Chapter 3

Cell Structure and Function

Chapter Concepts

3.1 Cell Size

- The amount of detail microscopes allow us to see varies from one type instrument to another. 42

3.2 Cellular Organization

- A cell is highly organized and contains organelles that carry out specific functions. 44
- The plasma membrane regulates the entrance and exit of molecules and ions into and out of the cell. 46
- The nucleus, a centrally located organelle, controls the metabolic functioning and structural characteristics of the cell. 49
- A system of membranous canals and vesicles works to produce, store, modify, transport, and digest macromolecules. 50
- Mitochondria are organelles concerned with the conversion of glucose energy into ATP molecules. 52
- The cell has a cytoskeleton composed of microtubules and filaments; the cytoskeleton gives the cell a shape and allows it and its organelles to move. 53

3.3 Cellular Metabolism

- The cytoplasm contains metabolic pathways, each a series of reactions controlled by enzymes. 54

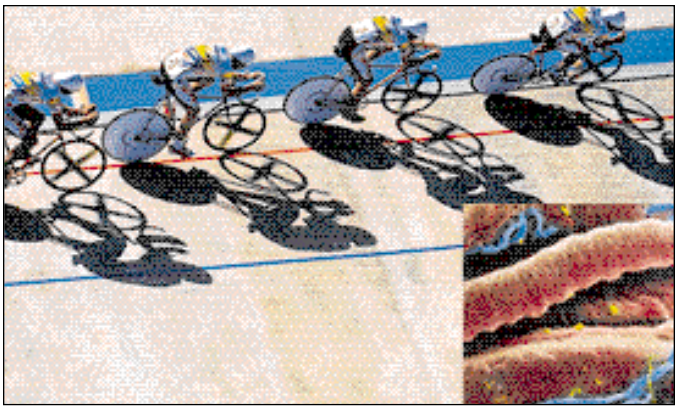


Figure 3.1 Racing cyclists.
Cycling or any human activity is dependent on the functioning of skeletal muscle cells (colored red in the micrograph). Oxygen reaches muscle cells by way of the capillaries (colored blue).

Helen is nervous. But when she hops on her bike at the start of the race, her body's harmonized network of 75 trillion cells answers the challenge. Her brain sends messages along nerves to her skeletal muscles, which are fastened to her bones. When her leg muscles contract, her bones move the bike. The energy to power her muscles comes from sugars absorbed by her digestive tract. Oxygen, used to release energy from sugars, is absorbed by her lungs. Sugar and oxygen molecules are delivered to muscle cells by the circulatory system. And the waste products are expelled from Helen's body by the lungs and kidneys.

The body's organs are composed of cells. Helen can win the race because each individual muscle cell has done its job of keeping her legs moving. Cells are small and it takes a microscope to see them; therefore it is sometimes hard to imagine that individual muscle cells account for the functioning of an organ like a skeletal muscle.

Use of a microscope does show that muscles and all organs are composed of cells. The electron microscope, developed in the last century, has revealed that cells contain organelles, little bodies that are specialized in structure to carry on a particular function. Mitochondria are the organelles that oxidize sugar molecules to release energy. When you are fit, your mitochondria are conditioned to start using oxygen right away so that acids don't build up and cause fatigue. Helen trained for many months to increase her endurance. Her muscle cells have more mitochondria than those of people who have not trained, and her mitochondria are all set to help her win the race.

Despite specialization—muscle cells are specialized to contract—all cells have the same basic structure and metabolism. This chapter discusses the generalized structure of cells. It also describes the structure and function of the various organelles that carry on the activities of a cell. The chapter ends by describing the cellular reactions that provide energy for the workings of a cell.

3.1 Cell Size

All living things are made up of fundamental units called **cells.** Because cells are so small, the study of cells did not begin until the invention of the first microscope in the seventeenth century. Then the **cell theory,** which states that *all living things are composed of cells, and new cells arise only from preexisting cells,* was formulated.

Regardless of a cell's size and shape, it must carry on the functions associated with life—interacting with the environment, obtaining chemicals and energy, growing, and reproducing. A few cells, like a hen's egg or a frog's egg, are large enough to be seen by the naked eye, but most are not. This is the reason a microscope is needed to see cells. Why are cells so small (most are less than one cubic millimeter)? The small size of cells and consequently our multicellularity is explained by considering 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:

1 mm tall cube: surface area/volume ratio = 6 : 1

2 mm tall cube: surface area/volume ratio = 3 : 1

We would expect, then, that there would be a limit to how large an actively metabolizing cell can become. Once a hen's egg is fertilized and starts actively metabolizing, it divides repeatedly without growth. Cell division restores the amount of surface area needed for adequate exchange of materials.

A cell needs a surface area that can adequately exchange materials with the environment. This explains why cells stay small.

Microscopy and Cell Structure

Three types of microscopes are most commonly used: the compound light microscope, transmission electron microscope, and scanning electron microscope. Figure 3.2 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 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 focus by a set of magnetic lenses, and the resulting image is projected onto a fluorescent screen or photographic film.

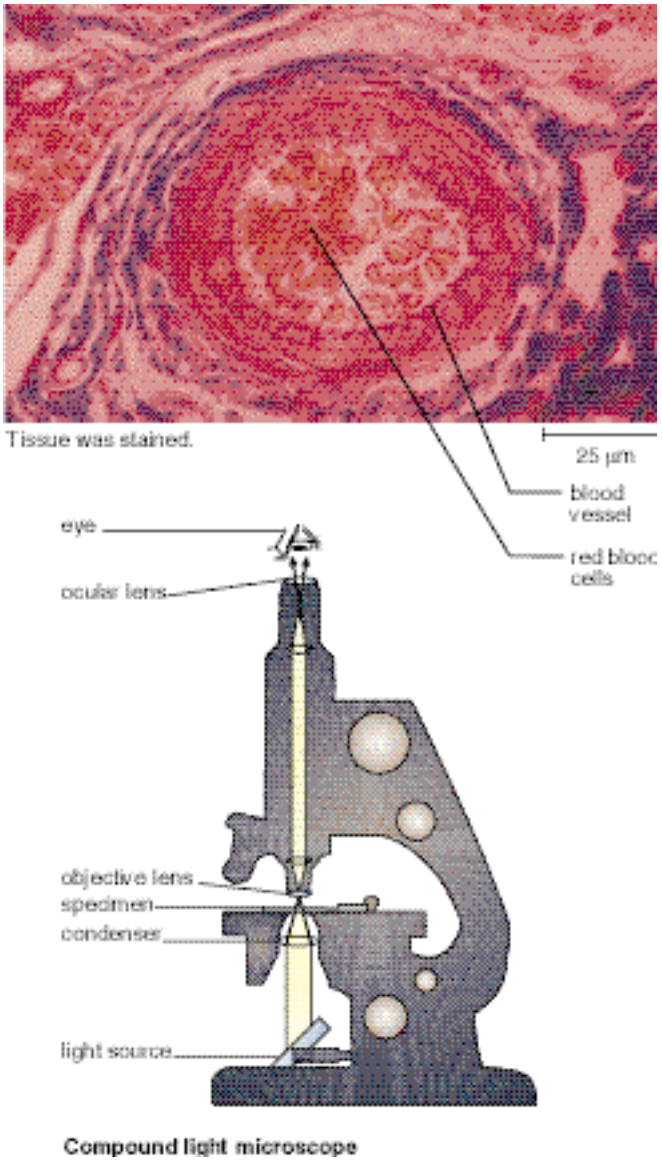


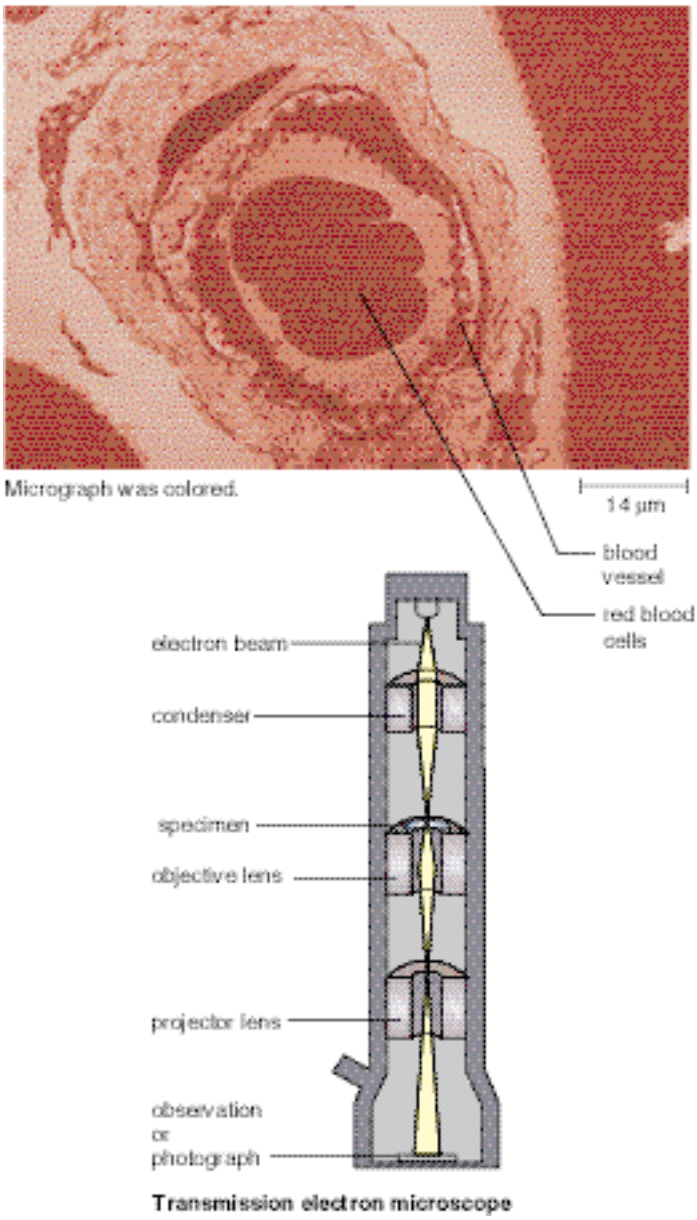
Figure 3.2 **Blood vessels and red blood cells viewed with three different types of microscopes.**

The magnification produced by an electron microscope is much higher than that of a light microscope. Also, the ability of the electron microscope to make out detail in enlarged images is much greater. In other words, the electron microscope has a higher resolving power—that is, the ability to distinguish between two adjacent points. The following lists the resolving power of the eye, the light microscope, and the electron microscope:

