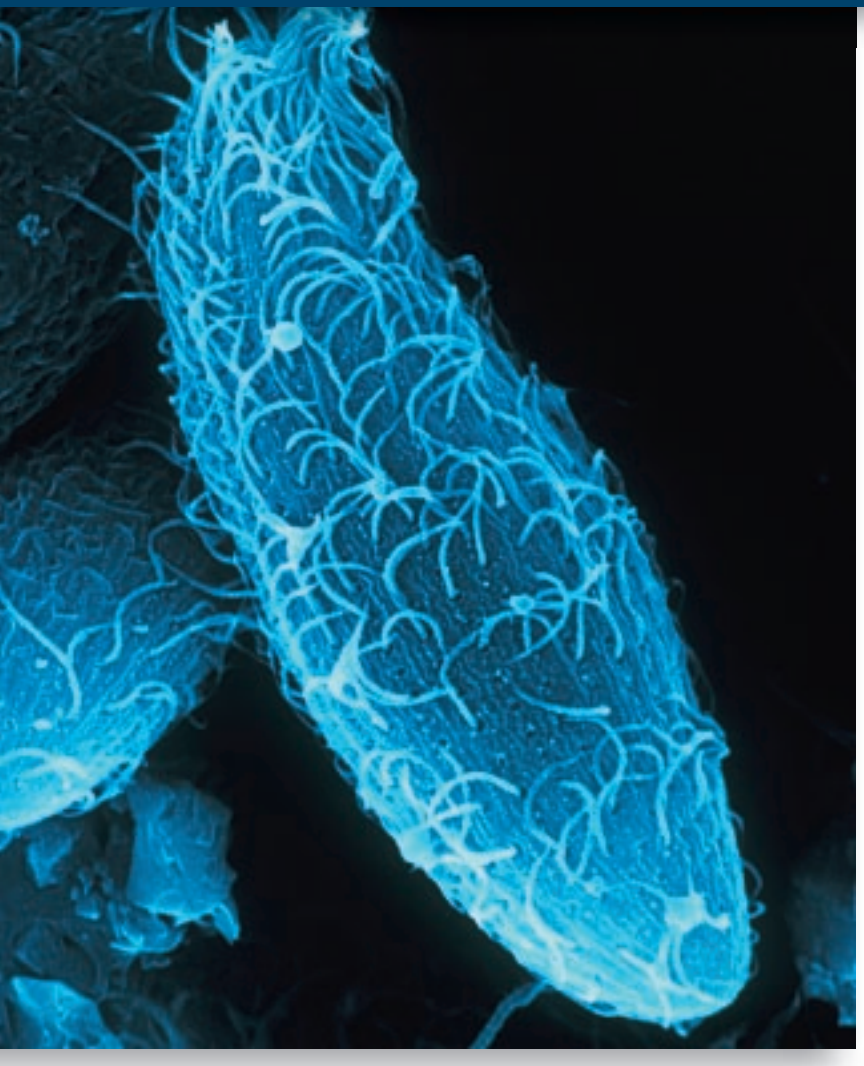


4
Cells

This alarming looking creature is the single-celled organism *Dileptus,* magnified a thousand times. Too small to see with the unaided eye, *Dileptus* is one of hundreds of inhabitants of a drop of pond water. Everything that a living organism does to survive and prosper, *Dileptus* must do with only the equipment this tiny cell provides. Just as you move about using legs to walk, so *Dileptus* uses the hairlike projections (called cilia) that cover its surface to propel itself through the water. Just as your brain is the control center of your body, so the compartment called the nucleus, deep within the interior of *Dileptus,* controls the many activities of this complex and very active cell. *Dileptus* has no mouth, but it takes in food particles and other molecules through its surface. This versatile protist is capable of leading a complex life because its interior is subdivided into compartments, in each of which it carries out different activities. Functional specialization is the hallmark of this cell's interior, a powerful approach to cellular organization which is shared by all eukaryotes.

Chapter-at-a-Glance

4.1 Cells

Hold your hand up and look at it closely. What do you see? Skin. It looks solid and smooth, creased with lines and flexible to the touch. But if you were able to remove a bit and examine it under a microscope (figure 4.1), it would look very different—a sheet of tiny, irregularly shaped bodies crammed together like tiles on a floor. What you would see are epithelial cells; in fact, every tissue of your body is made of cells, as are the bodies of all organisms. Some organisms are composed of a single cell, and some are composed of many cells. All cells, however, are very small. In this chapter we look more closely at cells and learn something of their internal structure and how they communicate with their environment.

The Cell Theory

Because cells are so small, no one observed them until microscopes were invented in the mid-seventeenth century. Robert Hooke first described cells in 1665, when he used a microscope he had built to examine a thin slice of nonliving plant tissue called cork. Hooke observed a honeycomb of tiny, empty (because the cells were dead) compartments. He called the compartments in the cork *cellulae* (Latin, small rooms), and the term has come down to us as **cells.** For another century and a half, however, biologists failed to rec-

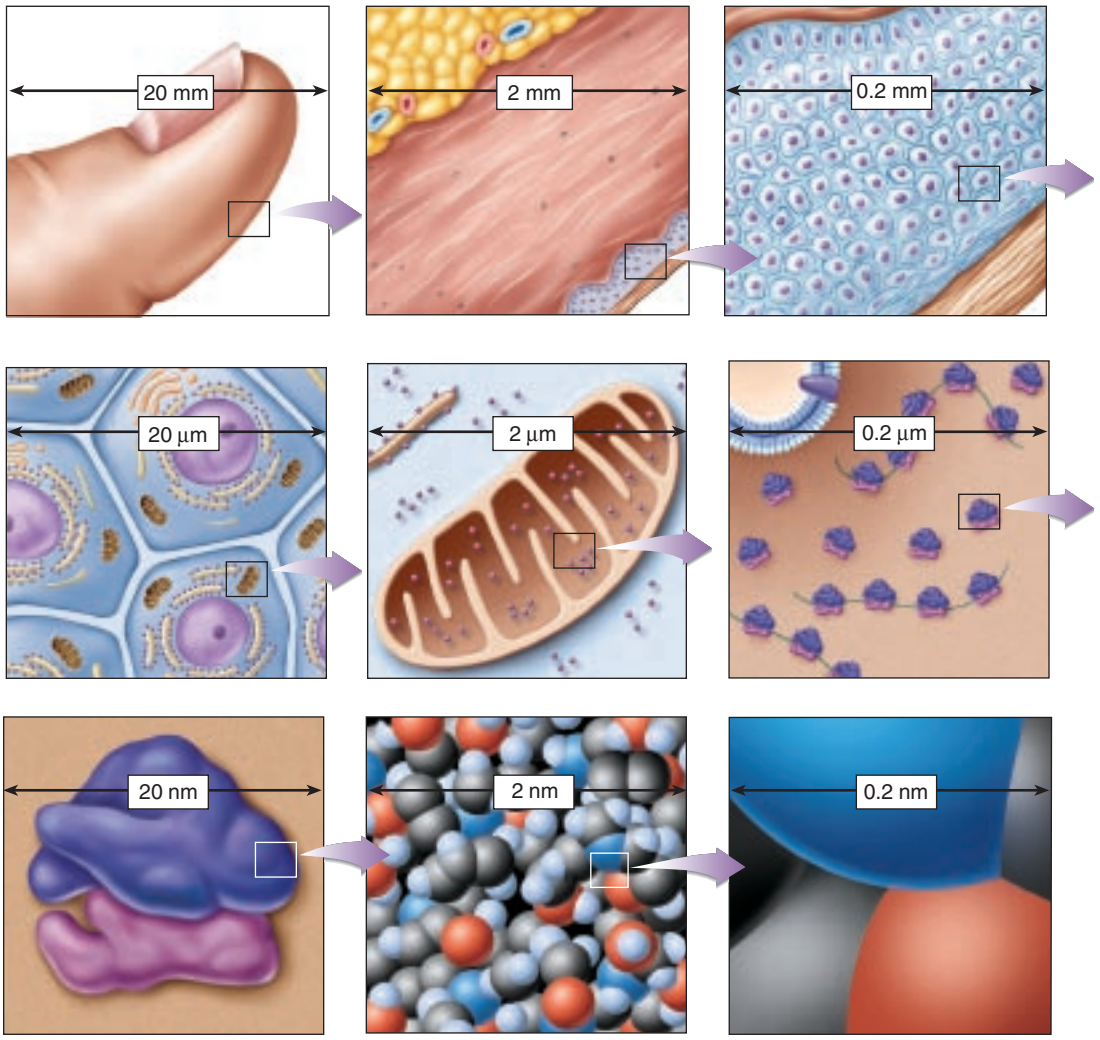


Figure 4.1 The size of cells and their contents.
This diagram shows the size of human skin cells, organelles, and molecules. In general, the diameter of a human skin cell is 20 micrometers (µm), of a mitochondrion is 2 µm, of a ribosome is 20 nanometers (nm), of a protein molecule is 2 nm, and of an atom is 0.2 nm.

ognize the importance of cells. In 1838, botanist Matthias Schleiden made a careful study of plant tissues and developed the first statement of the cell theory. He stated that all plants "are aggregates of fully individualized, independent, separate beings, namely the cells themselves." In 1839, Theodor Schwann reported that all animal tissues also consist of individual cells.

The idea that all organisms are composed of cells is called the **cell theory.** In its modern form, the cell theory includes three principles:

1. All organisms are composed of one or more cells, within which the processes of life occur.
2. Cells are the smallest living things. Nothing smaller than a cell is considered alive.
3. Cells arise only by division of a previously existing cell. Although life likely evolved spontaneously in the environment of the early earth, biologists have concluded that no additional cells are originating spontaneously at present. Rather, life on earth represents a continuous line of descent from those early cells.

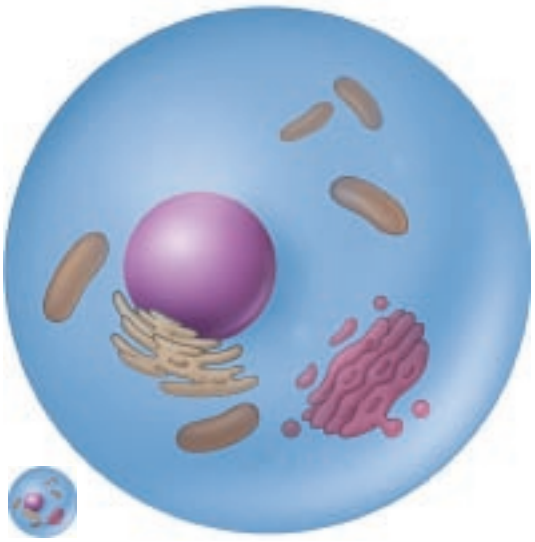
Most Cells Are Very Small

Cells are not all the same size. Individual cells of the marine alga *Acetabularia,* for example, are up to 5 centimeters long—as long as your little finger. In contrast, the cells of your body are typically from 5 to 20 micrometers in diameter, too small to see with the naked eye. It would take anywhere from 100 to 400 human cells to span the diameter of the head of a pin. The cells of bacteria are even smaller than yours, only a few micrometers thick.

Why Aren't Cells Larger?

Why are most cells so tiny? Most cells are small because larger cells do not function as efficiently. In the center of every cell is a command center that must issue orders to all parts of the cell, directing the synthesis of certain enzymes, the entry of ions and molecules from the exterior, and the assembly of new cell parts. These orders must pass from the core to all parts of the cell, and it takes them a very long time to reach the periphery of a large cell. For this reason, an organism made up of relatively small cells is at an advantage over one composed of larger cells.

Another reason cells are not larger is the advantage of having a greater **surface-to-volume ratio.** As cell size increases, volume grows much more rapidly than surface area (figure 4.2). For a round cell, surface area increases as the square of diameter, whereas volume increases as the cube. Thus a cell with 10 times greater diameter would have 100 (10^2) times the surface area but 1,000 (10^3) times the volume. A cell's surface provides the interior's only opportunity to interact with the environment with substances passing into and out of the cell across its surface, and large cells have far less surface for each unit of volume than do small ones.



Cell radius (r)	1 unit	10 units
Surface area ($4\pi r^2$)	12.57 units^2	1,257 units^2
Volume ($\frac{4}{3}\pi r^3$)	4.189 units^3	4,189 units^3

Figure 4.2 Surface-to-volume ratio.
As a cell gets larger, its volume increases at a faster rate than its surface area. If the cell radius increases by 10 times, the surface area increases by 100 times, but the volume increases by 1,000 times. A cell's surface area must be large enough to meet the needs of its volume.

Some larger cells, however, function quite efficiently in part because they have structural features that increase surface area. Cells in the nervous system, for example, called neurons, are long slender cells, extending more than a meter in length. These cells efficiently interact with their environment because although they are long, they are thin, some less than 1 micrometer in diameter, and so their interior regions are not far from the surface at any given point.

Another structural feature that increases the surface area of a cell are small "fingerlike" projections called microvilli. The cells that line the small intestines of the human digestive system are covered with microvilli that dramatically increase the surface area of the cells.

An Overview of Cell Structure

All cells are surrounded by a delicate membrane that controls the permeability of the cell to water and dissolved substances. A semifluid matrix called **cytoplasm** fills the interior of the cell. It used to be thought that the cytoplasm was uniform, like Jell-O, but we now know that it is highly organized. Your cells, for example, have an internal framework that both gives the cell its shape and positions components and materials within its interior. In the following sections, we explore the membranes that encase all living cells and then examine in detail their interiors.

Visualizing Cells

How many cells are big enough to see with the unaided eye? Other than egg cells, not many are (figure 4.3). Most are less than 50 micrometers in diameter, far smaller than the period at the end of this sentence.

The Resolution Problem. How do we study cells if they are too small to see? The key is to understand why we can't see them. The reason we can't see such small objects is the limited resolution of the human eye. **Resolution** is defined as the minimum distance two points can be apart and still be distinguished as two separated points. When two objects are closer together than about 100 micrometers, the light reflected from each strikes the same "detector" cell at the rear of the eye. Only when the objects are farther than 100 micrometers apart will the light from each strike different cells, allowing your eye to resolve them as two objects rather than one.

Microscopes. One way to increase resolution is to increase magnification, so that small objects appear larger. Robert Hooke and Antony van Leeuwenhoek used glass lenses to magnify small cells and cause them to appear larger than the 100-micrometer limit imposed by the human eye. The glass lens adds additional focusing power. Because the glass lens makes the object appear closer, the image on the back of the eye is bigger than it would be without the lens.

Modern light microscopes use two magnifying lenses (and a variety of correcting lenses) to achieve very high magnification and clarity (table 4.1). The first lens focuses the image of the object on the second lens, which magnifies it again and focuses it on the back of the eye. Microscopes that magnify in stages using several lenses are called **compound microscopes.** They can resolve structures that are separated by more than 200 nanometers (nm).

Increasing Resolution. Light microscopes, even compound ones, are not powerful enough to resolve many structures within cells. For example, a membrane is only 5 nanometers thick. Why not just add another magnifying stage to the microscope and so increase its resolving power? Because when two objects are closer than a few hundred nanometers, the light beams reflecting from the two images start to overlap. The only way two light beams can get closer together and still be resolved is if their wavelengths are shorter.

One way to avoid overlap is by using a beam of electrons rather than a beam of light. Electrons have a much shorter wavelength, and a microscope employing electron beams has 1,000 times the resolving power of a light microscope. **Transmission electron microscopes,** so called because the electrons used to visualize the specimens are transmitted through the material, are capable of resolving objects only 0.2 nanometer apart—just twice the diameter of a hydrogen atom!

A second kind of electron microscope, the **scanning electron microscope,** beams the electrons onto the surface of the specimen. The electrons reflected back from the surface of the specimen, together with other electrons that the specimen itself emits as a result of the bombardment, are amplified and transmitted to a screen, where the image can be viewed and photographed. Scanning electron microscopy yields striking three-dimensional images and has improved our understanding of many biological and physical phenomena (see table 4.1).

Visualizing Cell Structure by Staining Specific Molecules. A powerful tool for the analysis of cell structure has been the

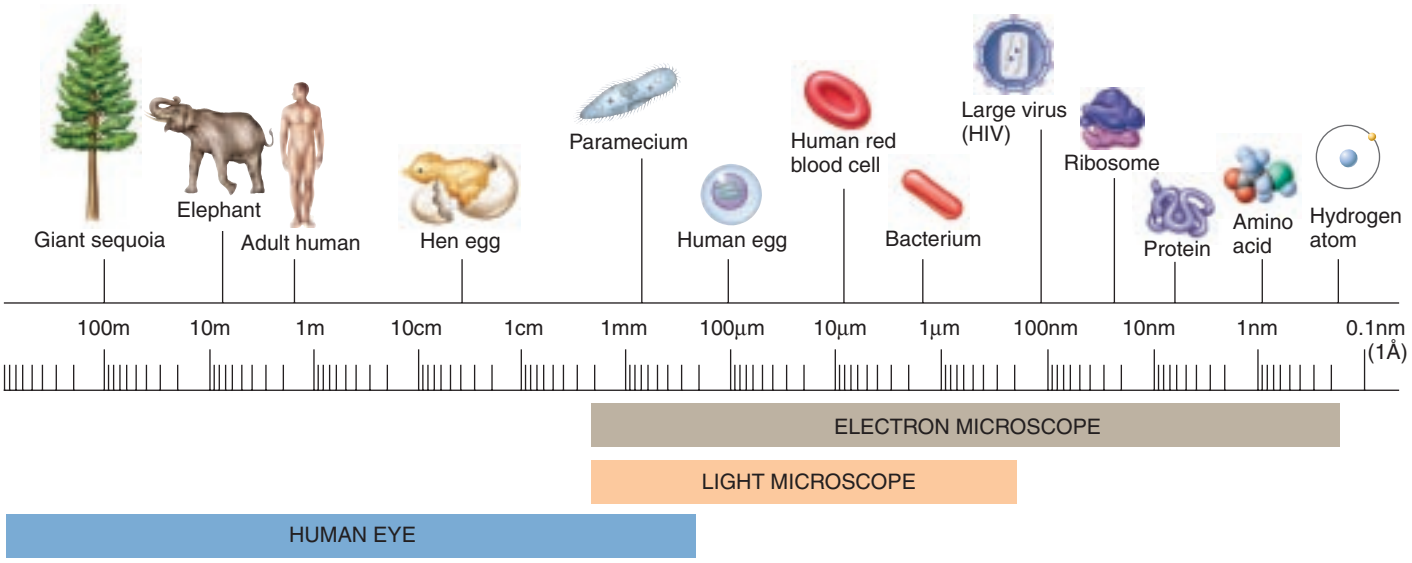
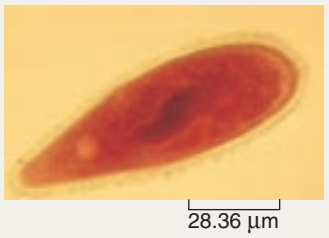


Figure 4.3 A scale of visibility.
Most cells are microscopic in size, although vertebrate eggs are typically large enough to be seen with the unaided eye. Prokaryotic cells are generally 1 to 2 micrometers (mm) across.

TABLE 4.1 TYPES OF MICROSCOPES

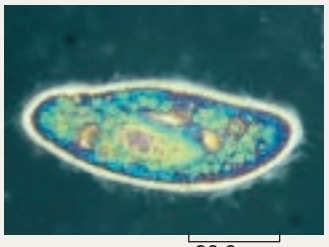
Light Microscopes



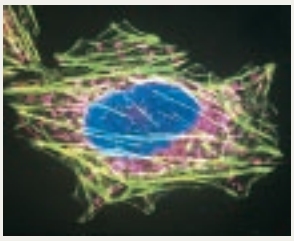
Bright-field microscope: Light is simply transmitted through a specimen in culture, giving little contrast. Staining specimens improves contrast but requires that cells be fixed (not alive), which can cause distortion or alteration of components.

Dark-field microscope: Light is directed at an angle toward the specimen; a condenser lens transmits only light reflected off the specimen. The field is dark, and the specimen is light against this dark background.

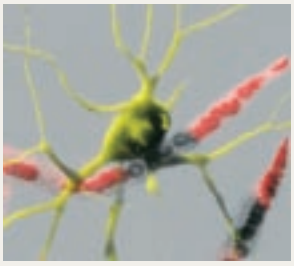
Phase-contrast microscope: Components of the microscope bring light waves out of phase, which produces differences in contrast and brightness when the light waves recombine.



Differential-interference-contrast microscope: Out-of-phase light waves to produce differences in contrast are combined with two beams of light travelling close together, which create even more contrast, especially at the edges of structures.



Fluorescence microscope: A set of filters transmits only light that is emitted by fluorescently stained molecules or tissues.



