Electrons do not encircle the atomic nucleus in two-dimensional paths. Some move around the atomic nucleus in a three-dimensional region that is spherical, forming cloud-like or fuzzy layers about the nucleus. Others move in a manner that resembles the figure 8, forming fuzzy regions that look like dumbbells or hourglasses (figure 2.5).

The first energy level is full when it has 2 electrons. The second energy level is full when it has 8 electrons; the third energy level, 8; and so forth (table 2.2). Also note in table 2.2 that, for some of the atoms (He, Ne, Ar), the outermost energy level contains the maximum number of electrons it can hold. Elements such as He and Ne, with filled outer energy levels, are particularly stable.

All atoms have a tendency to seek such a stable, filled outer energy level arrangement, a tendency referred to as the *octet (8) rule*. (Hydrogen and helium are exceptions to this rule and have a filled outer energy level when they have 2 electrons.) The rule states that atoms attempt to acquire an outermost energy level with 8 electrons through processes called **chemical reactions**. Because elements such as He and Ne have full outermost energy levels under ordinary circumstances, they do not normally undergo chemical reactions. These elements are referred to as *inert* or *noble* (implying that they are too special to interact with other elements). Atoms of other elements have outer energy levels that are not full. For example, H, C, Mg, and Ca will undergo reactions to fill their outermost energy level in order to become stable. *It is important for chemists and biologists to focus on electrons in the outermost energy level, because it is these electrons that are involved in the chemical activities of all life.*

2.2 CONCEPT REVIEW

3. What is meant by an "energy level"?
4. Define *subatomic particle*.
5. Why do chemicals undergo reactions?

2.3 The Kinetic Molecular Theory and Molecules

Greek philosopher Aristotle (384–322 B.C.) rejected the idea of atoms. He believed that matter was continuous and made up of only four parts: earth, air, fire, and water. Aristotle's belief about matter predominated through the 1600s. Galileo and Newton, however, believed the ideas about matter being composed of tiny particles, or atoms, because this theory seemed to explain matter's behavior. Widespread acceptance of the atomic model did not occur, however, until strong evidence was developed through the science of chemistry in the late 1700s and early 1800s. The experiments finally led to a collection of assumptions about the small particles of matter and the space around them; these assumptions came to be known as the kinetic molecular theory.