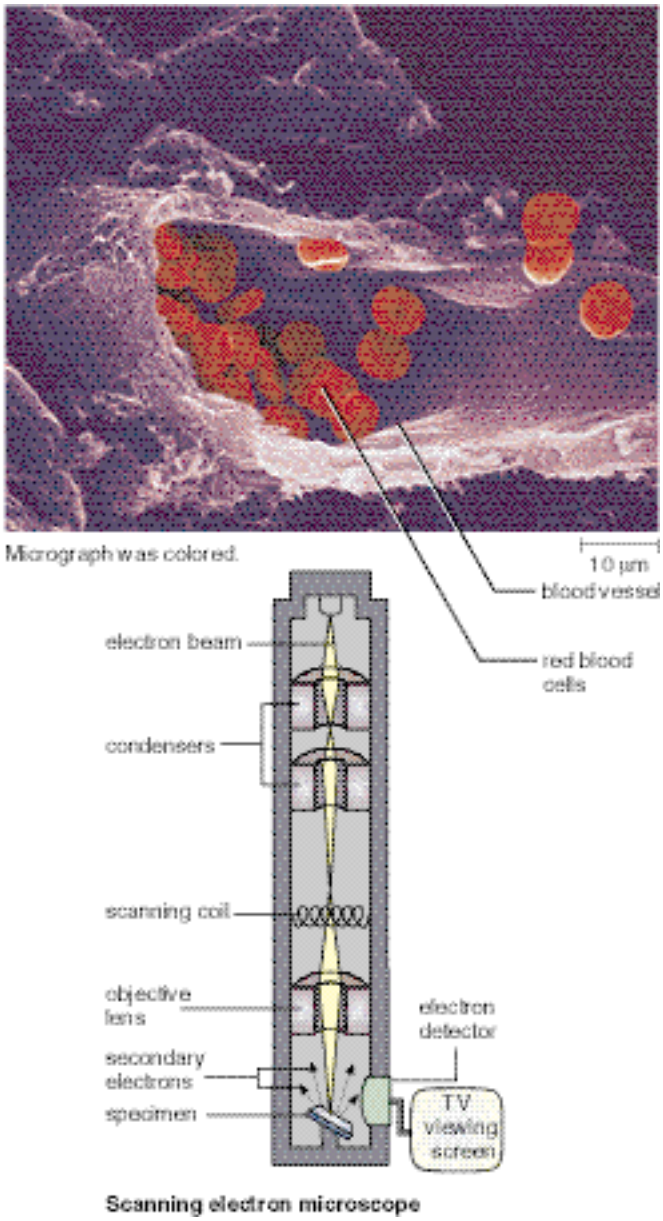
Eye:	0.2 mm	=	200 µm	=	200,000 nm
Light microscope: (1,000×)	0.0002 mm	=	0.200 µm	=	200 nm
Electron microscope (50,000×):	0.00001 mm	=	0.0001 µm	=	10 nm

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 sometimes is 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.



Transmission electron microscope



Scanning electron microscope

3.2 Cellular Organization

The **plasma membrane** that surrounds and keeps the cell intact regulates what enters and exits a cell. The plasma membrane is a phospholipid bilayer that is said to be semipermeable because it allows certain molecules but not others to enter the cell. Proteins present in the plasma membrane play important roles in allowing substances to enter the cell.

The **nucleus** is a large, centrally located structure that can often be seen with a light microscope. The nucleus contains the chromosomes and is the control center of the cell. It controls the metabolic functioning and structural characteristics of the cell. The **nucleolus** is a region inside the nucleus.

The **cytoplasm** is the portion of the cell between the nucleus and the plasma membrane. The matrix of the cytoplasm is a semifluid medium that contains water and various types of molecules suspended or dissolved in the medium. The presence of proteins accounts for the semifluid nature of the matrix.

The cytoplasm contains various **organelles.** Organelles are small membranous structures that can usually only be seen with an electron microscope. Each type of organelle has a specific function. One type of organelle transports substances, for example, and another type produces ATP for the cell. Since organelles are composed of membrane, it can be seen that membrane compartmentalizes, keeping the various cellular activities separated from one another (Table 3.1 and Fig. 3.3).

Cells also have a **cytoskeleton,** a network of interconnected filaments and microtubules that occur in the cytoplasm. The name cytoskeleton is convenient in that it allows us to compare the cytoskeleton to the bones and muscles of an animal. Bones and muscle give an animal structure and produce movement. Similarly, the elements of the cytoskeleton maintain cell shape and allow the cell and its contents to move. Some cells move by using cilia and flagella, which are also made up of microtubules.

The human cell has a central nucleus and an outer plasma membrane. Various organelles are found within the cytoplasm, the portion of the cell between the nucleus and the plasma membrane.

Table 3.1 Structures in Animal Cells

Name	Composition	Function
Plasma membrane	Phospholipid bilayer with embedded proteins	Selective passage of molecules into and out of cell
Nucleus	Nuclear envelope surrounding nucleoplasm, chromatin, and nucleolus	Storage of genetic information
Nucleolus	Concentrated area of chromatin, RNA, and proteins	Ribosomal formation
Ribosome	Protein and RNA in two subunits	Protein synthesis
Endoplasmic reticulum (ER)	Membranous saccules and 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 distributing molecules
Vacuole and vesicle	Membranous sacs	Storage and transport of substances
Lysosome	Membranous vesicle containing digestive enzymes	Intracellular digestion
Mitochondrion	Inner membrane (cristae) within outer membrane	Cellular respiration
Cytoskeleton	Microtubules, 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

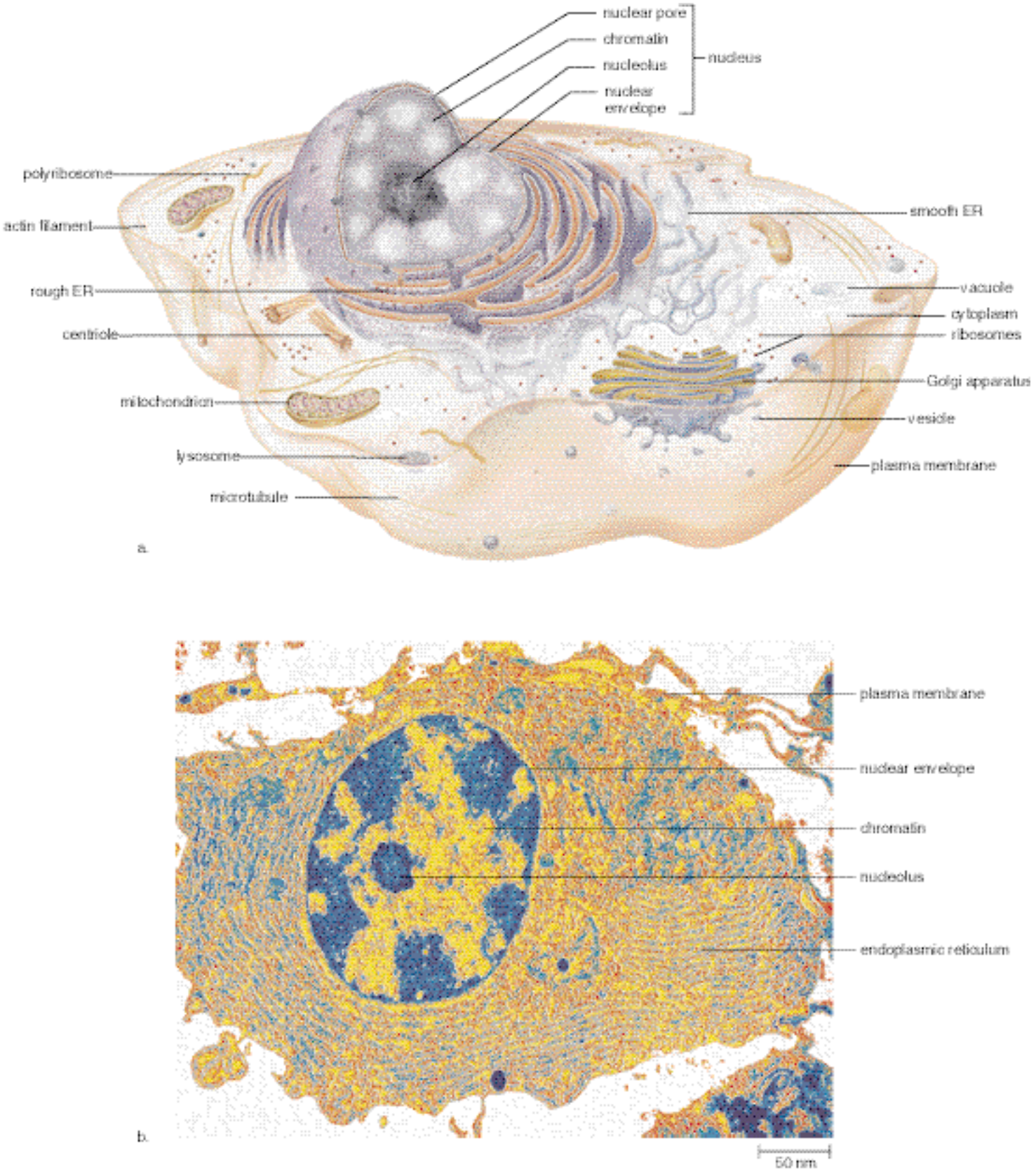


Figure 3.3 **Animal cell.**
a. Generalized drawing. **b.** Transmission electron micrograph. SeeTable 3.1 for a description of these structures, along with a listing of their functions.

The Plasma Membrane

An animal cell is surrounded by an outer plasma membrane. The plasma membrane marks the boundary between the outside of the cell and the inside of the cell. Plasma membrane integrity and function are necessary to the life of the cell.

The plasma membrane is a phospholipid bilayer with attached or embedded proteins. The structure of a phospholipid is such that the molecule has a polar head and nonpolar tails (Fig. 3.4). The polar heads, being charged, are hydrophilic (water loving) and face outward, toward the cytoplasm on one side and the tissue fluid on the other side, where they will encounter a watery environment. The nonpolar tails are hydrophobic (not attracted to water) and face inward toward each other, where there is no water. When phospholipids are placed in water, they naturally form a circular bilayer because of the chemical properties of the heads and the tails. At body temperature, the phospholipid bilayer is a liquid; it has the consistency of olive oil, and the proteins are able to change their position by moving laterally. The fluid-mosaic model, a working description of membrane structure, says that the protein molecules have a changing pattern (form a mosaic) within the fluid phospholipid bilayer (Fig. 3.4). Cholesterol lends support to the membrane.

Short chains of sugars are attached to the outer surface of some protein and lipid molecules (called glycoproteins and glycolipids, respectively). It is believed that these carbohydrate chains, specific to each cell, help mark it as belonging to a particular individual. They account for why people have different blood types, for example. Other glycoproteins have a special configuration that allows them to act as a receptor for a chemical messenger like a hormone. Some plasma membrane proteins form channels through which certain substances can enter cells; others are carriers involved in the passage of molecules through the membrane.