Confocal microscope: Light from a laser is focused to a point and scanned across the specimen in two directions. Clear images of one plane of the specimen are produced, while other planes of the specimen are excluded and do not blur the image. Fluorescent dyes and false coloring enhances the image.

Electron Microscopy

Transmission electron microscope: A beam of electrons is passed through the specimen. Electrons that pass through are used to form an image. Areas of the specimen that scatter electrons appear dark. False coloring enhances the image.

Scanning electron microscope: An electron beam is scanned across the surface of the specimen, and electrons are knocked off the surface. Thus, the surface topography of the specimen determines the contrast and the content of the image. False coloring enhances the image.

use of stains that bind to specific molecular targets. This approach has been used in the analysis of tissue samples, or histology, for many years and has been improved dramatically with the use of antibiotics that bind to very specific molecular structures. This process, called immunocytochemistry, uses antibodies generated in animals such as rabbits or mice. When these animals are injected with specific proteins, they will produce antibodies that specifically bind to the injected protein, which can be purified from their blood. These purified antibodies can then be chemically bonded to enzymes, stains, or fluorescent molecules that glow when exposed to specific wavelengths of light. When cells are washed in a solution containing the antibodies, they bind to cellular structures that contain the target molecule and can be seen with light microscopy. This approach has been used extensively in the analysis of cell structure and function.

4.1 All living things are composed of one or more cells, each a small volume of cytoplasm surrounded by a cell membrane. Most cells and their components are so small they can only be viewed using microscopes.

4.2 The Plasma Membrane

Encasing all living cells is a delicate sheet of molecules called the **plasma membrane.** It would take more than 10,000 of these sheets, which are about 7 nanometers thick, piled on top of one another to equal the thickness of this sheet of paper. However, the sheets are not simple in structure, like a soap bubble's skin. Rather, they are made up of a diverse collection of proteins floating within a lipid framework like small boats bobbing on the surface of a pond. Regardless of the kind of cell they enclose, all plasma membranes have the same basic structure of proteins embedded in a sheet of lipid, called the **fluid mosaic model.**

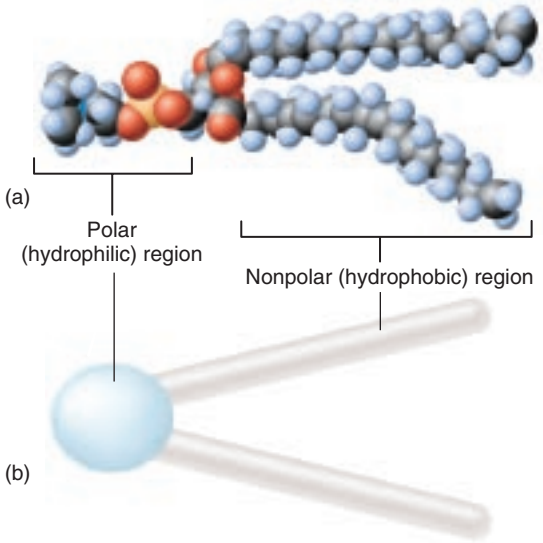


Figure 4.4 Phospholipid structure.
One end of a phospholipid molecule is polar and the other is nonpolar. (*a*) The molecular structure is shown by colored spheres representing individual atoms (*black* for carbon, *blue* for hydrogen, *red* for oxygen, and *yellow* for phosphorus). (*b*) The phospholipid is often depicted diagrammatically as a ball with two tails.

The lipid layer that forms the foundation of a plasma membrane is composed of modified fat molecules called **phospholipids.** One end of a phospholipid molecule has a phosphate chemical group attached to it, making it extremely polar (and thus water-soluble), whereas the other end is composed of two long fatty acid chains that are strongly nonpolar (and thus water-insoluble) (figure 4.4).

Imagine what happens when a collection of phospholipid molecules is placed in water. A structure called a **lipid bilayer** forms spontaneously (figure 4.5). How can this happen? The long nonpolar tails of the phospholipid molecules are pushed away by the water molecules that surround them, shouldered aside as the water molecules seek partners that can form hydrogen bonds. After much shoving and jostling, every phospholipid molecule ends up with its polar head facing water and its nonpolar tail facing away from water. The phospholipid molecules form a *double* layer. Because there are two layers with the tails facing each other, no tails are ever in contact with water.

Because the interior of a lipid bilayer is completely nonpolar, it repels any water-soluble molecules that attempt to pass through it, just as a layer of oil stops the passage of a drop of water (that's why ducks do not get wet).

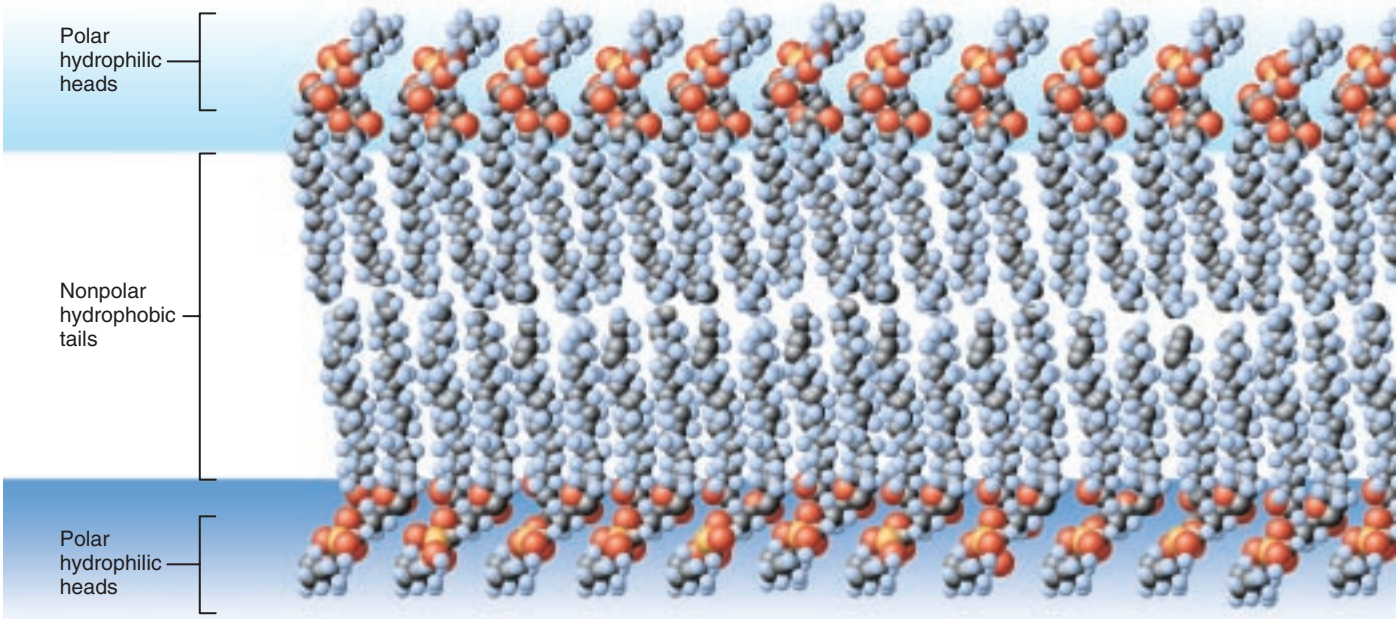


Figure 4.5 The lipid bilayer.
The basic structure of every plasma membrane is a double layer of lipid. This diagram illustrates how phospholipids aggregate to form a bilayer with a nonpolar interior.

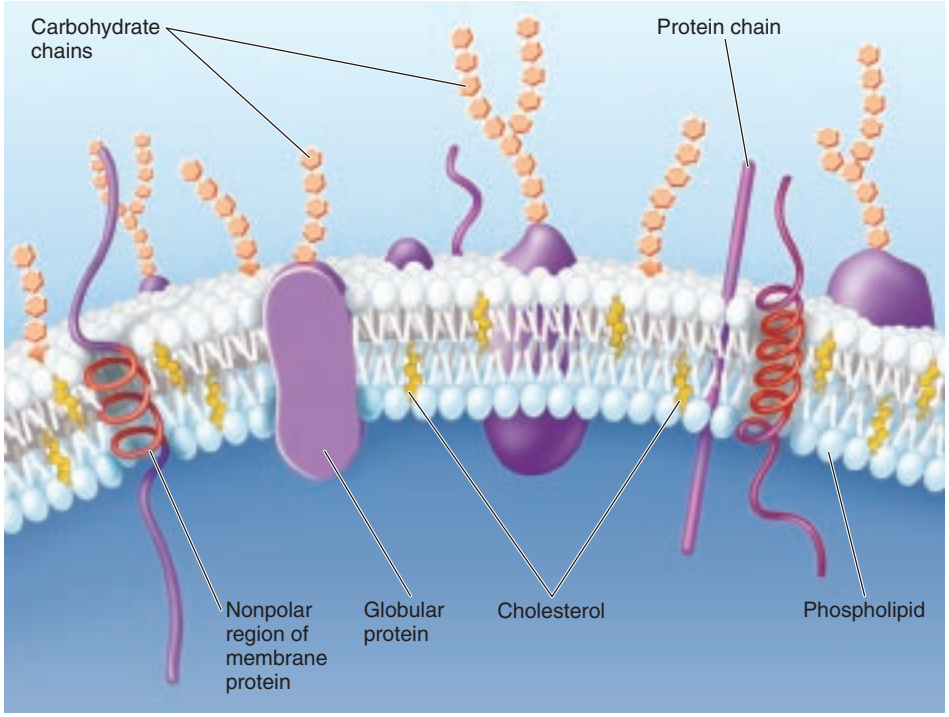


Figure 4.6 Proteins are embedded within the lipid bilayer.
A variety of proteins protrude through the lipid bilayer of animal cells. Membrane proteins function as channels, receptors, and cell surface markers. Carbohydrate chains are often bound to these proteins and to phospholipids in the membrane itself as well. These chains serve as distinctive identification tags, unique to particular types of cells.

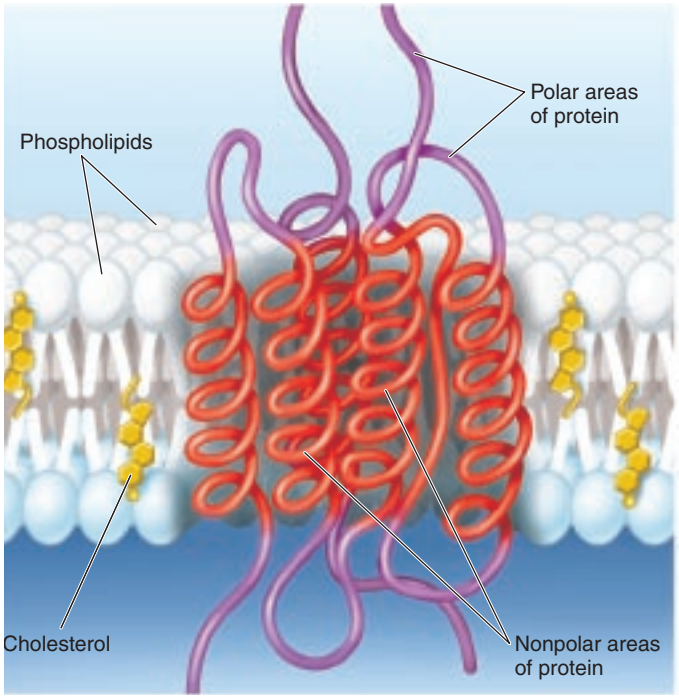


Figure 4.7 Nonpolar regions lock proteins into membranes.
A spiral helix of nonpolar amino acids (*red*) extends across the nonpolar lipid interior, while polar (*purple*) portions of the protein protrude out from the bilayer. The protein cannot move in or out because such a movement would drag polar segments of the protein into the nonpolar interior of the membrane.

It was once thought that plasma membranes were uniform seas of phospholipid, but we now know that they contain zones called **lipid rafts** that are heavily enriched in cholesterol and therefore more tightly packed than the surrounding membrane. Lipid rafts are involved in how cells move and communicate with each other. Interestingly, recent work indicates that they are also the sites where deadly Ebola virus enters human cells.

Proteins Within the Membrane

The second major component of every biological membrane is a collection of **membrane proteins** that float within the lipid bilayer (figure 4.6). In plasma membranes, these proteins provide channels through which molecules and information pass. Some membrane proteins are fixed into position but others are not fixed; instead, they move freely. Some membranes are crowded with proteins, packed tightly side by side. In other membranes the proteins are sparsely distributed.

Some membrane proteins project up from the surface of the plasma membrane like buoys, often with carbohydrate chains or lipids attached to their tips like flags. These **cell surface proteins** act as markers to identify particular types of cells or as beacons to bind specific hormones or proteins to the cell. The CD4 protein by which AIDS viruses dock onto human white blood cells is such a beacon.

Other proteins extend all the way across the bilayer, providing channels across which polar ions and molecules can pass into and out of the cell. How do these **transmembrane proteins** manage to span the membrane, rather than just floating on the surface in the way that a drop of water floats on oil? The part of the protein that actually traverses the lipid bilayer is a specially constructed spiral helix of nonpolar amino acids (figure 4.7). Water responds to nonpolar amino acids much as it does to nonpolar lipid chains, and the helical spiral is held within the lipid interior of the bilayer, anchored there by the strong tendency of water to avoid contact with these nonpolar amino acids. Many transmembrane proteins lock this arrangement in place by positioning amino acids with electrical charges (which are very polar) at the two ends of the helical region.

4.2 All cells are encased within a delicate lipid bilayer sheet, the plasma membrane, within which are embedded a variety of proteins that act as markers or channels through the membrane.

A Closer Look

Membrane Defects Can Cause Disease

The year 1993 marked an important milestone in the treatment of human disease. That year the first attempt was made to cure **cystic fibrosis** (**CF**), a deadly genetic disorder, by transferring healthy genes into sick individuals. Cystic fibrosis is a fatal disease in which the body cells of affected individuals secrete a thick mucus that clogs the airways of the lungs. The cystic fibrosis patient in the photograph is breathing into a Vitalograph, a device that measures lung function. These same secretions block the ducts of the pancreas and liver so that the few patients who do not die of lung disease die of liver failure. Cystic fibrosis is usually thought of as a children's disease because until recently few affected individuals lived long enough to become adults. Even today half die before their mid-twenties. There is no known cure.

Cystic fibrosis results from a defect in a single gene that is passed down from parent to child. It is the most common fatal genetic disease of Caucasians. One in 20 individuals possesses at least one copy of the defective gene. Most of these individuals are not afflicted with the disease; only those children who inherit a copy of the defective gene from each parent succumb to cystic fibrosis—about 1 in 2,500 infants.

Cystic fibrosis has proven difficult to study. Many organs are affected, and until recently it was impossible to identify the nature of the defective gene responsible for the disease. In 1985 the first clear clue was obtained. An investigator, Paul Quinton, seized on a commonly observed characteristic of cystic fibrosis patients, that their sweat is abnormally salty, and performed the following experiment. He isolated a sweat duct from a small piece of skin and placed it in a solution of salt (NaCl) that was three times as concentrated as the NaCl inside the duct. He then monitored the movement of ions. Diffusion tends to drive both the sodium (Na^+) and the chloride (Cl^-) ions into the duct because of the higher outer ion concentrations. In skin isolated from normal individuals, Na^+ and Cl^- both entered the duct, as expected. In skin isolated from cystic fibrosis individuals, however, only Na^+ entered the duct—no Cl^- entered. For the first time, the molecular nature of cystic fibrosis became clear. Water accompanies chloride, and was not entering the ducts because chloride was not, creating thick mucus. Cystic fibrosis is a defect in a plasma membrane protein called CFTR (*c*ystic *f*ibrosis *t*ransmembrane conductance *r*egulator) that normally regulates passage of Cl^- into and out of the body's cells.

The defective *cf* gene was isolated in 1987, and its position on a particular human chromosome (chromosome 7) was pinpointed in 1989. Interestingly, many cystic fibrosis patients produce a CFTR protein with a normal amino acid sequence. The *cf* mutation in these cases appears to interfere with how the CFTR protein folds, preventing it from folding into a functional shape.

Soon after the *cf* gene was isolated, experiments were begun to see if it would be possible to cure cystic fibrosis by gene therapy—that is, by transferring healthy *cf* genes into the cells with defective ones. In 1990 a working *cf* gene was successfully transferred into human lung cells growing in tissue culture, using adenovirus, a cold virus, to carry the gene into the cells. The CFTR-defective cells were "cured," becoming able to transport chloride ions across their plasma membranes. Then in 1991 a team of researchers successfully transferred a normal human *cf* gene into the lung cells of a living animal—a rat. The *cf* gene was first inserted into the adenovirus genome because adenovirus is a cold virus and easily infects lung cells. The treated virus was then inhaled by the rat. Carried piggyback, the *cf* gene entered the rat lung cells and began producing the normal human CFTR protein within these cells!

These results were very encouraging, and at first the future for all cystic fibrosis patients seemed bright. Clinical tests using adenovirus to introduce healthy *cf* genes into cystic fibrosis patients were begun with much fanfare in 1993.

They were not successful. As described in detail in chapter 12, there were insurmountable problems with the adenovirus being used to transport the *cf* gene into cystic fibrosis patients. The difficult and frustrating challenge that cystic fibrosis researchers had faced was not over. Research into clinical problems is often a time-consuming and frustrating enterprise, never more so than in this case. Recently, as chapter 12 recounts, new ways of introducing the healthy *cf* gene have been tried with better results. The long, slow journey toward a cure has taught us not to leap to the assumption that a cure is now at hand, but the steady persistence of researchers has taken us a long way, and again the future for cystic fibrosis patients seems bright.

4.3 Prokaryotic Cells

There are two major kinds of cells: prokaryotes and eukaryotes. **Prokaryotes** have a relatively uniform cytoplasm that is not subdivided by interior membranes into separate compartments. They do not, for example, have special membrane-bounded compartments, called *organelles,* or a *nucleus* (a membrane-bounded compartment that holds the hereditary information). All bacteria and archaea are prokaryotes; all other organisms are eukaryotes.

Prokaryotes are the simplest cellular organisms. Over 5,000 species are recognized, but doubtless many times that number actually exist and have not yet been described. Although these species are diverse in form, their organization is fundamentally similar (figure 4.8): small cells typically about 1 to 10 micrometers thick; enclosed like all cells by a plasma membrane, but with no distinct interior compartments. Outside of almost all bacteria is a *cell wall,* a framework of carbohydrates cross-linked into a rigid structure. In some bacteria another layer called the *capsule* encloses the cell wall. Bacterial cells assume many shapes or can adhere in chains and masses (figure 4.9), but individual cells are separate from one another.

If you were able to magnify your vision and peer into a prokaryotic cell, you would be struck by its simple organization. The entire interior of the cell, the cytoplasm, is one unit, with no internal support structure (the rigid wall supports the cell's shape) and no internal compartments bounded by membranes. Scattered throughout the cytoplasm of prokaryotic cells are small structures called *ribosomes,* the sites where proteins are made. Ribosomes are not considered organelles because they lack a membrane boundary. The DNA is found in a region of the cytoplasm called the *nucleoid region.* Although the DNA is localized in this region of the cytoplasm, it is not considered a nucleus because the nucleoid region and its associated DNA are not enclosed within an internal membrane.

Some prokaryotes use a *flagellum* (plural, flagella) to move. Flagella are long, threadlike structures projecting from the surface of a cell. They are used in locomotion and feeding. Prokaryotic flagella are protein fibers that extend out from the cell. There may be one or more per cell, or none, depending on the species. Bacteria can swim at speeds up to 20 cell diameters per second by rotating their flagella like screws.

Pili (singular, **pilus**) are other hairlike structures that occur on the cells of some prokaryotes. They are shorter than prokaryotic flagella, up to several micrometers long, and about 7.5 to 10 nanometers thick. Pili help the prokaryotic cells attach to appropriate substrates and exchange genetic information.

4.3 Prokaryotic cells lack a nucleus and do not have an extensive system of interior membranes.

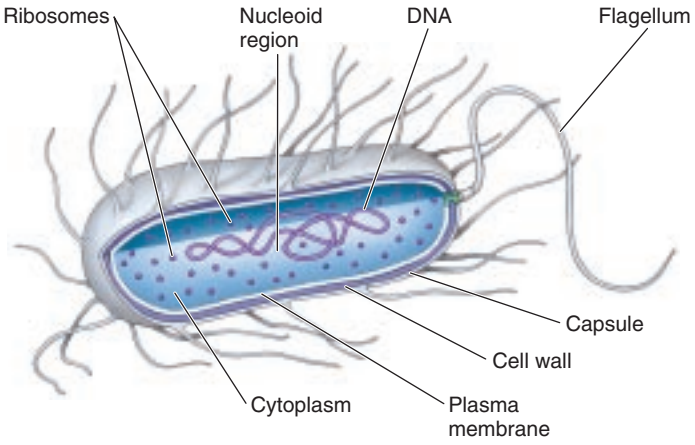


Figure 4.8 Organization of a prokaryotic cell.
Prokaryotic cells lack internal compartments. Not all prokaryotic cells have a flagellum or a capsule like the one illustrated here, but all do have a nucleoid region, ribosomes, a plasma membrane, cytoplasm, and a cell wall.