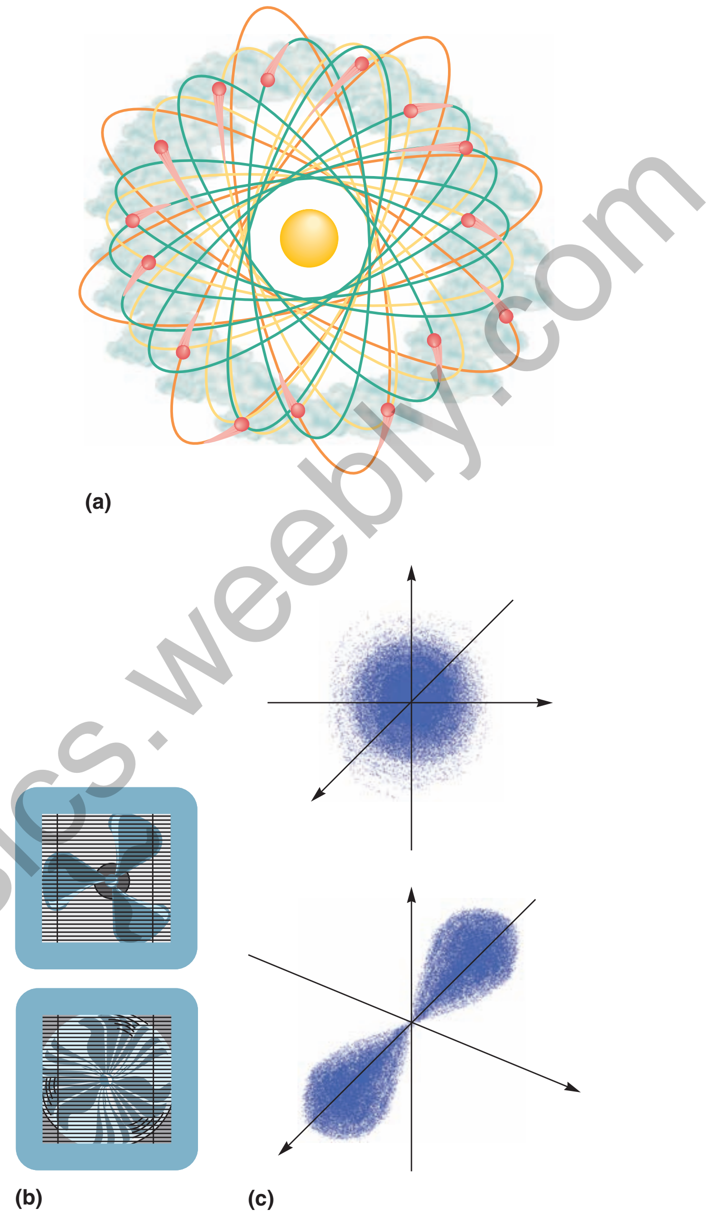


FIGURE 2.5 The Electron Cloud
Electrons are moving around the nucleus so fast that they can be thought of as forming a cloud around it, rather than an orbit or a single track. *(a)* You might think of the electron cloud as hundreds of photographs of an atom. Each photograph shows where an electron was at the time the picture was taken. However, when the next picture is taken, the electron has moved to a different place. In effect, an electron appears to be everyplace in its energy level at the same time, just as the fan blade of a window fan is everywhere at once when it is running. *(b)* No matter where you stick your finger in the fan, you will be touched by the moving blade. Although we are able to determine where an electron is at a given time, we do not know the exact path it uses to go from one place to another. *(c)* This is a better way to represent the positions of electrons in spherical and hourglass configurations.

TABLE 2.2 Number of Electrons in Energy Level

Element	Symbol	Atomic Number	Energy Level 1	Energy Level 2	Energy Level 3	Energy Level 4
Hydrogen	H	1	1			
Helium	**He**	**2**	**2**			
Carbon	C	6	2	4		
Nitrogen	N	7	2	5		
Oxygen	O	8	2	6		
Neon	**Ne**	**10**	**2**	8		
Sodium	Na	11	2	8	1	
Magnesium	Mg	12	2	8	2	
Phosphorus	P	15	2	8	5	
Sulfur	S	16	2	8	6	
Chlorine	Cl	17	2	8	7	
Argon	**Ar**	**18**	**2**	8	8	
Potassium	K	19	2	8	8	1
Calcium	Ca	20	2	8	8	2

The **kinetic molecular theory** states that all matter is made up of tiny particles, which are in constant motion.

The Formation of Molecules

Because atoms tend to fill their outer energy levels, they often interact with other atoms. Recall from chapter 1 that a **molecule** is the smallest particle of a chemical compound and is a definite and distinct, electrically neutral group of bonded atoms. Some atoms, such as oxygen, hydrogen, and nitrogen, bond to form *diatomic* (*di* = two) molecules. In our atmosphere, these elements are found as the gases H_2, O_2, and N_2. The subscript indicates the number of atoms of an element in a single molecule of a substance. Other elements are not normally diatomic but exist as single, or *monatomic* (*mon* = one), units—for example, the gases helium (He) and neon (Ne). These chemical symbols, or initials, indicate a single atom of that element.

Two or more different kinds of atoms can combine, forming a compound. A **compound** is a chemical substance made up of atoms of two or more elements combined in a specific ratio and arrangement. The attractive forces that hold the atoms of a molecule together are called **chemical bonds.** Molecules can consist of two or more atoms of the same element (such as O_2 or N_2) or of specific numbers of atoms of different elements (figure 2.6).

The **formula** of a compound describes what elements it contains (as indicated by a chemical symbol) and in what proportions they occur (as indicated by the subscript number). For example, pure water is composed of two atoms of hydrogen and one atom of oxygen. It is represented by the chemical formula H_2O. The subscript "2" indicates two atoms of the element hydrogen, and the symbol for oxygen without a subscript indicates that there is only 1 atom of oxygen present in this molecule.

