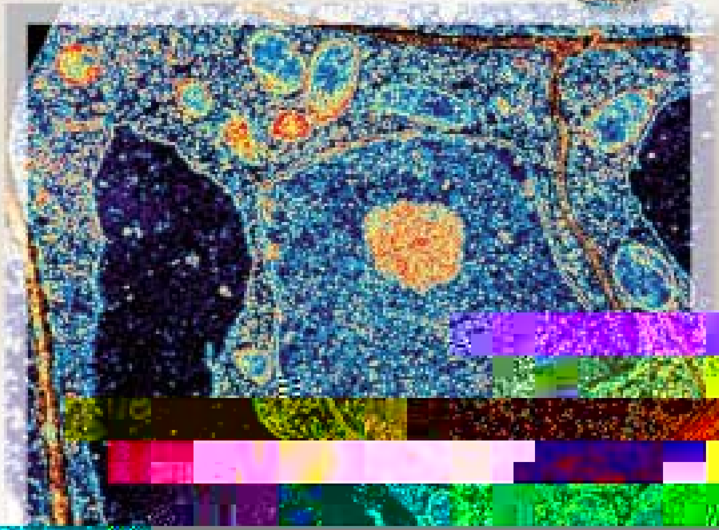
C H A P T E R 3

Cell Structure and Function



Chapter Concepts

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- What structures within eukaryotic cells are responsible for carrying out specific

I

3.1 The Cellular Level of Organization

The cell marks the boundary between the nonliving and the living. The molecules that serve as food for a cell and the macromolecules that make up a cell are not alive, and yet the cell is alive. Thus, the answer to what life is must lie within the cell, because the smallest living organisms are unicellular, while larger organisms are multicellular—that is, composed of many cells. The diversity of cells is exemplified by the many types in the human body, such as muscle cells and nerve cells. But despite variety of form and function, cells contain the same components. The basic components that are common to all cells regardless of their specializations are the subject of this chapter. The Science Focus on these two pages introduces you to the microscopes most used today to study cells. Electron microscopy and biochemical analysis have revealed that the cell actually contains **organelles,** tiny specialized structures performing specific cellular functions.

Today we are accustomed to thinking of living things as being constructed of cells. But the word cell didn't enter biology until the seventeenth century. Antonie van Leeuwenhoek of Holland is now famous for making his own microscopes and observing all sorts of tiny things that no one had seen before. Robert Hooke, an Englishman, confirmed Leeuwenhoek's observations and was the first to use the term **cell.** The tiny chambers he observed in the honeycomb structure of cork reminded him of the rooms, or cells, in a monastery.

A hundred years later—in the 1830s—the German microscopist Matthias Schleiden said that plants are composed of cells; his counterpart, Theodor Schwann, said that animals are also made up of living units called cells. This was quite a feat, because aside from their own exhausting work, both had to take into consideration the studies of many other microscopists. Rudolf Virchow, another German microscopist, later came to the conclusion that cells don't suddenly appear; rather, they come from preexisting cells.

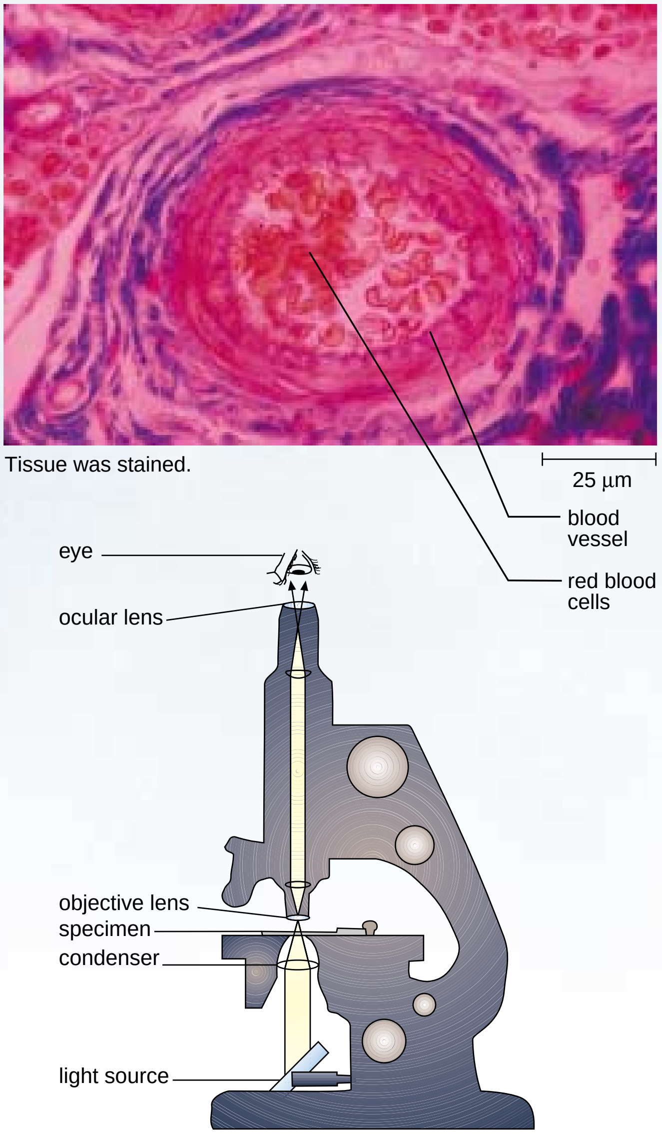
Today, the **cell theory,** which states that all organisms are made up of basic living units called cells and that cells come only from preexisting cells, is a basic theory of biology.

The cell theory states the following:

- All organisms are composed of one or more cells.
- Cells are the basic living unit of structure and function in organisms.
- All cells come only from other cells.

Three types of microscopes are most commonly used today: the compound light microscope, transmission electron microscope, and scanning electron microscope. Figure 3A depicts these microscopes, along with a micrograph of red blood cells viewed with each one.

In a compound light microscope, light rays passing through a specimen are brought to a focus by a set of glass lenses, and the resulting image is then viewed by the human eye. In the transmission electron microscope, electrons passing through a specimen are brought to a focus by a set of magnetic lenses, and the resulting image is projected onto a fluorescent screen or photographic film.



Compound light microscope

Figure 3A Blood vessels and red blood cells viewed with three different types of microscopes.

Science Focus

Microscopy Today

The magnification produced by an electron microscope is much higher than that of a light microscope (50,0003 compared to 1,0003). Also, the ability of the electron microscope to make out detail is much greater. The distance needed to distinguish two points as separate is much less for an electron microscope than for a light microscope (10 nm compared to 200 nm[1]). The greater resolving power of the electron microscope is due to the fact that electrons travel at a much shorter wavelength than do light rays. However, because electrons only travel in a vacuum, the object is always dried out before viewing, whereas even living objects can be observed with a light microscope.

A scanning electron microscope provides a three-dimensional view of the surface of an object. A narrow beam of electrons is scanned over the surface of the specimen, which has been coated with a thin layer of metal. The metal gives off secondary electrons, which are collected to produce a television-type picture of the specimen's surface on a screen.

A picture obtained using a light microscope is sometimes called a photomicrograph, and a picture resulting from the use of an electron microscope is called a transmission electron micrograph (TEM) or a scanning electron micrograph (SEM), depending on the type of microscope used.

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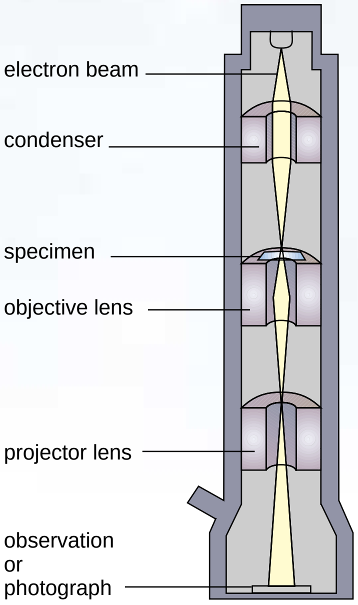
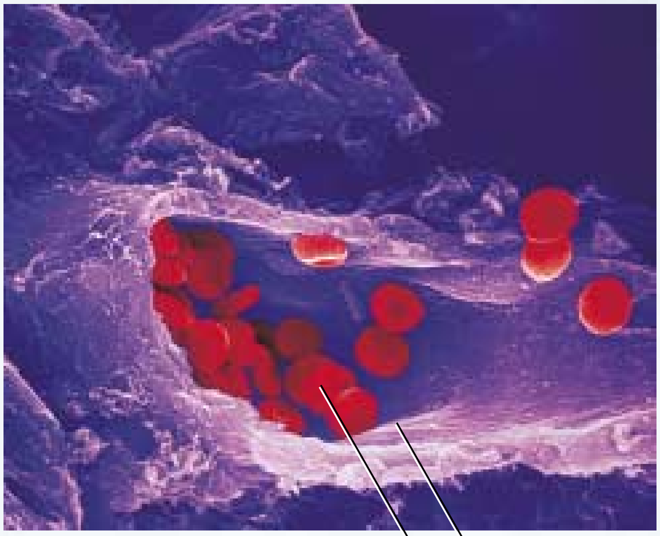
[1] nm = nanometer. See Appendix C, Metric System.

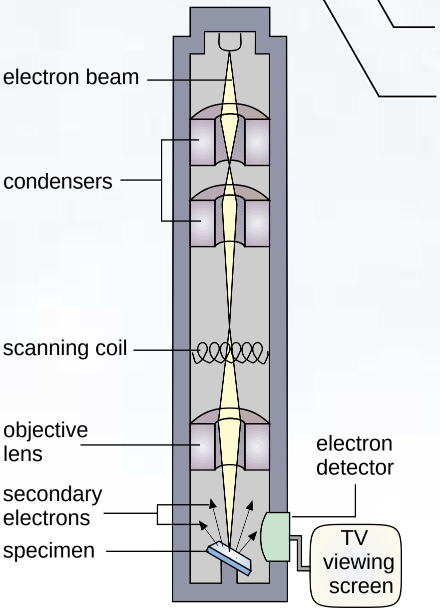
Tissue was stained.



Transmission electron microscope



Micrograph was colored.



Scanning electron microscope

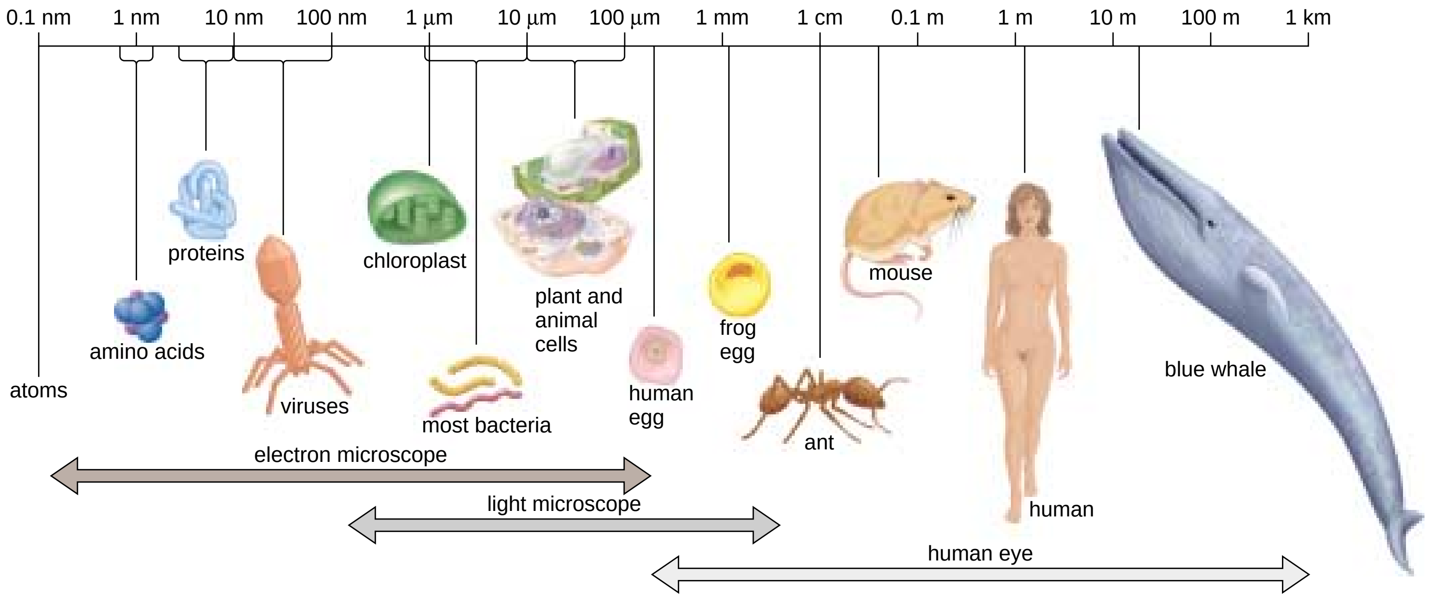
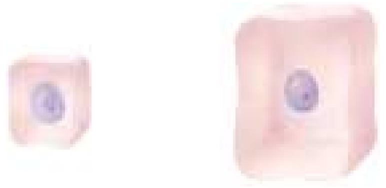


Figure 3.1 **The sizes of living things and their components.**
It takes a microscope to see most cells and lower levels of biological organization. Cells are visible with the light microscope, but not in much detail. An electron microscope is needed to see organelles in detail and to make out viruses and molecules. Notice that in this illustration each higher unit is 10 times greater than the lower unit. (In the metric system, 1 meter = 10^2 cm = 10^3 mm = 10^6 μm = 10^9 nm—see Appendix C.)