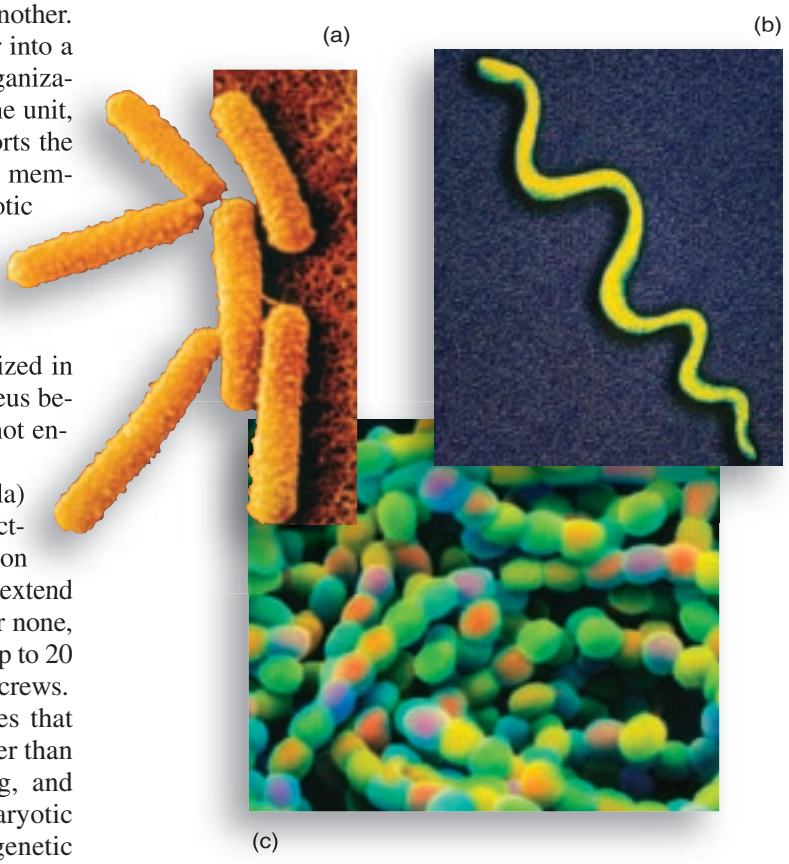


Figure 4.9 Bacterial cells have different shapes.
(*a*) *Bacillus* is a rod-shaped bacterium. (*b*) *Treponema* is a coil-shaped bacterium; rotation of internal filaments produces a cork screw movement. (*c*) *Streptococcus* is a more or less spherical bacterium in which the individuals adhere in chains.

4.4 Eukaryotic Cells

For the first 1 billion years of life on earth, all organisms were prokaryotes, cells with very simple interiors. Then, about 1.5 billion years ago, a new kind of cell appeared for the first time, much larger and with a complex interior organization. All cells alive today except bacteria and archaea are of this new kind. Unlike prokaryotes, these big cells have many membrane-bounded interior compartments and a variety of **organelles** (specialized structures within which particular cell processes occur). One of the organelles is very visible when these cells are examined with a microscope, filling the center of the cell like the pit of a peach. Seeing it, the English botanist Rob-

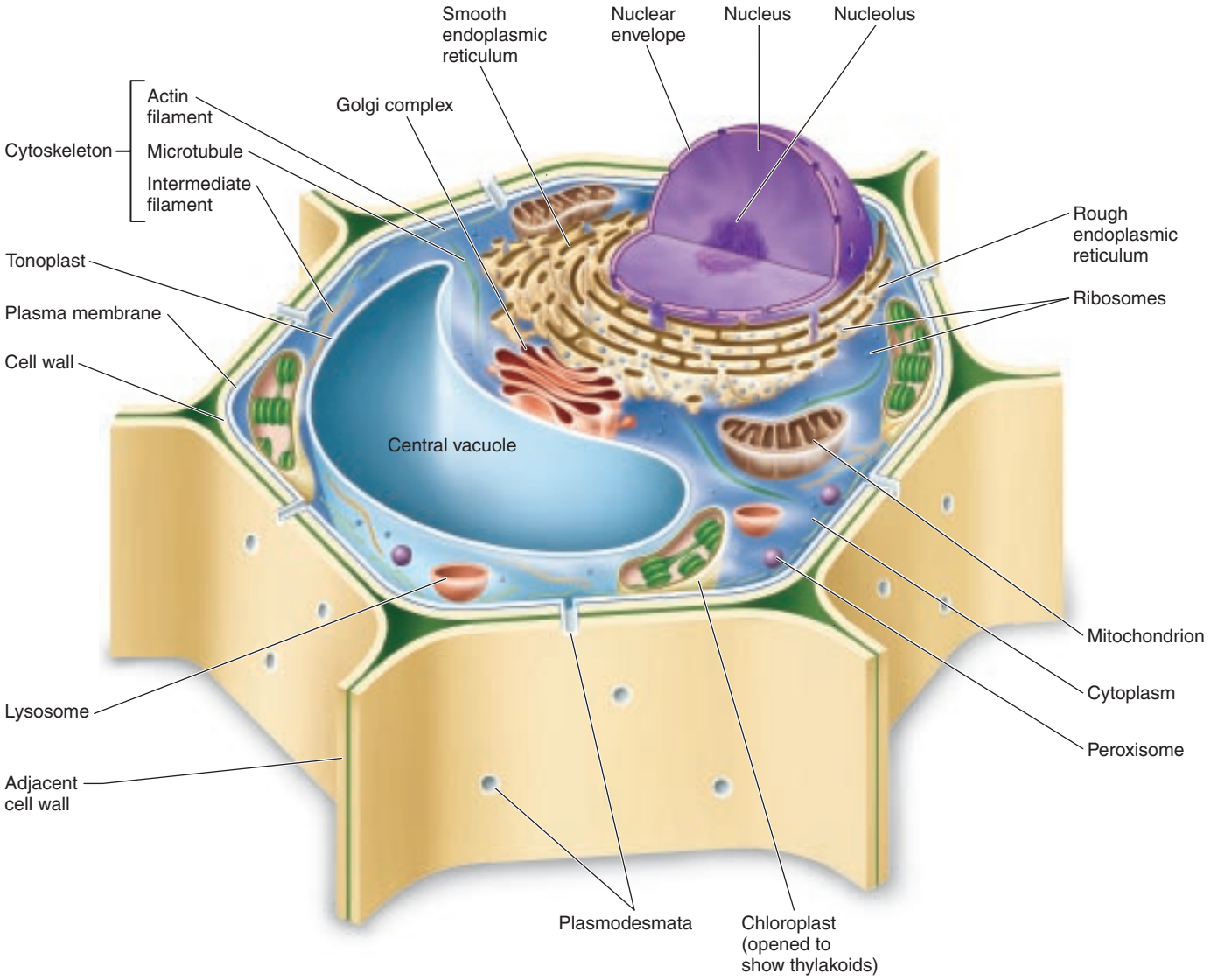


Figure 4.10 Structure of a plant cell.
Most mature plant cells contain large central vacuoles that occupy a major portion of the internal volume of the cell and organelles called chloroplasts, within which photosynthesis takes place. The cells of plants, fungi, and some protists have cell walls, although the composition of the walls varies among the groups. Plant cells have cytoplasmic connections through openings in the cell wall called plasmodesmata. Flagella occur in sperm of a few plant species, but are otherwise absent in plant and fungal cells. Centrioles are also absent in the plant and fungal cells.

ert Brown in 1831 called it the *nucleus* (plural, *nuclei*), from the Latin word for "kernel." Inside the nucleus, the DNA is wound tightly around proteins and packaged into compact units called *chromosomes.* All cells with nuclei are called **eukaryotes** (from the Greek words *eu,* true, and *karyon,* nut), whereas bacteria and archaea are called *prokaryotes* ("before the nut").

Both plant cells (figure 4.10) and animal cells (figure 4.11) are eukaryotic. The hallmark of the eukaryotic cell is compartmentalization, achieved by an extensive, *endomembrane system* that weaves through the cell interior, creating organelles and a variety of *vesicles* (small membrane-bound sacs that store and transport materials). These many closed-off compartments allow different processes to proceed simultaneously without interferring with one another, just as rooms do in a house. All eukaryotic cells are supported within internally by an internal protein scaffold, the *cytoskeleton.* The cells of plants and fungi have strong exterior *cell walls* composed of cellulose or chitin fibers, while the cells of animals lack cell walls. We now journey into the interior of a typical eukaryotic cell and explore its complex organization.

4.4 Eukaryotic cells have a system of interior membranes and membrane-bounded organelles that subdivide the interior into functional compartments.

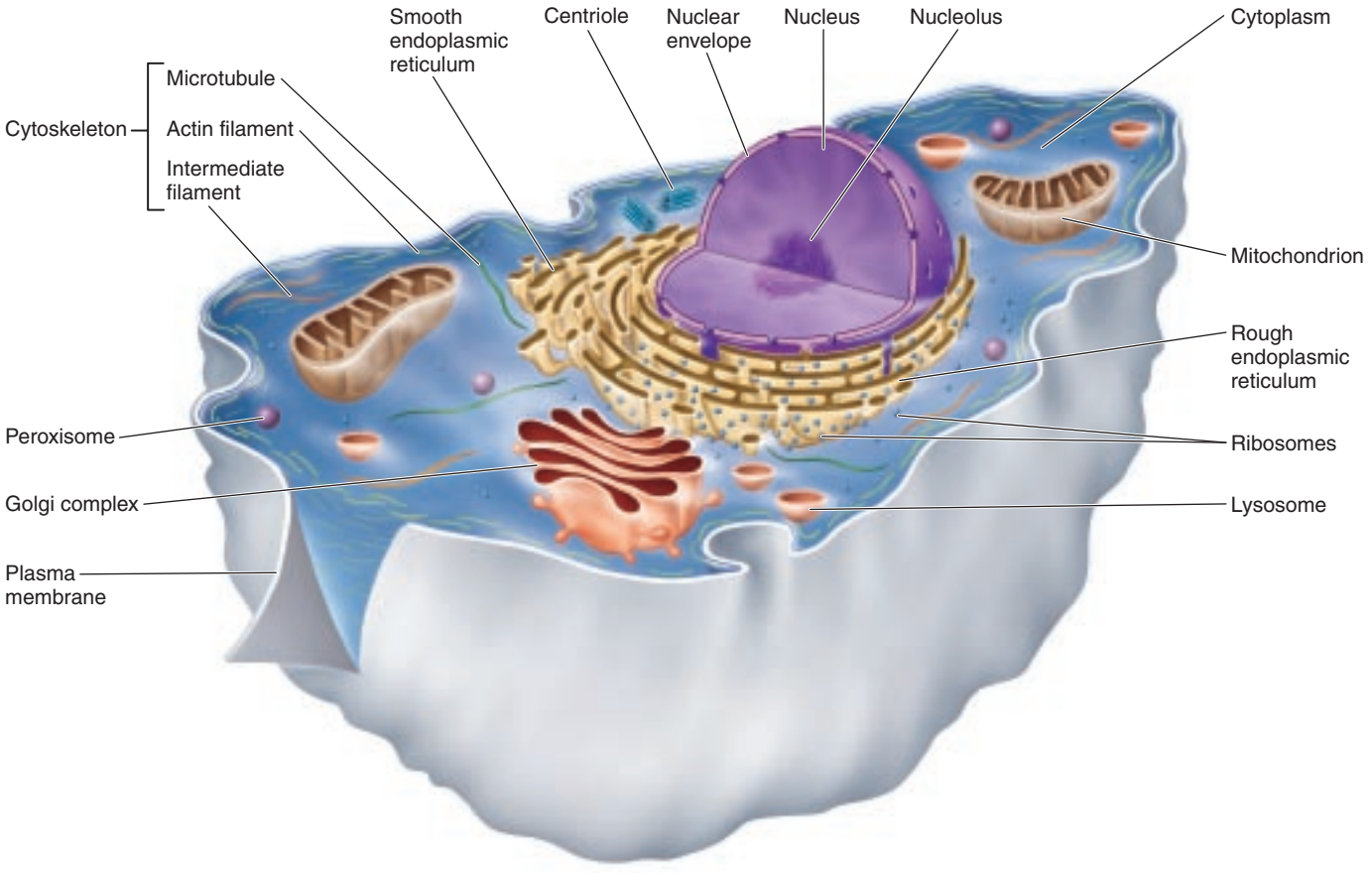


Figure 4.11 Structure of an animal cell.
In this generalized diagram of an animal cell, the plasma membrane encases the cell, which contains the cytoskeleton and various cell organelles and interior structures suspended in a semifluid matrix called the cytoplasm. Some kinds of animal cells possess fingerlike projections called microvilli. Other types of eukaryotic cells, for example many protist cells, may possess flagella, which aid in movement, or cilia, which can have many different functions.

4.5 The Nucleus: The Cell's Control Center

The many parts of the cell (table 4.2) are remarkably similar from plants to animals, or from paramecia to primates. Organelles look similar and carry out similar functions in all organisms. It is possible that these shared properties were derived from common ancestral cells several billion years ago.

If you were to journey far into the interior of one of your cells, you would eventually reach the center of the cell. There you would find, cradled within a network of fine filaments like a ball in a basket, the **nucleus** (figure 4.12). The nucleus is the command and control center of the cell, directing all of its activities. It is also the genetic library where the hereditary information is stored.

Nuclear Membrane

The surface of the nucleus is bounded by a special kind of membrane called the **nuclear envelope.** The nuclear envelope is actually *two* membranes, one outside the other, like a sweater over a shirt. Scattered over the surface of this envelope are selective openings called **nuclear pores.** Nuclear pores form when the two membrane layers of the nuclear envelope pinch together. A nuclear pore is not an empty opening like the hole in a doughnut; rather, it has many proteins embedded within it that permit proteins and RNA to pass into and out of the nucleus.

Chromosomes

In both prokaryotes and eukaryotes, all hereditary information specifying cell structure and function is encoded in DNA. However, unlike prokaryotic DNA, the DNA of eukaryotes is divided into several segments and associated with protein, forming **chromosomes.** The proteins in the chromosome permit the DNA to wind tightly and condense during cell division. Under a light microscope, these condensed chromosomes are readily seen in dividing cells as densely staining rods. After cell division, eukaryotic chromosomes uncoil and fully extend into threadlike strands called **chromatin** that can no longer be distinguished individually with a light microscope within the nucleoplasm.

Nucleolus

To make its many proteins, the cell employs a special structure called a **ribosome,** which reads the RNA copy of a gene and uses that information to direct the construction of a protein. Ribosomes are made up of several special forms of RNA called ribosomal RNA, or rRNA, bound up within a complex of several dozen different proteins.

One region of the nucleus appears darker than the rest; this darker region is called the **nucleolus.** There a cluster of several hundred genes encode rRNA where the ribosome subunits assemble. These subunits leave the nucleus through the nuclear pores and enter the cytoplasm, where final assembly of ribosomes takes place.

4.5 The nucleus is the command center of the cell, issuing instructions that control cell activities. It also stores the cell's hereditary information.

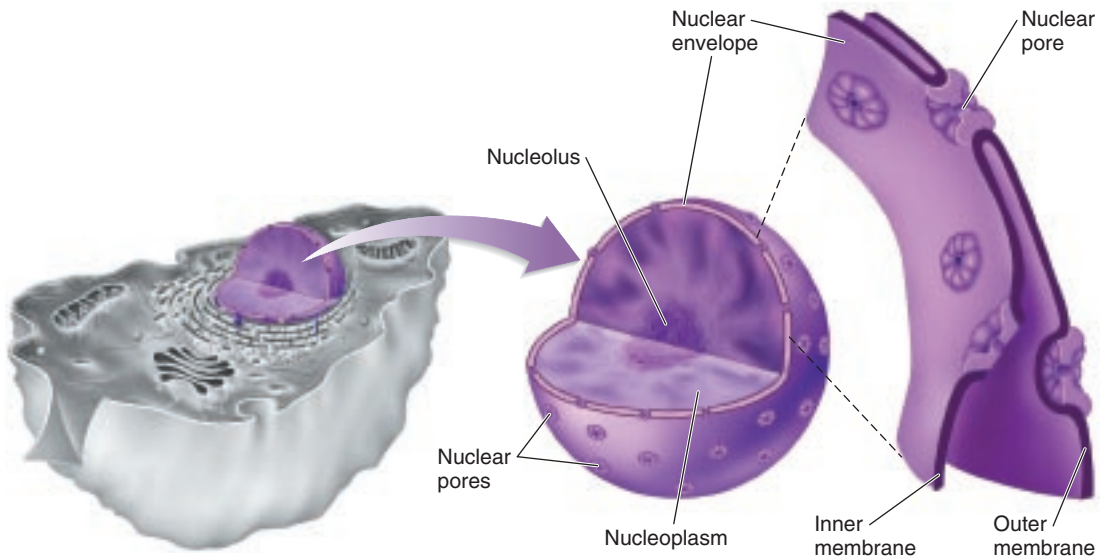


Figure 4.12 The nucleus.

The nucleus is composed of a double membrane, called a nuclear envelope, enclosing a fluid-filled interior containing the chromosomes. In cross section, the individual nuclear pores are seen to extend through the two membrane layers of the envelope; the dark material within the pore is protein, which acts to control access through the pore.

TABLE 4.2 EUKARYOTIC CELL STRUCTURES AND THEIR FUNCTIONS

Structure		Description	Function
Structural Elements			
Cell wall		Outer layer of cellulose or chitin; or absent	Protection; support
Cytoskeleton		Network of protein filaments	Structural support; cell movement
Flagella and cilia		Cellular extensions with 9 + 2 arrangement of pairs of microtubules	Motility or moving fluids over surfaces
Plasma Membrane and Endomembrane System			
Plasma membrane		Lipid bilayer in which proteins are embedded	Regulates what passes into and out of cell; cell-to-cell recognition
Endoplasmic reticulum		Network of internal membranes	Forms compartments and vesicles; participates in protein and lipid synthesis
Nucleus		Structure (usually spherical) surrounded by double membrane that contains chromosomes	Control center of cell; directs protein synthesis and cell reproduction
Golgi complex		Stacks of flattened vesicles	Packages proteins for export from the cell; forms secretory vesicles
Lysosomes		Vesicles derived from Golgi complex that contain hydrolytic digestive enzymes	Digest worn-out organelles and cell debris; play role in cell death
Peroxisomes		Vesicles formed from the ER containing oxidative and other enzymes	Isolate particular chemical activities from rest of cell
Energy-Producing Organelles			
Mitochondria		Bacteria-like elements with double membrane	Sites of oxidative metabolism; provides ATP for cellular energy
Chloroplast		Bacteria-like organelle found in plants and algae; complex inner membrane consists of stacked vesicles	Site of photosynthesis
Elements of Gene Expression			
Chromosomes		Long threads of DNA that form a complex with protein	Contain hereditary information
Nucleolus		Site of genes for rRNA synthesis	Assembles ribosomes
Ribosomes		Small, complex assemblies of protein and RNA, often bound to endoplasmic reticulum	Sites of protein synthesis

4.6 The Endomembrane System

Surrounding the nucleus within the interior of the eukaryotic cell is a tightly packed mass of membranes. They fill the cell, dividing it into compartments, channeling the transport of molecules through the interior of the cell and providing the surfaces on which enzymes act. The system of internal compartments created by these membranes in eukaryotic cells constitutes the most fundamental distinction between the cells of eukaryotes and prokaryotes.

Endoplasmic Reticulum: The Transportation System

The extensive system of internal membranes is called the **endoplasmic reticulum,** often abbreviated **ER** (figure 4.13). The term *endoplasmic* means "within the cytoplasm," and the term *reticulum* is a Latin word meaning "little net." The ER, weaving in sheets through the interior of the cell, creates a series of channels and interconnections, and it also isolates some spaces as membrane-enclosed sacs called **vesicles.**

The surface of the ER is the place where the cell makes proteins intended for export (such as enzymes secreted from the cell surface). The surface of those regions of the ER devoted to the synthesis of such transported proteins is heavily studded with ribosomes and appears pebbly, like the surface of sandpaper, when seen through an electron microscope. For this reason, these regions are called **rough ER.** Regions in which ER-bounded ribosomes are relatively scarce are correspondingly called **smooth ER.** The surface of the smooth ER is embedded with enzymes that aid in the manufacture of carbohydrates and lipids.

