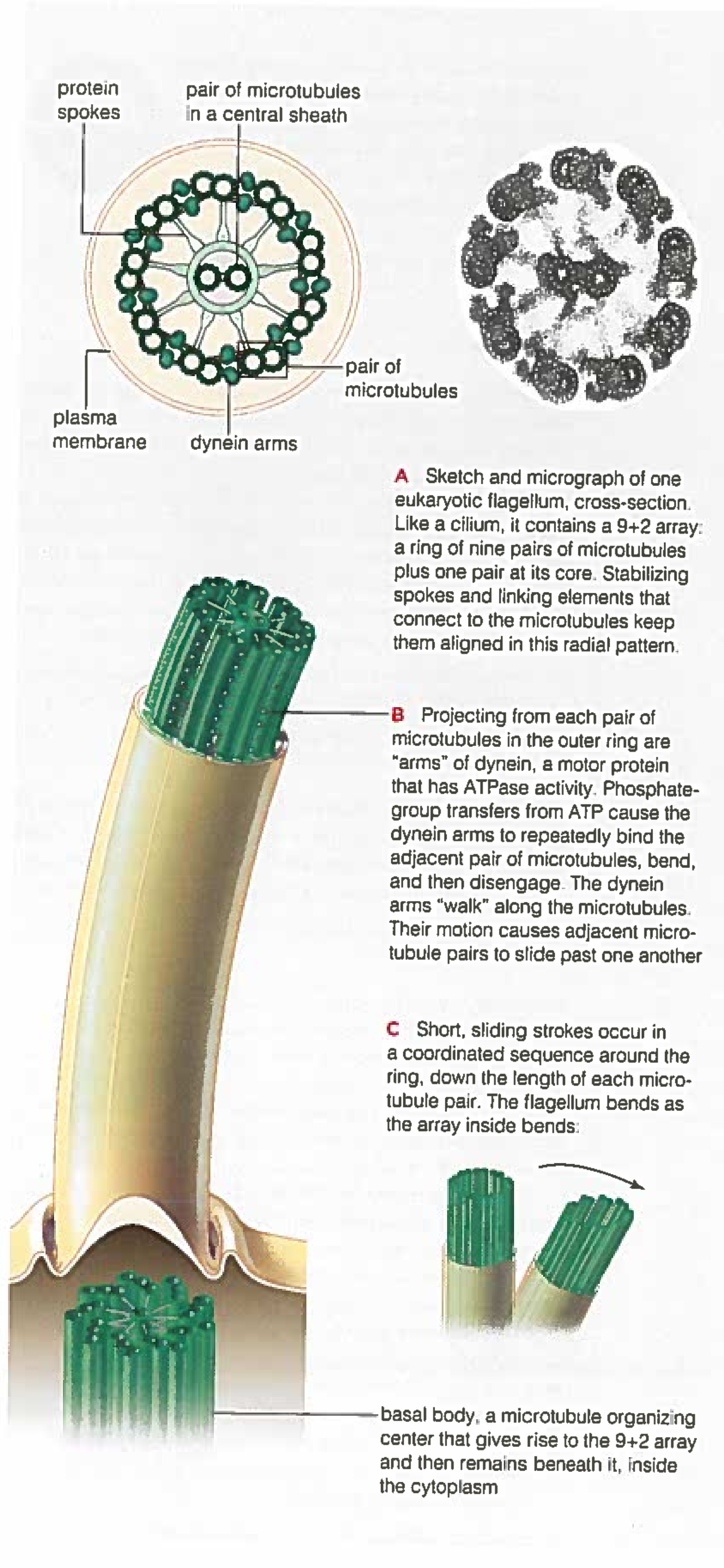


Figure 4.29 **Animated** Eukaryotic flagella and cilia.

IMPACTS, ISSUES REVISITED Food for Thought

Irradiated meat, poultry, milk, and fruits are now available in supermarkets. By law, irradiated foods must be marked with the symbol on the right. Items that bear this symbol have been exposed to radiation, but are not themselves radioactive. Irradiating fresh foods kills bacteria and prolongs shelf life. However, some worry that the irradiation process may alter the food and produce harmful chemicals.

How would you vote?

Many fresh foods are irradiated in order to kill contaminating bacteria. Would you eat irradiated food? See CengageNOW for details, then vote online.

Whether health risks are associated with consuming irradiated foods is still unknown.