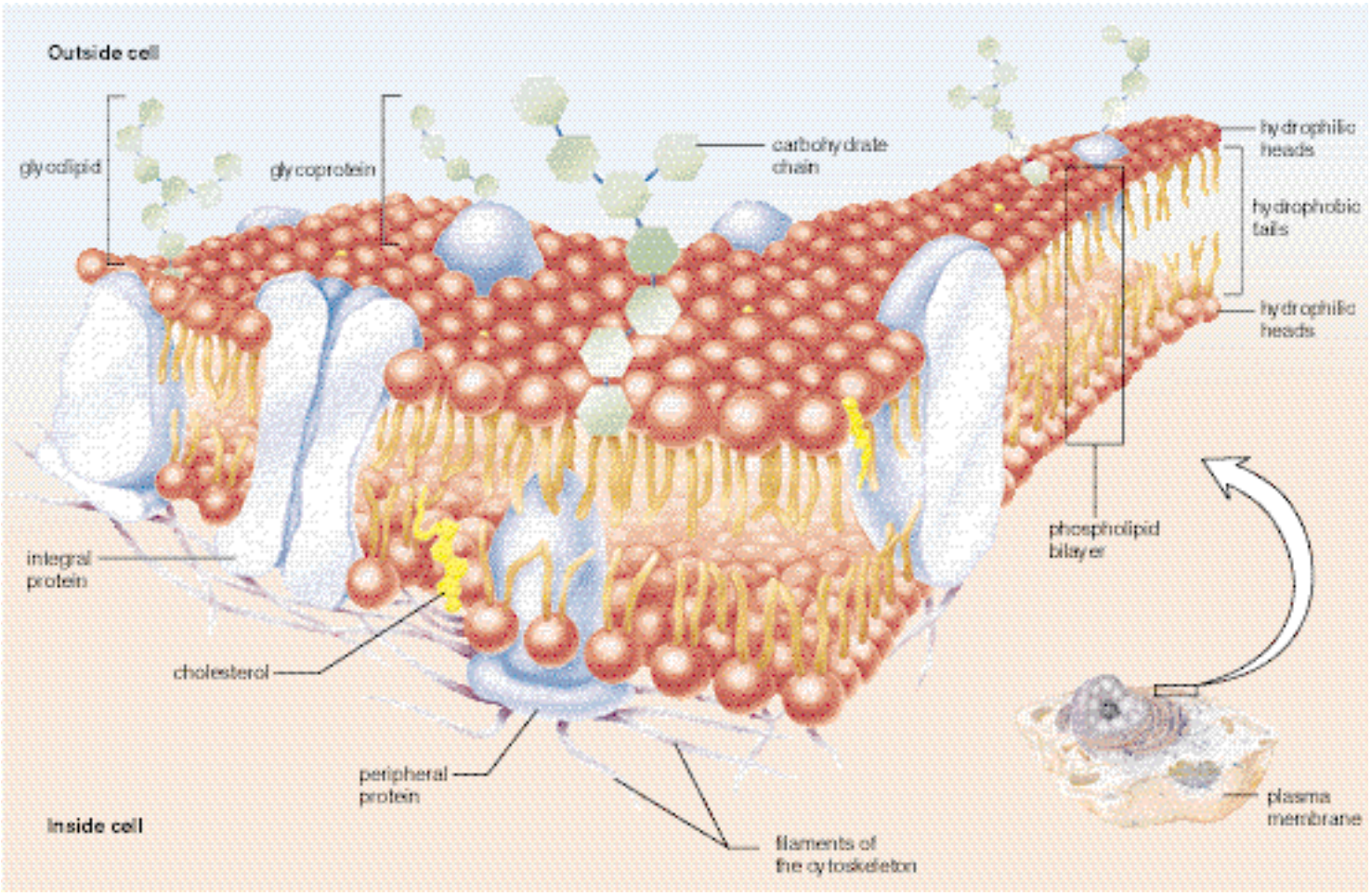


Figure 3.4 **Fluid-mosaic model of the plasma membrane.**
The membrane is composed of a phospholipid bilayer. The polar heads of the phospholipids are at the surfaces of the membrane; the nonpolar tails make up the interior of the membrane. Proteins are embedded in the membrane. Some of these function as receptors for chemical messengers, as conductors of molecules through the membrane, and as enzymes in metabolic reactions.

Plasma Membrane Functions

The plasma membrane keeps a cell intact. It allows only certain molecules and ions to enter and exit the cytoplasm freely; therefore, the plasma membrane is said to be **selectively permeable.** Small molecules that are lipid soluble, such as oxygen and carbon dioxide, can pass through the membrane easily. Certain other small molecules, like water, are not lipid soluble, but they still freely cross the membrane. Still other molecules and ions require the use of a carrier to enter a cell.

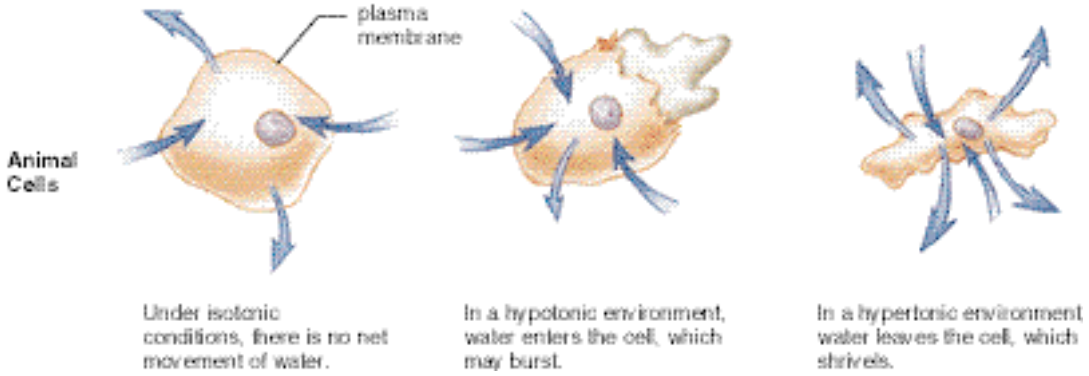


Figure 3.5 **Tonicity.**
The arrows indicate the movement of water.

The plasma membrane, composed of phospholipid and protein molecules, is selectively permeable and regulates the entrance and exit of molecules and ions into and out of the cell.

Diffusion **Diffusion** is the random movement of molecules from the area of higher concentration to the area of lower concentration until they are equally distributed. To illustrate diffusion, imagine opening a perfume bottle in the corner of a room. The smell of the perfume soon permeates the room because the molecules that make up the perfume move to all parts of the room. Another example is putting a tablet of dye into water. The water eventually takes on the color of the dye as the dye molecules diffuse.

The chemical and physical properties of the plasma membrane allow only a few types of molecules to enter and exit a cell simply by diffusion. Lipid-soluble molecules such as alcohols can diffuse through the membrane because lipids are the membrane's main structural components. Gases can also diffuse through the lipid bilayer; this is the mechanism by which oxygen enters cells and carbon dioxide exits cells. As an example, consider the movement of oxygen from the alveoli (air sacs) of the lungs to blood in the lung capillaries. After inhalation (breathing in), the concentration of oxygen in the alveoli is higher than that in the blood; therefore, oxygen diffuses into the blood.

When molecules simply diffuse down their concentration gradients across plasma membranes, no cellular energy is involved.

Molecules diffuse down their concentration gradients. A few types of small molecules can simply diffuse through the plasma membrane, and no carrier protein or cellular energy is involved.

Osmosis **Osmosis** is the diffusion of water across a plasma membrane. It occurs whenever there is an unequal concentration of water on either side of a selectively permeable membrane. Normally, body fluids are isotonic to cells (Fig. 3.5)—that is, there is an equal concentration of substances (solutes) and water (solvent) on both sides of the plasma membrane, and cells maintain their usual size and shape. Intravenous solutions medically administered usually have this tonicity. **Tonicity** is the degree to which a solution's concentration of solute versus water causes water to move into or out of cells.

Solutions that cause cells to swell or even to burst due to an intake of water are said to be hypotonic solutions. If red blood cells are placed in a hypotonic solution, which has a higher concentration of water (lower concentration of solute) than do the cells, water enters the cells and they swell to bursting. The term lysis is used to refer to disrupted cells; hemolysis, then, is disrupted red blood cells.

Solutions that cause cells to shrink or to shrivel due to a loss of water are said to be hypertonic solutions. If red blood cells are placed in a hypertonic solution, which has a lower concentration of water (higher concentration of solute) than do the cells, water leaves the cells and they shrink. The term crenation refers to red blood cells in this condition.

These changes have occurred due to osmotic pressure. Osmotic pressure is the force exerted on a selectively permeable membrane because water has moved from the area of higher to lower concentration of water (higher concentration of solute).

In an isotonic solution, a cell neither gains nor loses water. In a hypotonic solution, a cell gains water. In a hypertonic solution, a cell loses water and the cytoplasm shrinks.

Transport by Carriers Most solutes do not simply diffuse across a plasma membrane; rather, they are transported by means of protein carriers within the membrane. During

facilitated transport, a molecule (e.g., an amino acid or glucose) is transported across the plasma membrane from the side of higher concentration to the side of lower concentration. The cell does not need to expend energy for this type of transport because the molecules are moving down their concentration gradient.

During **active transport,** a molecule is moving contrary to the normal direction—that is, from lower to higher concentration (Fig. 3.6). For example, iodine collects in the cells of the thyroid gland; sugar is completely absorbed from the gut by cells that line the digestive tract; and sodium (Na^+) is sometimes almost completely withdrawn from urine by cells lining kidney tubules. Active transport requires a protein carrier and the use of cellular energy obtained from the breakdown of ATP. When ATP is broken down, energy is released, and in this case the energy is used by a carrier to carry out active transport. Therefore, it is not surprising that cells involved in active transport, such as kidney cells, have a large number of mitochondria near the membrane at which active transport is occurring.

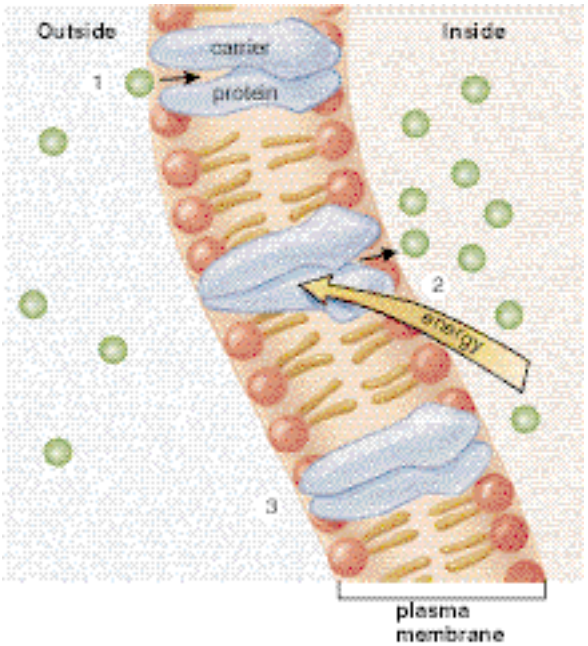


Figure 3.6 **Active transport through a plasma membrane.** Active transport allows a solute to cross the membrane from lower solute concentration to higher solute concentration. ① Molecule enters carrier. ② Chemical energy of ATP is needed to transport the molecule, which exits inside of cell. ③ Carrier returns to its inactive state.