The Golgi Complex: The Delivery System

As new molecules are made on the surface of the ER, they are passed from the ER in flattened stacks of membranes called **Golgi bodies.** These structures are named for Camillo Golgi, the nineteenth-century Italian physician who first called attention to them. The number of Golgi bodies a cell contains ranges from 1 or a few in protists, to 20 or more in animal cells and several hundred in plant cells. Golgi bodies function in the collection, packaging, and distribution of molecules manufactured in the cell. Scattered through the cytoplasm, Golgi bodies are collectively referred to as the **Golgi complex** (figure 4.14).

The proteins and lipids that are manufactured on the ER membranes are transported through the channels of the ER, or as vesicles budded off from it, into the Golgi bodies. Within the Golgi bodies, many of these molecules become tagged with carbohydrates. The molecules collect at the ends of the membranous folds of the Golgi bodies; these folds are given the special name *cisternae* (Latin, collecting vessels). Vesicles

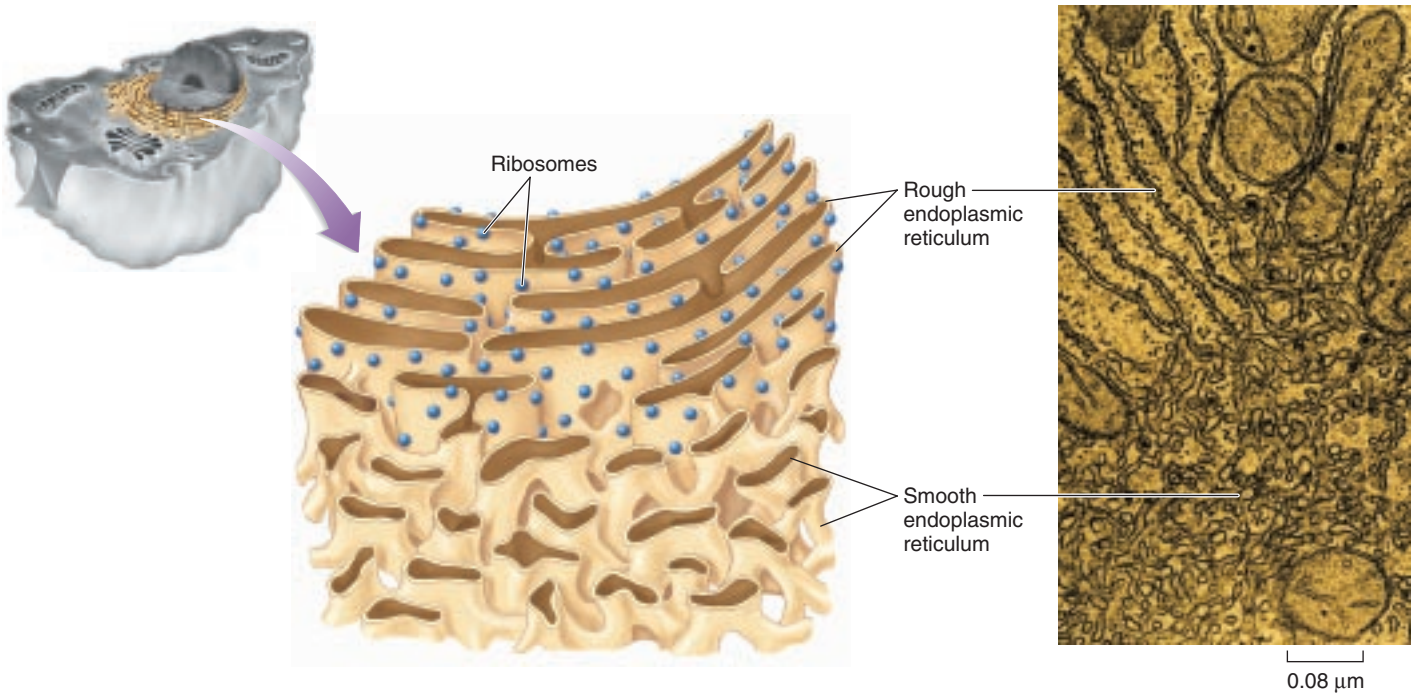


Figure 4.13 The endoplasmic reticulum (ER).
The endoplasmic reticulum provides the cell with an extensive system of internal membranes for the synthesis and transport of materials. Ribosomes are associated with only one side of the rough ER; the other side is the boundary of a separate compartment within the cell into which the ribosomes extrude newly made proteins destined for secretion. Smooth endoplasmic reticulum has few to no bound ribosomes.

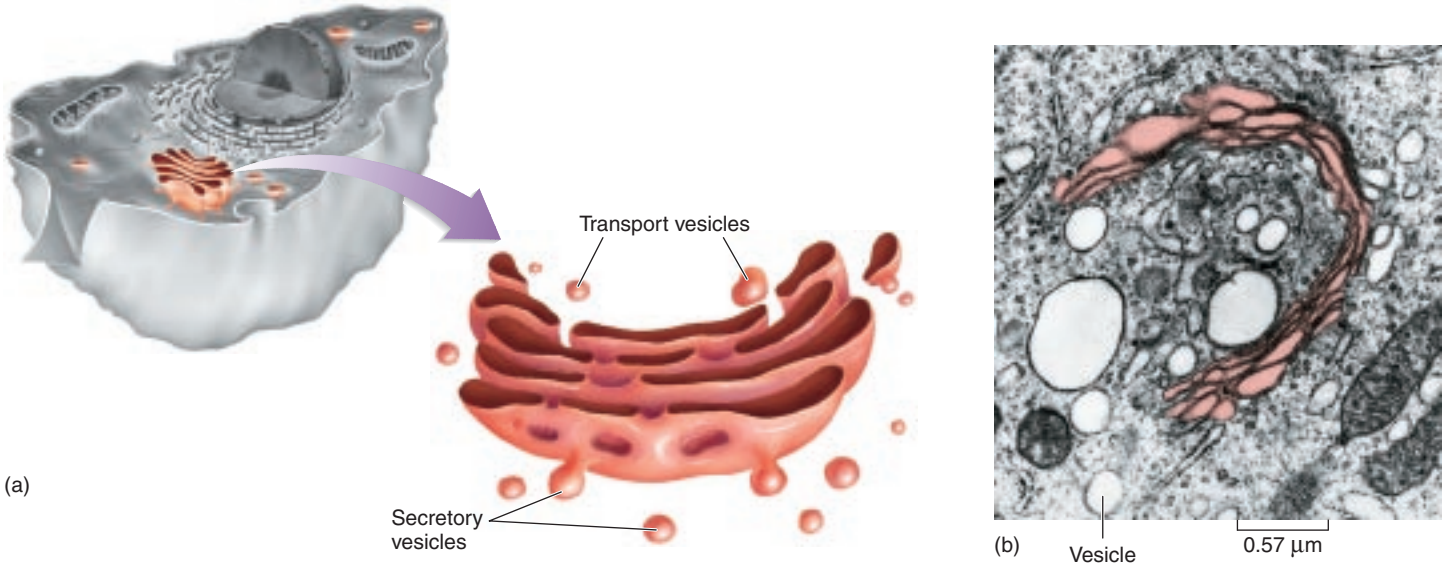


Figure 4.14 Golgi complex.
This vesicle-forming system, called the Golgi complex after its discoverer, is an integral part of the cell's internal membrane system. The Golgi complex processes and packages materials for transport to another region within the cell and/or for export from the cell. It receives material for processing in transport vesicles on one side and sends the material packaged in secretory vesicles off the other side. (*a*) Diagram of a Golgi body. (*b*) Micrograph of a Golgi body showing vesicles.

that pinch off from the cisternae carry the molecules to the different compartments of the cell and to the inner surface of the plasma membrane (figure 4.15), where molecules to be secreted are released to the outside.

Lysosomes: Recycling Centers

Other organelles called **lysosomes** arise from the Golgi complex and contain a concentrated mix of the powerful enzymes that break down macromolecules. Lysosomes are also the recycling centers of the cell, digesting worn-out cell components to make way for newly formed ones while recycling the proteins and other materials of the old parts. Large organelles called mitochondria are replaced in some human tissues every 10 days, with lysosomes digesting the old ones as the new ones are produced. In addition to breaking down organelles and other structures within cells, lysosomes also eliminate particles (including other cells) that the cell has engulfed.

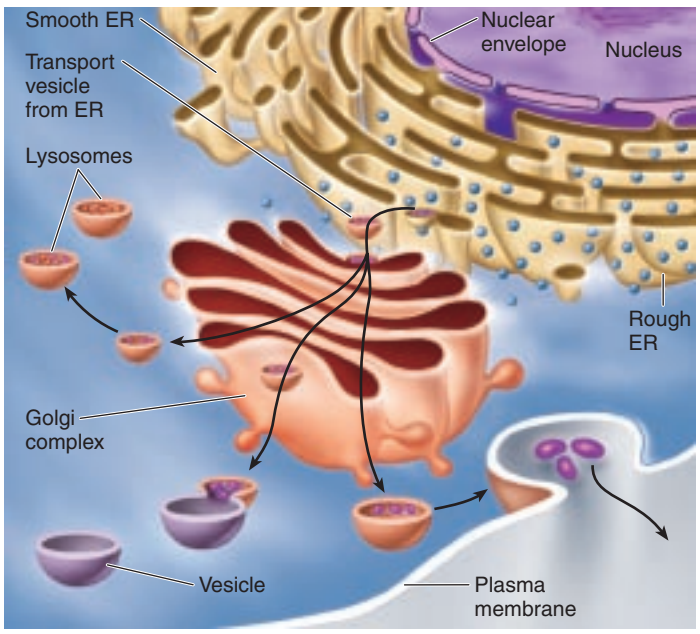


Figure 4.15 How the endomembrane system works.
A highly efficient highway system within the cell, the endomembrane system transports material from the ER to the Golgi and from there to other destinations.

Peroxisomes: Chemical Specialty Shops

The interior of the eukaryotic cell contains a variety of membrane-bounded spherical organelles derived from the ER that carry out particular chemical functions. Almost all eukaryotic cells, for example, contain **peroxisomes,** vesicles that contain two sets of enzymes and that are about the same size as lysosomes. One set found in plant seeds converts fats to carbohydrates, and the other set found in all eukaryotes detoxifies various potentially harmful molecules—strong oxidants—that form in cells. They do this by using molecular oxygen to remove hydrogen atoms from specific molecules. These chemical reactions would be very destructive to the cell if not confined to the peroxisomes.

4.6 An extensive system of interior membranes organizes the interior of the cell into functional compartments that manufacture and deliver proteins and carry out a variety of specialized chemical processes.

4.7 Organelles That Contain DNA

Eukaryotic cells contain several kinds of complex, cell-like organelles that contain their own DNA and appear to have been derived from ancient bacteria assimilated by ancestral eukaryotes in the distant past. The two principal kinds are mitochondria (which occur in the cells of all but a very few eukaryotes) and chloroplasts (which do not occur in animal cells—they occur only in algae and plants).

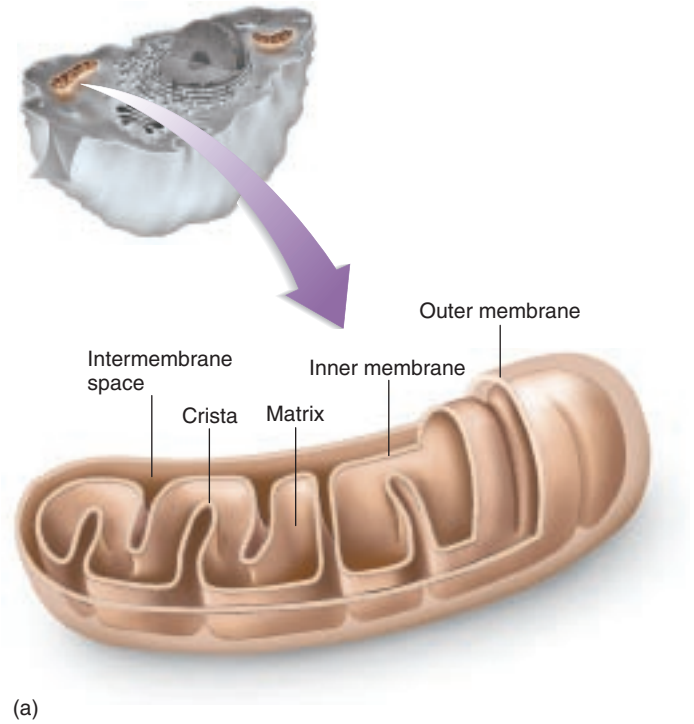
Mitochondria: Powerhouses of the Cell

Eukaryotic organisms extract energy from organic molecules ("food") in a complex series of chemical reactions called **oxidative metabolism,** which takes place only in their mitochondria. **Mitochondria** (singular, **mitochondrion**) are sausage-shaped organelles about the size of a bacterial cell (figure 4.16). Mitochondria are bounded by two membranes. The outer membrane is smooth and apparently derives from the plasma membrane of the host cell that first took up the bacterium long ago. The inner membrane, apparently the plasma membrane of the bacterium that gave rise to the mitochondrion, is bent into numerous folds called **cristae** (singular, **crista**) that resemble the folded plasma membranes in various groups of bacteria. The cristae partition the mitochondrion into two compartments, an inner **matrix** and an outer compartment. As you will learn in chapter 6, this architecture is critical to successfully carrying out oxidative metabolism.

During the 1.5 billion years in which mitochondria have existed in eukaryotic cells, most of their genes have been transferred to the chromosomes of the host cells. But mitochondria still have some of their original genes, contained in a circular, closed, naked molecule of DNA (called mitochondrial DNA, or mtDNA) that closely resembles the circular DNA molecule of a bacterium. On this mtDNA are several genes that produce some of the proteins essential for oxidative metabolism. In both mitochondria and bacteria, the circular DNA molecule is replicated during the process of division. When a mitochondrion divides, it copies its DNA located in the matrix and splits into two by simple fission, dividing much as bacteria do.

Chloroplasts: Energy-Capturing Centers

All photosynthesis in plants and algae takes place within another bacteria-like organelle, the **chloroplast** (figure 4.17). There is strong evidence that chloroplasts, like mitochondria, were derived by symbiosis from bacteria. A chloroplast is bounded, like a mitochondrion, by two membranes, the inner derived from the original bacterium and the outer resembling the host cell's ER. Chloroplasts are larger than mitochondria, and their inner membranes have a more complex organization. The inner membranes are fused to form stacks of closed vesicles called **thylakoids.** The light-powered reactions of photosynthesis take place within the thylakoids. The thylakoids are stacked on top of one another to form a column called a **granum** (plural, **grana**). The interior of a chloroplast is bathed with a semiliquid substance called the **stroma.**



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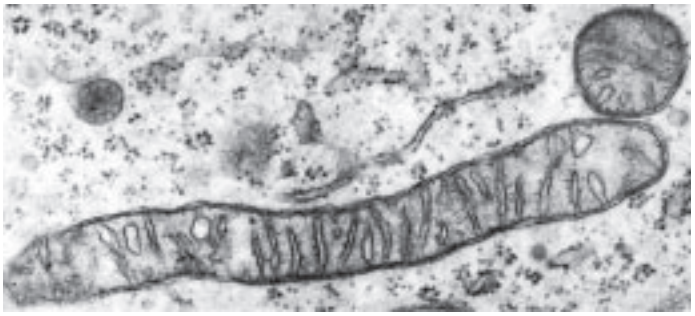


(b)

Figure 4.16 Mitochondria.
The mitochondria of a cell are sausage-shaped organelles within which oxidative metabolism takes place, and energy is extracted from food using oxygen. (*a*) A mitochondrion has a double membrane. The inner membrane is shaped into folds called cristae. The space within the cristae is called the matrix. The cristae greatly increase the surface area for oxidative metabolism. (*b*) Micrograph of two mitochondria, one in cross section, the other cut lengthwise.

Like mitochondria, chloroplasts have a circular DNA molecule. On this DNA are located many of the genes coding for the proteins necessary to carry out photosynthesis. Plant cells can contain from one to several hundred chloroplasts, depending on the species. Neither mitochondria nor chloroplasts can be grown in a cell-free culture; they are totally dependent on the cells within which they occur.

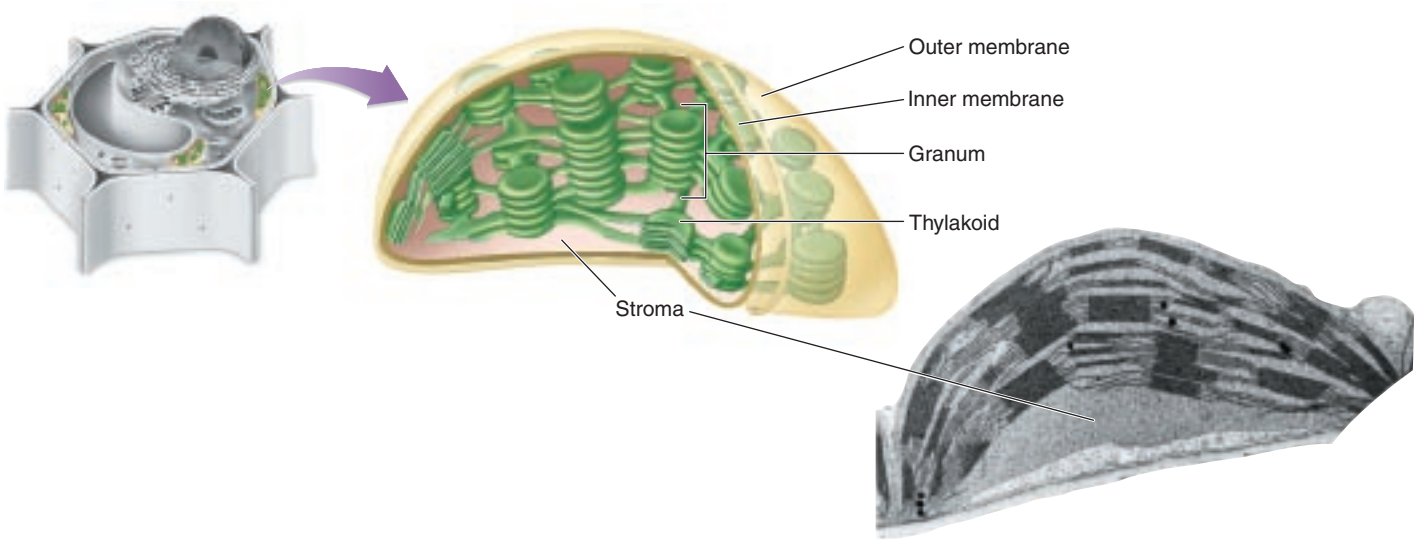


Figure 4.17 A chloroplast.
Bacteria-like organelles called chloroplasts are the sites of photosynthesis in photosynthetic eukaryotes. Like mitochondria, they have a complex system of internal membranes on which chemical reactions take place. The inner membrane of a chloroplast is fused to form stacks of closed vesicles called thylakoids. Photosynthesis occurs within these thylakoids. Thylakoids are stacked one on top of the other in columns called grana. The interior of the chloroplast is bathed in a semiliquid substance called the stroma.

Endosymbiosis

Symbiosis is a close relationship between organisms of different species that live together. The theory of **endosymbiosis** proposes that some of today's eukaryotic organelles evolved by a symbiosis in which one cell of a prokaryotic species was engulfed by and lived inside the cell of another species of prokaryote that was a precursor to eukaryotes (figure 4.18). According to the endosymbiont theory, the engulfed prokaryotes provided their hosts with certain advantages associated with their special metabolic abilities. Two key eukaryotic organelles just described are believed to be the descendants of these endosymbiotic prokaryotes: mitochondria, which are thought to have originated as bacteria capable of carrying out oxidative metabolism; and chloroplasts, which apparently arose from photosynthetic bacteria.

The endosymbiont theory is supported by a wealth of evidence. Both mitochondria and chloroplasts are surrounded by two membranes; the inner membrane probably evolved from the plasma membrane of the engulfed bacterium, while the outer membrane is probably derived from the plasma membrane or endoplasmic reticulum of the host cell. Mitochondria are about the same size as most bacteria, and the cristae formed by their inner membranes resemble the folded membranes in various groups of bacteria. Mitochondrial ribosomes are also similar to bacterial ribosomes in size and structure. Both mitochondria and chloroplasts contain circular molecules of DNA similar to those in bacteria. Finally, mitochondria divide by simple fission, splitting in two just as bacterial cells do, and they apparently replicate and partition their DNA in much the same way as bacteria.