Summary

Sections 4.1–4.3 All organisms consist of one or more **cells**. By the **cell theory**, the cell is the smallest unit of life, and it is the basis of life's continuity. The **surface-to-volume** ratio limits cell size.

All cells start out life with a **plasma membrane**, a **nucleus** (in **eukaryotic cells**) or **nucleoid** (in **prokaryotic cells**), and **cytoplasm** in which structures such as **ribosomes** are suspended. The **lipid bilayer** is the foundation of all cell membranes. Different types of microscopes use light or electrons to reveal different details of cells.

- *Use the interactions on CengageNOW to investigate basic membrane structure and the physical limits on cell size.*
- *Use the animation on CengageNOW to learn how different types of microscopes function.*

Sections 4.4, 4.5 Bacteria and archaeans are prokaryotes (Table 4.3). None has a nucleus. Many have a **cell wall** and one or more **flagella** or **pili**. **Biofilms** are shared living arrangements among bacteria and other microbes.

- *Use the animation on CengageNOW to view prokaryotic cell structure.*

Sections 4.6–4.11 Eukaryotic cells start out life with a nucleus and other membrane-enclosed **organelles**. The nucleus contains **nucleoplasm** and **nucleoli**. **Chromatin** in the nucleus of a eukaryotic cell is divided into a characteristic number of **chromosomes**. Pores, receptors, and transport proteins in the **nuclear envelope** control the movement of molecules into and out of the nucleus.

The **endomembrane system** includes rough and smooth **endoplasmic reticulum, vesicles,** and **Golgi bodies**. This set of organelles functions mainly to make and modify lipids and proteins; it also recycles molecules and particles such as worn-out cell parts, and inactivates toxins.

Mitochondria produce ATP by breaking down organic compounds in the oxygen-requiring pathway of aerobic respiration. **Chloroplasts** are **plastids** that specialize in photosynthesis. Other organelles include **peroxisomes, lysosomes,** and **vacuoles** (including **central vacuoles**).

- *Use the interaction on CengageNOW to survey the major types of eukaryotic organelles.*
- *Use the animations on CengageNOW to view the nuclear membrane and the endomembrane system.*
- *Use the animation on CengageNOW to view a chloroplast.*

Section 4.12 Cells of most prokaryotes, protists, fungi, and all plant cells have a wall around the plasma membrane. Older plant cells secrete a rigid, **lignin-containing secondary wall** inside their pliable **primary wall**. Many eukaryotic cell types also secrete a **cuticle**. Plasmodesmata connect plant cells. **Cell junctions** connect animal cells to one another and to **extracellular matrix** (ECM).

- *Study the structure of cell walls and junctions with the animation on CengageNOW.*

Section 4.13 Eukaryotic cells have a **cytoskeleton**. The **cell cortex** consists of **intermediate filaments**. **Motor proteins** that are the basis of movement interact with **microfilaments** in **pseudopods**, or (in **cilia** and **eukaryotic flagella**) **microtubules** that grow from **centrioles**.

- *Learn more about cytoskeletal elements and their actions with the animation on CengageNOW.*

Self-Quiz

Answers in Appendix III

1. The ______ is the smallest unit of life.
2. True or false: Some protists are prokaryotes.
3. Cell membranes consist mostly of ______ .
4. Unlike eukaryotic cells, prokaryotic cells ______ .
   a. have no plasma membrane
   b. have RNA but not DNA
   c. have no nucleus
   d. a and c
5. Organelles enclosed by membranes are typical features of ______ cells.
6. The main function of the endomembrane system is building and modifying ______ and ______ .
7. Ribosome subunits are built inside the ______ .
8. No animal cell has a ______ .
9. Is this statement true or false? The plasma membrane is the outermost component of all cells. Explain.
10. Enzymes contained in ______ break down worn-out organelles, bacteria, and other particles.
11. Match each cell component with its function.

___ mitochondrion	a. protein synthesis
___ chloroplast	b. associates with ribosomes
___ ribosome	c. ATP by sugar breakdown
___ smooth ER	d. sorts and ships
___ Golgi body	e. assembles lipids; other tasks
___ rough ER	f. photosynthesis

- *Visit CengageNOW for additional questions.*

Data Analysis Exercise

An abnormal form of the motor protein dynein causes Kartagener syndrome, a genetic disorder characterized by chronic sinus and lung infections. Biofilms form in the thick mucus that collects in the airways, and the resulting bacterial activities and inflammation damage tissues.