Proteins involved in active transport often are called pumps because just as a water pump uses energy to move water against the force of gravity, proteins use energy to move substances against their concentration gradients. One type of pump that is active in all cells but is especially associated with nerve and muscle cells moves sodium ions (Na^+) to the outside of the cell and potassium ions (K^+) to the inside of the cell.

The passage of salt (NaCl) across a plasma membrane is of primary importance in cells. First, sodium ions are pumped across a membrane; then, chloride ions simply diffuse through channels that allow their passage. Chloride ion channels malfunction in persons with cystic fibrosis, and this leads to the symptoms of this inherited (genetic) disorder.

Endocytosis and Exocytosis During endocytosis, a portion of the plasma membrane invaginates to envelop a substance, and then the membrane pinches off to form an intracellular vesicle. Digestion may be required before molecules can cross a vesicle membrane to enter the cytoplasm. During exocytosis, the vesicle often formed at the Golgi apparatus fuses with the plasma membrane as secretion occurs. This is the way insulin leaves insulin-secreting cells, for instance. Table 3.2 summarizes the various ways molecules get into and out of cells.

Table 3.2 **Passage of Molecules into and out of Cells**

	Name	Direction	Requirement	Examples
PASSIVE TRANSPORT	Diffusion	Toward lower concentration	Concentration gradient	Lipid-soluble molecules, water, and gases
	Facilitated Transport	Toward lower concentration	Carrier and concentration gradient	Sugars and amino acids
ACTIVE TRANSPORT	Active Transport	Toward greater concentration	Carrier plus energy ions	Sugars, amino acids, and
	Endocytosis	Toward inside	Vesicle formation	Macromolecules
	Exocytosis	Toward outside	Vesicle fuses with plasma membrane	Macromolecules

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 contains a complex copy of 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 during protein synthesis. 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 but you can see chromatin (Fig. 3.7). **Chromatin** looks grainy, but actually it is a threadlike material that undergoes coiling into rodlike structures called **chromosomes** just before the cell divides. Chemical analysis shows that chromatin, and therefore chromosomes, contains DNA and much protein, as well as some RNA. 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

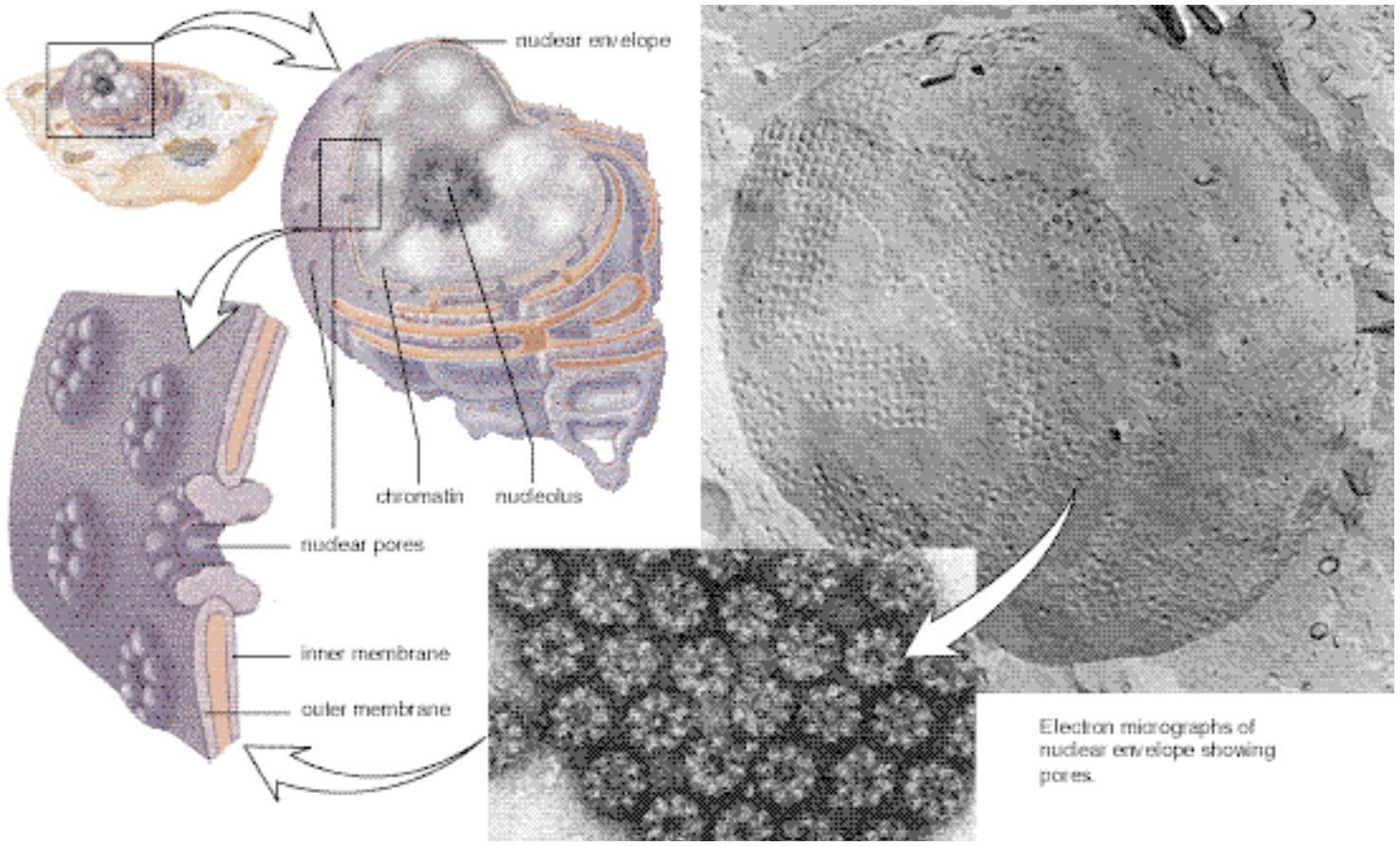


Figure 3.7 **The nucleus and the nuclear envelope.**
The nucleus contains chromatin. Chromatin has a special region called the nucleolus, which is where rRNA is produced and ribosomal subunits are assembled. The nuclear envelope contains pores, as shown in this micrograph of a freeze-fractured nuclear envelope. Each pore is lined by a complex of eight proteins.

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 are found free within the cytoplasm either singly or in groups called **polyribosomes.** Ribosomes are often attached to the endoplasmic reticulum, a membranous system of saccules and channels discussed in the next section. Proteins synthesized by cytoplasmic ribosomes are used inside the cell for various purposes. Those produced by ribosomes attached to endoplasmic reticulum may eventually be secreted from the cell.

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

Membranous Canals and Vesicles

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. Membranes that make up the endomembrane system are connected by direct physical contact and/or by the transfer of vesicles from one part to the other.

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. 3.8). Here proteins are synthesized and enter the ER interior where processing and modification begin. 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 large molecules are transported to other parts of the cell. Often these vesicles are on their way to the plasma membrane or the Golgi apparatus.

ER is involved in protein synthesis (rough ER) and various other processes such as lipid synthesis (smooth ER). Molecules that are produced or modified in the ER are eventually enclosed in vesicles that often transport them to the Golgi apparatus.

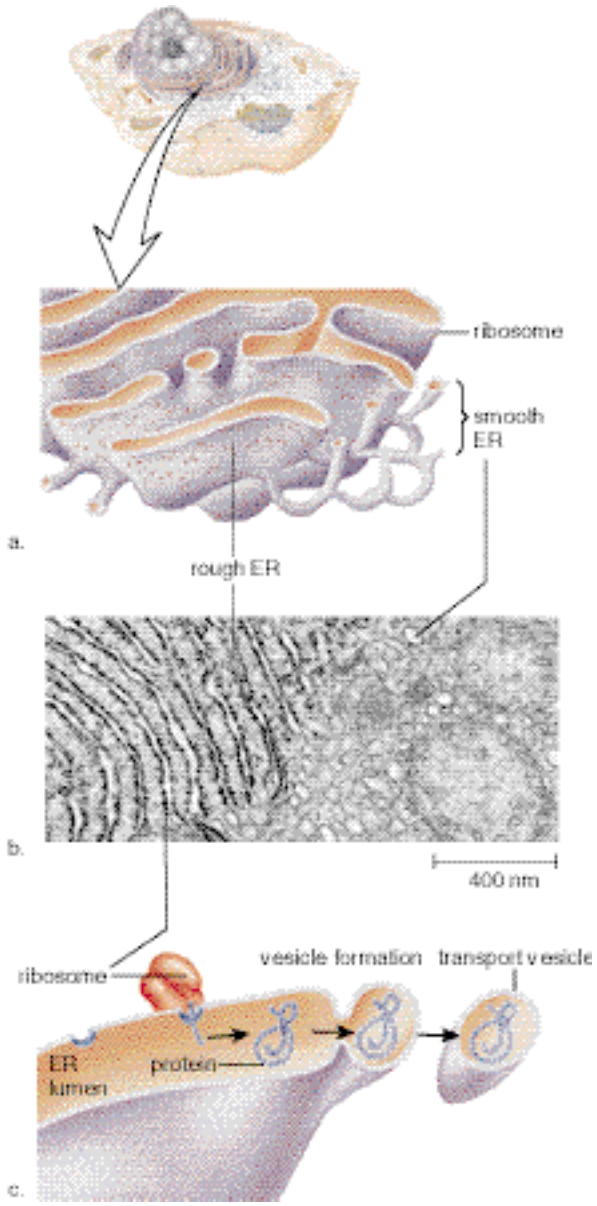


Figure 3.8 **The endoplasmic reticulum (ER).**
a. Rough ER has attached ribosomes, but smooth ER does not. **b.** Rough ER appears to be flattened saccules, while smooth ER is a network of interconnected tubules. **c.** A protein made at a ribosome moves into the lumen of the system and eventually is packaged in a transport vesicle for distribution inside the cell.

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. 3.9). 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.