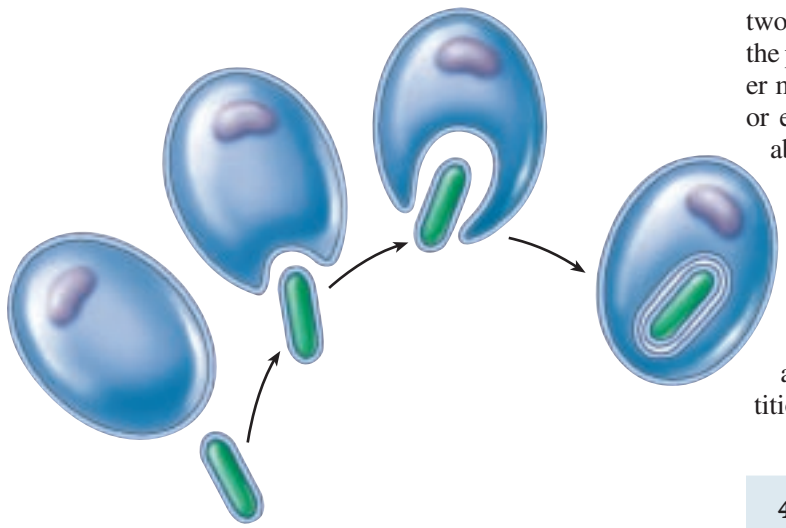


Figure 4.18 Endosymbiosis
This figure shows how a double membrane may have been created during the symbiotic origin of mitochondria or chloroplasts.

4.7 Eukaryotic cells contain several complex organelles that have their own DNA and are thought to have arisen by endosymbiosis from ancient bacteria.

4.8 The Cytoskeleton: Interior Framework of the Cell

If you were to shrink down and enter into the interior of a eukaryotic cell, the first thing you would encounter is a dense network of protein fibers called the **cytoskeleton,** which supports the shape of the cell and anchors organelles such as the nucleus to fixed locations. This network cannot be seen with a light microscope because the individual fibers are single chains of protein, much too fine for microscopes to resolve. To "see" the cytoskeleton, scientists attach fluorescent antibodies to the protein fibers and then photograph them under fluorescent light.

The protein fibers of the cytoskeleton are a dynamic system, constantly being formed and disassembled. There are three different kinds of protein fibers (figure 4.19): long, slender **microfilaments** made of the protein actin, hollow tubes called **microtubules** made of the protein tubulin, and thick ropes of intertwined protein called **intermediate filaments.** The microfilaments, microtubules, and intermediate filaments are anchored to membrane proteins embedded within the plasma membrane.

The cytoskeleton plays a major role in determining the shape of animal cells, which lack rigid cell walls. Because filaments can form and dissolve readily, the shape of an animal cell can change rapidly. If you examine the surface of an animal cell with a microscope, you will often find it alive with motion, projections shooting out from the surface and then retracting, only to shoot out elsewhere moments later.

The cytoskeleton is not only responsible for the cell's shape, but it also provides a scaffold both for ribosomes to carry out protein synthesis and for enzymes to be localized within defined areas of the cytoplasm. By anchoring particular enzymes near one another, the cytoplasm participates with organelles in organizing the cell's activities.

Centrioles

Complex structures called **centrioles** (figure 4.20) assemble microtubules from tubulin subunits in the cells of animals and most protists. Centrioles occur in pairs within the cytoplasm, usually located at right angles to one another near the nuclear envelope. They are among the most structurally complex microtubular assemblies of the cell. In cells that contain flagella or cilia, each cilium or flagellum is anchored by a form of centriole called a basal body. Most animal and protist cells have both centrioles and basal bodies; higher plants and fungi lack them, instead organizing microtubules without such structures. Although they lack a membrane, centrioles resemble spirochete bacteria in many other respects. Some biologists believe that centrioles, like mitochondria and chloroplasts, originated as symbiotic bacteria.

Cell Movement

Essentially, all cell motion is tied to the movement of actin microfilaments, microtubules, or both. Intermediate filaments act as intracellular tendons, preventing excessive stretching of cells, and actin microfilaments play a major role in determining the shape of cells. Because actin microfilaments can form and dissolve so readily, they enable some cells to change shape quickly. If you look at the surfaces of such cells under a microscope, you will find them moving and changing shape.

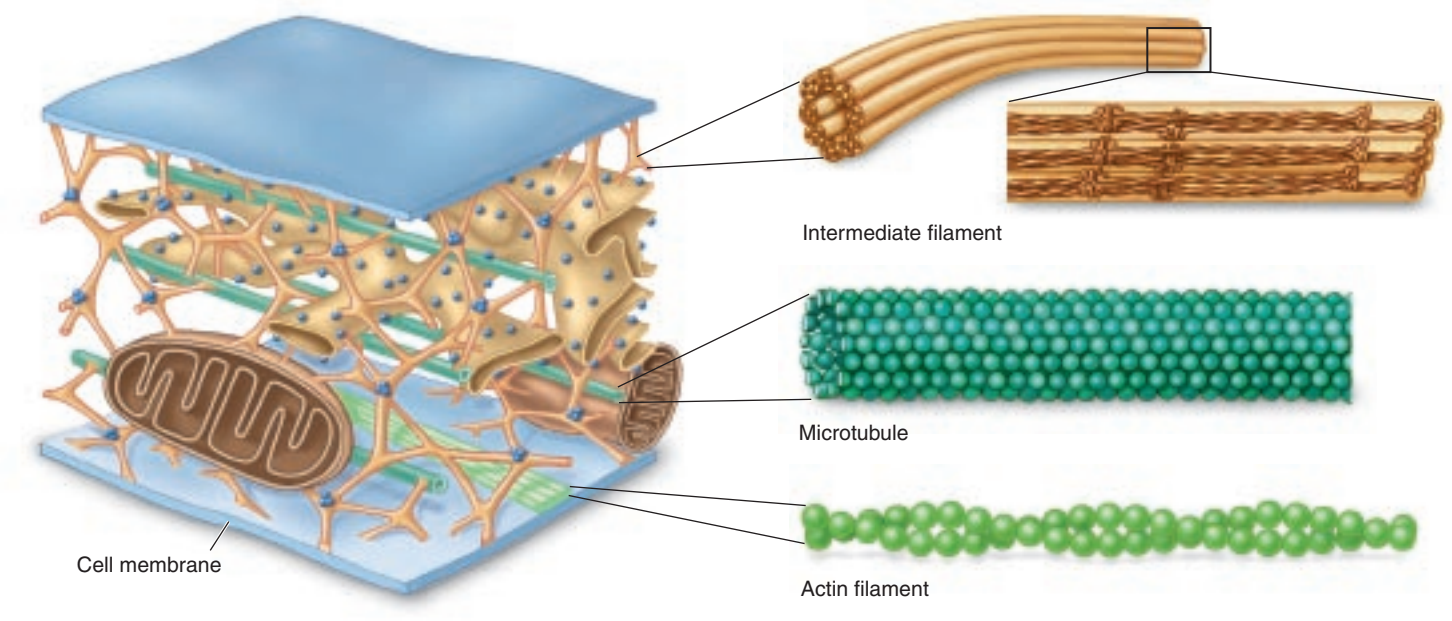


Figure 4.19 The three protein fibers of the cytoskeleton.
Organelles such as mitochondria are anchored to fixed locations in the cytoplasm by the cytoskeleton, a network or protein fibers. *Intermediate filaments* are composed of overlapping proteins that allows for a ropelike structure that provides tremendous mechanical strength to the cell. *Microtubules* are composed of tubulin protein subunits arranged side by side to form a tube. Microtubules are comparatively stiff cytoskeletal elements that function in intracellular transport and stabilizing cell structure. *Actin microfilaments* are made of two strands of the fibrous protein actin twisted together and usually occur in bundles. Actin microfilaments are responsible for cell movement.

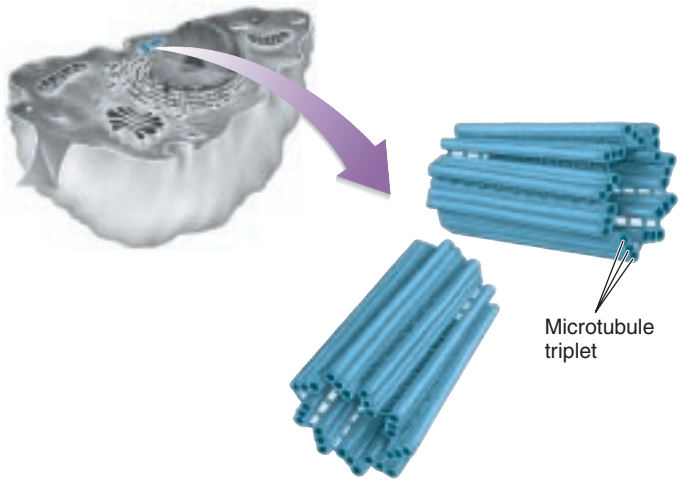
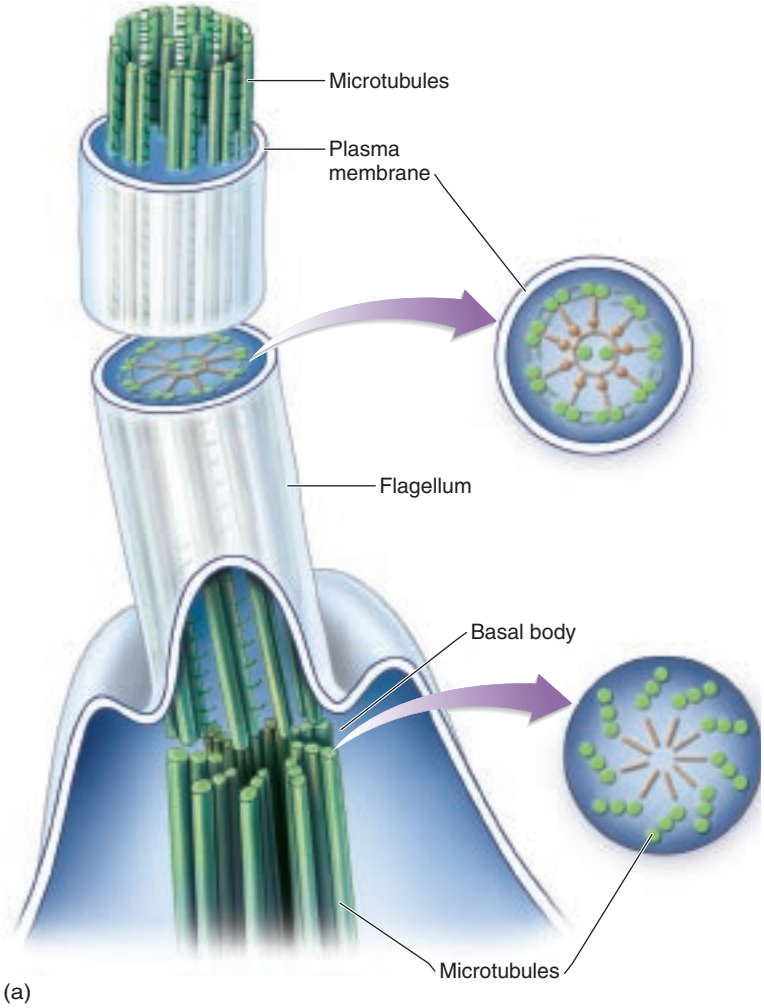


Figure 4.20 Centrioles.
Centrioles anchor and assemble microtubules. In their anchoring capacity, they can be seen as the basal bodies of eukaryotic flagella. In their organizing capacity, they function during cell division to indicate the plane along which the cell separates.
Centrioles usually occur in pairs and are located in the cell in characteristic planes. One centriole typically lies parallel to the cell surface, while another lies perpendicular to the surface. Centrioles are composed of nine triplets of microtubules.

Some Cells Crawl. It is the arrangement of actin microfilaments within the cell cytoplasm that allows cells to "crawl," literally! Crawling is a significant cellular phenomenon, essential to inflammation, clotting, wound healing, and the spread of cancer. White blood cells in particular exhibit this ability. Produced in the bone marrow, these cells are released into the circulatory system and then eventually crawl out of capillaries and into the tissues to destroy potential pathogens. The crawling mechanism is an exquisite example of cellular coordination.

Actin microfilaments play a role in other types of cell movement. For example, during animal cell reproduction (see chapter 7), chromosomes move to opposite sides of a dividing cell because they are attached to shortening microtubules. The cell then pinches in two when a belt of actin microfilaments contracts like a purse string. Muscle cells also use actin microfilaments to contract their cytoskeletons. The fluttering of an eyelash, the flight of an eagle, and the awkward crawling of a baby all depend on these cytoskeletal movements within muscle cells.

Swimming with Flagella and Cilia. **Flagella** (singular, **flagellum**) are fine, long, threadlike organelles protruding from the cell surface. Each flagellum arises from a structure called a **basal body** and consists of a circle of nine microtubule pairs surrounding two central ones (figure 4.21). This **9 + 2 arrangement** is a fundamental feature of eukaryotes and apparently evolved early in their history. Even in cells that lack flagella, derived structures with the same 9 + 2 arrangement often occur, like in the sensory hairs of the human ear. If flagella are numerous and organized in dense rows, they are called **cilia.** Cilia do not differ from flagella in their structure, but cilia are usually short. In humans, we find a single long flagellum on each sperm cell that propels the cell in a swimming motion, and dense mats of cilia project from cells that line our breathing tube, the trachea, to move mucus and dust particles out of the respiratory tract into the throat (where we can expel these unneeded contaminants by spitting or swallowing).



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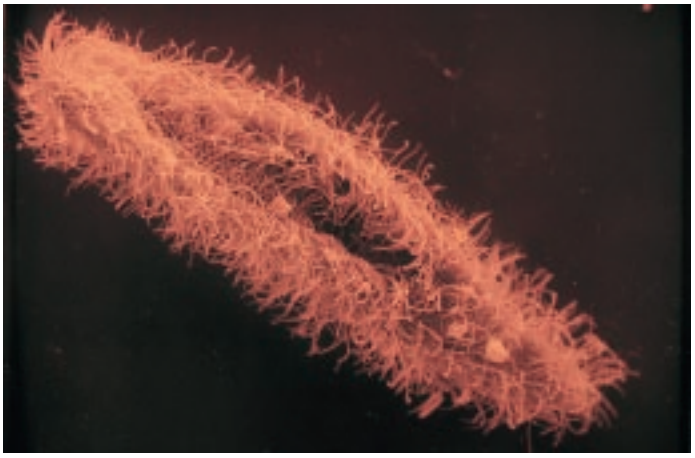


(b)

Figure 4.21 Flagella and cilia.
(*a*) A eukaryotic flagellum springs directly from a basal body and is composed of a ring of nine pairs of microtubules with two microtubules in its core. (*b*) The surface of this paramecium is covered with a dense forest of cilia.

Moving Materials Within the Cell

All eukaryotic cells must move materials from one place to another in the cytoplasm. Most cells use the endomembrane system as an intracellular highway; the Golgi complex packages materials into vesicles that come from the channels of the endoplasmic reticulum to the far reaches of the cell. However, this highway is only effective over short distances. When a cell has to transport materials through long extensions like the axon of a nerve cell, the ER highways are too slow. For these situations, eukaryotic cells have developed high-speed locomotives that run along microtubular tracks.

Four components are required: (1) a vesicle or organelle that is to be transported, (2) a motor molecule that provides the energy-driven motion, (3) a connector molecule that connects the vesicle to the motor molecule, and (4) microtubules on which the vesicle will ride like a train on a rail. As nature's tiniest motors, these motor proteins literally pull the transport vesicles along the microtubular tracks. The motor protein **kinesin** uses ATP to power its movement toward the cell periphery, dragging the vesicle with it as it travels along the microtubule. Another motor protein, **dynein** (figure 4.22), directs movement in the opposite direction, inward toward the cell's center. The destination of a particular transport vesicle and its contents is thus determined by the nature of the linking protein embedded within the vesicle's membrane. Like possessing a ticket to one of two destinations, if a vesicle links to kinesin, it moves outward; if it links to dynein, it moves inward.

Vacuoles: Storage Compartments

Within the interiors of plant and many protist cells, the cytoskeleton positions not only organelles, but also storage compartments that are not membrane-bounded, called **vacuoles.** The center of a plant cell usually contains a large, apparently empty space, called the *central vacuole* (figure 4.23). This vacuole is not really empty; it contains large amounts of water and other materials, such as sugars, ions, and pigments. The center vacuole functions as a storage center for these important substances and also helps to increase the surface-to-volume ratio of the plant cell outside the vacuole by applying pressure to the plasma membrane. The plasma membrane expands outward under this pressure, thereby increasing its surface area.

In protists like *Paramecium,* cells contain a **contractile vacuole** near the cell surface that accumulates excess water. This vacuole is bounded by actin microfilaments and has a small pore that opens onto the outside of the cell. By rhythmic ATP-powered contractions, it pumps accumulated water out through the pore.

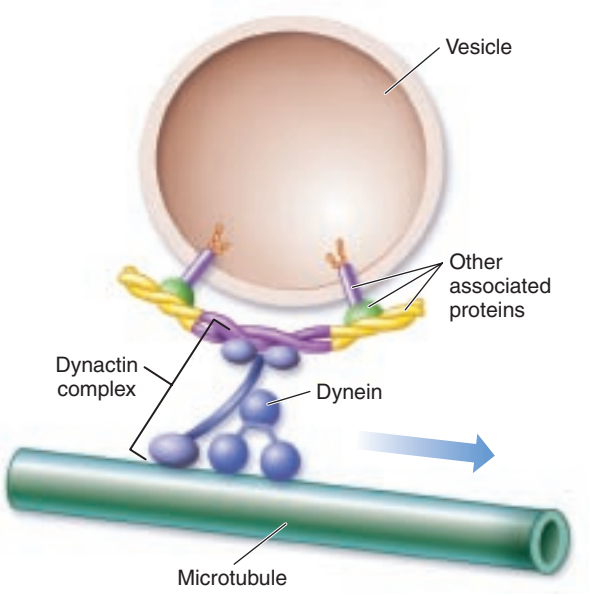


Figure 4.22 Molecular motors.
Vesicles that are transported within cells are attached with connector molecules, such as the dynactin complex shown here, to motor molecules, like dynein, which move along microtubules.

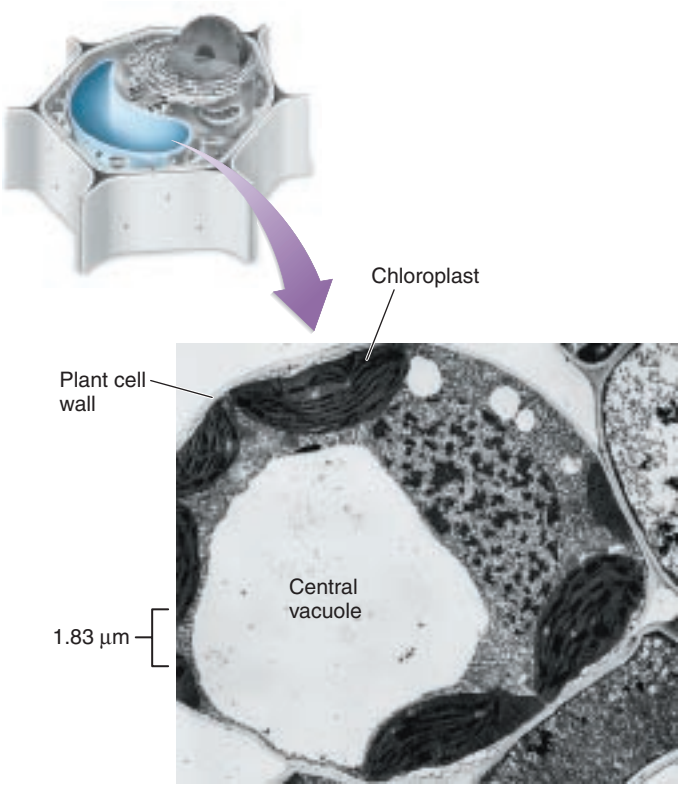


Figure 4.23 A plant central vacuole.
A plant's central vacuole stores dissolved substances and can increase in size to increase the surface area of a plant cell.

4.8 The cytoskeleton is a latticework of protein fibers that determines a cell's shape and anchors organelles to particular locations within the cytoplasm. Cells can move by changing their shape.