Cell Size

Figure 3.1 outlines the visual ranges of the eye, light microscope, and electron microscope. Cells are quite small. A frog's egg, at about one millimeter (mm) in diameter, is large enough to be seen by the human eye. But most cells are far smaller than one millimeter; some are even as small as one micrometer (μm)—one-thousandth of a millimeter. Cell inclusions and macromolecules are even smaller than a micrometer and are measured in terms of nanometers (nm).

To understand why cells are so small and why we are multicellular, consider the surface/volume ratio of cells. Nutrients enter a cell and wastes exit a cell at its surface; therefore, the amount of surface represents the ability to get material in and out of the cell. A large cell requires more nutrients and produces more wastes than a small cell. In other words, the volume represents the needs of the cell. Yet, as cells get larger in volume, the proportionate amount of surface area actually decreases, as you can see by comparing these two cells:


small cell—
more surface area
per volume

large cell—
less surface area
per volume

A small cube that is 1 mm tall has a surface area of 6 mm^2 because each side has a surface area of 1 mm^2, and 6 × 1 mm^2 is 6 mm^2. Notice that the ratio of surface area to volume is 6:1 because the surface area is 6 mm^2 and the volume is 1 mm^3. Contrast this with a larger cube that is 2 mm tall. The surface area increases to 24 mm^2 because the surface area of each side is 4 mm^2, and 6 × 4 is 24 mm^2. The volume of this larger cube is 8 mm^3 because height × width × depth is 8 mm^3. The ratio of surface area to volume of the larger cube is 3:1 because the surface area is 24 mm^2 and the volume is 8 mm^3. We can conclude then that a small cell has a greater surface area to volume ratio than does a larger cell.

Therefore, small cells, not large cells, are likely to have an adequate surface area for exchanging wastes for nutrients. We would expect, then, a size limitation for an actively metabolizing cell. A chicken's egg is several centimeters in diameter, but the egg is not actively metabolizing. Once the egg is incubated and metabolic activity begins, the egg divides repeatedly without growth. Cell division restores the amount of surface area needed for adequate exchange of materials. Further, cells that specialize in absorption have modifications that greatly increase the surface area per volume of the cell. For example, the columnar cells along the surface of the intestinal wall have surface foldings called microvilli (sing., microvillus), which increase their surface area.

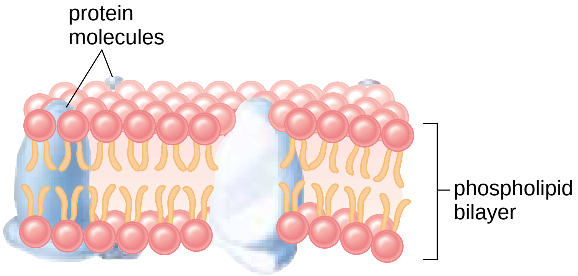
A cell needs a surface area that can adequately exchange materials with the environment. Surface-area-to-volume considerations require that cells stay small.

3.2 Eukaryotic Cells

Eukaryotic cells have a nucleus, a large structure that controls the workings of the cell because it contains the genes.

Outer Boundaries of Animal and Plant Cells

All cells, including plant and animal cells, are surrounded by a **plasma membrane,** a phospholipid bilayer in which protein molecules are embedded.



The plasma membrane is a living boundary that separates the living contents of the cell from the nonliving surrounding environment. Inside the cell, the nucleus is surrounded by the **cytoplasm,** a semifluid medium that contains organelles. The plasma membrane regulates the entrance and exit of molecules into and out of the cytoplasm.

Plant cells (but not animal cells) have a permeable but protective **cell wall** in addition to a plasma membrane. Many plant cells have both a primary and secondary cell wall. A main constituent of a primary cell wall is cellulose molecules. Cellulose molecules form fibrils that lie at right angles to one another for added strength. A cell wall sometimes forms inside the primary cell wall. Such secondary cell walls contain lignin, a substance that makes them even stronger than primary cell walls.

Organelles of Animal and Plant Cells

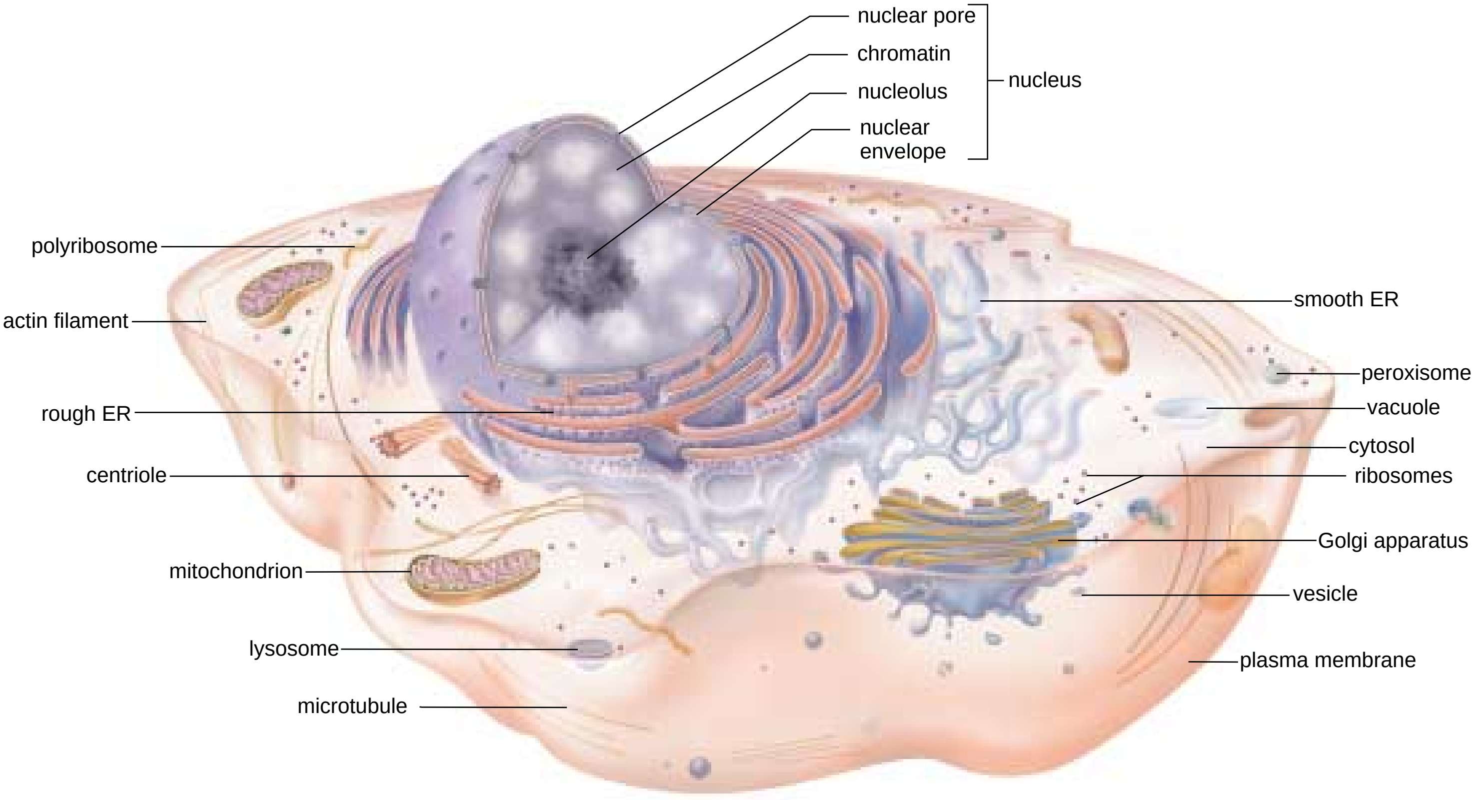
Animal and plant cells contain **organelles,** small bodies that have a specific structure and function. Originally the term organelle referred to only membranous structures, but we will use it to include any well-defined internal subcellular structure (Table 3.1). Still, membranes compartmentalize the cell so that its various functions are kept separate from one another. Just as all the assembly lines of a factory are in operation at the same time, so all the organelles of a cell function simultaneously. Raw materials enter a factory and then are turned into various products by different departments. In the same way, chemicals are taken up by the cell and then processed by the organelles. The cell is a beehive of activity the entire twenty-four hours of every day.

Both animal cells (Fig. 3.2) and plant cells (Fig. 3.3) contain mitochondria, while only plant cells have chloroplasts. Only animal cells have centrioles. Note that the color chosen to represent each structure in the plant and animal cell is used for that structure throughout the chapters of this part.

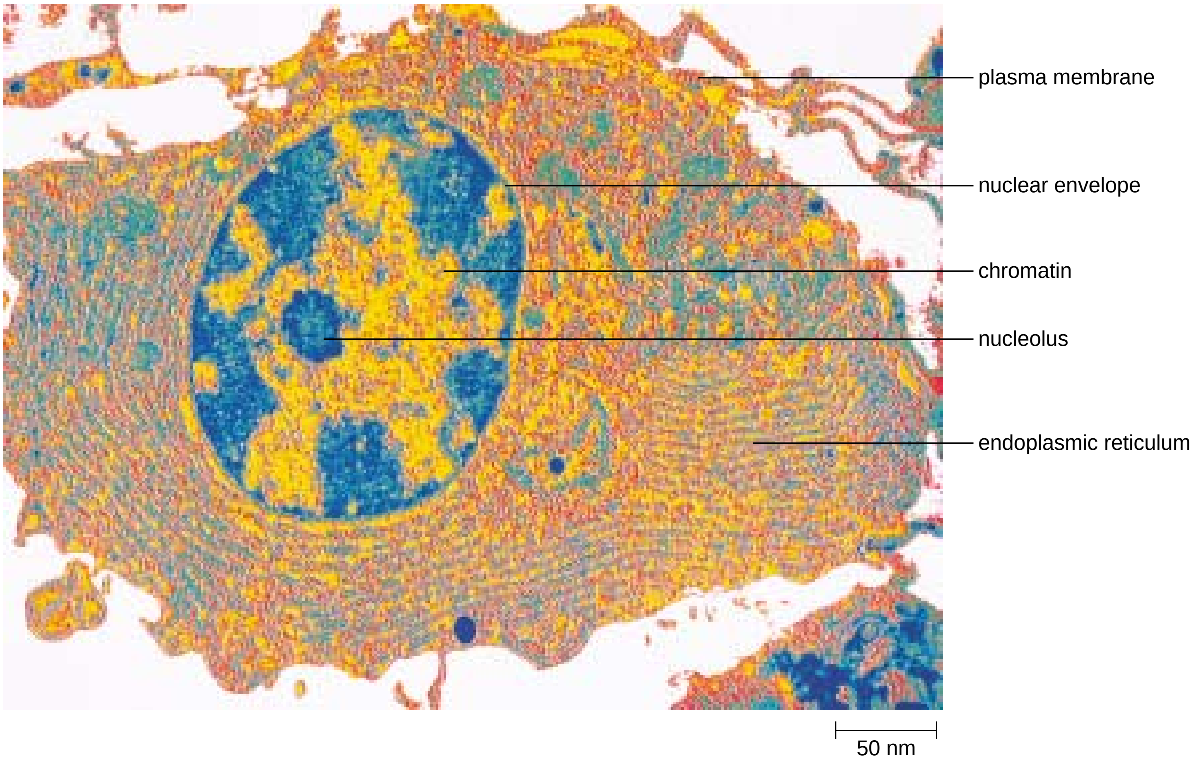
Table 3.1 Eukaryotic Structures in Animal Cells and Plant Cells

Name	Composition	Function
Cell wall*	Contains cellulose fibrils	Support and protection
Plasma membrane	Phospholipid bilayer with embedded proteins	Defines cell boundary; regulation of molecule passage into and out of cells
Nucleus	Nuclear envelope nucleoplasm, chromatin, and nucleoli	Storage of genetic information; synthesis of DNA and RNA
Nucleolus	Concentrated area of chromatin, RNA, and proteins	Ribosomal subunit formation
Ribosome	Protein and RNA in two subunits	Protein synthesis
Endoplasmic reticulum (ER)	Membranous flattened channels and tubular canals	Synthesis and/or modification of proteins and other substances, and transport by vesicle formation
Rough ER	Studded with ribosomes	Protein synthesis
Smooth ER	Having no ribosomes	Various; lipid synthesis in some cells
Golgi apparatus	Stack of membranous saccules	Processing, packaging, and distribution of proteins and lipids
Vacuole and vesicle	Membranous sacs	Storage of substances
Lysosome	Membranous vesicle containing digestive enzymes	Intracellular digestion
Peroxisome	Membranous vesicle containing specific enzymes	Various metabolic tasks
Mitochondrion	Inner membrane (cristae) bounded by an outer membrane	Cellular respiration
Chloroplast*	Membranous grana bounded by two membranes	Photosynthesis
Cytoskeleton	Microtubules, intermediate filaments, actin filaments	Shape of cell and movement of its parts
Cilia and flagella	9 + 2 pattern of microtubules	Movement of cell
Centriole**	9 + 0 pattern of microtubules	Formation of basal bodies

*Plant cells only
**Animal cells only



a.



b.

Figure 3.2 **Animal cell anatomy.**
a. Generalized drawing. **b.** Transmission electron micrograph. See Table 3.1 for a description of these structures, along with a listing of their functions.