Affected men can produce sperm but are infertile (Figure 4.30). Some have become fathers after a doctor injects their sperm cells directly into eggs. Review Figure 4.30, then explain how abnormal dynein could cause the observed effects.

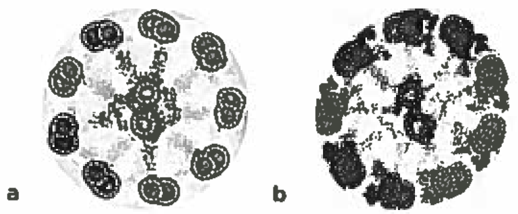


Figure 4.30 Cross-section of the flagellum of a sperm cell from (**a**) a human male affected by Kartagener syndrome and (**b**) an unaffected male.

Critical Thinking

1. In a classic episode of *Star Trek*, a gigantic amoeba engulfs an entire starship. Spock blows the cell to bits before it reproduces. Think of at least one problem a biologist would have with this particular scenario.

2. Many plant cells form a secondary wall on the inner surface of their primary wall. Speculate on the reason why the secondary wall does not form on the outer surface.

3. A student is examining different samples with a transmission electron microscope. She discovers a single-celled organism swimming in a freshwater pond (*below*).

Which of this organism's structures can you identify? Is it a prokaryotic or eukaryotic cell? Can you be more specific about the type of cell based on what you know about cell structure? Look ahead to Section 22.2 to check your answers.

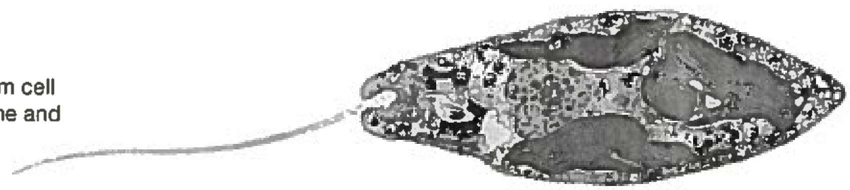


Table 4.3 Summary of Typical Components of Prokaryotic and Eukaryotic Cells

Cell Component	Main Functions	Prokaryotic: Bacteria, Archaea	Eukaryotic: Protists	Fungi	Plants	Animals
Cell wall	Protection, structural support	*	*	✓	✓	—
Plasma membrane	Control of substances moving into and out of cell	✓	✓	✓	✓	✓
Nucleus	Physical separation of DNA from cytoplasm	—•	✓	✓	✓	✓
DNA	Encodes hereditary information	✓	✓	✓	✓	✓
Nucleolus	Assembly of ribosome subunits	—	✓	✓	✓	✓
Ribosome	Protein synthesis	✓	✓	✓	✓	✓
Endoplasmic reticulum (ER)	Synthesis, modification of membrane proteins; lipid synthesis	—	✓	✓	✓	✓
Golgi body	Final modification of membrane proteins; sorting, packaging lipids and proteins into vesicles	—	✓	✓	✓	✓
Lysosome	Intracellular digestion	—	✓	*	*	✓
Centriole	Organization of cytoskeletal elements	★	✓	✓	*	✓
Mitochondrion	ATP formation	—	✓	✓	✓	✓
Chloroplast	Photosynthesis	—	*	—	✓	—
Central vacuole	Storage	—	—	*	✓	—
Bacterial flagellum	Locomotion through fluid surroundings	*	—	—	—	—
Flagellum or cilium with 9+2 microtubule array	Locomotion through or motion within fluid surroundings	—	*	*	*	✓
Cytoskeleton	Cell shape; internal organization; basis of cell movement and, in many cells, locomotion	★	*	*	*	✓

✓ Present in at least part of the life cycle of most or all groups.
* Known to be present in cells of at least some groups.
★ Occurs in a form unique to prokaryotes.
• Some planctomycete bacteria have a double membrane around their DNA.

5 A Closer Look at Cell Membranes

IMPACTS, ISSUES One Bad Transporter and Cystic Fibrosis

Every cell actively engages in the business of living. Think of how it has to move something as ordinary as water in one direction or the other across its plasma membrane. Water crosses a cell membrane freely. The cell has to be able to take in or send out water at different times in order to keep the cytoplasm from getting too concentrated or too dilute. If all goes well, the cell takes in or sends out water in just the right amounts—not too little, not too much.