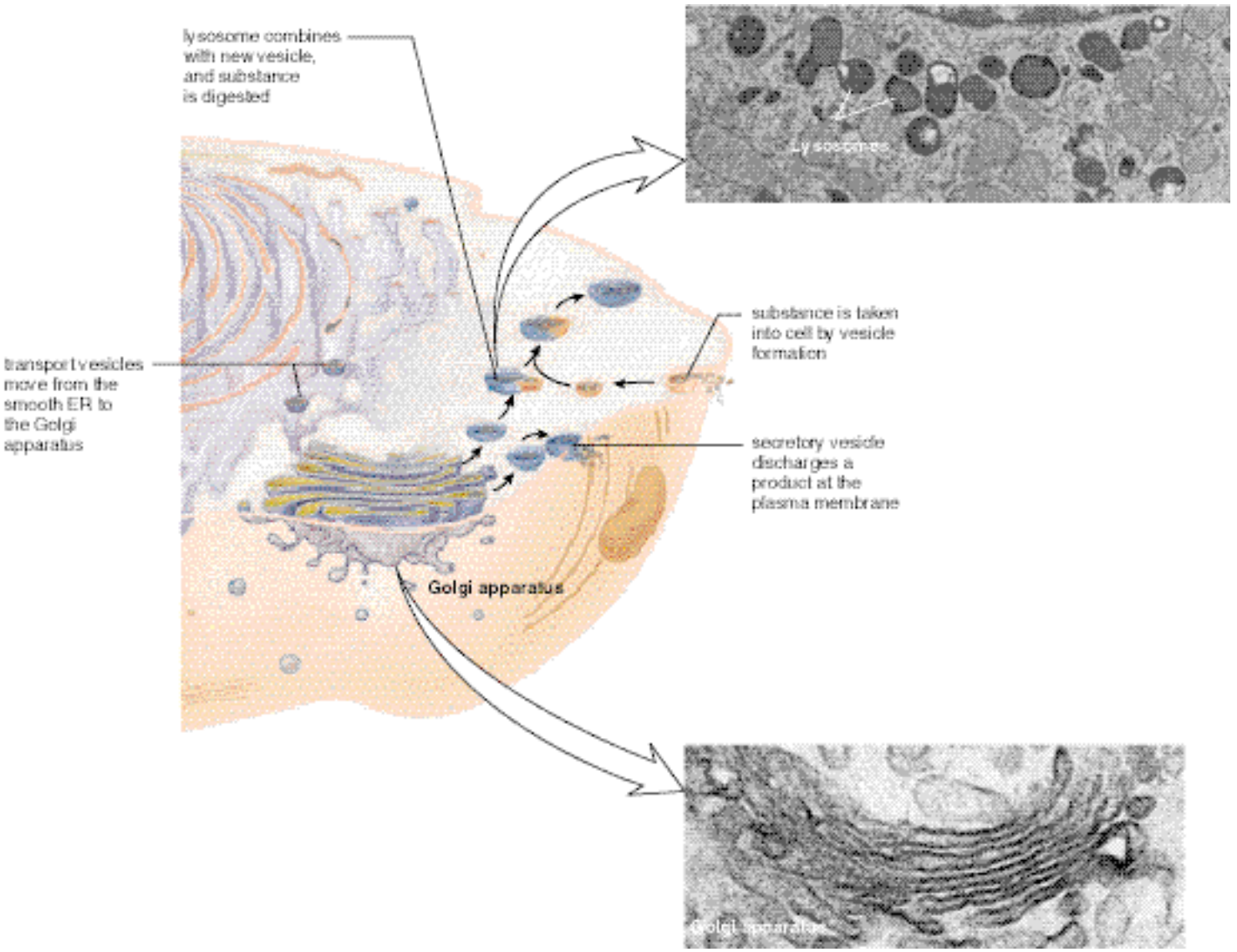


Figure 3.9 **The Golgi apparatus.**
The Golgi apparatus modifies proteins and packages them either in vesicles for secretion from the cell or in lysosomes. Lysosomes function as digestive vesicles.

The Golgi apparatus receives protein and/or lipid-filled vesicles that bud from the ER. Some biologists believe that these fuse to form a saccule at the inner face and that this saccule remains as a part of the Golgi apparatus until the molecules are repackaged in new vesicles at the outer face. Others believe that the vesicles from the ER proceed directly to the outer face of the Golgi apparatus, where processing and packaging occur within its saccules. The Golgi apparatus contains enzymes that modify proteins and lipids. For example, it can add a chain of sugars to proteins, thereby making them glycoproteins and glycolipids, which are molecules found in the plasma membrane.

The vesicles that leave the Golgi apparatus move about the cell. Some vesicles proceed to the plasma membrane, where they discharge their contents. Because this is secretion, it is often said that the Golgi apparatus is involved in processing, packaging, and secretion. Other vesicles that leave the Golgi apparatus are lysosomes.

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

Lysosomes

Lysosomes, vesicles produced by the Golgi apparatus, contain hydrolytic digestive enzymes. Sometimes macromolecules are brought into a cell by vesicle formation at the plasma membrane (see Fig. 3.9). When a lysosome fuses with such a vesicle, its contents are digested by lysosomal enzymes into simpler subunits that then enter the cytoplasm. Even parts of a cell are digested by its own lysosomes (called autodigestion). Normal cell rejuvenation most likely takes place in this manner, but autodigestion is also important during development. For example, when a tadpole becomes a frog, lysosomes digest away the cells of the tail. The fingers of a human embryo are at first webbed, but they are freed from one another as a result of lysosomal action.

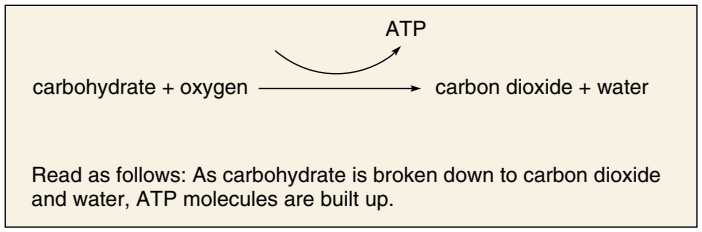
Occasionally, a child is born with Tay-Sachs disease, a metabolic disorder involving a missing or inactive lysosomal enzyme. In these cases, the lysosomes fill to capacity with macromolecules that cannot be broken down. The cells become so full of these lysosomes that the child dies. Someday soon it may be possible to provide the missing enzyme for these children.

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

Mitochondria

Most mitochondria (sing., **mitochondrion**) are between 0.5 µm and 1.0 µm in diameter and about 7 µm in length, although the size and the shape can vary. Mitochondria are bounded by a double membrane. The inner membrane is folded to form little shelves called cristae, which project into the matrix, an inner space filled with a gel-like fluid (Fig. 3.10).

Mitochondria are the site of ATP (adenosine triphosphate) production involving complex metabolic pathways. ATP molecules are the common carrier of energy in cells. A shorthand way to indicate the chemical transformation that involves mitochondria is as follows:



Mitochondria are often called the powerhouses of the cell: just as a powerhouse burns fuel to produce electricity, the mitochondria convert the chemical energy of glucose products into the chemical energy of ATP molecules. In the process, mitochondria use up oxygen and give off carbon dioxide and water. The oxygen you breathe in enters cells

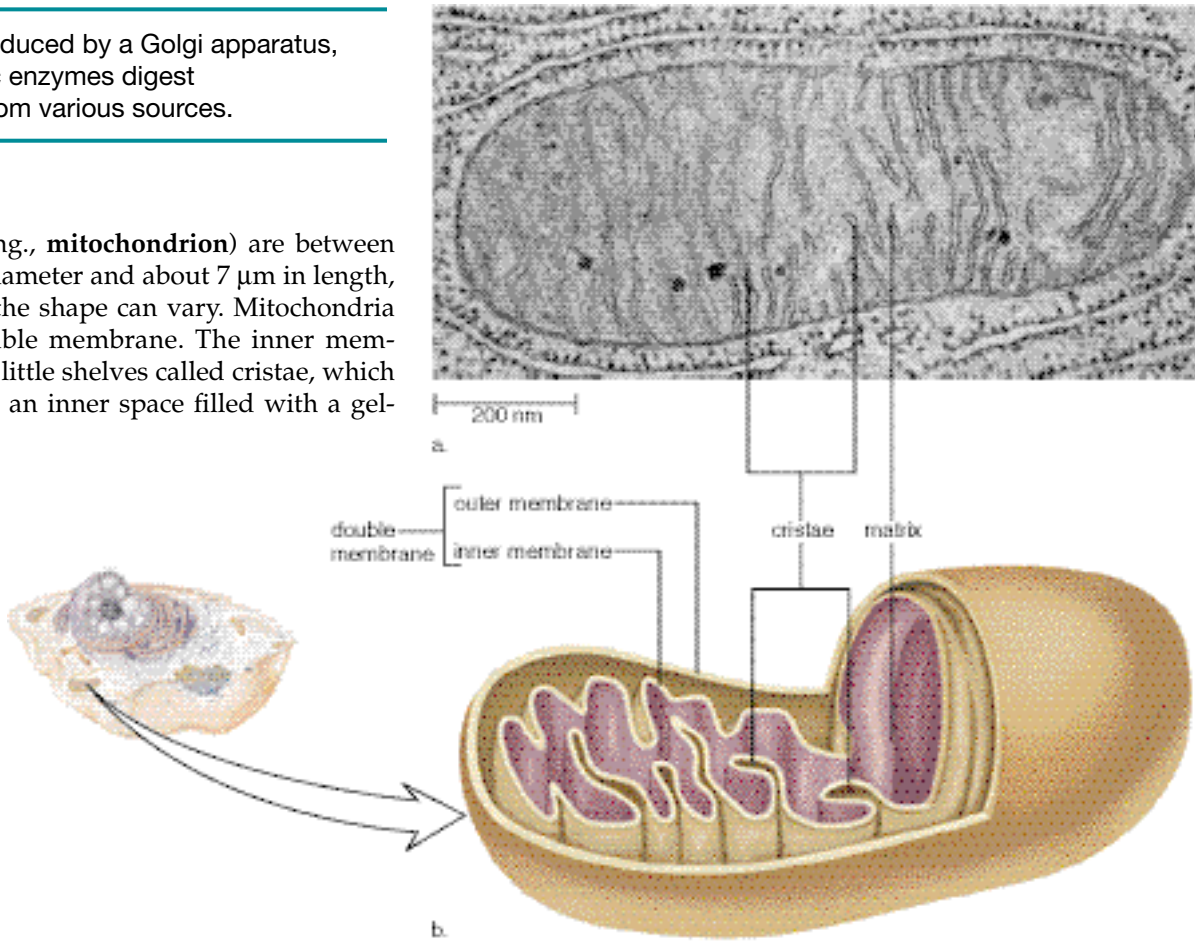


Figure 3.10 **Mitochondrion structure.**
Mitochondria are involved in cellular respiration. **a.** Electron micrograph. **b.** Generalized drawing in which the outer membrane and portions of the inner membrane have been cut away to reveal the cristae.