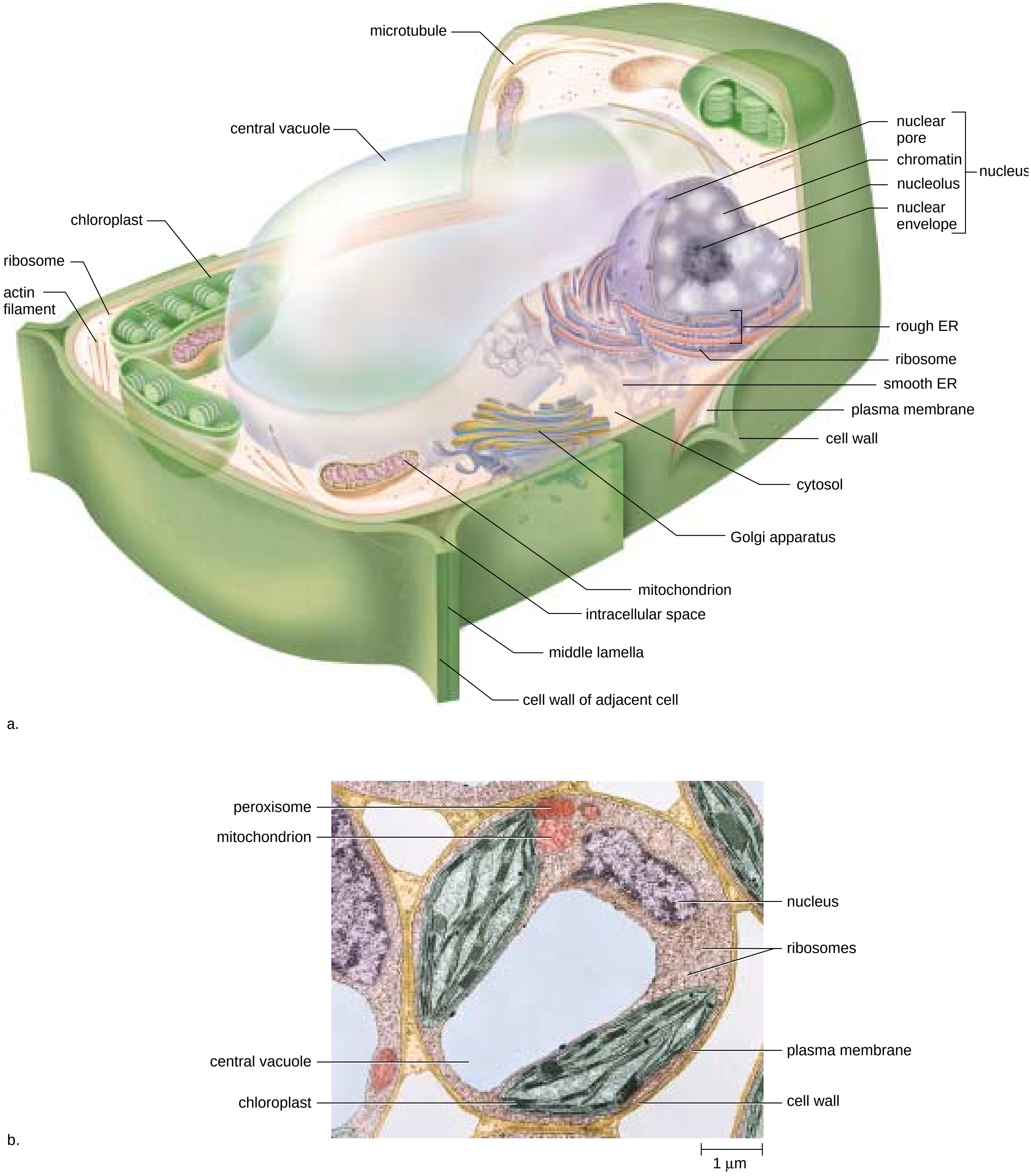


Figure 3.3 **Plant cell anatomy.**

a. Generalized drawing. **b.** Transmission electron micrograph of a young leaf cell. See Table 3.1 for a description of these structures, along with a listing of their functions.

The Nucleus

The **nucleus,** which has a diameter of about 5 μm, is a prominent structure in the eukaryotic cell. The nucleus is of primary importance because it stores genetic information that determines the characteristics of the body's cells and their metabolic functioning. Every cell in the same individual contains the identical genetic information, but each cell type has certain genes, or segments of DNA, turned on, and others turned off. Activated DNA, with RNA acting as an intermediary, specifies the sequence of amino acids when a protein is synthesized. The proteins of a cell determine its structure and the functions it can perform.

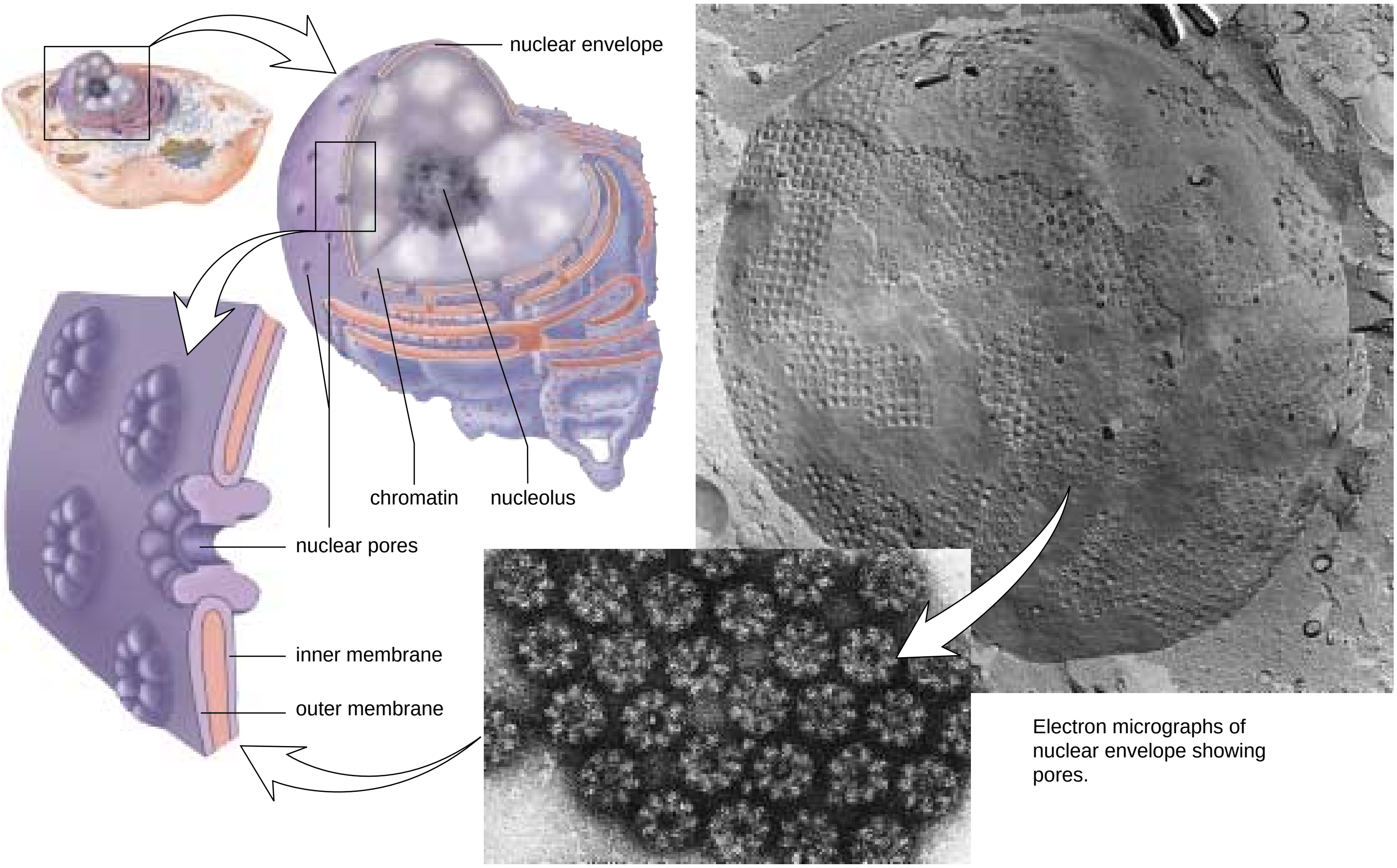
When you look at the nucleus, even in an electron micrograph, you cannot see DNA molecules. You can see chromatin, which consists of DNA and associated proteins (Fig. 3.4). **Chromatin** looks grainy, but actually it is a threadlike material that undergoes coiling to form rodlike structures, called **chromosomes,** just before the cell divides. Chromatin is immersed in a semifluid medium called the **nucleoplasm.** A difference in pH between the nucleoplasm and the cytoplasm suggests that the nucleoplasm has a different composition.

Most likely, too, when you look at an electron micrograph of a nucleus, you will see one or more regions that look darker than the rest of the chromatin. These are nucleoli (sing., **nucleolus**) where another type of RNA, called ribosomal RNA (rRNA), is produced and where rRNA joins with proteins to form the subunits of ribosomes. (Ribosomes are small bodies in the cytoplasm that contain rRNA and proteins.)

The nucleus is separated from the cytoplasm by a double membrane known as the **nuclear envelope,** which is continuous with the endoplasmic reticulum discussed on the next page. The nuclear envelope has **nuclear pores** of sufficient size (100 nm) to permit the passage of proteins into the nucleus and ribosomal subunits out of the nucleus.

The structural features of the nucleus include the following.

Chromatin: DNA and proteins
Nucleolus: Chromatin and ribosomal subunits
Nuclear envelope: Double membrane with pores



Electron micrographs of nuclear envelope showing pores.

Figure 3.4 **The nucleus and the nuclear envelope.**
The nucleoplasm contains chromatin. Chromatin has a special region called the nucleolus, where rRNA is produced and ribosomal subunits are assembled. The nuclear envelope, consisting of two membranes separated by a narrow space, contains pores. The electron micrographs show that the pores cover the surface of the envelope.

Ribosomes

Ribosomes are composed of two subunits, one large and one small. Each subunit has its own mix of proteins and rRNA. Protein synthesis occurs at the ribosomes. Ribosomes can be found free within the cytoplasm, either singly or in groups called **polyribosomes.** Ribosomes can also be found attached to the endoplasmic reticulum, a membranous system of saccules and channels discussed in the next section. Proteins synthesized at cytoplasmic ribosomes are used in the cell, such as in the mitochondria and chloroplasts. Those proteins produced at ribosomes attached to endoplasmic reticulum are eventually secreted from the cell or become a part of its external surface.

Ribosomes are small organelles where protein synthesis occurs. Ribosomes occur in the cytoplasm, both singly and in groups (i.e., polyribosomes). Numerous ribosomes are also attached to the endoplasmic reticulum.

The Endomembrane System

The endomembrane system consists of the nuclear envelope, the endoplasmic reticulum, the Golgi apparatus, and several **vesicles** (tiny membranous sacs). This system compartmentalizes the cell so that particular enzymatic reactions are restricted to specific regions. Organelles that make up the endomembrane system are connected either directly or by transport vesicles.

The Endoplasmic Reticulum

The **endoplasmic reticulum** (ER), a complicated system of membranous channels and saccules (flattened vesicles), is physically continuous with the outer membrane of the nuclear envelope. Rough ER is studded with ribosomes on the side of the membrane that faces the cytoplasm (Fig. 3.5). Here proteins are synthesized and enter the ER interior where processing and modification begin. Most of them are modified by the addition of a sugar chain, which makes them a **glycoprotein.**

Smooth ER, which is continuous with rough ER, does not have attached ribosomes. Smooth ER synthesizes the phospholipids that occur in membranes and has various other functions depending on the particular cell. In the testes, it produces testosterone, and in the liver it helps detoxify drugs. Regardless of any specialized function, smooth ER also forms vesicles in which proteins are transported to the Golgi apparatus.

ER is involved in protein synthesis (rough ER) and various other processes such as lipid synthesis (smooth ER). Vesicles transport proteins from the ER to the Golgi apparatus.

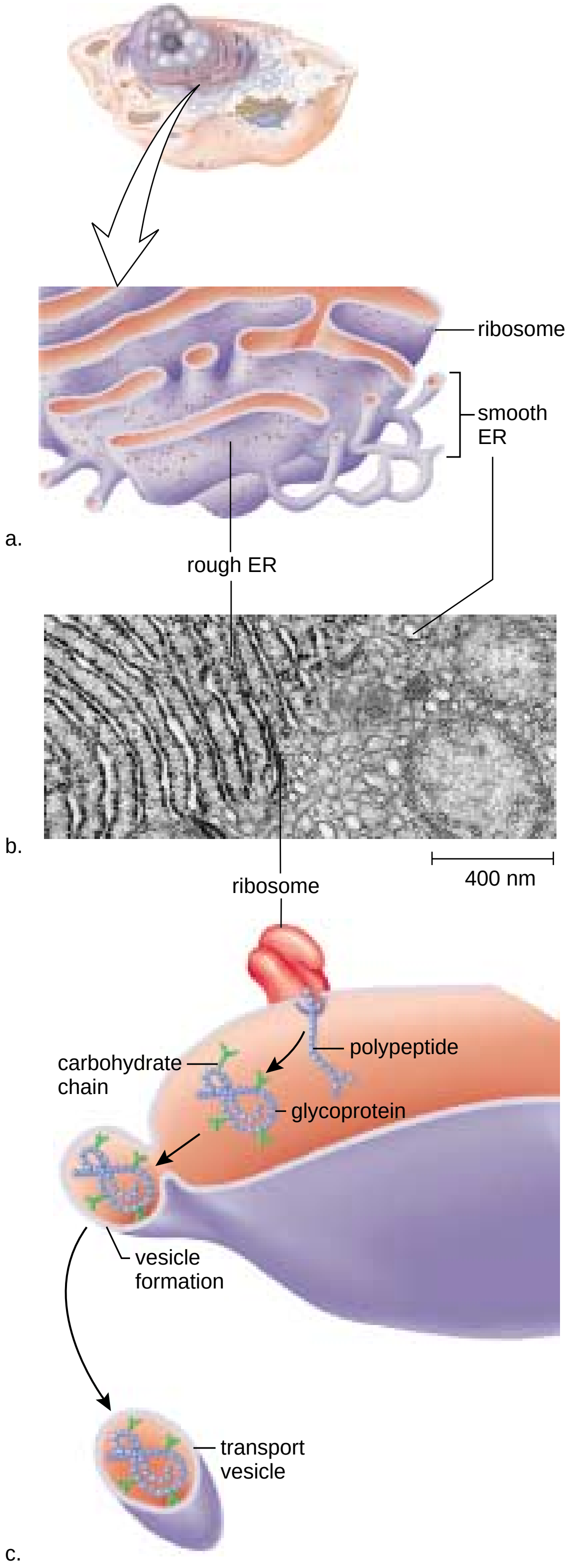


Figure 3.5 **The endoplasmic reticulum (ER).** **a.** Rough ER has attached ribosomes, but smooth ER does not. **b.** Rough ER appears to be flattened saccules, while smooth ER is a network of interconnected tubules. **c.** A protein made at a ribosome moves into the lumen of the system, is modified, and is eventually packaged in a transport vesicle for distribution to the Golgi apparatus.