4.9 Outside the Plasma Membrane

Cell Walls Offer Protection and Support

Plants, fungi, and many protists cells share a characteristic with bacteria that is not shared with animal cells—that is, they have **cell walls,** which protect and support their cells. Eukaryotic cell walls are chemically and structurally different from bacterial cell walls. In plants, cell walls are composed of fibers of the polysaccharide cellulose, while in fungi they are composed of chitin. The **primary walls** of plant cells are laid down when the cell is still growing, and between the walls of adjacent cells is a sticky substance called the **middle lamella,** which glues the cells together (figure 4.24). Some plant cells produce strong **secondary walls,** which are deposited inside the primary walls of fully expanded cells.

An Extracellular Matrix Surrounds Animal Cells

As we discussed, many types of eukaryotic cells possess a cell wall exterior to the plasma membrane that protects the cell, maintains its shape, and prevents excessive water uptake. Animal cells are the great exception, lacking the cell walls that encase plants, fungi, and most protists. Instead, animal cells secrete an elaborate mixture of **glycoproteins** (proteins with short chains of sugars attached to them) into the space around them, forming the **extracellular matrix** (**ECM**) (figure 4.25).

The fibrous protein collagen, the same protein in fingernails and hair, is abundant in the ECM. Strong fibers of collagen and another fibrous protein, elastin, are embedded within a complex web of other glycoproteins called proteoglycans, which form a protective layer over the cell surface.

The ECM is attached to the plasma membrane by a third kind of glycoprotein, **fibronectin.** Fibronectin molecules bind not only to ECM glycoproteins but also to proteins called **integrins,** which are an integral part of the plasma membrane. Integrins extend into the cytoplasm, where they are attached to the microfilaments of the cytoskeleton. Linking ECM and cytoskeleton, integrins allow the ECM to influence cell behavior in important ways, altering gene expression and cell migration patterns by a combination of mechanical and chemical signalling pathways. In this way, the ECM can help coordinate the behavior of all the cells in a particular tissue.

4.9 Plant and protist cells encase themselves within a strong cell wall. In animal cells, which lack a cell wall, the cytoskeleton is linked by integrin proteins to a web of glycoproteins called the extracellular matrix.

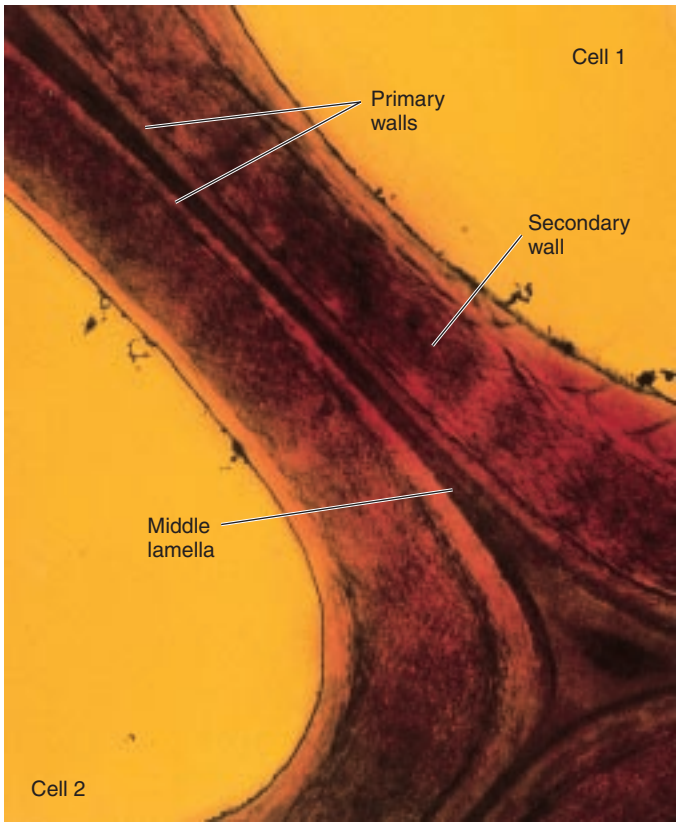


Figure 4.24 Cell walls in plants.
Plant cell walls are thick, strong, and rigid. Primary cell walls are laid down when the cell is young. Thicker secondary cell walls may be added later when the cell is fully grown. The middle lamella lies between the walls of adjacent cells and glues the cell together.

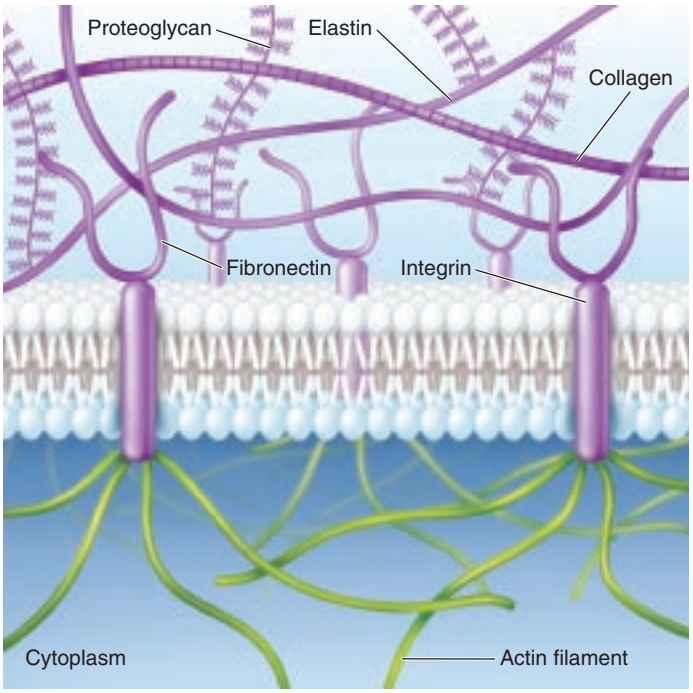


Figure 4.25 The extracellular matrix.
Animal cells are surrounded by an extracellular matrix composed of various glycoproteins that give the cells support, strength, and resilience.

4.10 Diffusion and Osmosis

For cells to survive, food particles, water, and other materials must pass into the cell, and waste materials must be eliminated. All of this moving back and forth across the cell's plasma membrane occurs in one of three ways: (1) water and other substances diffuse through the membrane; (2) food particles and sometimes liquids are engulfed by the membrane folding around them; or (3) proteins in the membrane act as doors that admit certain molecules only. First we will examine diffusion.

Diffusion

How a molecule moves—just where it goes—is totally random, like shaking marbles in a cup, so if two kinds of molecules are added together, they soon mix. The random motion of molecules always tends to produce uniform mixtures when a substance moves from regions where its concentration is high to regions where its concentration is lower (that is, *down* the **concentration gradient**). How does a molecule "know" in what direction to move? It doesn't—molecules don't "know" anything. A molecule is equally likely to move in any direction and is constantly changing course in random ways. There are simply more molecules able to move from where they are common than from where they are scarce. This mixing process is called **diffusion** (figure 4.26). Diffusion is the net movement of molecules down a concentration gradient toward regions of lower concentration (that is, where there are relatively fewer of them) as a result of random motion. Eventually, the substance will achieve a state of **equilibrium,** where there is no net movement toward any particular direction. The individual molecules of the substance are still in motion, but there is no overall directionality of the motion.

Osmosis

Diffusion allows molecules like oxygen, carbon dioxide, and nonpolar lipids to cross the plasma membrane. The movement of water molecules is not blocked because there are many small channels, called aquaporins that pass water freely through the membrane.

As in diffusion, water passes into and out of a cell down its concentration gradient, a process called **osmosis.** However, the movement of water into and out of a cell is dependent upon the concentration of other substances in solution. To understand how water moves into and out of a cell, let's focus on the water molecules already present inside a cell. What are they

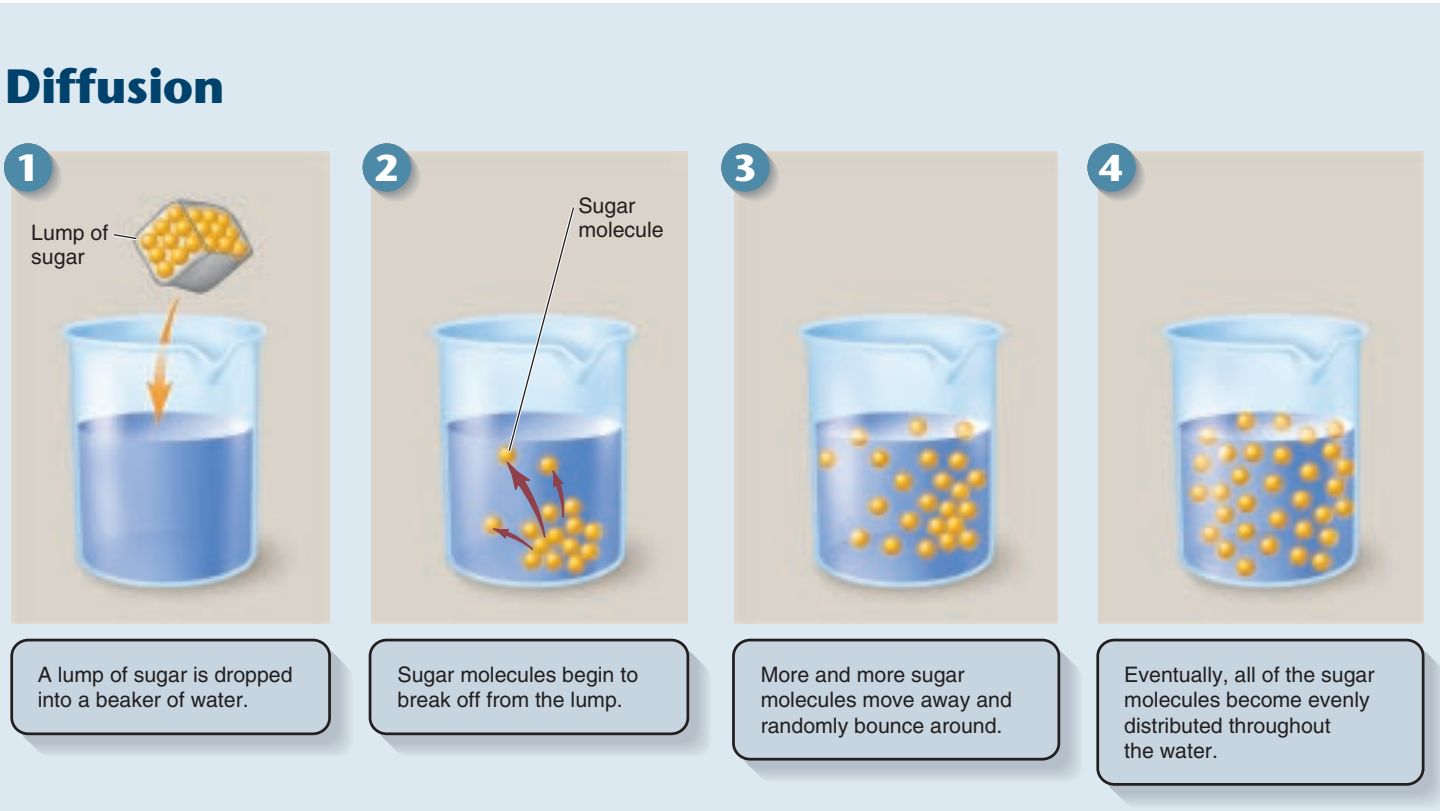


Figure 4.26 How diffusion works.
Diffusion is the mixing process that spreads molecules through the cell interior. To see how diffusion works, visualize a simple experiment in which a lump of sugar is dropped into a beaker of water.

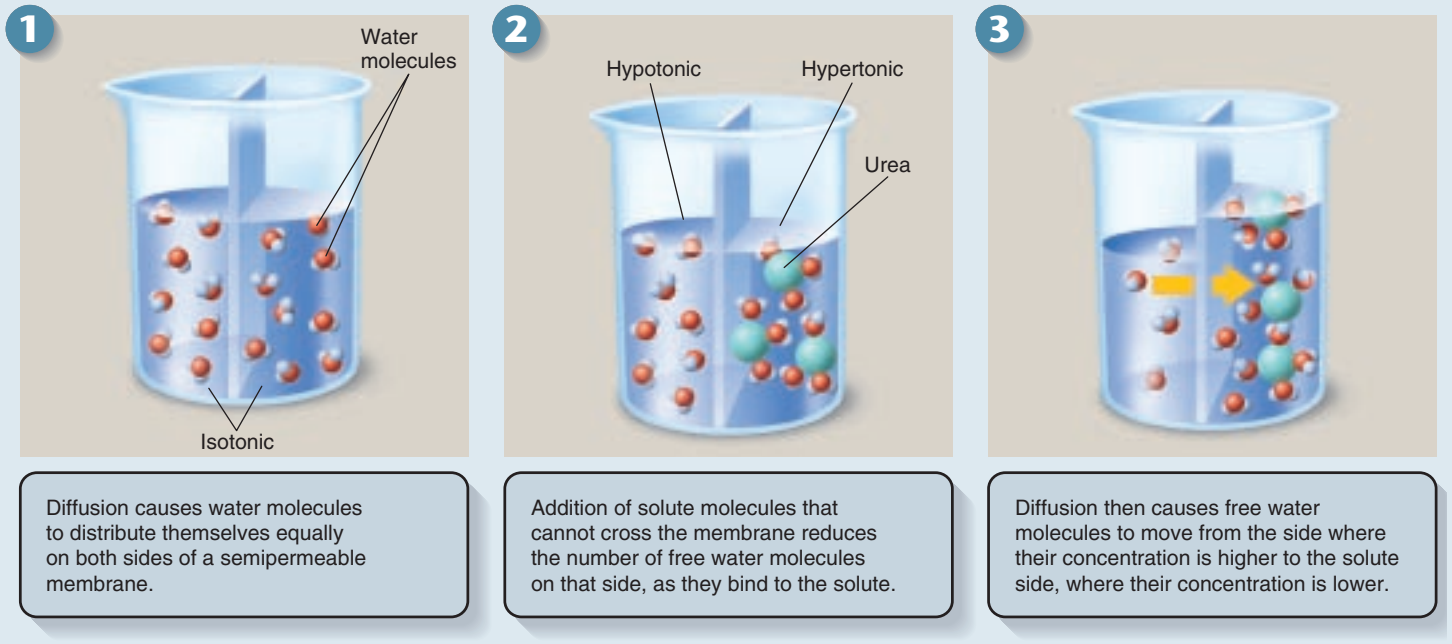


Figure 4.27 How osmosis works.
Osmosis is the net movement of water across a membrane toward the side with less "free" water. To visualize this, imagine adding polar urea molecules to one side of a vessel of water divided in the middle by a semipermeable membrane (lets water pass but not larger molecules). When such a polar solute is added, the water molecules that gather around each urea molecule are no longer free to diffuse across the membrane—in effect, the polar solute has reduced the number of free water molecules. Because the side of the membrane with less solute (the left) has more unbound water molecules than the side on the right with more solute, water moves by diffusion from the left to the right.

doing? Many of them are interacting with the sugars, proteins, and other polar molecules inside. Remember, water is very polar itself and readily interacts with other polar molecules. These social water molecules are not randomly moving about as they were outside; instead, they remain clustered around the polar molecules they are interacting with. As a result, while water molecules keep coming into the cell by random motion, they don't randomly come out again. Because more water molecules come in than go out, there is a net movement of water into the cell (figure 4.27).

The concentration of *all* molecules dissolved in a solution (called **solutes**) is called the osmotic concentration of the solution. If two solutions have unequal osmotic concentrations, the solution with the higher solute concentration is said to be **hypertonic** (Greek *hyper,* more than), and the solution with the lower one is **hypotonic** (Greek *hypo,* less than). If the osmotic concentrations of the two solutions are equal, the solutions are **isotonic** (Greek *iso,* the same).

Movement of water into a cell by osmosis creates pressure, called **osmotic pressure,** which can cause a cell to swell and burst. Most cells cannot withstand osmotic pressure unless their plasma membranes are braced to resist the swelling. If placed in pure water, they soon burst like over-inflated balloons (figure 4.28). That is why the cells of so many kinds of organisms have cell walls to stiffen their exteriors. In animals, the fluids bathing the cells have as many polar molecules dissolved in them as the cells do, so the problem doesn't arise.

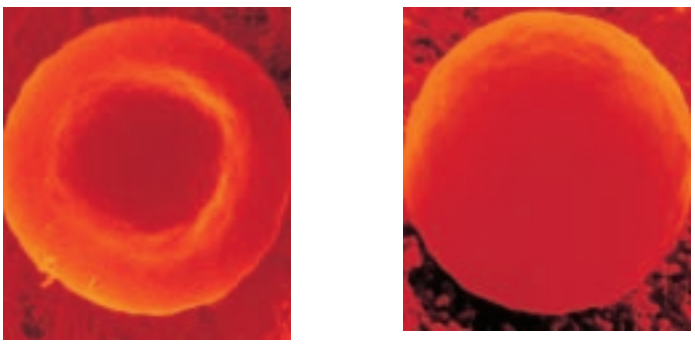


Figure 4.28 Osmotic pressure in a red blood cell.
(*a*) Normally, a red blood cell has a flattened, pillowlike appearance, the concentrations of solutes inside the cell and in the surrounding fluid are the same, and there is no net movement of water across the membrane. (*b*) If placed in pure water, a red blood cell swells and will ultimately burst because the concentration of solutes is higher inside the cell, and there is a net movement of water into the cell.

4.10 Random movements of molecules cause them to mix uniformly in solution, a process called diffusion. Water associated with polar solutes is not free to diffuse, and there is a net movement of water across a membrane toward the side with less "free" water, a process called osmosis.

4.11 Bulk Passage into and out of Cells

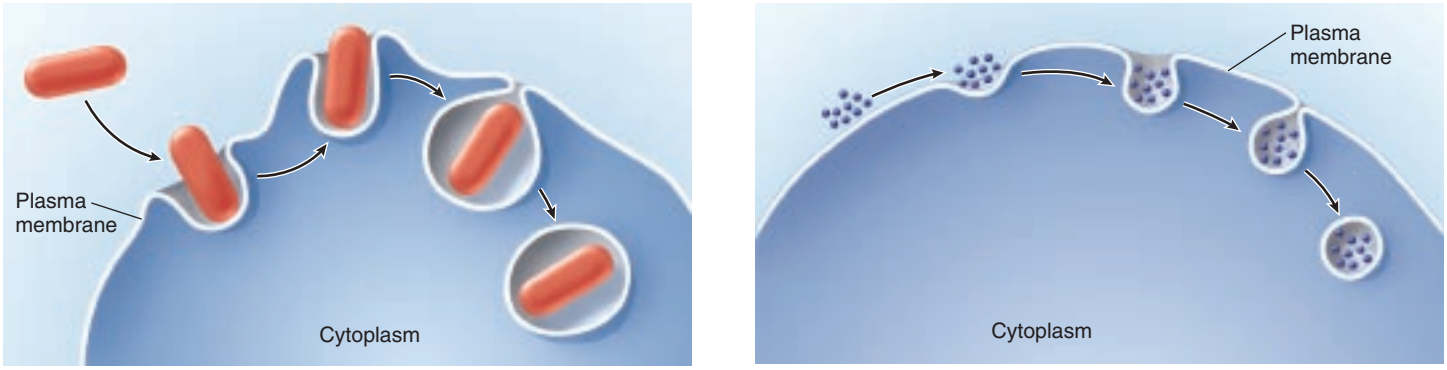
Endocytosis and Exocytosis

The cells of many eukaryotes take in food and liquids by extending their plasma membranes outward toward food particles. The membrane engulfs the particle and forms a vesicle—a membrane-bordered sac—around it. This process is called **endocytosis** (figure 4.29).

The reverse of endocytosis is **exocytosis,** the discharge of material from vesicles at the cell surface (figure 4.30). In plant cells, exocytosis is an important means of exporting the materials needed to construct the cell wall through the plasma membrane. Among protists, the discharge of a contractile vacuole is a form of exocytosis. In animal cells, exocytosis provides a mechanism for secreting many hormones, neurotransmitters, digestive enzymes, and other substances.