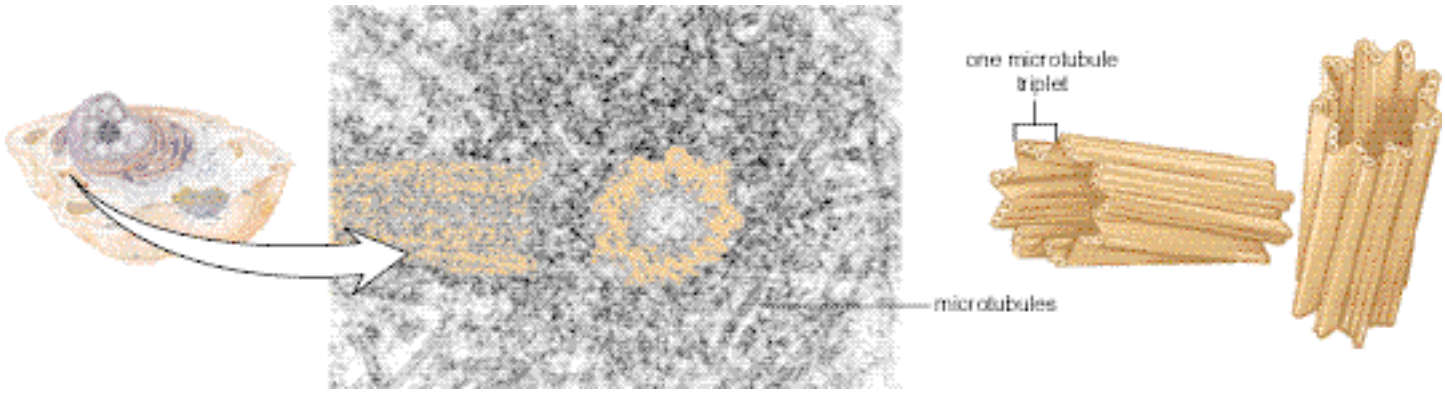


Figure 3.11 **Centrioles.**
Centrioles are composed of nine microtubule triplets. They lie at right angles to one another within the microtubule organizing center (MTOC), which is believed to assemble microtubules at the time of cell division.

and then mitochondria; the carbon dioxide you breathe out is released by mitochondria. Because oxygen is involved, it is said that mitochondria carry on cellular respiration.

The matrix of a mitochondrion contains enzymes for breaking down glucose products. ATP production then occurs at the cristae. The protein complexes that aid in the conversion of energy are located in an assembly-line fashion on these membranous shelves.

Every cell uses a certain amount of ATP energy to synthesize molecules, but many cells use ATP to carry out their specialized function. For example, muscle cells use ATP for muscle contraction, which produces movement, and nerve cells use it for the conduction of nerve impulses, which make us aware of our environment.

Mitochondria are involved in cellular respiration, a process that provides ATP molecules to the cell.

The Cytoskeleton

Several types of filamentous protein structures form a cytoskeleton that helps maintain the cell's shape and either anchors the organelles or assists their movement as appropriate. The cytoskeleton includes microtubules and actin filaments (see Fig. 3.3).

Microtubules are shaped like thin cylinders and are several times larger than actin filaments. Each cylinder contains 13 rows of tubulin, a globular protein, arranged in a helical fashion. Remarkably, microtubules can assemble and disassemble. In many cells, the regulation of microtubule assembly is under the control of a microtubule organizing center (MTOC), which lies near the nucleus. Microtubules radiate from the MTOC, helping to maintain the shape of the cell and acting as tracks along which organelles move. It is well known that during cell division, microtubules form spindle fibers, which assist the movement of chromosomes.

Actin filaments are long, extremely thin fibers that usually occur in bundles or other groupings. Actin filaments have been isolated from various types of cells, especially those in which movement occurs. Microvilli, which project from certain cells and can shorten and extend, contain actin filaments. Actin filaments, like microtubules, can assemble and disassemble.

The cytoskeleton contains microtubules and actin filaments. Microtubules (13 rows of tubulin protein molecules arranged to form a hollow cylinder) and actin filaments (thin actin strands) maintain the shape of the cell and also direct the movement of cell parts.

Centrioles

In animal cells, **centrioles** are short cylinders with a 9 + 0 pattern of microtubules. There are nine outer microtubule triplets and no center microtubules (Fig. 3.11). There is always one pair of centrioles lying at right angles to one another near the nucleus. Before a cell divides, the centrioles duplicate, and the members of the new pair are also at right angles to one another. During cell division, the pairs of centrioles separate so that each daughter cell gets one pair of centrioles.

Centrioles are part of a microtubule organizing center that also includes other proteins and substances. Microtubules begin to assemble in the center, and then they grow outward, extending through the entire cytoplasm. In addition, centrioles may be involved in other cellular processes that use microtubules, such as movement of material throughout the cell or formation of the spindle, a structure that distributes the chromosomes to daughter cells during cell division. Their exact role in these processes is uncertain, however. Centrioles also give rise to basal bodies that direct the formation of cilia and flagella.

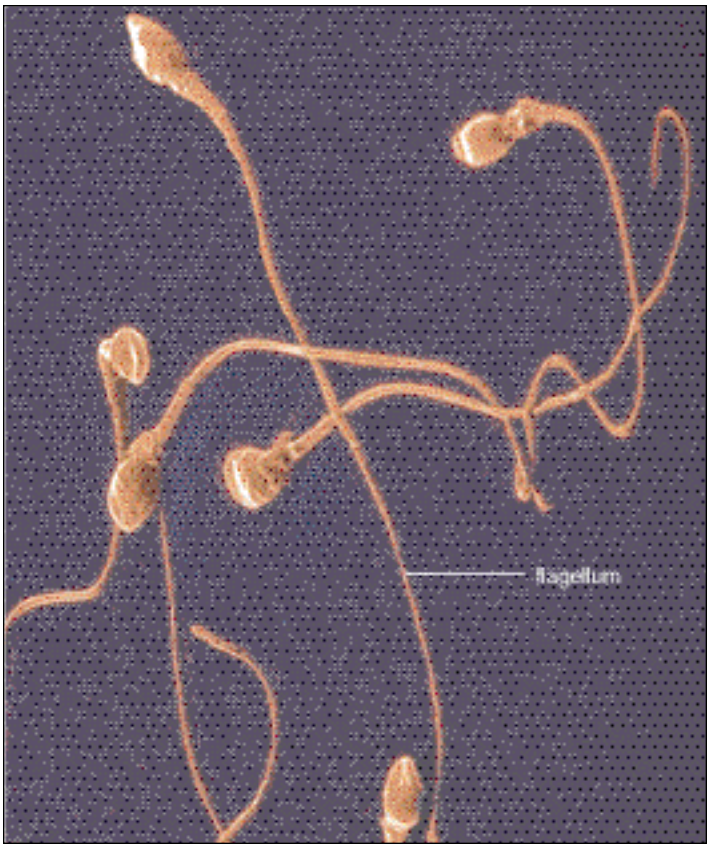


Figure 3.12 **Sperm cells.**
Sperm cells use long, whiplike flagella to move about.

Cilia and Flagella

Cilia and flagella (sing., **cilium, flagellum**) are projections of cells that can move either in an undulating fashion, like a whip, or stiffly, like an oar. Cilia are short (2–10 µm) while flagella are longer (usually no longer than 200 µm). Cells that have these organelles are capable of self-movement or moving material along the surface of the cell. For example, sperm cells, carrying genetic material to the egg, move by means of flagella (Fig. 3.12). The cells that line our respiratory tract are ciliated. These cilia sweep debris trapped within mucus back up the throat, and this action helps keep the lungs clean.

Each cilium and flagellum has a basal body at its base, which lies in the cytoplasm. **Basal bodies,** like centrioles, have a 9 + 0 pattern of microtubule triplets. They are believed to organize the structure of cilia and flagella even though cilia and flagella have a 9 + 2 pattern of microtubules. In cilia and flagella, there are nine microtubule doublets surrounding two central microtubules. This arrangement is believed to be necessary to their ability to move.

Centrioles give rise to basal bodies that organize the pattern of microtubules in cilia and flagella.

3.3 Cellular Metabolism

Cellular **metabolism** includes all the chemical reactions that occur in a cell. Quite often these reactions are organized into metabolic pathways, which can be diagrammed as follows:

$$A \xrightarrow{1} B \xrightarrow{2} C \xrightarrow{3} D \xrightarrow{4} E \xrightarrow{5} F \xrightarrow{6} G$$

The letters, except *A* and *G*, are **products** of the previous reaction and the **reactants** for the next reaction. *A* represents the beginning reactant(s), and *G* represents the end product(s). The numbers in the pathway refer to different enzymes. *Every reaction in a cell requires a specific enzyme.* In effect, no reaction occurs in a cell unless its enzyme is present. For example, if enzyme 2 in the diagram is missing, the pathway cannot function; it will stop at *B*. Since enzymes are so necessary in cells, their mechanism of action has been studied extensively.

Most metabolic pathways are regulated by feedback inhibition: the end product of the pathway binds to a special site on the first enzyme of the pathway. This binding shuts down the pathway, and no more product is produced.

Metabolic pathways contain many enzymes that perform their reactions in a sequential order.