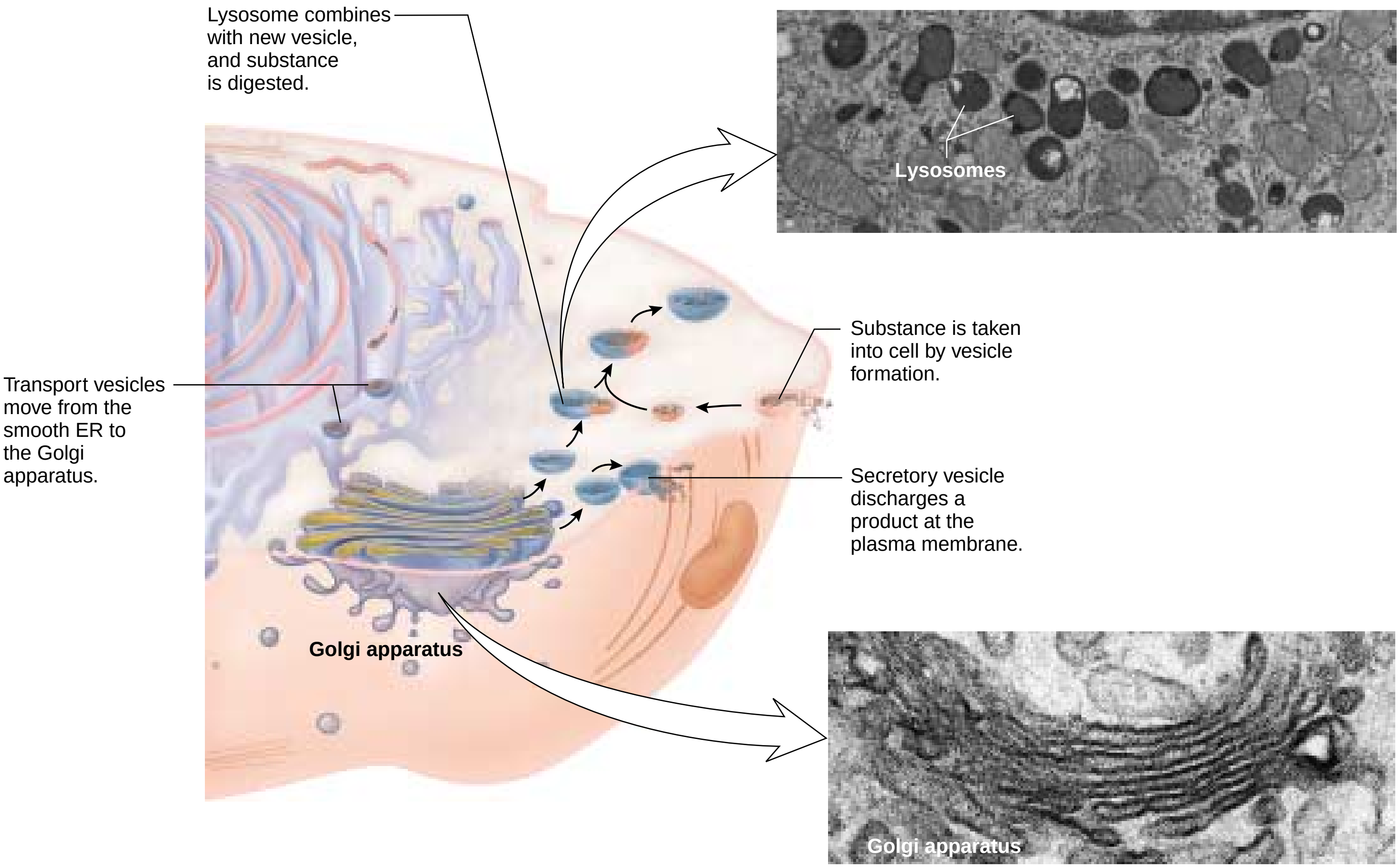


Figure 3.6 **The Golgi apparatus.**
The Golgi apparatus receives transport vesicles containing proteins from smooth ER. After modifying the proteins, it repackages them in either secretory vesicles or lysosomes. When lysosomes combine with newly formed vesicles, their contents are digested. Lysosomes also break down cellular components.

The Golgi Apparatus

The **Golgi apparatus** is named for Camillo Golgi, who discovered its presence in cells in 1898. The Golgi apparatus consists of a stack of three to twenty slightly curved saccules whose appearance can be compared to a stack of pancakes (Fig. 3.6). In animal cells, one side of the stack (the inner face) is directed toward the ER, and the other side of the stack (the outer face) is directed toward the plasma membrane. Vesicles can frequently be seen at the edges of the saccules.

The Golgi apparatus receives protein and also lipid-filled vesicles that bud from the smooth ER. These molecules then move through the Golgi from the inner face to the outer face. How this occurs is still being debated. According to the maturation saccule model, the vesicles fuse to form an inner face saccule, which matures as it gradually becomes a saccule at the outer face. According to the stationary saccule model, the molecules move through stable saccules from the inner face to the outer face by shuttle vesicles. It is likely that both models apply, depending on the organism and the type of cell.

During their passage through the Golgi apparatus, glycoproteins have their sugar chains modified before they are repackaged in secretory vesicles. Secretory vesicles proceed to the plasma membrane, where they discharge their contents. Because this is **secretion,** the Golgi apparatus is said to be involved in processing, packaging, and secretion.

The Golgi apparatus is also involved in the formation of lysosomes, vesicles that contain proteins and remain within the cell. How does the Golgi apparatus direct traffic—in other words, what makes it direct the flow of proteins to different destinations? It now seems that proteins made at the rough ER have specific molecular tags that serve as “zip codes” to tell the Golgi apparatus whether they belong in a lysosome or secretary vesicle. The final sugar chain serves as a tag that directs proteins to their final destination.

The Golgi apparatus processes, packages, and distributes molecules about or from the cell. It is also said to be involved in secretion.

Lysosomes

Lysosomes are membrane-bounded vesicles produced by the Golgi apparatus. Lysosomes contain hydrolytic digestive enzymes.

Sometimes macromolecules are brought into a cell by vesicle formation at the plasma membrane (Fig. 3.6). When a lysosome fuses with such a vesicle, its contents are digested by lysosomal enzymes into simpler subunits that then enter the cytoplasm. For example, some white blood cells defend the body by engulfing pathogens that are then enclosed within vesicles. When lysosomes fuse with these vesicles, the bacteria are digested. It should come as no surprise then, that even parts of a cell are digested by its own lysosomes (called autodigestion). Normal cell rejuvenation takes place in this manner.

Lysosomes contain many enzymes for digesting all sorts of molecules. The absence or malfunction of one of these results in a so-called lysosomal storage disease. Instead of being degraded, the molecule accumulates inside lysosomes, and illness develops when they swell and crowd the other organelles. Occasionally, a child inherits the inability to make a lysosomal enzyme, and therefore has a lysosomal storage disease. In Tay Sachs disease, the cells that surround nerve cells cannot break down a particular lipid, and the nervous system is affected. At about six months, the infant can no longer see, and then gradually also loses hearing and even the ability to move. Death follows at about three years of age.

Lysosomes are produced by a Golgi apparatus, and their hydrolytic enzymes digest macromolecules from various sources.

Vacuoles

A **vacuole** is a large membranous sac. A vesicle is smaller than a vacuole. Animal cells have vacuoles, but they are much more prominent in plant cells. Typically, plant cells have a large central vacuole so filled with a watery fluid that it gives added support to the cell (see Fig. 3.3).

Vacuoles store substances. Plant vacuoles contain not only water, sugars, and salts but also pigments and toxic molecules. The pigments are responsible for many of the red, blue, or purple colors of flowers and some leaves. The toxic substances help protect a plant from herbivorous animals. The vacuoles present in unicellular protozoans are quite specialized, and they include contractile vacuoles for ridding the cell of excess water and digestive vacuoles for breaking down nutrients.

The endomembrane system contains the endoplasmic reticulum (rough and smooth), Golgi apparatus, lysosomes, and vacuoles.

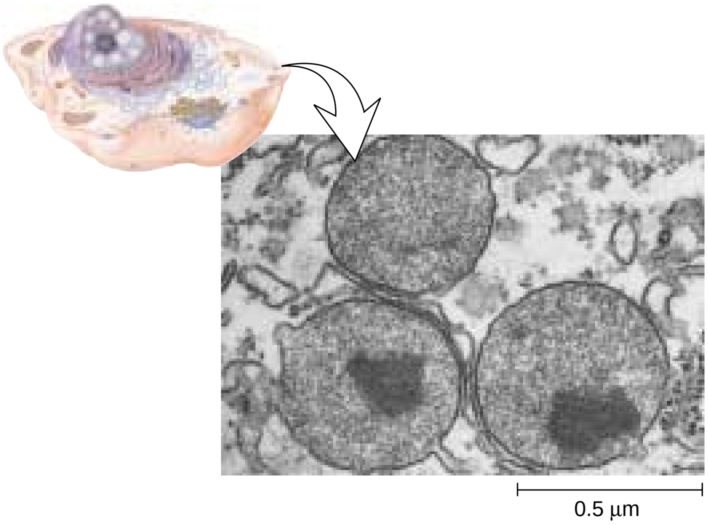


Figure 3.7 **Peroxisomes.**
Peroxisomes are vesicles that oxidize organic substances with a resulting buildup of hydrogen peroxide. Peroxisomes contain the enzyme catalase, which breaks down hydrogen peroxide (H_2O_2) to water and oxygen.

Peroxisomes

Peroxisomes, similar to lysosomes, are membrane-bounded vesicles that enclose enzymes (Fig. 3.7). However, the enzymes in peroxisomes are synthesized by free ribosomes and transported into a peroxisome from the cytoplasm. All peroxisomes contain enzymes whose action results in hydrogen peroxide (H_2O_2):

$$RH_2 + O_2 \rightarrow R + H_2O_2$$

Hydrogen peroxide, a toxic molecule, is immediately broken down to water and oxygen by another peroxisomal enzyme called catalase.

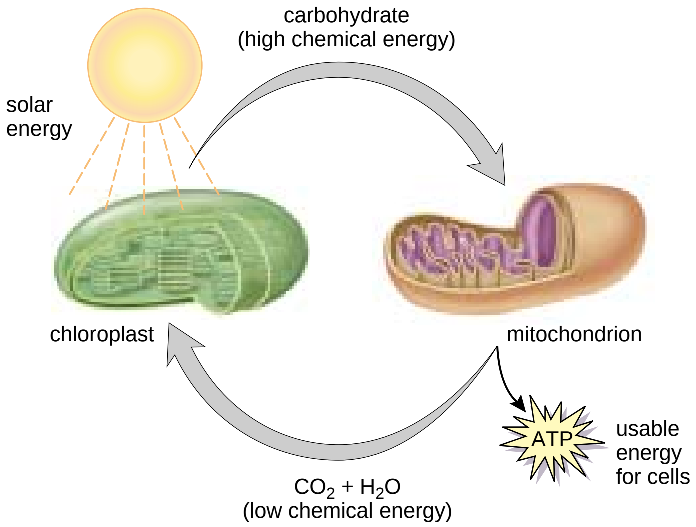
The enzymes in a peroxisome depend on the function of a particular cell. However, peroxisomes are especially prevalent in cells that are synthesizing and breaking down fats. In the liver, some peroxisomes produce bile salts from cholesterol, and others break down fats. In the movie *Lorenzo's Oil,* a boy's cells lacked a carrier protein to transport a specific enzyme into peroxisomes, and he died because a type of lipid accumulated in his cells.

Plant cells also have peroxisomes. In germinating seeds, they oxidize fatty acids into molecules that can be converted to sugars needed by the growing plant. In leaves, peroxisomes can carry out a reaction that is opposite to photosynthesis—the reaction uses up oxygen and releases carbon dioxide.

The enzymes in peroxisomes produce hydrogen peroxide because they use oxygen to break down molecules.