Proteins called transporters move ions and molecules, including water, across cell membranes. Different transporters move different substances. One, called CFTR, is a transporter in the plasma membrane of epithelial cells. Sheets of these cells line the passageways and ducts of the lungs, liver, pancreas, intestines, reproductive system, and skin. CFTR pumps chloride ions out of these cells, and water follows the ions. A thin, watery film forms on the surface of the epithelial cell sheets. Mucus slides easily over the wet sheets of cells.

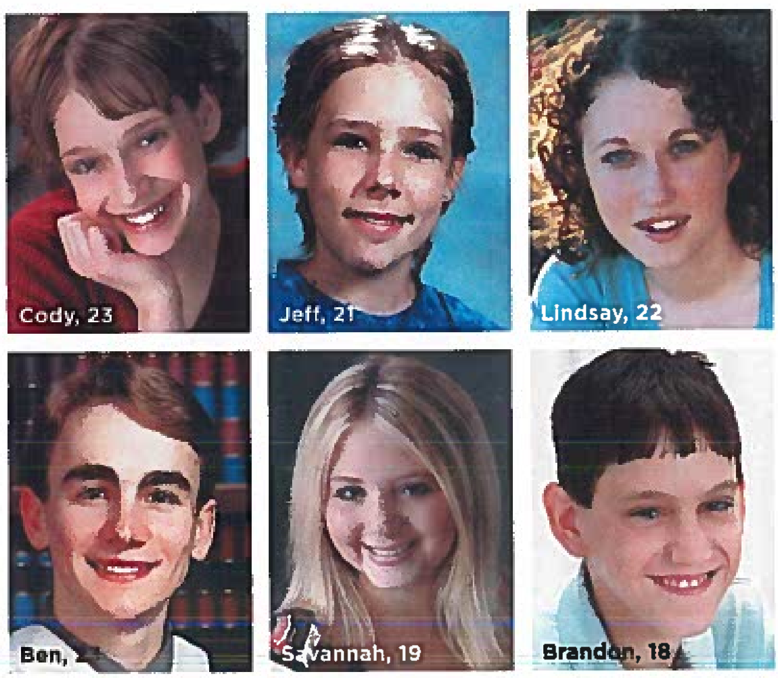
Sometimes a mutation changes the structure of CFTR. When epithelial cell membranes do not have enough working copies of the CFTR protein, chloride ion transport is disrupted. Not enough chloride ions leave the cells, and so not enough water leaves them either. The result is thick, dry mucus that sticks to the epithelial cell sheets.

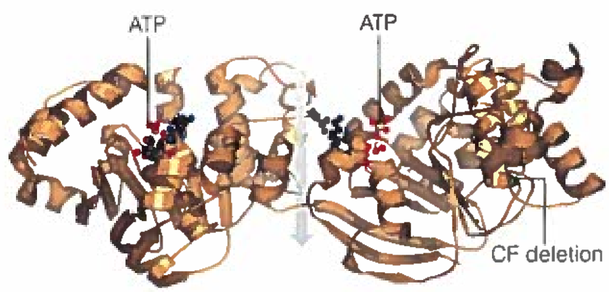
In the respiratory tract, the mucus clogs airways to the lungs and makes breathing difficult. It is too thick for the ciliated cells lining the airways to sweep out, and bacteria thrive in it. Low-grade infections occur and may persist for years.

These symptoms—outcomes of mutation in the CFTR protein—characterize cystic fibrosis (CF), the most common fatal genetic disorder in the United States. Even with a lung transplant, most CF patients live no longer than thirty years, at which time their lungs usually fail. There is no cure.

More than 10 million people carry a mutated form of the CFTR gene. Some of them have sinus problems, but no other symptoms develop. Most do not know they carry the mutated gene. CF develops when a person inherits a mutated gene from both parents—an unlucky event that occurs in about 1 of 3,300 births (Figure 5.1). Think about it. A startling percentage of the human population can develop severe problems when even one kind of membrane protein does not work.

Your life depends on the functions of thousands of kinds of proteins and other molecules that keep cells working. Each cell functions properly only if it is responsive to conditions in the environments on both sides of its membranes. Cell membranes—these thin boundary layers make the difference between organization and chaos.





See the video! Figure 5.1 Cystic fibrosis. *Left*, a few of the many victims of cystic fibrosis, which occurs most often in people of northern European ancestry. At least one young person dies every day in the United States from complications of this disease.

Above, model of CFTR. The parts shown here are ATP-driven motors that widen or narrow a channel (*gray* arrow) across the plasma membrane. The tiny part of the protein that is lost in most cystic fibrosis mutations is shown on the ribbon in *green*.