Enzymes and Coenzymes

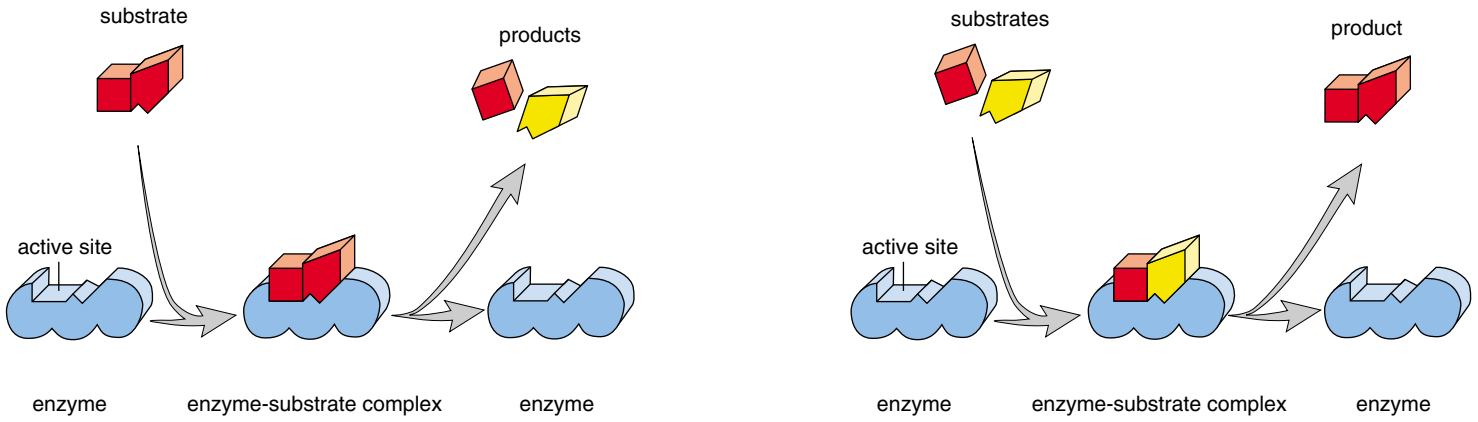
When an enzyme speeds up a reaction, the reactant(s) that participate(s) in the reaction is called the enzyme's **substrate(s).** Enzymes are often named for their substrates (Table 3.3). Enzymes have a specific region, called an **active site,** where the substrates are brought together so that they can react. An enzyme's specificity is caused by the shape of the active site, where the enzyme and its substrate(s) fit together in a specific way, much as the pieces of a jigsaw puzzle fit together (Fig. 3.13). After one reaction is complete, the product or products are released, and the enzyme is ready to catalyze another reaction. This can be summarized in the following manner:

$$E + S \rightarrow ES \rightarrow E + P$$

(where *E* = enzyme, *S* = substrate, *ES* = enzyme-substrate complex, and *P* = product). The arrows in the diagram are

Table 3.3 **Enzymes Named for Their Substrates**

Substrate	Enzyme
Lipid	Lipase
Urea	Urease
Maltose	Maltase
Ribonucleic acid	Ribonuclease
Lactose	Lactase



a. Degradation

b. Synthesis

Figure 3.13 **Enzymatic action.**
An enzyme has an active site where the substrates and enzyme fit together in such a way that the substrates are oriented to react. Following the reaction, the products are released and the enzyme is ready to participate in the reaction again. **a.** Some enzymes carry out degradation **b.** Some enzymes carry out synthesis.

not reversible. The energy content of the product(s) is (are) always lower than that of the substrate(s). Therefore, for the reverse reaction to occur energy has to be added.

Environmental conditions such as an incorrect pH or high temperature can cause an enzyme to become denatured. A denatured enzyme no longer has its usual shape and is therefore unable to speed up its reaction.

Many enzymes require cofactors. Some cofactors are inorganic, such as copper, zinc, or iron. Other cofactors are organic, nonprotein molecules and are called **coenzymes.** These cofactors assist the enzyme and may even accept or contribute atoms to the reaction. It is interesting that vitamins are often components of coenzymes. The vitamin niacin is a part of the coenzyme NAD, which removes hydrogen (H) atoms from substrates and therefore is called a **dehydrogenase.** Hydrogen atoms are sometimes removed by NAD as molecules are broken down. NAD that is carrying hydrogen atoms is written as $NADH_2$ because NAD removes two hydrogen atoms at a time. As we shall see, the removal of hydrogen atoms releases energy that can be used for ATP buildup.

Enzymes are specific because they have an active site that accommodates their substrates. Enzymes often have organic, nonprotein helpers called coenzymes. NAD is a dehydrogenase, a coenzyme that removes hydrogen from substrates.

Cellular Respiration

During **cellular respiration,** glucose is broken down to carbon dioxide and water. The energy released as glucose breakdown occurs is used to build up ATP molecules, the common energy carrier in cells. Even though it is possible to write an overall equation for the process, cellular respiration does not occur in one step. Glucose breakdown requires three subpathways: glycolysis, the Krebs cycle, and the electron transport system. The location of these subpathways is as follows:

- **Glycolysis** occurs in the cytoplasm, outside a mitochondrion.
- The **Krebs cycle** occurs in the matrix of a mitochondrion.
- The **electron transport system** occurs on the cristae of a mitochondrion.

Glycolysis and the Krebs cycle are a series of reactions in which the product of the previous reaction becomes the substrate for the next reaction. Every reaction that occurs during glycolysis and the Krebs cycle requires a specific enzyme. Each pathway resembles a conveyor belt in which a beginning substrate continuously enters at the start and, after a series of reactions, end products leave at the termination of the belt. It is important to realize, too, that these two pathways and the electron transport system occur at the same time. They can be compared to the inner workings of a watch, in which all parts are synchronized.

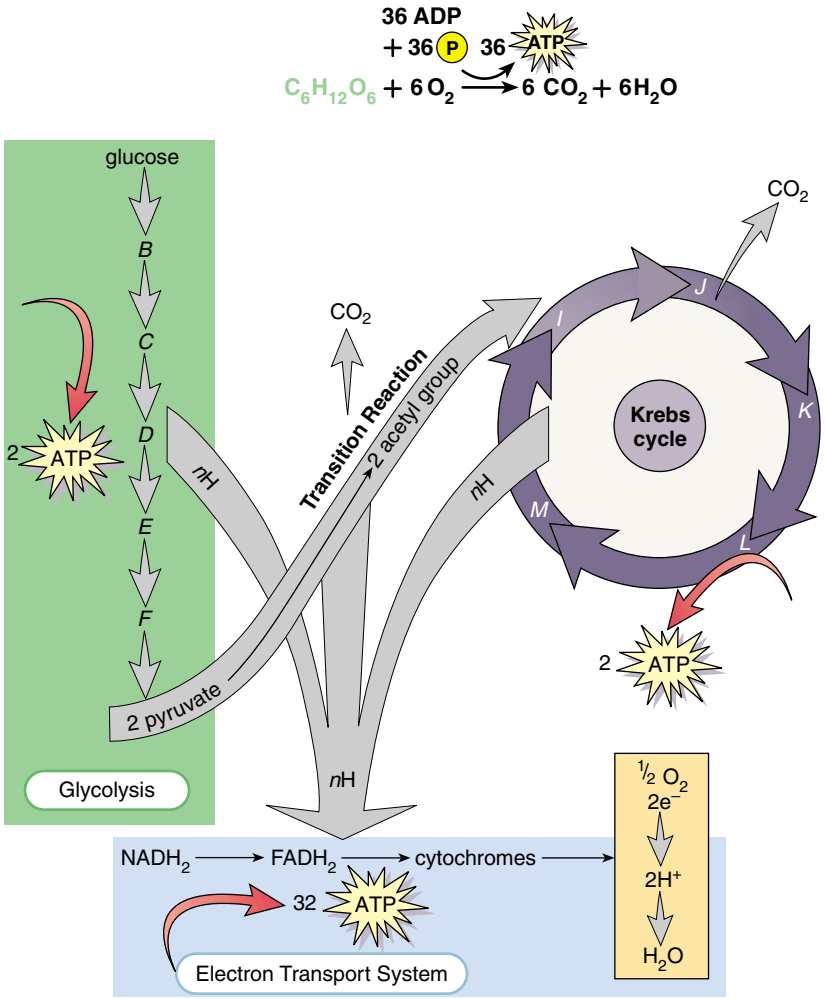


Figure 3.14 **Cellular respiration.**
The overall reaction shown at the top actually requires three subpathways: glycolysis, the Krebs cycle, and the electron transport system. As the reactions occur, a number of hydrogen (H) atoms and carbon dioxide (CO_2) molecules are removed from the various substrates. Oxygen (O_2) acts as the final acceptor for hydrogen atoms ($2e^- + 2H^+$) and becomes water (H_2O).

Table 3.4 **Overview of Cellular Respiration**

Name of Pathway	Result
Glycolysis	Removal of H from substrates produces 2 ATP
Transition reaction	Removal of H from substrates releases 2 CO_2
Krebs cycle	Removal of H from substrates releases 4 CO_2
	Produces 2 ATP after 2 turns
Electron transport system	Accepts H from other pathways and passes electrons on to O_2, producing H_2O
	Produces 32 ATP

The reactants of cellular respiration, namely glucose and oxygen, and the products, namely carbon dioxide and water, are related to the subpathways in the manner described next.

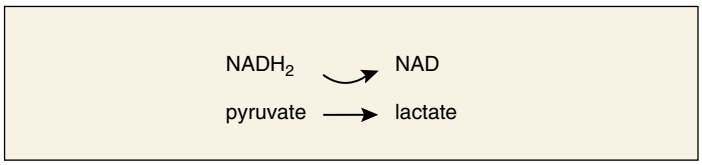
1. Glucose, a C_6 molecule, is to be associated with **glycolysis,** the breakdown of glucose to two molecules of pyruvate (pyruvic acid), a C_3 molecule. During glycolysis, energy is released as hydrogen (H) atoms are removed and added to NAD, forming $NADH_2$. This energy is used to form two ATP molecules (Fig. 3.14).
2. Carbon dioxide (CO_2) is to be associated with the transition reaction and the Krebs cycle, both of which occur in mitochondria. During the transition reaction, pyruvate is converted to a C_2 acetyl group after CO_2 comes off. Because the transition reaction occurs twice per glucose molecule, two molecules of CO_2 are released. Hydrogen (H) atoms are also removed at this time.

   The acetyl group enters the **Krebs cycle,** a cyclical series of reactions that gives off two CO_2 molecules and produces one ATP molecule. Since the Krebs cycle occurs twice per glucose molecule, altogether four CO_2 and two ATP are produced per glucose molecule. Hydrogen (H) atoms are removed from the substrates and added to NAD, forming $NADH_2$ as the Krebs cycle occurs.
3. Oxygen (O_2) and water (H_2O) are to be associated with the electron transport system. The **electron transport system** begins with $NADH_2$, a coenzyme that carries hydrogen (H) atoms to the system, but after that it consists of molecules that carry electrons. High-energy electrons are removed from the hydrogen atoms, leaving behind hydrogen ions (H^+), and then the electrons are passed from one molecule to another until the electrons are received by an oxygen atom. At this point, 2 H^+ combine with an oxygen to give water. As the electrons are passed down the system, their energy is released to allow the buildup of 32 ATP.
4. ATP is to be associated with glycolysis, the Krebs cycle, and the electron transport system. Altogether, 36 ATP molecules result from the breakdown of one glucose molecule (Table 3.4).

Cellular respiration requires glycolysis, which takes place in the cytoplasm; the Krebs cycle, which is located in the matrix of the mitochondria; and the electron transport system, which is located on the cristae of the mitochondria.

Fermentation

Fermentation is an anaerobic process. When oxygen is not available to cells, the electron transport system soon becomes inoperative because oxygen is not present to accept electrons. In this case, most cells have a safety valve so that some ATP can still be produced. Glycolysis operates as long as it is supplied with "free" NAD—that is, NAD that can pick up hydrogen atoms. Normally, $NADH_2$ takes hydrogens to the electron transport system and thereby becomes "free" of hydrogen atoms. However, if the system is not working due to lack of oxygen, $NADH_2$ passes its hydrogen atoms to pyruvate as shown in the following reaction:



The Krebs cycle and electron transport system do not function as part of fermentation. When oxygen is available again, lactate (lactic acid) can be converted back to pyruvate, and metabolism can proceed as usual.