Energy-Related Organelles

Life is possible only because of a constant input of energy used for maintenance and growth. Chloroplasts and mitochondria are the two eukaryotic membranous organelles that specialize in converting energy to a form that can be used by the cell. **Chloroplasts** use solar energy to synthesize carbohydrates, and carbohydrate-derived products are broken down in mitochondria (sing., **mitochondrion**) to produce ATP molecules, as shown in the following diagram:



Trace the cyclic path of carbon and the noncyclic flow of energy in this diagram.

Photosynthesis takes place in chloroplasts. During photosynthesis, solar energy is converted to chemical energy within carbohydrates. The process can be represented by this equation:

solar energy + carbon dioxide + water ⟶ carbohydrate + oxygen

Only plants, algae, and cyanobacteria are capable of carrying on photosynthesis in this manner. Solar energy is the ultimate source of energy for cells because nearly all organisms, either directly or indirectly, use the carbohydrates produced by photosynthesizers as an energy source.

Cellular respiration is the process by which the chemical energy of carbohydrates is converted to that of ATP (adenosine triphosphate), the common carrier of chemical energy in cells. Cellular respiration can be represented by this equation:

carbohydrate + oxygen ⟶ carbon dioxide + water + energy

Here *energy* is in the form of ATP molecules. When a cell needs energy, ATP supplies it. The energy of ATP is used for synthetic reactions, active transport, and all energy-requiring processes in cells. All organisms carry on cellular respiration, and all organisms except bacteria complete the process in mitochondria.

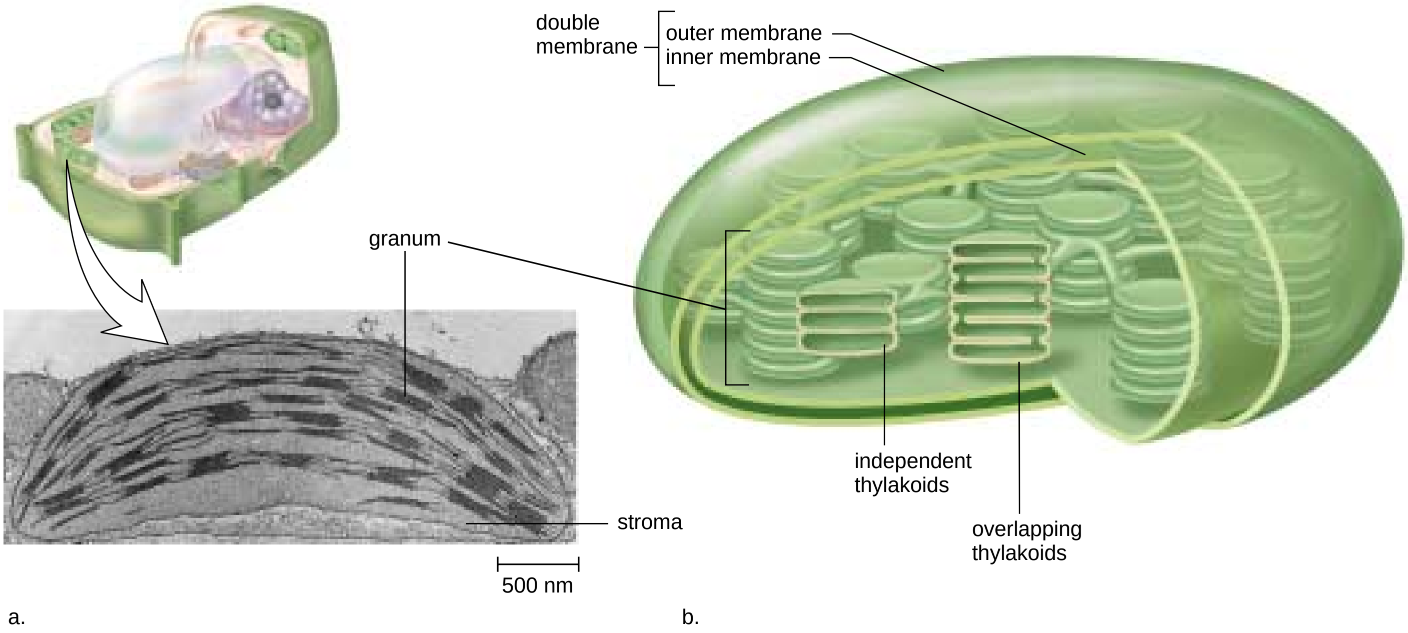


Figure 3.8 **Chloroplast structure.**
a. Electron micrograph. **b.** Generalized drawing in which the outer and inner membranes have been cut away to reveal the grana.

Chloroplasts

Plant cells contain chloroplasts, the organelles that allow them to produce their own organic food. Chloroplasts are about 4–6 μm in diameter and 1–5 μm in length; they belong to a group of organelles known as plastids. Among the plastids are also the *amyloplasts,* common in roots, which store starch, and the *chromoplasts,* common in leaves, which contain red and orange pigments. A chloroplast is green, of course, because it contains the green pigment chlorophyll.

A chloroplast is bounded by two membranes that enclose a fluid-filled space called the **stroma.** A membrane system within the stroma is organized into interconnected flattened sacs called **thylakoids.** In certain regions, the thylakoids are stacked up in structures called grana (sing., **granum**). There can be hundreds of grana within a single chloroplast (Fig. 3.8). Chlorophyll, which is located within the thylakoid membranes of grana, captures the solar energy needed to enable chloroplasts to produce carbohydrates. The stroma also contains DNA, ribosomes, and enzymes that synthesize carbohydrates from carbon dioxide and water.

Mitochondria

All eukaryotic cells, including plant cells, contain mitochondria. This means that plant cells contain both chloroplasts and mitochondria. Most mitochondria are usually 0.5–1.0 μm in diameter and 2–5 μm in length.

Mitochondria, like chloroplasts, are bounded by a double membrane (Fig. 3.9). In mitochondria, the inner fluid-filled space is called the **matrix.** The matrix contains DNA, ribosomes, and enzymes that break down carbohydrate products, releasing energy to be used for ATP production.

The inner membrane of a mitochondrion invaginates to form **cristae.** Cristae provide a much greater surface area to accommodate the protein complexes and other participants that produce ATP.

Mitochondria and chloroplasts are able to make some proteins, but others are imported from the cytoplasm.

Chloroplasts and mitochondria are membranous organelles whose structures lend themselves to the energy transfers that occur within them.

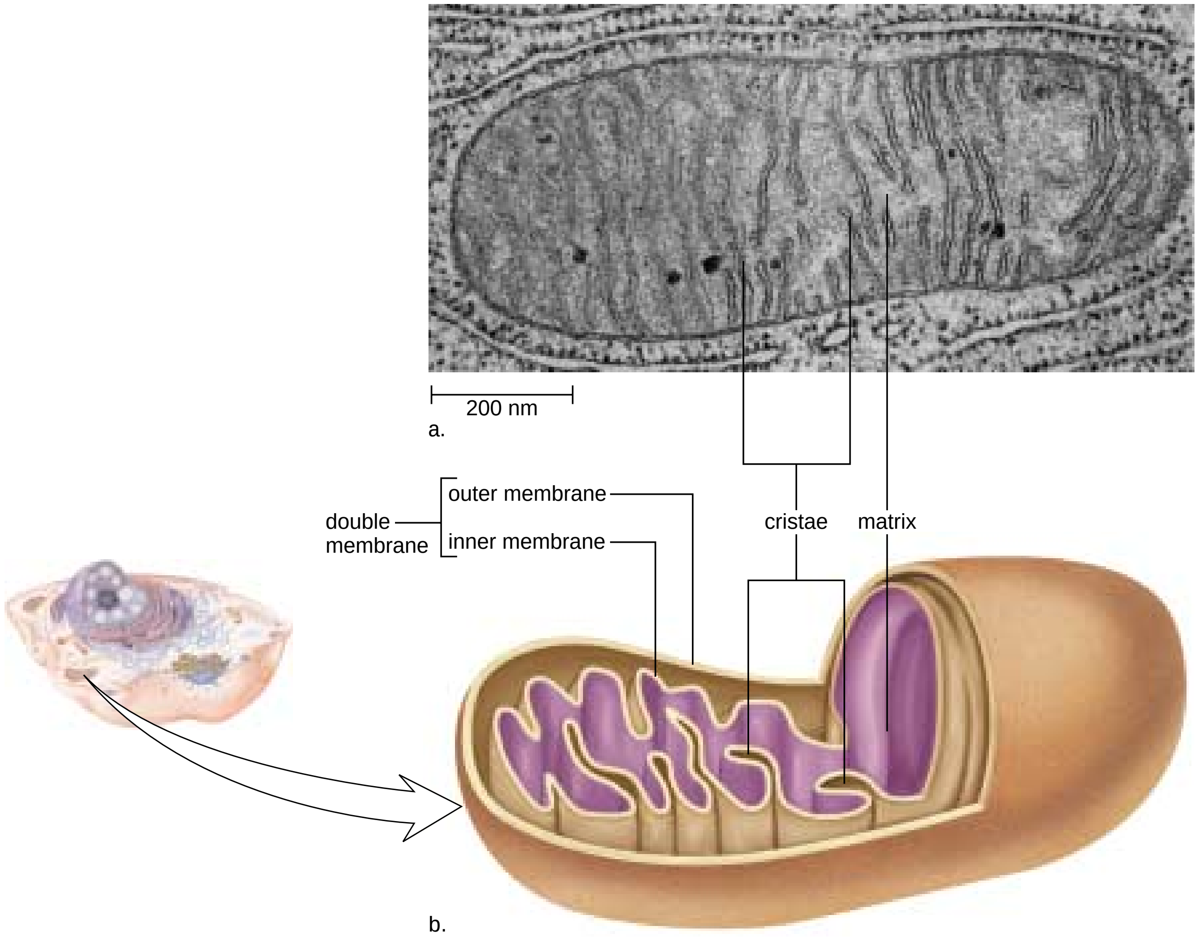


Figure 3.9 **Mitochondrion structure.**

a. Electron micrograph. **b.** Generalized drawing in which the outer membrane and portions of the inner membrane have been cut away to reveal the cristae.

The Cytoskeleton

The **cytoskeleton** is a network of interconnected filaments and tubules that extends from the nucleus to the plasma membrane in eukaryotic cells. Prior to the 1970s, it was believed that the cytoplasm was an unorganized mixture of organic molecules. Then, high-voltage electron microscopes, which can penetrate thicker specimens, showed that the cytoplasm is instead highly organized. The technique of immunofluorescence microscopy identified the makeup of specific protein fibers within the cytoskeletal network (Fig. 3.10).

The name *cytoskeleton* is convenient in that it compares the cytoskeleton to the bones and muscles of an animal. Bones and muscles give an animal structure and produce movement. Similarly, the elements of the cytoskeleton maintain cell shape and cause the cell and its organelles to move. The cytoskeleton is dynamic; elements undergo rapid assembly and disassembly by monomers continuously entering or leaving the polymer. These changes occur at rates that are measured in seconds and minutes. The entire cytoskeletal network can even disappear and reappear at various times in the life of a cell. Before a cell divides, for instance, the elements disassemble and then reassemble into a structure called a spindle that distributes chromosomes in an orderly manner. At the end of cell division, the spindle disassembles, and the elements reassemble once again into their former array.

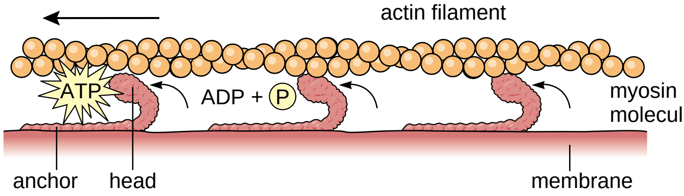
The cytoskeleton contains three types of elements that are responsible for cell shape and movement: actin filaments, microtubules, and intermediate filaments.

Actin Filaments

Actin filaments (formerly called microfilaments) are long, extremely thin fibers (about 7 nm in diameter) that occur in bundles or meshlike networks. The actin filament contains two chains of globular actin monomers twisted about one another in a helical manner.

Actin filaments play a structural role when they form a dense complex web just under the plasma membrane, to which they are anchored by special proteins. They are also seen in the microvilli that project from intestinal cells, and their presence most likely accounts for the ability of microvilli to alternately shorten and extend into the intestine. In plant cells, they apparently form the tracks along which chloroplasts circulate or stream in a particular direction. Also, the presence of a network of actin filaments lying beneath the plasma membrane accounts for the formation of pseudopods, extensions that allow certain cells to move in an amoeboid fashion.

How are actin filaments involved in the movement of the cell and its organelles? They interact with **motor molecules,** which are proteins that move along either actin filaments or microtubules. These motor molecules accomplish this by attaching, detaching, and reattaching farther along the actin filament or microtubule. In the presence of ATP, the motor molecule myosin attaches, detaches, and reattaches to actin filaments. Myosin has both a head and a tail. In muscle cells, the tails of several muscle myosin molecules are joined to form a thick filament. In nonmuscle cells, cytoplasmic myosin tails are bound to membranes, but the heads still interact with actin.



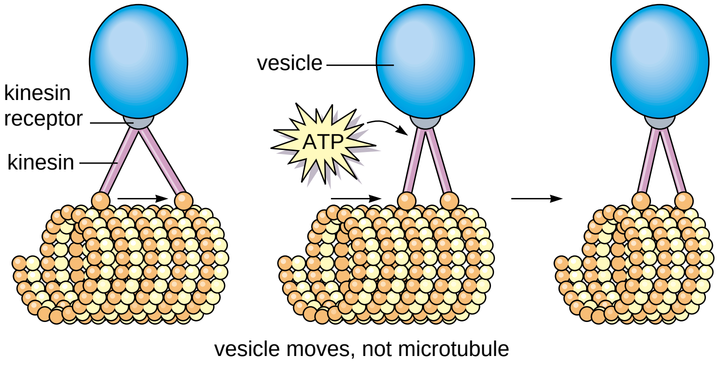
During animal cell division, the two new cells form when actin, in conjunction with myosin, pinches off the cells from one another.