2.3 CONCEPT REVIEW

6. What is the difference between an atom and an element?
7. What is the difference between a molecule and a compound?

2.4 Molecules and Kinetic Energy

Common experience shows that all matter has a certain amount of kinetic energy. For instance, if you were to open a bottle of perfume in a closed room with no air movement, it wouldn't take long for the aroma to move throughout the room. The kinetic molecular theory explains this by saying that the molecules *diffuse,* or spread, throughout the room because they are in constant, random motion. This theory also predicts that the rate at which they diffuse depends on the temperature of the room—the higher the air temperature, the greater the kinetic energy of the molecules and the more rapid the diffusion of the perfume.

Temperature is a measure of the average kinetic energy of the molecules making up a substance. The two most common numerical scales used to measure temperature are the Fahrenheit scale and the Celsius scale. When people comment on the temperature of something, they usually are making a comparison. For example, they may say that the air temperature today is

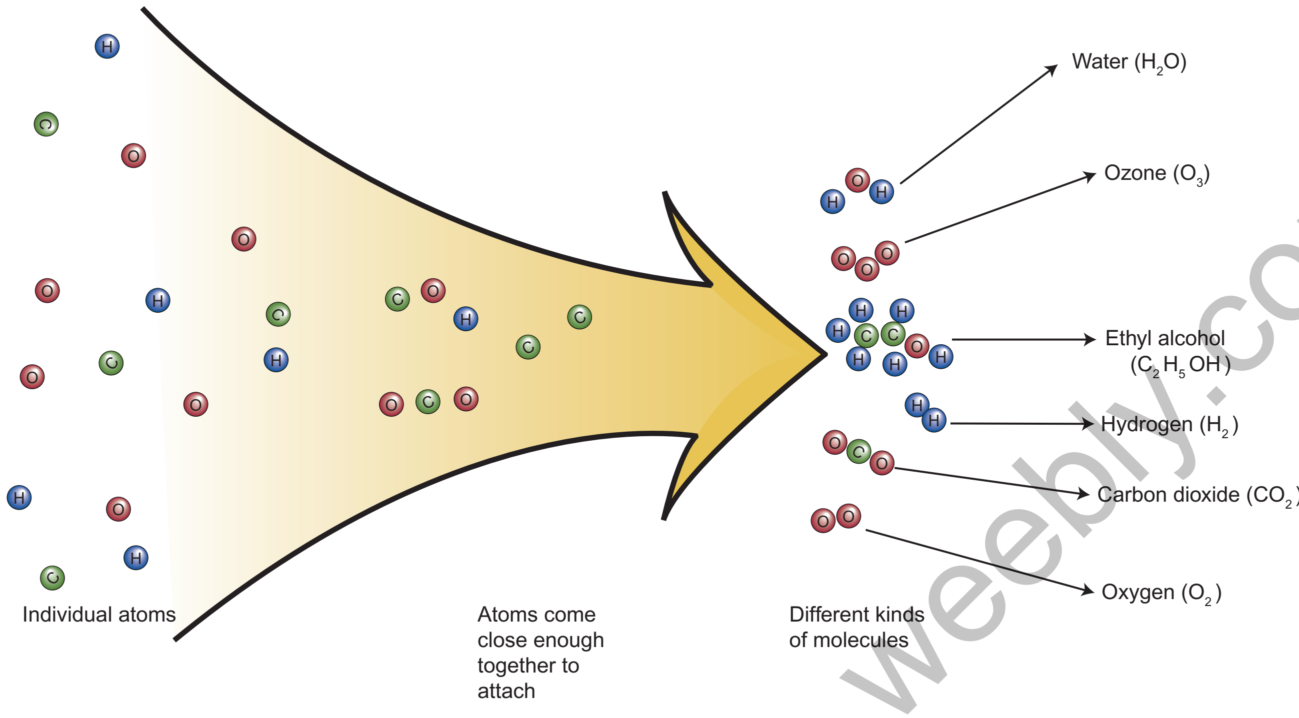
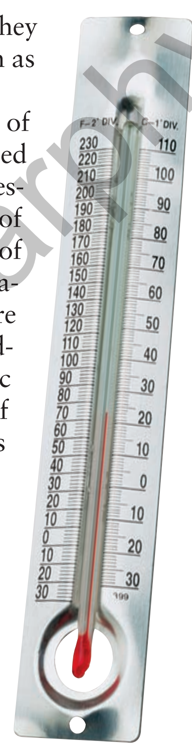


FIGURE 2.6 The Formation of Molecules
This figure shows how atoms of carbon, hydrogen and oxygen come together to form different kinds of molecules. If two atoms of hydrogen attach to one of oxygen, the result is a molecule of water (H_2O). Depending on the kinds of atoms involved and their numbers, other kinds of molecules, compounds, can be formed.