Fermentation takes less time than cellular respiration, but since glycolysis alone is occurring, it produces only 2 ATP per glucose molecule. Also, fermentation results in the buildup of lactate. Lactate is toxic to cells and causes muscles to cramp and fatigue. If fermentation continues for any length of time, death follows.

It is of interest to know that fermentation takes its name from yeast fermentation. Yeast fermentation produces alcohol and carbon dioxide (instead of lactate). When yeast is used to leaven bread, it is the carbon dioxide that produces the desired effect. When yeast is used to produce alcoholic beverages, it is the alcohol that humans make use of.

> Fermentation is an anaerobic process, a process that does not require oxygen but produces very little ATP per glucose molecule and results in the buildup of lactate or alcohol and carbon dioxide.

Summarizing the Concepts

3.1 Cell Size

Cells are quite small, and it usually takes a microscope to see them. Small cubes, like cells, have a more favorable surface/volume ratio than do large cubes. Only inactive eggs are large enough to be seen by the naked eye; once development begins, cell division results in small-size cells.

3.2 Cellular Organization

A cell is surrounded by a plasma membrane, which regulates the entrance and exit of molecules and ions. Some molecules, such as water and gases, diffuse through the membrane. The direction in which water diffuses is dependent on its concentration within the cell compared to outside the cell.

Table 3.1 lists the cell organelles we have studied in the chapter. The nucleus is a large organelle of primary importance because it controls the rest of the cell. Within the nucleus lies the chromatin, which condenses to become chromosomes during cell division.

Proteins are made at the rough ER before being modified and packaged by the Golgi apparatus into vesicles for secretion. During secretion, a vesicle discharges its contents at the plasma membrane. Golgi-derived lysosomes fuse with incoming vesicles to digest any material enclosed within, and lysosomes also carry out autodigestion of old parts of cells.

Mitochondria are the powerhouses of the cell. During the process of cellular respiration, mitochondria convert carbohydrate energy to ATP energy.

Microtubules and actin filaments make up the cytoskeleton, which maintains the cell's shape and permits movement of cell parts. Centrioles are a part of the microtubule organizing center, which is associated with the formation of microtubules in general and the spindle that appears during cell division. Centrioles also produce basal bodies that give rise to cilia and flagella.

3.3 Cellular Metabolism

Cellular metabolism is the sum of all biochemical pathways of the cell. In a pathway, a series of reactions proceeds in an orderly step-by-step manner. Each of these reactions requires a specific enzyme. Sometimes enzymes require coenzymes, nonprotein portions that participate in the reaction. NAD is a coenzyme.

Cellular respiration (the breakdown of glucose to carbon dioxide and water) includes three pathways: glycolysis, the Krebs cycle, and the electron transport system. If oxygen is not available in cells, the electron transport system is inoperative, and fermentation (an anaerobic process) occurs. Fermentation makes use of glycolysis only, plus one more reaction in which pyruvate is reduced to lactate.

Bioethical Focus

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.

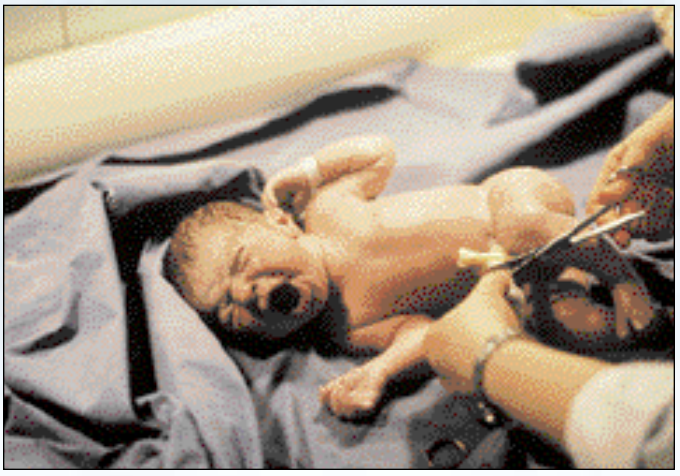


Figure 3A **Umbilical cords are valuable.**
Banking the blood from a baby's umbilical cord can be a source of blood stem cells. Investigators are learning how to convert blood stem cells to other types of mature cells aside from blood cells.

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?

Looking at Both Sides www.mhhe.com/biosci/genbio/maderhuman7/

Every bioethical issue has at least two sides. Even if you already have an opinion, it is important to explore the opposite opinion before finalizing your position. The Online Learning Center at www.mhhe.com/biosci/genbio/maderhuman7/ will help you fine-tune your initial opinion, explore both sides, and finalize your position. You may acquire new arguments for your original opinion, or you may even change your opinion. Be sure to complete these activities in sequence:

Taking Sides Decide your initial opinion by answering a series of questions. Then see if your opinion changes after completing the next two activities.

Further Debate Read opposing articles that give you further information on this particular bioethical issue.

Explain Your Position Answer another series of questions and then defend your original or changed opinion. You can e-mail your position to your instructor if he or she wishes.

Studying the Concepts

1. Describe the structure and biochemical makeup of a plasma membrane. 46
2. What are three mechanisms by which substances enter and exit cells? Define isotonic, hypertonic, and hypotonic solutions. 47
3. Describe the nucleus and its contents, including the terms DNA and RNA in your description. 49
4. Describe the structure and function of endoplasmic reticulum. Include the terms rough and smooth ER and ribosomes in your description. 50
5. Describe the structure and function of the Golgi apparatus and its relationship to vesicles and lysosomes. 50–51
6. Describe the structure of mitochondria, and relate this structure to the pathways of cellular respiration. 52–53
7. Describe the composition of the cytoskeleton. 53
8. Describe the structure and function of centrioles, cilia, and flagella. 53–54
9. Discuss and draw a diagram for a metabolic pathway. Discuss and give a reaction to describe the specificity theory of enzymatic action. Define coenzyme. 54–55
10. Name and describe the events within the three subpathways that make up cellular respiration. Why is fermentation necessary but potentially harmful to the human body? 55–57

Testing Your Knowledge of the Concepts

In questions 1–4, match the organelles to the functions below.

a. mitochondria
b. nucleus
c. Golgi apparatus
d. rough ER

_____ 1. packaging and secretion

_____ 2. powerhouses of the cell

_____ 3. protein synthesis

_____ 4. control center for cell

In questions 5–7, indicate whether the statement is true (T) or false (F).

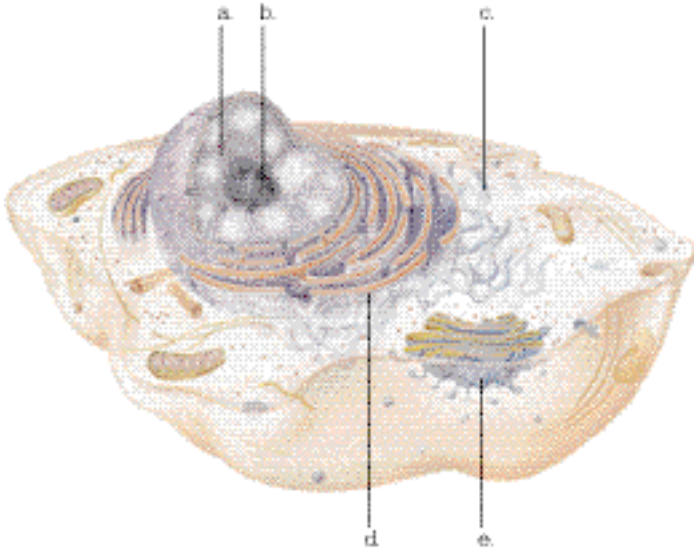
_____ 5. Microtubules and actin filaments are a part of the cytoskeleton, the framework of the cell that provides its shape and regulates movement of organelles.

_____ 6. Water enters a cell when the cell is placed in a hypertonic solution.

_____ 7. Substrates react at the active site, located on the surface of their enzyme.

In questions 8 and 9, fill in the blanks.

8. During cellular respiration, most of the ATP molecules are produced at the _____, a series of carriers located on the _____ of mitochondria.
9. Fermentation of a glucose molecule produces only _____ ATP compared to the _____ ATP produced by cellular respiration.
10. Label the parts of the cell that are involved in protein synthesis and modification. Explain your choices.



Understanding Key Terms

active site 54
active transport 48
basal body 54
cell 42
cell theory 42
cellular respiration 55
centriole 53
chromatin 49
chromosome 49
cilium 54
coenzyme 55
cytoplasm 44
cytoskeleton 44
dehydrogenase 55
diffusion 47
electron transport system 55
endoplasmic reticulum (ER) 50
facilitated transport 48
fermentation 57
flagellum 54
glycolysis 55
Golgi apparatus 50
Krebs cycle 55
lysosome 52
metabolism 54
microtubule 53
mitochondrion 52
nuclear envelope 49
nuclear pore 49
nucleolus 44
nucleoplasm 49
nucleus 44
organelle 44
osmosis 47
plasma membrane 44
polyribosome 50
product 54
reactant 54
ribosome 50
selectively permeable 47
substrate 54
tonicity 47
vesicle 50

e-Learning Connection

www.mhhe.com/biosci/genbio/maderhuman7/

3.1 Cell Structure and Function


Cell Size *simulation*

3.2 Cellular Organization


Energy Organelles *Essential Study Partner*
Cytoskeleton *Essential Study Partner*
Membrane Structure *Essential Study Partner*
Diffusion *Essential Study Partner*
Osmosis *Essential Study Partner*
Facilitated Diffusion *Essential Study Partner*
Active Transport *Essential Study Partner*
Exo/Endocytosis *Essential Study Partner*


Animal Cell I *art labeling activity*
Animal Cell II *art labeling activity*
Anatomy of the Nucleus *art labeling activity*
Golgi Apparatus Structure *art labeling activity*
Mitochondrion Structure *art labeling activity*
The Cytoskeleton *art labeling activity*
Fluid-Mosaic Model of the Plasma Membrane Structure I *art labeling activity*
Fluid-Mosaic Model of the Plasma Membrane Structure II *art labeling activity*
Active Transport *simulation*

3.3 Cellular Metabolism


Enzymes *Essential Study Partner*
Pathways *Essential Study Partner*
Glycolysis *Essential Study Partner*
Krebs Cycle *Essential Study Partner*
Electron Transport System *Essential Study Partner*

Chapter Summary

Key Term Flashcards *vocabulary quiz*
Chapter Quiz *objective quiz*