Microtubules

Microtubules are small, hollow cylinders about 25 nm in diameter and from 0.2 to 25 μm in length.

Microtubules are made of a globular protein called tubulin. When microtubules assemble, tubulin molecules come together as dimers, and the dimers arrange themselves in rows. Microtubules have 13 rows of tubulin dimers surrounding what appears in electron micrographs to be an empty central core.

In many cells, microtubule assembly is under the control of a microtubule organizing center, called the **centrosome,** which lies near the nucleus. Microtubules help maintain the shape of the cell and act as tracks along which organelles can move. Whereas the motor molecule myosin is associated with actin filaments, the motor molecules kinesin and dynein move along microtubules. One type of kinesin is responsible for moving vesicles along microtubules, including those that arise from the ER.



There are different types of kinesin proteins, each specialized to move one kind of vesicle or cellular organelle. One

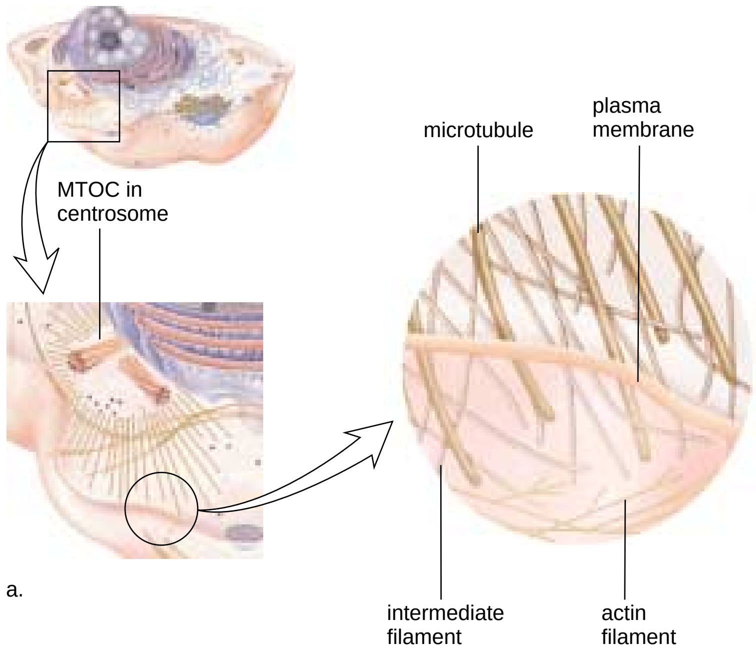
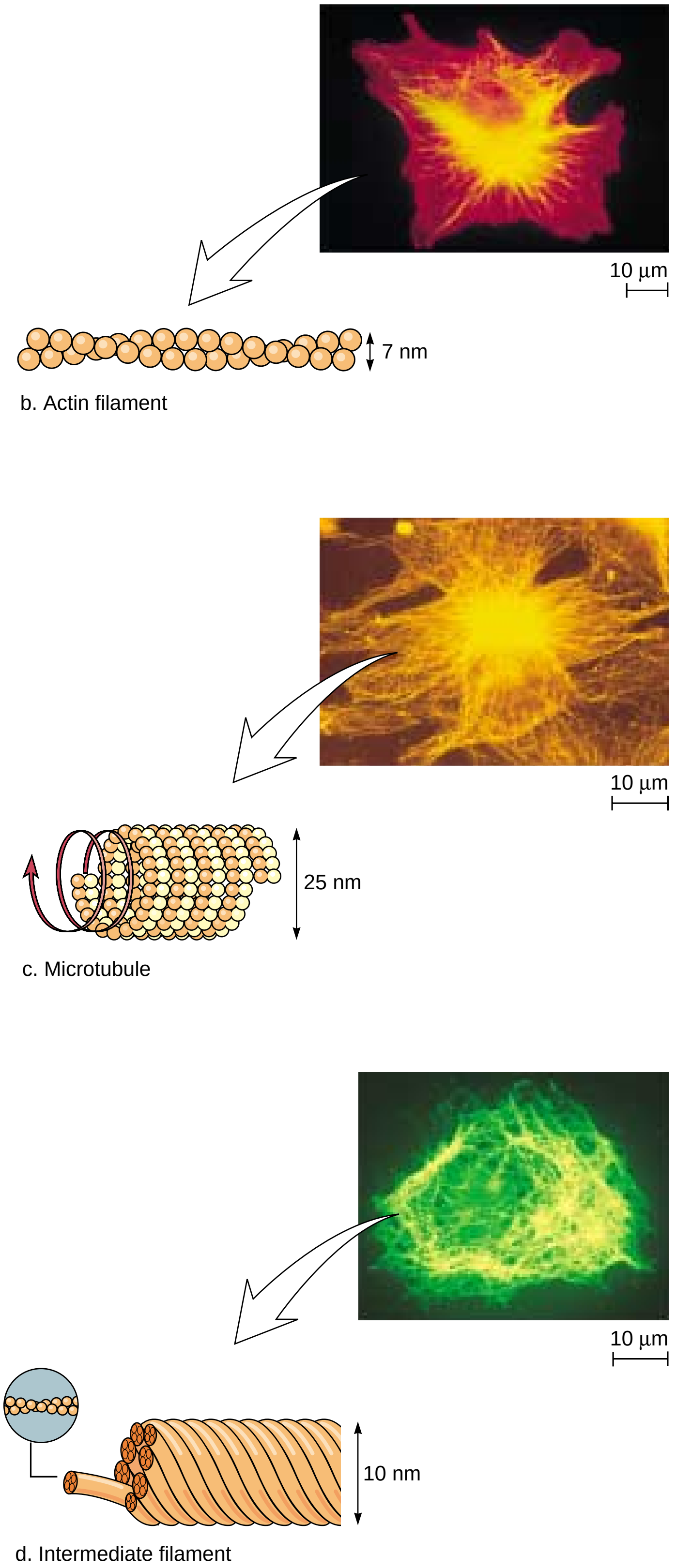


Figure 3.10 **The cytoskeleton.**
a. Diagram comparing the size relationship of actin filaments, intermediate filaments, and microtubules. **b.** Actin filaments as they appear in the cell and in diagram. **c.** Microtubules as they appear in the cell and in diagram. The filaments and tubules are visible following immunofluorescence, a technique that binds fluorescent antibodies to specific proteins in cells. **d.** Intermediate filaments as they appear in the cell and in diagram.



b. Actin filament

c. Microtubule

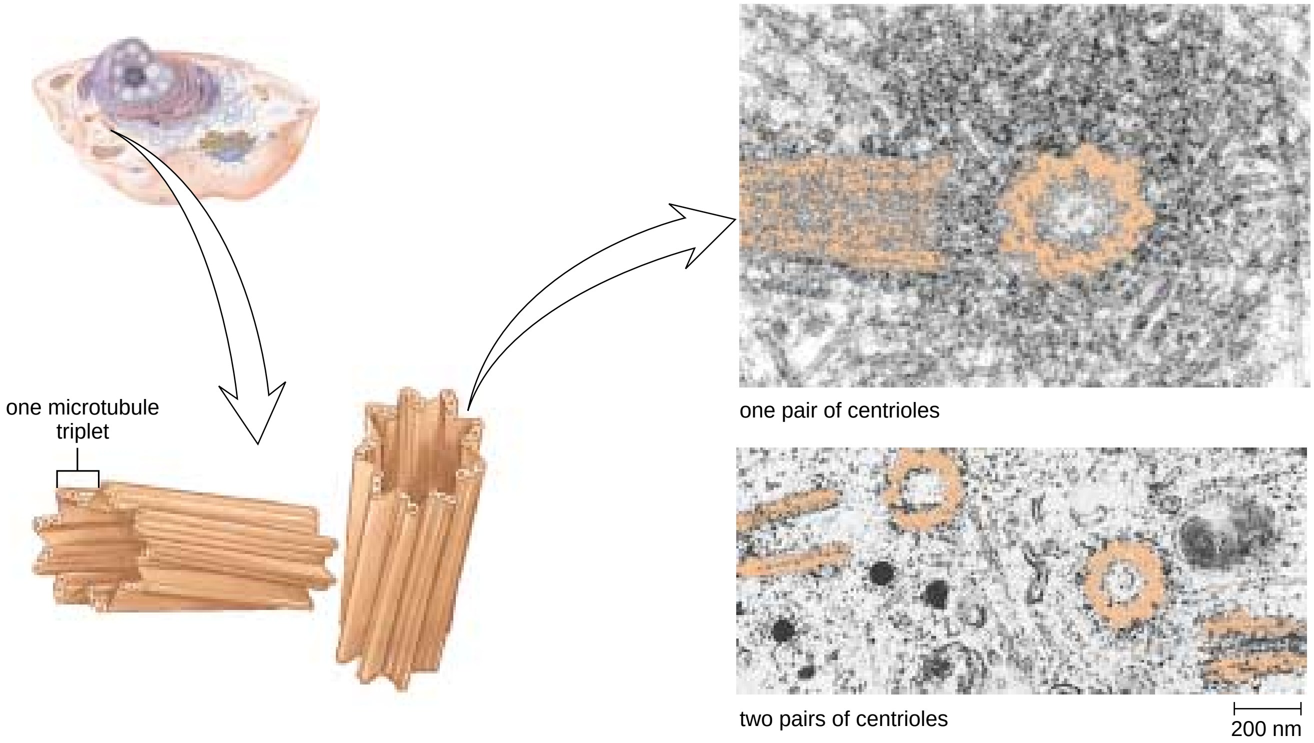
d. Intermediate filament

type of dynein molecule, called cytoplasmic dynein, is closely related to the dynein found in flagella (see Fig. 3.12).

Intermediate Filaments

Intermediate filaments (8–11 nm in diameter) are intermediate in size between actin filaments and microtubules. They are ropelike assemblies of fibrous polypeptides that support the nuclear envelope and the plasma membrane. In the skin, intermediate filaments made of the protein keratin give great mechanical strength to skin cells. Recent work has shown intermediate filaments to be highly dynamic. They also are able to assemble and disassemble in the same manner as actin filaments and microtubules.

The cytoskeleton contains actin filaments, microtubules and intermediate filaments. These maintain cell shape and allow organelles to move within the cytoplasm. Sometimes they are also involved in movement of the cell itself.



one pair of centrioles

two pairs of centrioles

Figure 3.11 **Centrioles.**
Top, right: A nondividing cell contains a pair of centrioles in a centrosome outside the nucleus. *Left and top right:* Just before a cell divides, the centrosome divides so that there are two pairs of centrioles. (*Bottom, right*). During cell division, the centrosomes separate so that each new cell has one pair of centrioles.

Centrioles

Centrioles are short cylinders with a 9 + 0 pattern of microtubule triplets—that is, a ring having nine sets of triplets with none in the middle (Fig. 3.11). In animal cells, a centrosome contains two centrioles lying at right angles to each other. The centrosome is the major microtubule organizing center for the cell, and centrioles may be involved in the process of microtubule assembly and disassembly.

Before an animal cell divides, the centrioles replicate, and the members of each pair are at right angles to one another (Fig. 3.11). Then, each pair becomes part of a separate centrosome. During cell division, the centrosomes move apart and may function to organize the mitotic spindle. Plant cells have the equivalent of a centrosome, but it does not contain centrioles, suggesting that centrioles are not necessary to the assembly of cytoplasmic microtubules.

Centrioles are believed to give rise to basal bodies that direct the organization of microtubules within cilia and flagella. In other words, a basal body does for a cilium (or flagellum) what the centrosome does for the cell.

Centrioles, which are short cylinders with a 9 + 0 pattern of microtubule triplets, may be involved in microtubule formation and in the organization of cilia and flagella.