"colder" or "hotter" than it was yesterday. They may also refer to a scale for comparison, such as "the temperature is 20°C [68°F]."

Heat is the total internal kinetic energy of molecules. Heat is measured in units called *calories*. A **calorie** is the amount of heat necessary to raise the temperature of 1 gram of water 1 degree Celsius (°C). The concept of heat is not the same as the concept of temperature. Heat is a *quantity* of energy. Temperature deals with the comparative hotness or coldness of things. The heat, or internal kinetic energy, of molecules can change as a result of interactions with the environment. This is what happens when you rub your hands together. Friction results in increased temperatures because molecules on one moving surface catch on another surface, stretching the molecular forces that are holding them. They are pulled back to their original position with a "snap," resulting in an increase of vibrational kinetic energy. *Heat (measured in calories) and temperature (measured in Celsius or Fahrenheit) are not the same thing but are related to one another.* The heat that an object possesses cannot be measured with a thermometer. What a thermometer measures is the temperature of an object. The temperature is really a measure of how fast the molecules of the substance are moving and how often they bump into other molecules, a measure of their kinetic energy. If heat energy is added to an object, the molecules vibrate faster. Consequently, the temperature rises, because the added heat energy results in a speeding up of the movement of the molecules. Although there is a relationship between heat and temperature, the amount of heat, in calories, that an object has depends on the size of the object and its particular properties, such as its density, volume, and pressure.



Thermometer

Why do we take a person's body temperature? The body's size and composition usually do not change in a short time, so any change in temperature means that the body has either gained or lost heat. If the temperature is high, the body has usually gained heat as a result of increased metabolism. This increase in temperature is a symptom of abnormality, as is a low body temperature.

2.4 CONCEPT REVIEW

8. On what basis are solids, liquids, and gases differentiated?
9. What relationship does kinetic energy have to the three phases of matter?
10. What is the difference between temperature and heat?
11. What is a calorie?

2.5 Physical Changes—Phases of Matter

There are implications to the kinetic molecular theory. First, the amount of kinetic energy that particles contain can change. Molecules can gain from or lose energy to their surroundings, resulting in changes in their behavior. Second, molecules have an attraction for one another. This force of attraction is important in determining the phase in which a particular kind of matter exists.

The amount of kinetic energy molecules have, the strength of the attractive forces between molecules, and the kind of arrangements they form result in three **phases of matter:** solid, liquid, and gas (figure 2.7). A **solid** (e.g., bone) consists of molecules with strong attractive forces and low kinetic energy. The molecules are packed tightly together. With the least amount of kinetic energy of all the phases of matter, these molecules vibrate in place and are at fixed distances from one another. Powerful forces bind them together. Solids have definite shapes and volumes under ordinary temperature and pressure conditions. The hardness of a solid is its resistance to forces that tend to push its molecules farther apart. There is less kinetic energy in a solid than in a liquid of the same material.

A **liquid** (e.g., the water component of blood and lymph) has molecules with enough kinetic energy to overcome the attractive forces that hold molecules together. Thus, although the molecules are still strongly attracted to each other, they are slightly farther apart than in a solid. Because they are moving more rapidly, and the attractive forces can be overcome, they sometimes slide past each other. Although liquids can change their shape under ordinary conditions, they maintain a fixed volume under ordinary temperature and pressure conditions—that is, a liquid of a certain volume will take the shape of the container into which it is poured, but it will take up the same amount of space regardless of the container's shape. This gives liquids the ability to *flow,* so they are called *fluids.*

A **gas** (e.g., air) is made of molecules that have a great deal of kinetic energy. The attraction the gas molecules have for each other is overcome by the speed with which the individual molecules move. Because gas molecules are moving faster than the molecules of solids or liquids, their collisions tend to push them farther apart, so a gas expands to fill its container. The shape of the container and the pressure determine the shape and volume of the gas. The term *vapor* is used to describe the gaseous form of a substance, that is normally in the liquid phase. For example, water vapor is the gaseous form of liquid water and mercury vapor in CFLs is the gaseous form of liquid mercury (How Science Works 2.2).