Phagocytosis and Pinocytosis

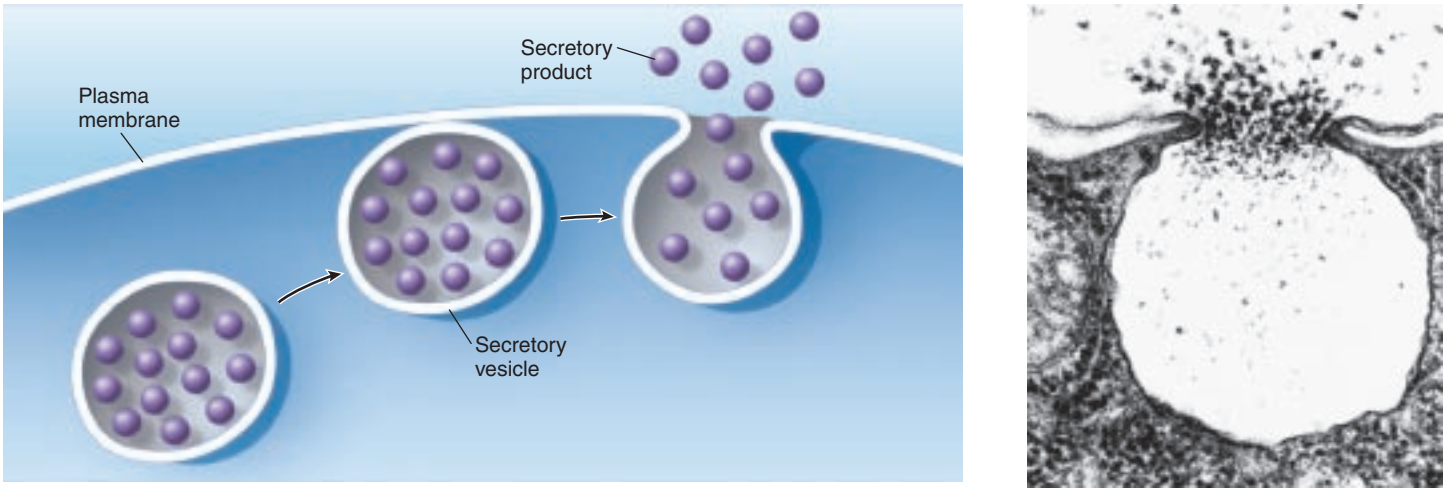
If the material the cell takes in is particulate (made up of discrete particles), such as an organism or some other fragment of organic matter (figure 4.29*a*), the process is called **phagocytosis** (Greek *phagein,* to eat, and *cytos,* cell). If the material



(a) Phagocytosis (b) Pinocytosis

Figure 4.29 Endocytosis

Endocytosis is the process of engulfing material by folding the plasma membrane around it, forming a vesicle. (*a*) When the material is an organism or some other relatively large fragment of organic matter, the process is called phagocytosis. (*b*) When the material is a liquid, the process is called pinocytosis.



(a) (b)

Figure 4.30 Exocytosis.

Exocytosis is the discharge of material from vesicles at the cell surface. (*a*) Proteins and other molecules are secreted from cells in small pockets called secretory vesicles, whose membranes fuse with the plasma membrane, thereby allowing the secretory vesicles to release their contents to the cell surface. (*b*) In the photomicrograph, you can see exocytosis taking place explosively.

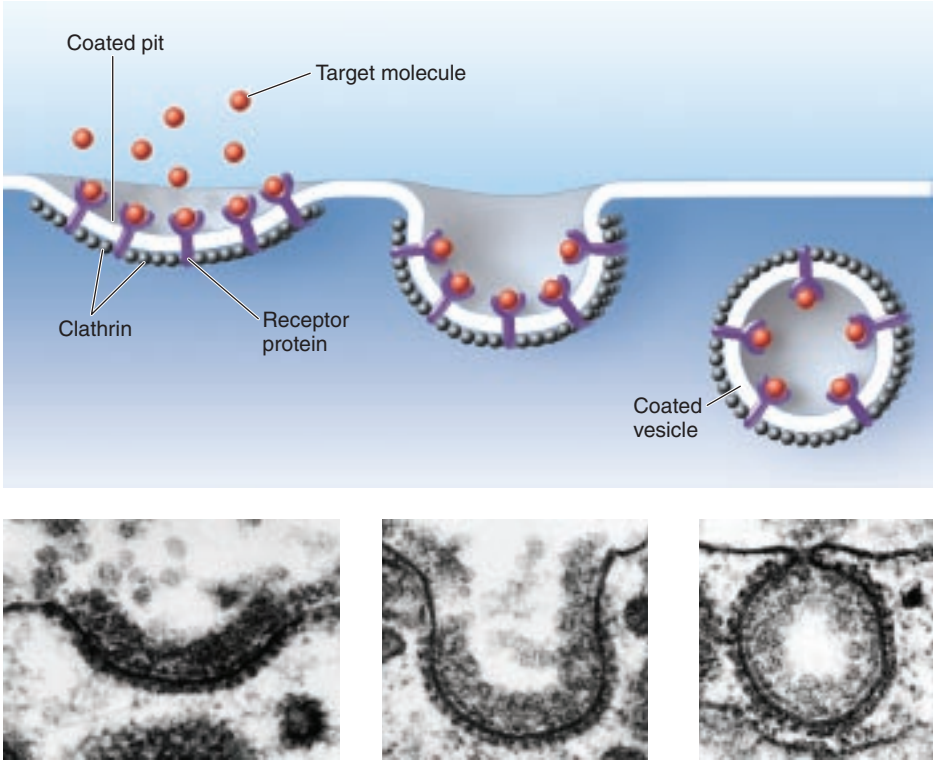


Figure 4.31 Receptor-mediated endocytosis.
Cells that undergo receptor-mediated endocytosis have pits coated with the protein clathrin that initiate endocytosis when target molecules bind to receptor proteins in the plasma membrane. In the photomicrographs, coated pit appears in the plasma membrane of a developing egg cell, covered with a layer of proteins (80,000X). When an appropriate collection of molecules gathers in the coated pit, the pit deepens, and eventually seals off to form a vesicle.

the cell takes in is liquid (figure 4.29*b*), it is called **pinocytosis** (Greek *pinein,* to drink). Pinocytosis is common among animal cells. Mammalian egg cells, for example, "nurse" from surrounding cells; the nearby cells secrete nutrients that the maturing egg cell takes up by pinocytosis. Virtually all eukaryotic cells constantly carry out these kinds of endocytosis, trapping particles and extracellular fluid in vesicles and ingesting them. Endocytosis rates vary from one cell type to another. They can be surprisingly high: some types of white blood cells ingest 25% of their cell volume each hour!

Receptor-Mediated Endocytosis

Specific molecules are often transported into eukaryotic cells through **receptor-mediated endocytosis.** Molecules to be transported first bind to specific receptors in the plasma membrane. The transport process is specific to only molecules that have a shape that fits snugly into the receptor. The plasma membrane of a particular kind of cell contains a characteristic battery of receptor types, each for a different kind of molecule.

The portion of the receptor molecule inside the membrane is trapped in an indented pit coated with the protein clathrin. The pits act like molecular mousetraps, closing over to form an internal vesicle when the right molecule enters the pit (figure 4.31). The trigger that releases the trap is the binding of the properly fitted target molecule to a receptor embedded in the membrane of the pit. When binding occurs, the cell reacts by initiating endocytosis. The process is highly specific and very fast.

One type of molecule that is taken up by receptor-mediated endocytosis is called low density lipoprotein (LDL). The LDL molecules bring cholesterol into the cell where it can be incorporated into membranes. Cholesterol plays a key role in determining the stiffness of the body's membranes. In the human genetic disease called hypercholesteremia, the receptors lack tails and so are never caught in the clathrin-coated pits and, thus, are never taken up by the cells. The cholesterol stays in the bloodstream of affected individuals, coating their arteries and leading to heart attacks.

It is important to understand that receptor-mediated endocytosis in itself does not bring substances directly into the cytoplasm of a cell. The material taken in is still separated from the cytoplasm by the membrane of the vesicle.

4.11 The plasma membrane can engulf materials by endocytosis, folding the membrane around the material to encase it within a vesicle.

4.12 Selective Permeability

From the point of view of efficiency, the problem with endocytosis is that it is expensive to carry out—the cell must make and move a lot of membrane. Also, endocytosis is not picky—in pinocytosis particularly, engulfing liquid does not allow the cell to choose which molecules come in. Cells solve this problem by using proteins in the plasma membrane as channels to pass molecules into and out of the cell. Because each kind of channel passes only a certain kind of molecule, the cell can control what enters and leaves, an ability called **selective permeability.**

Selective Diffusion

Some channels act like open doors. As long as a molecule fits the channel, it is free to pass through in either direction. Diffusion tends to equalize the concentration of such molecules on both sides of the membrane, with the molecules moving toward the side where they are scarcest. This mechanism of transport is called **selective diffusion.** One class of selectively open channels consists of ion channels, which are pores that span the membrane. Ions that fit the pore can diffuse through it in either direction. Such ion channels play an essential role in signaling by the nervous system.

Facilitated Diffusion

Most diffusion occurs through use of a special carrier protein. This protein binds only certain kinds of molecules, such as a particular sugar, amino acid, or ion, physically binding them on one side of the membrane and releasing them on the other. The direction of the molecule's net movement depends on its concentration gradient across the membrane. If the concentration is greater in the cytoplasm, the molecule is more likely to bind to the carrier on the cytoplasmic side of the membrane and be released on the extracellular side. If the concentration of the molecule is greater outside in the fluid surrounding the cell, the net movement will be from outside to inside. Thus the net movement always occurs from high concentration to low, just as it does in simple diffusion, but the process is facilitated by the carriers. For this reason, this mechanism of transport is given a special name, **facilitated diffusion** (figure 4.32).

A characteristic feature of transport by carrier proteins is that its rate can be saturated. If the concentration of a substance is progressively increased, the rate of transport of the substance increases up to a certain point and then levels off. There are a limited number of carrier proteins in the membrane, and when the concentration of the transported substance is raised high enough, all the carriers will be in use. The transport system is then said to be "saturated." When an investigator wishes to know if a particular substance is being transported across a membrane by a carrier system, or is diffusing across, he or she conducts experiments to see if the transport system can be saturated. If it can be saturated, it is carrier-mediated; if it cannot be saturated, it is not.

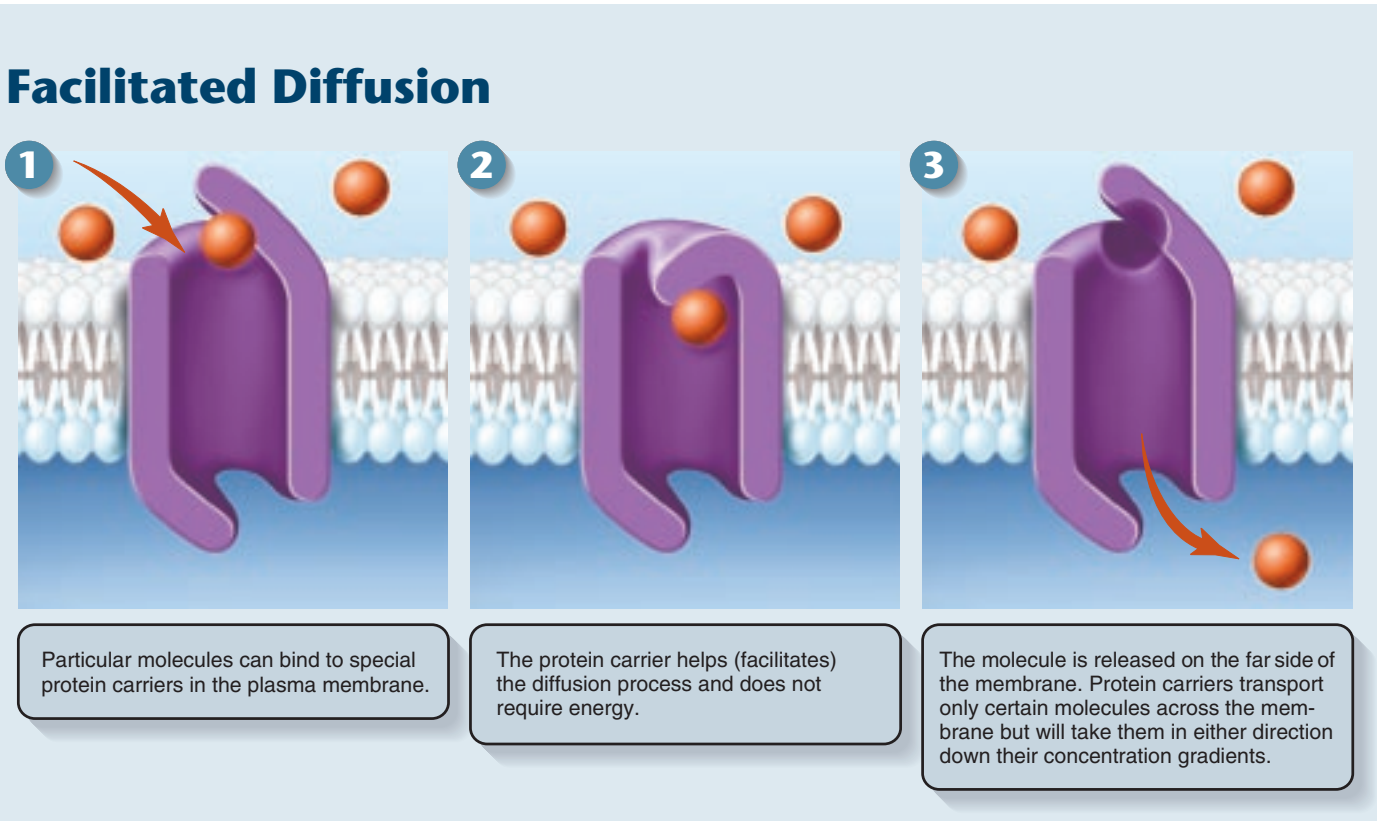


Figure 4.32 How facilitated diffusion works.

Active Transport

Other channels through the plasma membrane are closed doors. These channels open only when energy is provided. They are designed to enable the cell to maintain high or low concentrations of certain molecules, much more or less than exists outside the cell. If the doors were open, the molecules would simply flood in or out by facilitated diffusion. Instead, like motor-driven turnstiles, the channels operate only when energy is provided, and they move a certain substance only in one direction (up its concentration gradient). The operation of these one-way, energy-requiring channels results in **active transport,** the movement of molecules across a membrane to a region of higher concentration by the expenditure of energy.

You might think that the plasma membrane possesses all sorts of active transport channels for the transport of important sugars, amino acids, and other molecules, but in fact, almost all of the active transport in cells is carried out by only two kinds of channels, the sodium-potassium pump and the proton pump.

The Sodium-Potassium Pump. The first of these, the **sodium-potassium** (Na^+-K^+) **pump,** expends metabolic energy to actively pump sodium ions (Na^+) in one direction, out of cells, and potassium ions (K^+) in one direction, into cells (figure 4.33). More than one-third of all the energy expended by your body's cells is spent driving Na^+-K^+ pump channels. This energy is derived from *adenosine triphosphate (ATP),* a molecule we will learn about in chapter 5. Each channel can move over 300 sodium ions per second when working full tilt. As a result of all this pumping, there are far fewer sodium ions in the cell. This concentration gradient, paid for by the expenditure of considerable metabolic energy in the form of ATP molecules, is exploited by your cells in many ways. Two of the most important are (1) the conduction of signals along nerve cells (discussed in detail in chapter 28) and (2) the pulling into the cell of valuable molecules such as sugars and amino acids *against* their concentration gradient!

We will focus for a moment on this second process. The plasma membranes of many cells are studded with facilitated diffusion channels, which offer a path for sodium ions that have been pumped out by the Na^+-K^+ pump to diffuse back in. There is a catch, however; these channels require that the sodium ions have a partner in order to pass through—like a dancing party where only couples are admitted through the door. These special channels won't let sodium ions across unless another molecule tags along, crossing hand in hand with the sodium ion. In some cases the partner molecule is a sugar, in others an amino acid or other molecule. Because so many sodium ions are trying to get back in, this diffusion pressure drags in the partner molecules as well, even if they are already in high concentration within the cell. In this way, sugars and other actively transported molecules enter the cell—via special **coupled channels** (figure 4.34). Their movement is in fact a form of facilitated diffusion driven by the active transport of sodium ions.

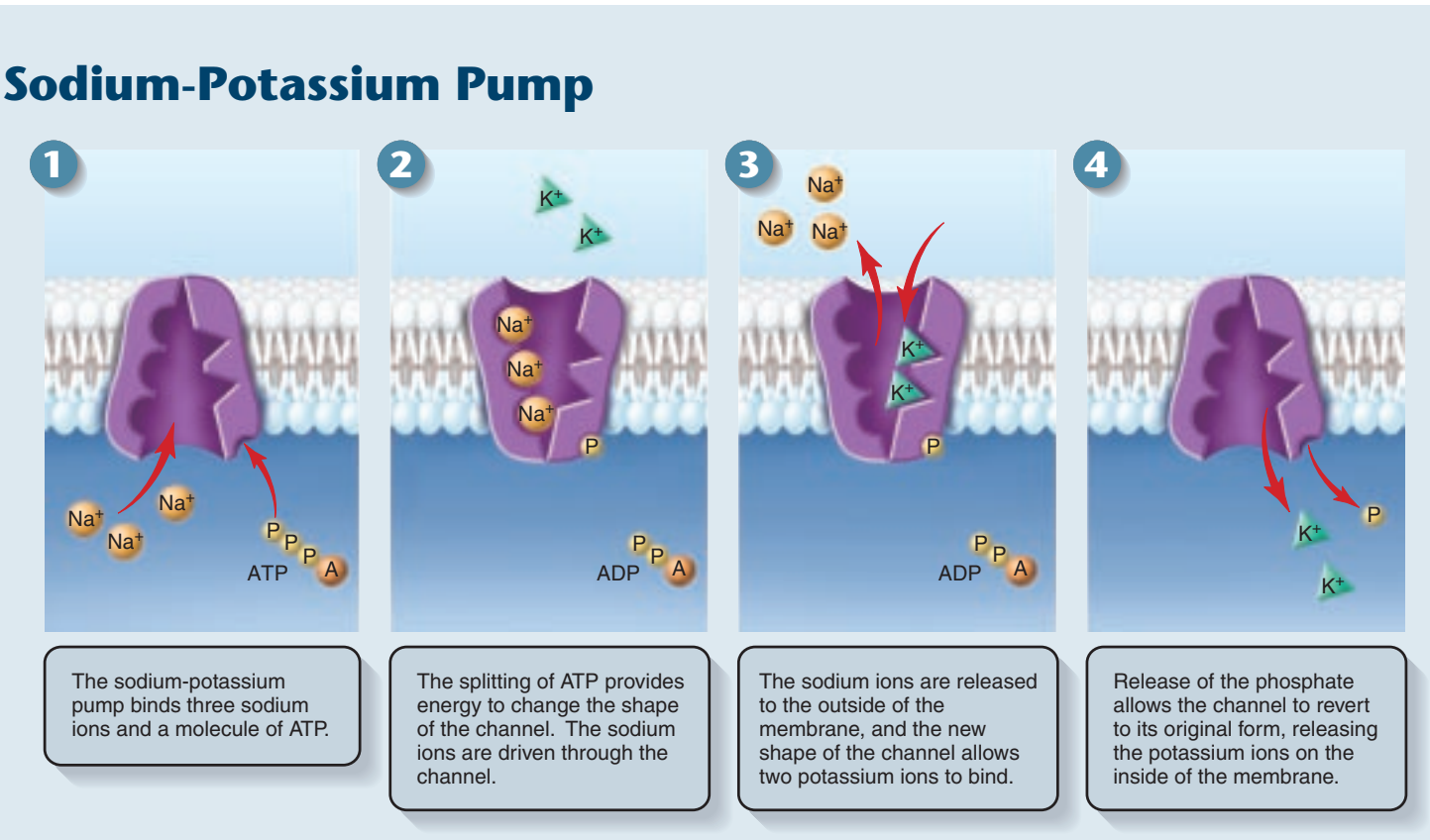


Figure 4.33 How the sodium-potassium pump works.

The Proton Pump. The second major active transport channel is the **proton pump,** a complex channel that expends metabolic energy to pump protons across membranes (figure 4.35). Just as in the sodium-potassium pump, this creates a diffusion pressure that tends to drive protons back across again, but in this case the only channels open to them are not coupled channels but rather channels that make ATP, the energy currency of the cell. This pump is the key to cell metabolism, which is the way cells convert photosynthetic energy or chemical energy from food into ATP. Its activity is referred to as **chemiosmosis.** We discuss chemiosmosis at greater length in chapter 6. Table 4.3 summarizes the mechanisms for transport across cell membranes that we have discussed.

How Cells Get Information

A cell's ability to respond appropriately to changes in its environment is a key element in its ability to survive. Cells have evolved a variety of ways of sensing things about them. Almost all cells sense their environment primarily by detecting chemical or electrical signals. To do this, cells employ a battery of special proteins called cell surface proteins embedded within the plasma membrane. The many proteins that protrude from the surface of a cell are the cell's only contact with the outside world—its only avenue of communication with its environment.