Cilia and Flagella

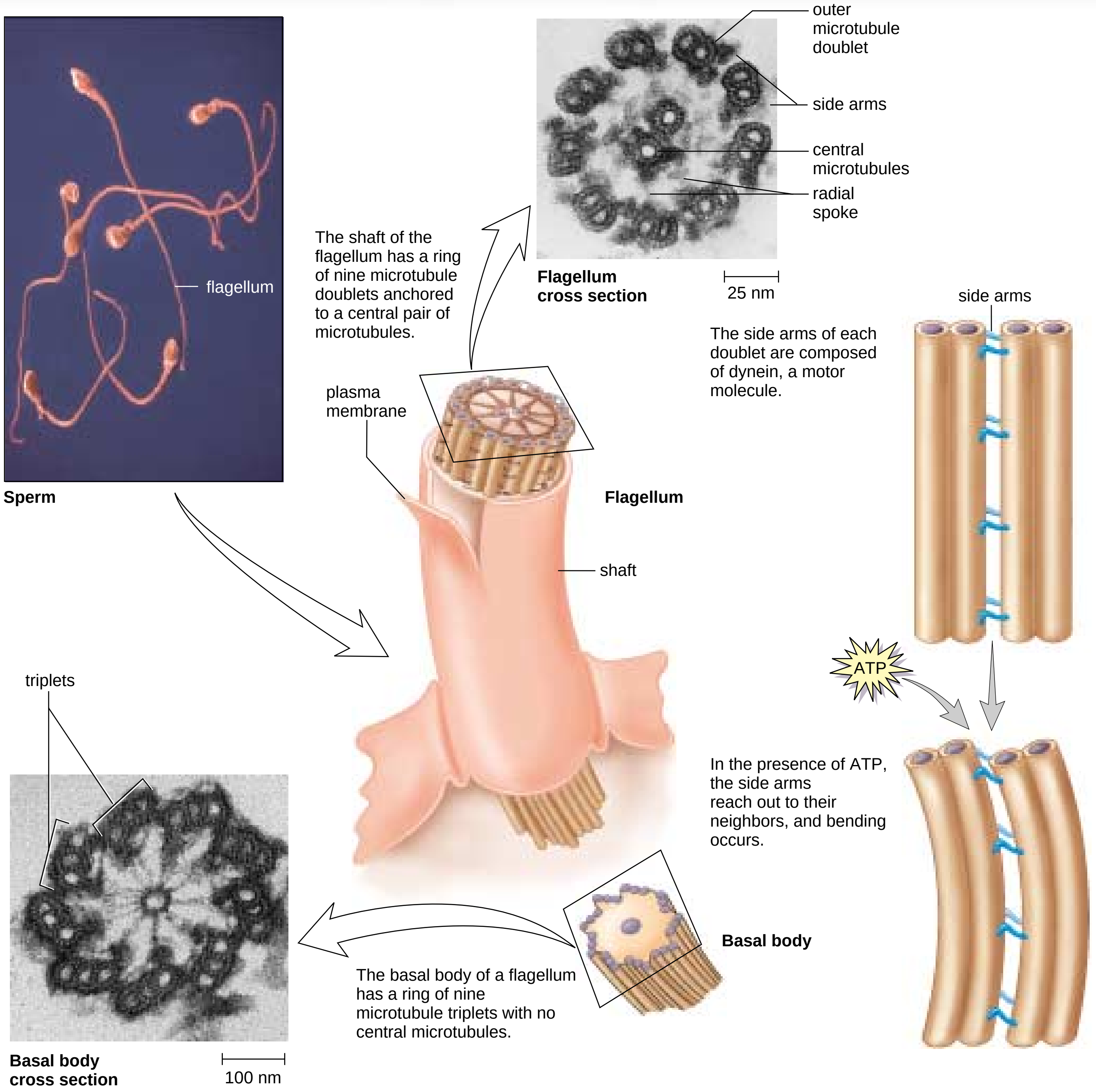
Cilia and **flagella** are hairlike projections that can move either in an undulating fashion, like a whip, or stiffly, like an oar. Cells that have these organelles are capable of movement. For example, unicellular paramecia move by means of cilia, whereas sperm cells move by means of flagella. The cells that line our upper respiratory tract have cilia that sweep debris trapped within mucus back up into the throat, where it can be swallowed. This action helps keep the lungs clean.

In eukaryotic cells, cilia are much shorter than flagella, but they have a similar construction. Both are membrane-bounded cylinders enclosing a matrix area. In the matrix are nine microtubule doublets arranged in a circle around two central microtubules. Therefore, they have a 9 + 2 pattern of microtubules. Cilia and flagella move when the microtubule doublets slide past one another (Fig. 3.12).

As mentioned, each cilium and flagellum has a basal body lying in the cytoplasm at its base. Basal bodies have the same circular arrangement of microtubule triplets as centrioles and are believed to be derived from them. The basal body initiates polymerization of the nine outer doublets of a cilium or flagellum

Cilia and flagella, which have a 9 + 2 pattern of microtubules, enable some cells to move.

Visual Focus



The shaft of the flagellum has a ring of nine microtubule doublets anchored to a central pair of microtubules.

The side arms of each doublet are composed of dynein, a motor molecule.

In the presence of ATP, the side arms reach out to their neighbors, and bending occurs.

The basal body of a flagellum has a ring of nine microtubule triplets with no central microtubules.

Figure 3.12 **Structure of a flagellum or cilium.**
A basal body derived from a centriole is at the base of a flagellum or cilium. The shaft of a flagellum (or cilium) contains microtubule doublets whose side arms are motor molecules that cause the flagellum (such as those of sperm) to move. Without the ability of sperm to move to the egg, human reproduction would not be possible.

3.3 Prokaryotic Cells

Prokaryotic cells, the archaea and bacteria, do not have the nucleus found in eukaryotic cells. Most prokaryotes are 1–10 μm in size; therefore, they are just visible with the light microscope.

Figure 3.13 illustrates the main features of bacterial anatomy. The **cell wall** contains peptidoglycan, a complex molecule with chains of a unique amino disaccharide joined by peptide chains. In some bacteria, the cell wall is further surrounded by a **capsule** and / or gelatinous sheath called a **slime layer.** Motile bacteria usually have long, very thin appendages called flagella (sing., **flagellum**) that are composed of subunits of the protein called flagellin. The flagella, which rotate like propellers, rapidly move the bacterium in a fluid medium. Some bacteria also have *fimbriae,* which are short appendages that help them attach to an appropriate surface.

Prokaryotic cells also have a **plasma membrane** which regulates the movement out of the cytoplasm. The cytoplasm consists of a semifluid medium and thousands of **ribosomes** that coordinate the synthesis of proteins. Prokaryotes have a single chromosome (loop of DNA) located within a region called the **nucleoid** because it is not bounded by membrane. Many prokaryotes also have small accessory rings of DNA called **plasmids.** In addition, the photosynthetic cyanobacteria have light-sensitive pigments, usually within the membranes of flattened disks called **thylakoids.**

Although prokaryotes seem fairly simple, they are actually metabolically complex and contain many different kinds of enzymes. Prokaryotes are adapted to living in almost any kind of environment and are diversified to the extent that almost any type of organic matter can be used as a nutrient for some particular one. Given an energy source, most prokaryotes are able to synthesize any kind of molecule they may need. Therefore, the cytoplasm is the site of thousands of chemical reactions, and they are more metabolically competent than are human beings. Indeed, the metabolic capability of bacteria is exploited by humans, who use them to produce a wide variety of chemicals and products for human use.

Bacteria are prokaryotic cells with these constant features.

Outer boundaries:	Cell wall Plasma membrane
Cytoplasm:	Ribosomes Thylakoids (cyanobacteria) Innumerable enzymes
Nucleoid:	Chromosome (DNA only)

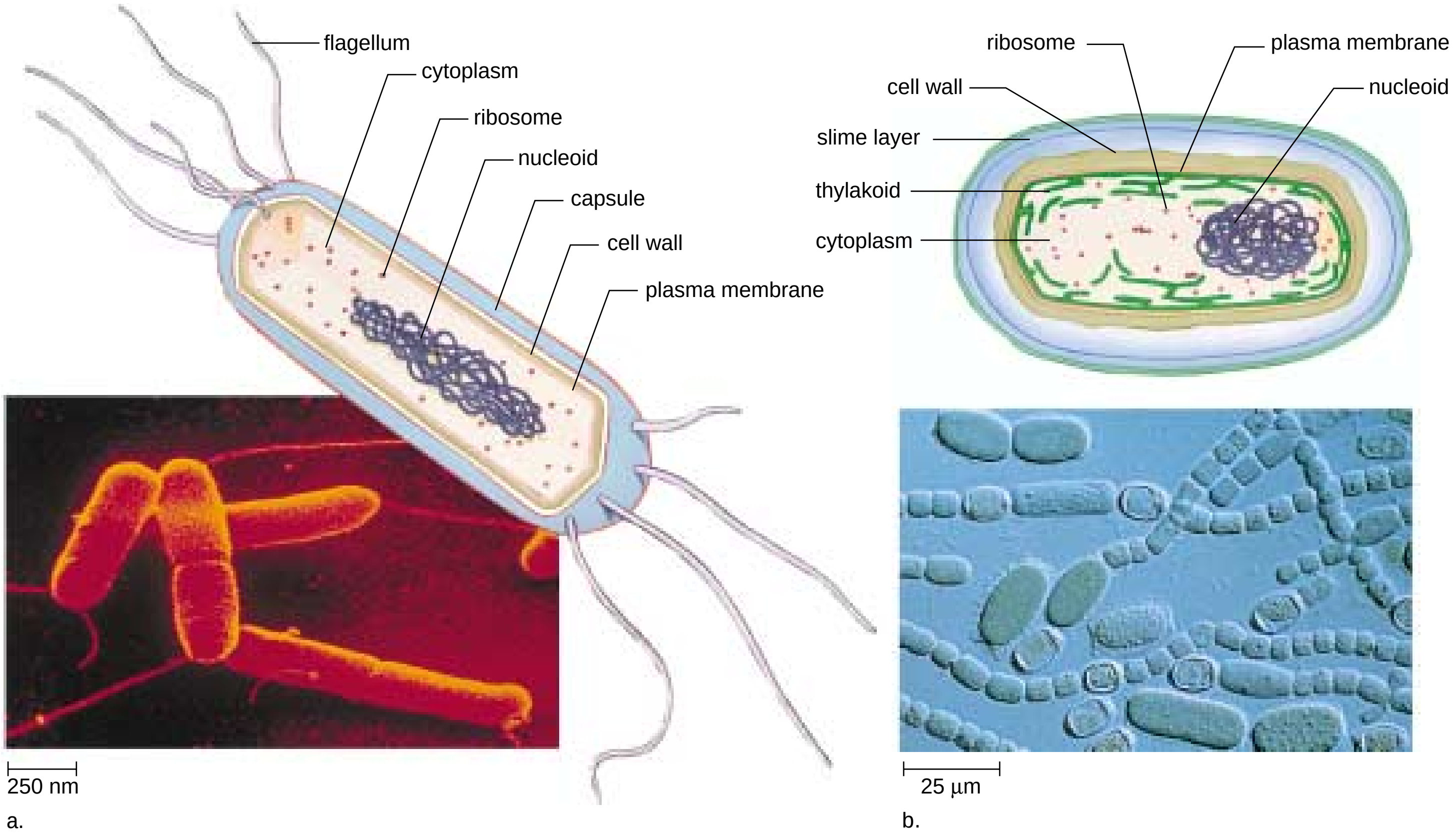


Figure 3.13 **Prokaryotic cells.**
a. Nonphotosynthetic bacterium. **b.** Cyanobacterium, a photosynthetic bacterium, formerly called a blue-green alga.

3.4 Evolution of the Eukaryotic Cell

How did the eukaryotic cell arise? Invagination of the plasma membrane might explain the origin of the nuclear envelope and organelles such as the endoplasmic reticulum and the Golgi apparatus. Some believe that the other organelles could also have arisen in this manner.

Another, more interesting, hypothesis has been put forth. It has been observed that in the laboratory an amoeba infected with bacteria can become dependent upon them. Some investigators believe that mitochondria and chloroplasts are derived from prokaryotes that were taken up by a much larger cell (Fig. 3.14). Perhaps mitochondria were originally aerobic heterotrophic bacteria, and chloroplasts were originally cyanobacteria. The host cell would have benefited from an ability to utilize oxygen or synthesize organic food when by chance the prokaryote was taken up and not destroyed. In other words, after these prokaryotes entered by *endocytosis*, a *symbiotic* relationship would have been established. Some of the evidence for this **endosymbiotic hypothesis** is as follows:

1. Mitochondria and chloroplasts are similar to bacteria in size and in structure.
2. Both organelles are bounded by a double membrane—the outer membrane may be derived from the engulfing vesicle, and the inner one may be derived from the plasma membrane of the original prokaryote.
3. Mitochondria and chloroplasts contain a limited amount of genetic material and divide by splitting. Their DNA (deoxyribonucleic acid) is a circular loop like that of prokaryotes.
4. Although most of the proteins within mitochondria and chloroplasts are now produced by the eukaryotic host, they do have their own ribosomes and they do produce some proteins. Their ribosomes resemble those of prokaryotes.
5. The RNA (ribonucleic acid) base sequence of the ribosomes in chloroplasts and mitochondria also suggests a prokaryotic origin of these organelles.

It is also just possible that the flagella of eukaryotes are derived from an elongated bacterium that became attached to a host cell (Fig. 3.14). However, it is important to remember that the flagella of eukaryotes are constructed differently. In any case, the acquisition of basal bodies, which could have become centrioles, may have led to the ability to form a spindle during cell division.

According to the endosymbiotic hypothesis, heterotrophic bacteria became mitochondria, and cyanobacteria became chloroplasts after being taken up by precursors to modern-day eukaryotic cells.

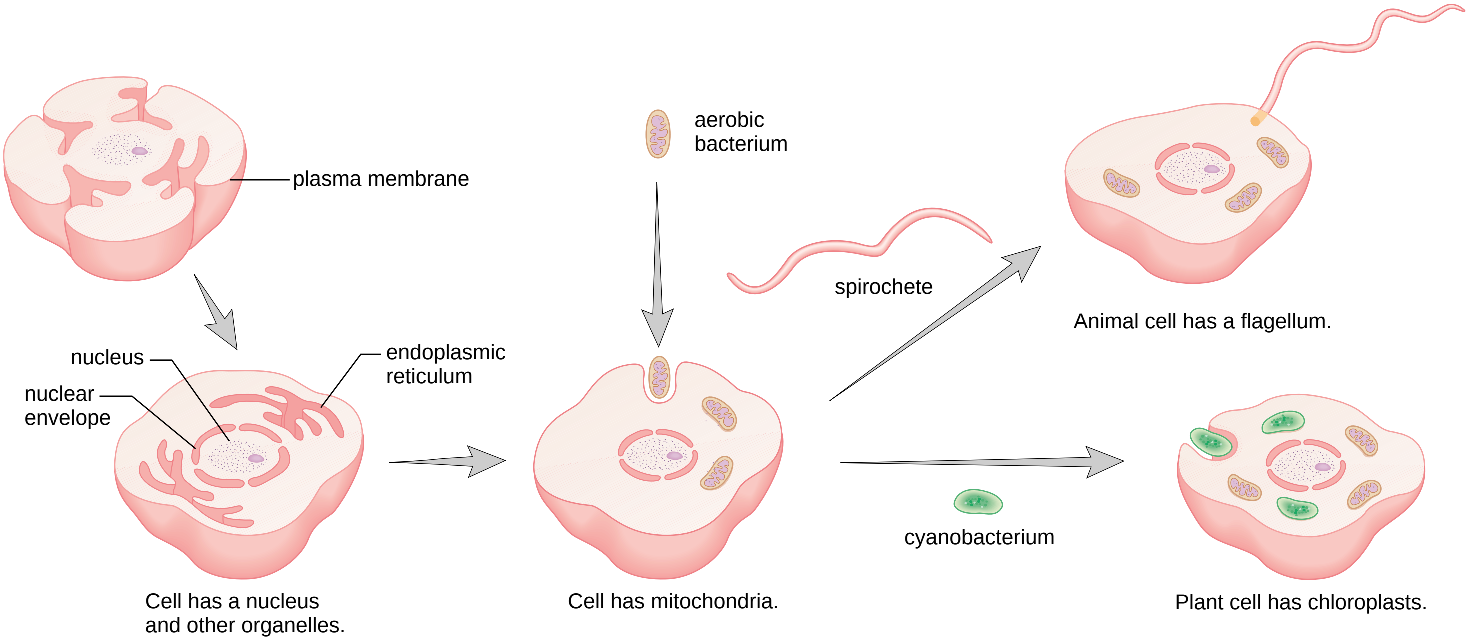


Figure 3.14 **Evolution of the eukaryotic cell.**
Invagination of the plasma membrane could account for the formation of the nucleus and certain other organelles. The endosymbiotic hypothesis suggests that mitochondria, chloroplasts, and flagella are derived from prokaryotes that were taken up by a much larger eukaryotic cell.

Bioethical Focus Use of Stem Cells

Stem cells are immature cells that develop into mature, differentiated cells that make up the adult body. For example, the red bone marrow contains stem cells for all the many different types of blood cells in the bloodstream. Embryonic cells are an even more suitable source of stem cells. The early embryo is simply a ball of cells and each of these cells has the potential to become any type of cell in the body—a muscle cell, a nerve cell, or a pancreatic cell, for example.

The use of stem cells from aborted embryos or frozen embryos left over from fertility procedures is controversial. Even though quadriplegics, like Christopher Reeve and others with serious illnesses, may benefit from this research, it is difficult to get governmental approval for use of such stem cell sources. One senator said it reminds him of the rationalization used by Nazis when they experimented on death camp inmates—“after all, they are going to be killed anyway.”

Parkinson and Alzheimer are debilitating neurological disorders that people fear. It is possible that one day these disorders could be cured by supplying the patient with new nerve cells in a critical area of the brain. Suppose you had one of these disorders. Would you want to be denied a cure because the government didn’t allow experimentation on human embryonic stem cells?

There are other possible sources of stem cells. It turns out that the adult body not only has blood stem cells, it also has neural stem cells in the brain. It has even been possible to coax blood stem cells and neural stem cells to become some other types of mature cells in the body. A possible source of blood stem cells is a baby’s umbilical cord and it is now possible to store umbilical blood for future use. Once researchers have the know-how, it may be possible to use any type of stem cell to cure many of the afflicting human beings.

Decide Your Opinion

1. Should researchers have access to embryonic stem cells? Any source or just certain sources? Which sources and why?
2. Should an individual have access to stem cells from just his own body? Also from a relative’s body? Also from a child’s umbilical cord? From embryonic cells?
3. Should differentiated cells from whatever source eventually be available for sale to patients who need them? After all, you are now able to buy artificial parts, why not living parts?

Summarizing the Concepts

3.1 The Cellular Level of Organization

All organisms are composed of cells, the smallest units of living matter. Cells are capable of self-reproduction, and new cells come only from preexisting cells. Cells are so small they are measured in micrometers. Cells must remain small in order to have an adequate amount of surface area per cell volume for exchange of molecules with the environment.

3.2 Eukaryotic Cells

The nucleus of eukaryotic cells, which include animal and plant cells, is bounded by a nuclear envelope containing pores. These pores serve as passageways between the cytoplasm and the nucleoplasm. Within the nucleus, the chromatin is a complex of DNA and protein. In dividing cells, the DNA is found in discrete structures called chromosomes. The nucleolus is a special region of the chromatin where rRNA is produced and where proteins from the cytoplasm gather to form ribosomal subunits. These subunits are joined in the cytoplasm.

Ribosomes are organelles that function in protein synthesis. They can be bound to ER or can exist within the cytoplasm singly or in groups called polyribosomes.

The endomembrane system includes the ER (both rough and smooth), the Golgi apparatus, the lysosomes, and other types of vesicles and vacuoles. The endomembrane system serves to compartmentalize the cell and keep the various biochemical reactions separate from one another. Newly produced proteins enter the ER lumen, where they may be modified before proceeding to the interior of the smooth ER. The smooth ER has various metabolic functions depending on the cell type, but it also forms vesicles that carry proteins and lipids to the Golgi apparatus. The Golgi apparatus processes proteins and repackages them into lysosomes, which carry out intracellular digestion, or into vesicles that fuse with the plasma membrane. Following fusion, secretion occurs. Vacuoles are large storage sacs, and vesicles are smaller ones. The large single plant cell vacuole not only stores substances but also lends support to the plant cell.

Peroxisomes contain enzymes that were produced by free ribosomes in the cytoplasm. These enzymes oxidize molecules by producing hydrogen peroxide that is subsequently broken down.

Cells require a constant input of energy to maintain their structure. Chloroplasts capture the energy of the sun and carry on photosynthesis, which produces carbohydrates. Carbohydrate-derived products are broken down in mitochondria at the same time as ATP is produced. This is an oxygen-requiring process called cellular respiration.

The cytoskeleton contains actin filaments, intermediate filaments, and microtubules. These maintain cell shape and allow the cell and its organelles to move. Actin filaments, the thinnest filaments, interact with the motor molecule myosin in muscle cells to bring about contraction; in other cells, they pinch off daughter cells and have other dynamic functions. Intermediate filaments support the nuclear envelope and the plasma membrane and probably participate in cell-to-cell junctions. Microtubules radiate out from the centrosome and are present in centrioles, cilia, and flagella. They serve as tracks along which vesicles and other organelles move due to the action of specific motor molecules.

3.3 Prokaryotic Cells

The two major groups of cells are prokaryotic and eukaryotic. Both types have a plasma membrane and cytoplasm. Eukaryotic cells also have a nucleus and various organelles. Prokaryotic cells have a nucleoid that is not bounded by a nuclear envelope. They also lack most of the other organelles that compartmentalize eukaryotic cells.

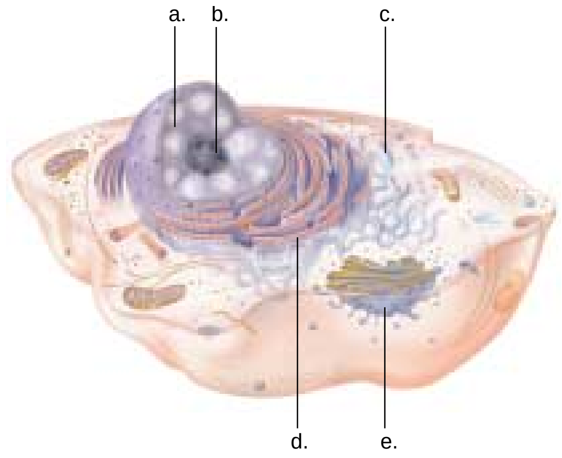
3.4 Evolution of the Eukaryotic Cell

The nuclear envelope most likely evolved through invagination of the plasma membrane, but mitochondria and chloroplasts may have arisen through endosymbiotic events.

Testing Yourself

Choose the best answer for each question.

1. The cell theory states:
   a. Cells form as organelles and molecules become grouped together in an organized manner.
   b. The normal functioning of an organism does not depend on its individual cells.
   c. The cell is the basic unit of life.
   d. Only eukaryotic organisms are made of cells.
2. The small size of cells is best correlated with
   a. the fact that they are self-reproducing.
   b. their prokaryotic versus eukaryotic nature.
   c. an adequate surface area for exchange of materials.
   d. their vast versatility.
   e. All of these are correct.
3. Vesicles carrying proteins for secretion move between smooth ER and the
   a. rough ER.
   b. lysosomes.
   c. Golgi apparatus.
   d. plant cell vacuole only.
   e. cell walls of adjoining cells.
4. Lysosomes function in
   a. protein synthesis.
   b. processing and packaging.
   c. intracellular digestion.
   d. lipid synthesis.
   e. All of these are correct.
5. Mitochondria
   a. are involved in cellular respiration.
   b. break down ATP to release energy for cells.
   c. contain grana and cristae.
   d. have a convoluted outer membrane.
   e. All of these are correct.
6. Which of these is broken down during cellular respiration?
   a. carbon dioxide
   b. water
   c. carbohydrate
   d. oxygen
   e. Both c and d are correct.
7. Which of the following is NOT one of the three components of the cytoskeleton?
   a. flagella
   b. actin filaments
   c. microtubules
   d. intermediate filaments
8. Which of these is NOT true?
   a. Actin filaments are found in muscle cells.
   b. Microtubules radiate out from the ER.
   c. Intermediate filaments sometimes contain keratin.
   d. Motor molecules use microtubules as tracks.
   e. Cilia and flagella are constructed similarly.
9. Cilia and flagella
   a. bend when microtubules try to slide past one another.
   b. contain myosin that pulls on actin filaments.
   c. are organized by basal bodies derived from centrioles.
   d. are of the same length.
   e. Both a and c are correct.
10. Which of the following structures would be found in BOTH plant and animal cells?
    a. centrioles
    b. chloroplasts
    c. cell wall
    d. mitochondria
    e. All of these are found in both types of cells.
11. Which of the following organelles contains enzymes?
    a. peroxisomes
    b. lysosomes
    c. chloroplasts
    d. mitochondria
    e. All of these are correct.
12. Which of the following would NOT be in or a part of a prokaryotic cell?
    a. flagella
    b. ribosomes
    c. DNA
    d. endoplasmic reticulum
    e. enzymes
13. Which of the following organelles contains its (their) own DNA, which is evidence that supports the endosymbiotic hypothesis?
    a. Golgi apparatus
    b. mitochondria
    c. chloroplasts
    d. ribosomes
    e. Both b and c are correct.
14. Which organelle would NOT have originated by endosymbiosis?
    a. mitochondria
    b. flagella
    c. nucleus
    d. chloroplasts
    e. All of these are correct.
15. List structures found in a prokaryotic cell.
    a. cell wall, ribosomes, thylakoids, chromosome
    b. cell wall, plasma membrane, nucleus, flagellum
    c. nucleoid region, ribosomes, chloroplasts, capsule
    d. plasmid, ribosomes, enzymes, DNA, mitochondria
    e. chlorophyll, enzymes, Golgi apparatus, plasmids
16. Label these parts of the cell which are involved in protein synthesis and modification. Give a function for each structure.



e-Learning Connection www.mhhe.com/maderinquiry10

Concepts	*Questions*	*Media Resources**
3.1 The Cellular Level of Organization • All organisms are composed of cells, which arise from preexisting cells. • A microscope is usually needed to see a cell because most cells are quite small.	1. List three main ideas of the cell theory. 2. Why are cells so small?	Essential Study Partner Surface to Volume Explorations Cell Size General Biology Weblinks Microscopy Art Quizzes Cell Size
3.2 Eukaryotic Cells • All cells have a plasma membrane that regulates the entrance and exit of molecules into and out of the cell. Some cells also have a protective cell wall. • Eukaryotic cells have a number of membranous organelles that carry out specific functions. • The nucleus controls the metabolic functions and the structural characteristics of the cell. • A system of membranous canals and vacuoles work together to produce, modify, transport, store, secrete, and/or digest macromolecules. • Mitochondria and chloroplasts transform one form of energy into another. Mitochondria produce ATP and chloroplasts produce carbohydrates. • The cell has a cytoskeleton composed of microtubules, actin filaments, and intermediate filaments. The cytoskeleton gives the cell shape and allows it and its organelles to move. • Centrioles are related to cilia and flagella, which enable the cell to move.	1. What are the components of the endomembrane system and what is its function? 2. What are the three cytoskeletal components of a eukaryotic cell?	Essential Study Partner Endomembrane Organelles Energy Organelles Cytoskeleton General Biology Weblinks Cell Biology BioCourse Study Guide Cell Structure and Function Labeling Exercises Animal Cell (1) Animal Cell (2) Plant Cell (1) Plant Cell (2) Anatomy of the Nucleus Golgi Apparatus Mitochondrion Structure Chloroplast Structure The Cytoskeleton
3.3 Prokaryotic Cells • In contrast to the eukaryotic cell, the prokaryotic cell lacks a well-defined nucleus.	1. Explain the statement “Although bacteria seem simple, they are metabolically diverse.” 2. What are plasmids?	Essential Study Partner Prokaryotes Labeling Exercises Nonphotosynthetic Bacterium Cyanobacterium
3.4 Evolution of the Eukaryotic Cell • The endosymbiotic hypothesis suggests that certain organelles of eukaryotic cells were once prokaryotic cells.	1. How did prokaryotic cells give rise to eukaryotic cells according to the endosymbiotic hypothesis?	Essential Study Partner Eukaryotes

*For additional Media Resources, see the Online Learning Center.