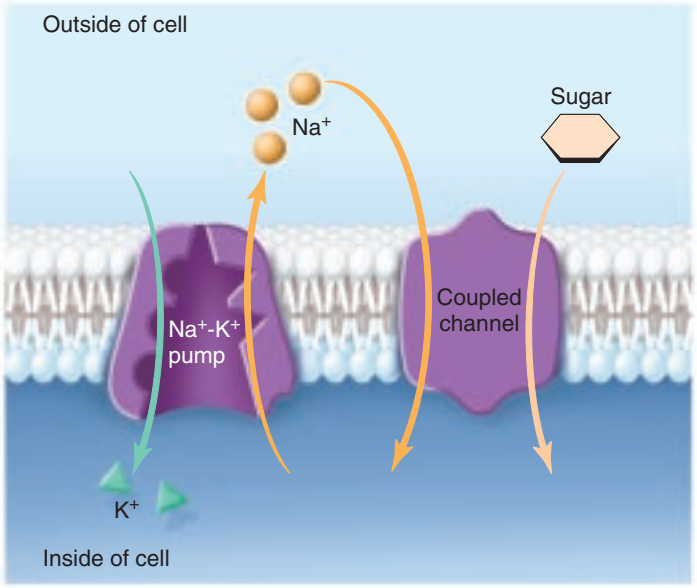


Figure 4.34 A coupled channel.
The active transport of a sugar molecule into a cell typically takes place in two stages—facilitated diffusion of the sugar coupled to active transport of sodium ions. The sodium-potassium pump keeps the Na^+ concentration higher outside the cell than inside. For Na^+ to diffuse back in through the coupled channel requires the simultaneous transport of a sugar molecule as well. Because the concentration gradient for Na^+ is steeper than the opposing gradient for sugar, Na^+ and sugar move into the cell.

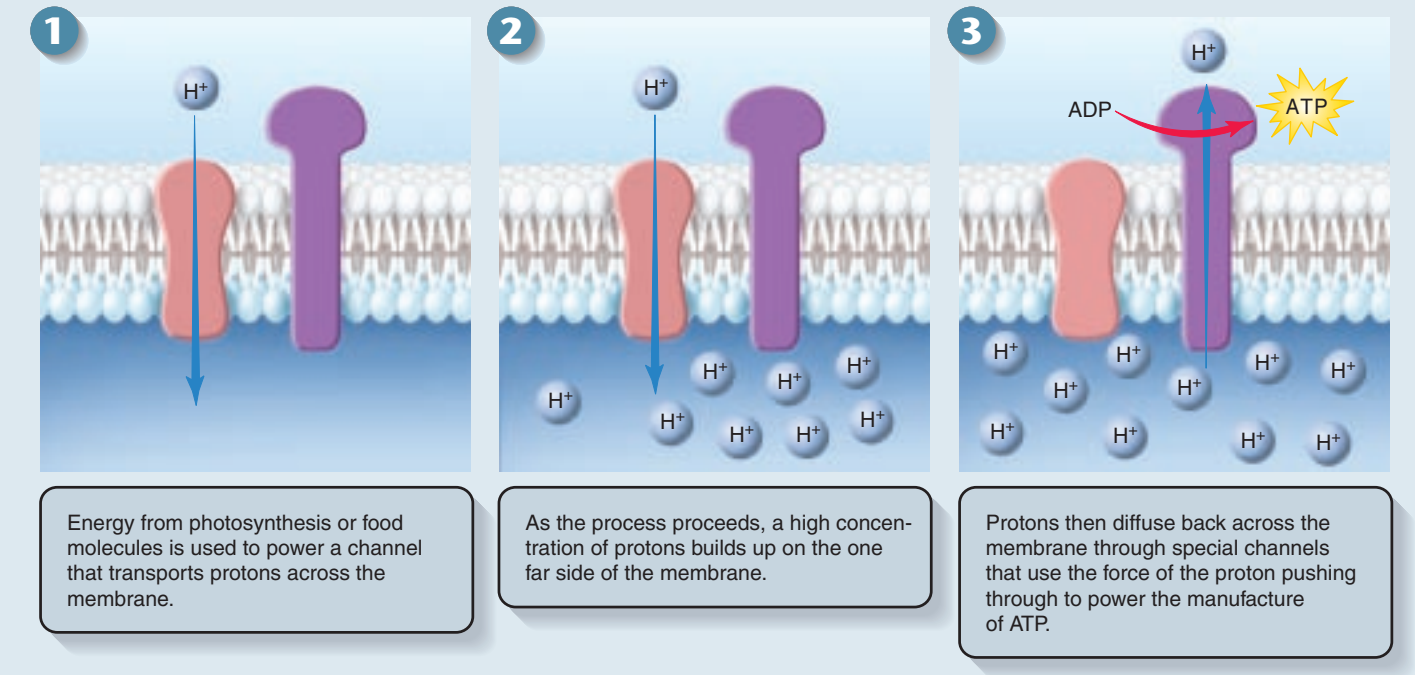
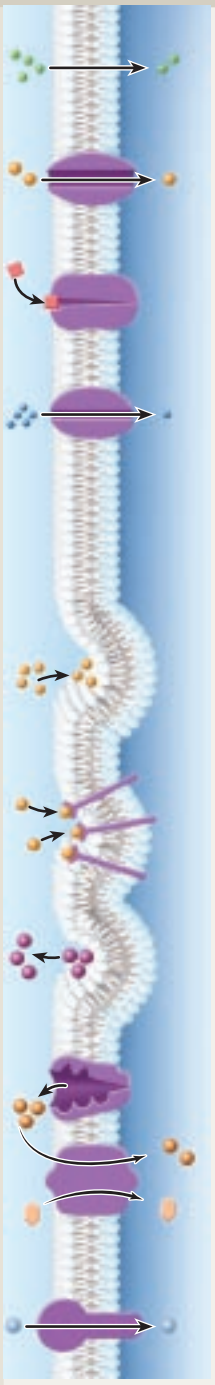


Figure 4.35 How the proton pump works.

TABLE 4.3 MECHANISMS FOR TRANSPORT ACROSS CELL MEMBRANES

Process	Passage Through Membrane	How It Works	Example
PASSIVE PROCESSES			
Diffusion			
Direct		Random molecular motion produces net migration of molecules toward region of lower concentration.	Movement of oxygen into cells
Protein channel		Polar molecules pass through a protein channel.	Movement of ions in or out of cell
Facilitated Diffusion			
Protein carrier		Molecule binds to carrier protein in membrane and is transported across; net movement is toward region of lower concentration.	Movement of glucose into cells
Osmosis			
Aquaporins		Diffusion of water across differentially permeable membrane.	Movement of water into cells placed in a hypotonic solution
ACTIVE PROCESSES			
Endocytosis			
Membrane vesicle			
Phagocytosis		Particle is engulfed by membrane, which folds around it and forms a vesicle.	Ingestion of bacteria by white blood cells
Pinocytosis		Fluid droplets are engulfed by membrane, which forms vesicles around them.	"Nursing" of human egg cells
Receptor-mediated endocytosis		Endocytosis is triggered by a specific receptor.	Cholesterol uptake
Exocytosis Membrane vesicle		Vesicles fuse with plasma membrane and eject contents.	Secretion of mucus
Active Transport			
Protein carrier			
Na^+-K^+ pump		Carrier expends energy to export a substance across a membrane against its concentration gradient.	Na^+ and K^+ against their concentration gradients
Coupled transport		Molecules are transported across a membrane against their concentration gradients by the cotransport of another substance down its concentration gradient.	Coupled uptake of glucose into cells against its concentration gradients
Proton pump		Protons are pumped across membranes against their concentration gradient. The proton gradient then drives the formation of ATP through another channel.	Proton pump in chemiosmosis

Sensing Chemical Information. Cells sense chemical information by means of cell surface proteins called **receptor proteins** projecting from their plasma membranes. These proteins bind a particular kind of molecule, but they do not provide a channel for the molecule to enter the cell. What the receptors do transmit into the cell is information. Often the information is about the presence of other cells in the vicinity—sensing cellular identity is the basis of the immune system, which defends your body from infection. In other instances the information may be a chemical signal sent from other cells.

Your body uses chemical signals called **hormones,** which provide a good example of how receptor proteins work. The end of a receptor protein exposed to the cell surface has a shape that fits to a specific hormone molecule, like insulin. Most of your cells have only a few insulin receptors, but your liver cells possess as many as 100,000 each! When

an insulin molecule encounters an insulin receptor on the surface of a liver cell, the insulin molecule binds to the receptor. This binding produces a change in the shape of the other end of the receptor protein (the end protruding into the interior of the cell), just as stamping hard on your foot causes your mouth to open. This change in receptor shape at the interior end initiates a change in cell activity—in this case, the end protruding into the cytoplasm begins to add phosphate groups to proteins, and so it activates a variety of cell processes involved with regulating glucose levels in the blood.

Sensing Voltage. Many cells can sense electrical as well as chemical information. Embedded within their plasma membranes are special channels for sodium or other ions, channels that are usually closed. Unlike the sodium-potassium pump, these closed channels do not open in response to chemical energy. What does open these channels is voltage. Like little magnets, they flip open or shut in response to electrical signals.

It is not difficult to understand how **voltage-sensitive channels** work. The center of the protein that provides the channel through the membrane is occupied by a voltage-sensitive "door"—a portion of the protein containing charged amino acids. When a voltage charge in the vicinity changes, the door flips up out of the way and the channel is open to the passage of sodium or other ions. Voltage-sensitive channels play many important roles within excitable cells of muscle tissue and the nervous system (see chapter 28).

Sensing Information Within the Cell. In eukaryotic cells, which have many compartments, it is very important that the different parts of the cell be able to sense what is going on elsewhere in the cytoplasm. This sort of communication is provided by the diffusion of molecules within the cytoplasm. Some of the chemical signals are molecules used in metabolism; others are within-cell hormones; and still others are ions, particularly those that indicate cell pH.

4.12 Cells are selectively permeable, admitting only certain molecules. Facilitated diffusion is selective transport across a membrane in the direction of lower concentration. Active transport is energy-driven transport across a membrane toward a region of higher concentration. Cells obtain information about their surroundings from a battery of proteins protruding from the cell membrane.

Exploring Current Issues

Additional Resources

Go to your campus library or look online to find the following articles, which further develop some of the concepts found in this chapter.

Dartmouth Medical School. (2002). Drink at least eight glasses of water a day—really? *Dartmouth Medical School News. Retrieved from www.dartmouth.edu/dms/news/2002_h2/08aug2002_water.shtml.*

Nadis, S. (2003). The cells that rule the seas. *Scientific American,* 289(6), 52.

Pray, L. (2003). Microbial multicellularity. *The Scientist,* 17(23), 20.

Spinney, L. (2004). The gene chronicles: your DNA doesn't just reveal where you came from, it also tells stories about the way your ancestors lived. *New Scientist,* 181(2433), 40.

Westphal, S. P. (2003). Rewrite the textbooks. *New Scientist,* 178(2401), 22.

Biology and Society Lecture: Cystic Fibrosis—A Membrane Disorder

Cystic fibrosis is the most common fatal gene disorder of Caucasians. The body cells of affected individuals secrete a thick mucus that clogs the airways of the lungs and blocks the ducts of the pancreas and liver. Most patients do not survive past their mid-twenties. There is no known cure.

Cystic fibrosis results from a defect in a gene encoding a plasma membrane protein called CFTR (*c*ystic *f*ibrosis *t*ransmembrane conductance *r*egulator). This protein channel regulates the passage of chloride ions into and out of the body's cells. A defective CFTR channel leads to a buildup of chloride ions within lung, pancreas, and liver cells, causing water to move into the cells by osmosis. Removing water from the surrounding mucus causes it to thicken, clogging the passageways. Attempts are under way to cure cystic fibrosis with gene therapy, using a virus to ferry healthy CFTR genes into patients lacking them.

Find these lectures, delivered by the author to his class at Washington University, online at www.mhhe.com/tlw4/exp4.

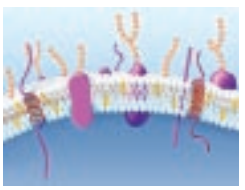
Summary

The World of Cells

4.1 Cells

- Cells are the smallest living structure. They consist of the cytoplasm enclosed in a plasma membrane. Organisms may be composed of a single cell or multiple cells.
- Materials pass into and out of cells across the plasma membrane. A smaller cell has a larger surface-to-volume ratio, which increases the area through which materials may pass (**figure 4.2**). Because cells are so small, a microscope is needed to view and study them (**table 4.1**).

4.2 The Plasma Membrane



- The plasma membrane that encloses all cells consists of a double layer of lipids, called the lipid bilayer, in which proteins are embedded. The structure of the plasma membrane is called the fluid mosaic model (**figure 4.6**).
- The lipid bilayer is made up of special lipid molecules called phospholipids (**figure 4.4**), which have a polar (water-soluble) end and a nonpolar (water-insoluble) end. The bilayer forms

because the nonpolar ends move away from the watery surroundings, forming the two layers (**figure 4.5**). Membrane proteins are either attached to the surface of the cell or are embedded within the membrane (**figure 4.7**).

Kinds of Cells

4.3 Prokaryotic Cells

- Prokaryotic cells are simple cellular organisms that lack nuclei or other internal organelles and are usually encased in a rigid cell wall (**figures 4.8 and 4.9**).

4.4 Eukaryotic Cells

- Eukaryotic cells are larger and more structurally complex compared with prokaryotic cells. They contain nuclei and have internal membrane systems (**figures 4.10 and 4.11**).

Tour of a Eukaryotic Cell

4.5 The Nucleus: The Cell's Control Center

- The nucleus is the command and control center of the cell. It contains the cell's DNA, which encodes the hereditary information that runs the cell (**figure 4.12**).

4.6 The Endomembrane System

- The endomembrane system is a collection of interior membranes that organize and divide the cell's interior into functional areas. The endoplasmic reticulum is a transport system that modifies and moves proteins and other molecules produced in the ER to the Golgi complex (**figure 4.13**). The Golgi complex is a delivery system that carries molecules to the surface of the cell where they are released to the outside (**figure 4.14 and 4.15**).

4.7 Organelles That Contain DNA

- Mitochondria and chloroplasts are cell-like organelles that appear to be ancient bacteria that formed endosymbiotic relationships with early eukaryotic cells (**figure 4.18**). The mitochondrion is called the powerhouse of the cell because it is the site of oxidative metabolism, an energy-extracting process (**figure 4.16**). Chloroplasts are the site of photosynthesis and are present in plants and algal cells (**figure 4.17**).

4.8 The Cytoskeleton: Interior Framework of the Cell

- The interior of the cell contains a network of protein fibers, called the cytoskeleton, that supports the shape of the cell and anchors organelles in place (**figure 4.19**).
- Cells are dynamic structures. Centrioles, microtubules, and molecular motors move materials around inside the cell. Cilia and flagella propel the cell through its environment (**figures 4.20–4.22**).

4.9 Outside the Plasma Membrane

- The cells of plants, fungi, and many protists have cell walls that serve a similar function as prokaryotic cell walls, but are composed of different molecules (**figure 4.24**). Animal cells lack cell walls but contain an outer layer of glycoproteins, called the extracellular matrix (**figure 4.25**).

Transport Across Plasma Membranes

4.10 Diffusion and Osmosis

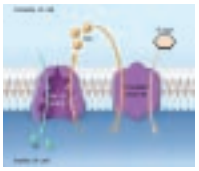
- Materials pass into and out of the cell passively through diffusion and osmosis. Diffusion is the movement of molecules from an area of high concentration to an area of low concentration (**figure 4.26**). Molecules pass into and out of cells down their concentration gradients. Osmosis is the movement of water into and out of the cell, driven by differing concentrations of solute. Water molecules move to areas of higher solute concentrations (**figure 4.27**).

4.11 Bulk Passage into and out of Cells

- Larger structures or larger quantities of material move into and out of the cell through endocytosis and exocytosis, respectively (**figures 4.29 and 4.30**). Receptor-mediated endocytosis is a selective transport process, bringing in only those substances that are able to bind to specific receptors (**figure 4.31**).

4.12 Selective Permeability

- Selective transport of materials across the membrane is accomplished by facilitated diffusion and active transport.
- Facilitated diffusion is driven by the concentration gradient, transporting substances down their concentration gradient, but substances must bind to a membrane transporter, called a carrier, in order to pass across the membrane (**figure 4.32**).
- Active transport involves the input of energy to transport substances against (or up) their concentration gradients. Examples include the sodium-potassium pump (**figure 4.33**), coupled channels (**figure 4.34**), and the proton pump (**figure 4.35**).



- Cells gain information from their environment through specialized membrane protein receptors and channels.

Self-Test

1. Cell theory includes the principle that
   a. cells are the smallest living things. Nothing smaller than a cell is considered alive.
   b. all cells are surrounded by cell walls that protect them.
   c. all organisms are made up of many cells arranged in specialized, functional groups.
   d. all cells are made of smaller subunits called organelles. Nothing smaller than an organelle is considered alive.

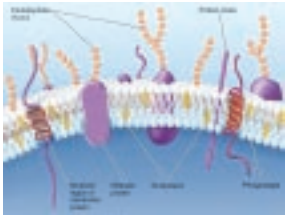
2. The plasma membrane is
   a. a carbohydrate layer that surrounds groups of cells, called tissues, to protect them.
   b. a double lipid layer with proteins inserted in it, which surrounds every cell individually.
   c. a thin sheet of structural proteins that lines the inside of some body cavities.
   d. composed of blood plasma that has solidified into a protective barrier.

3. Organisms that have cells with a relatively uniform cytoplasm and no organelles are called _____, and organisms whose cells have organelles and a nucleus are called _____.
   a. cellulose, nuclear
   b. flagellated, streptococcal
   c. eukaryotes, prokaryotes
   d. prokaryotes, eukaryotes
4. Within the nucleus of a cell you can find
   a. a nucleolus.
   b. many ribosomes.
   c. a cytoskeleton.
   d. all of these.
5. The endomembrane system within a cell includes the
   a. cytoskeleton and the ribosomes.
   b. prokaryotes and the eukaryotes.
   c. endoplasmic reticulum and the Golgi complex.
   d. mitochondria and the chloroplasts.
6. Until fairly recently, it was thought that only the nucleus of each cell contained DNA. We now know that DNA is also carried in the
   a. cytoskeleton and the ribosomes.
   b. prokaryotes and the eukaryotes.
   c. endoplasmic reticulum and the Golgi bodies.
   d. mitochondria and the chloroplasts.
7. Which of the following statements is true.
   a. All cells have a cell wall for protection and structure.
   b. Eukaryotic cells in plants and fungi, and all prokaryotes, have a cell wall.
   c. There is a second membrane composed of structural carbohydrates surrounding all cells.
   d. Prokaryotes and all cells of eukaryotic animals have a cell wall.
8. If you put a drop of food coloring into a glass of water, the drop of color will
   a. fall to the bottom of the glass and sit there unless you stir the water; this is because of hydrogen bonds.
   b. float on the top of the water, like oil, unless you stir the water; this is because of surface tension.
   c. instantly disperse throughout the water; this is because of osmosis.
   d. slowly disperse throughout the water; this is because of diffusion.
9. When large molecules such as food particles need to get into a cell, they cannot easily pass through the plasma membrane, and so they move across the membrane through the processes of
   a. diffusion and osmosis.
   b. endocytosis and phagocytosis.
   c. exocytosis and pinocytosis.
   d. permeability and reception.
10. Active transport of certain molecules involves
   a. diffusion and osmosis.
   b. endocytosis and phagocytosis.
   c. energy and specialized pumps or channels.
   d. permeability and reception.

Visual Understanding

1. **Figure 4.3** The first microscope was used in about 1590. Electron microscopes came into common use about 70 years ago. Just over 100 years ago most physicians did not wash up between patients, even when someone had just died, or was very sick. Explain why it took so long to convince doctors to wash their hands.

2. **Figure 4.6** A hormone molecule is a messenger, circulating through the bloodstream. It needs to find only a particular subset of cells to deliver its message. How does the hormone find the correct cells?



Challenge Questions

World of Cells You are designing a new single-celled organism. Discuss the problems of size, getting molecules such as nutrients and wastes in and out, temperature, and energy.

Kinds of Cells Antibiotics are medicines that target bacterial infections in vertebrates. How can an antibiotic kill all the bacterial cells and not harm vertebrate cells; what part of the bacterial cell must antibiotics be targeting and why?

Tour of a Eukaryotic Cell Compare the cellular organelles and other structures to the parts of a city—for example, the nucleus is city hall and the DNA is all the city's laws and instructions.

Transport Across Cell Membranes Compare the mechanisms required for a cell to obtain all the different kinds of molecules that it needs.

Online Learning Center

Visit the Online Learning Center for this chapter at www.mhhe.com/tlw4/ch4 for quizzes, animations, interactive learning exercises, and other study tools. At the site you will also find extended answers to the end-of-chapter questions.