2.5 CONCEPT REVIEW

12. Which phase of matter is composed of molecules that vibrate around a fixed position and are held in place by strong molecular forces?
13. Which phase of matter is composed of molecules that can rotate and roll over each other because the kinetic energy of the molecules is able to overcome the molecular forces?
14. Which phase of matter is composed of atoms or molecules with the greatest amount of kinetic energy?

2.6 Chemical Changes—Forming New Kinds of Matter

Atoms interact with other atoms to fill their outermost energy level with electrons to become more stable. When these chemical reactions take place, the result is a change in matter in which different chemical substances are created by forming or breaking chemical bonds. When a chemical reaction occurs

(a) (b) (c)

FIGURE 2.7 Phases of Matter
(a) In a solid, such as this rock, molecules vibrate around a fixed position and are held in place by strong molecular forces. *(b)* In a liquid, molecules can rotate and roll over each other, because the kinetic energy of the molecules is able to overcome the molecular forces. *(c)* Inside the bubble, gas molecules move rapidly in random, free paths.

HOW SCIENCE WORKS 2.2

Greenhouse Gases and Their Relationship to Global Warming

What actually causes global warming? An explanation is relatively straightforward: several greenhouse gases. Carbon dioxide (CO_2), chlorofluorocarbons (CCl_3F), methane (CH_4), and nitrous oxide (N_2O) are called greenhouse gases because they let sunlight enter the atmosphere to warm the Earth's surface. When this energy is reradiated as infrared radiation (heat), it is absorbed by these gases in the atmosphere. Because the effect is similar to what happens in a greenhouse (the glass allows light to enter but retards the loss of heat), these gases are called *greenhouse gases*, and the warming thought to occur from their increase is called the *greenhouse effect*. What do we know about these gases?

Carbon dioxide (CO_2)

- The most abundant of the greenhouse gases
- Sources include
  - Cellular respiration
  - Burning of fossil fuels (i.e., gasoline, coal)
  - Deforestation (i.e., the loss of plants using CO_2 in photosynthesis)

Chlorofluorocarbons (CCl_3F)

- Sole source is from human activities
- Used as coolants in refrigerators and air conditioners, as cleaning solvents, propellants in aerosol containers, and as expanders in foam products
- 15,000 times more efficient than the greenhouse gas, CO_2
- Use of chlorofluorocarbons and similar compounds is being phased out worldwide.

Methane (CH_4)

- Small amount found naturally in the atmosphere
- Sources include
  - Burning of fossil fuels
  - Most from biological sources (i.e., wetlands, rice fields, livestock, bacteria)

Nitrous oxide (N_2O)

- Minor part of atmosphere
- Sources include
  - Burning of fossil fuels
  - Nitrogen-containing fertilizers
  - Deforestation

Greenhouse Gas	Pre-1750 Concentration (ppm)	Concentration (ppm) (2007)	Contribution to Global Warming (percent)
Carbon dioxide (CO_2)	280	382	60
Methane (CH_4)	0.608	1.78	20
Chlorofluoro-carbons (CCl_3F)	0	0.00088	14
Nitrous oxide (N_2O)	0.270	0.321	6

Source: Data from Intergovernmental Panel on Climate Change, with updates from Oak Ridge National Laboratory.

the interacting atoms may become attached, or bonded, to one another by a chemical bond. Two types of bonds are (1) ionic bonds and (2) covalent bonds.

Ionic Bonds and Ions

Any positively or negatively charged atom or molecule is called an **ion. Ionic bonds** are formed after atoms *transfer* electrons to achieve a full outermost energy level. Electrons are donated or received in the transfer, forming a positive and a negative ion, a process called *ionization*. The force of attraction between oppositely charged ions forms ionic bonds, and *ionic compounds* are the result. Ionic compounds are formed when an element from the left side of the periodic table (those eager to gain electrons) reacts with an element from the right side (those eager to donate electrons). This results in the formation of a stable group, which has an orderly arrangement and is a crystalline solid.

Ions and ionic compounds are very important in living systems. For example, sodium chloride is a crystal solid known as table salt. A positively charged sodium ion is formed when a sodium atom loses 1 electron. This results in a stable, outermost energy level with 8 electrons. When an atom of chlorine receives an electron to stabilize its outermost

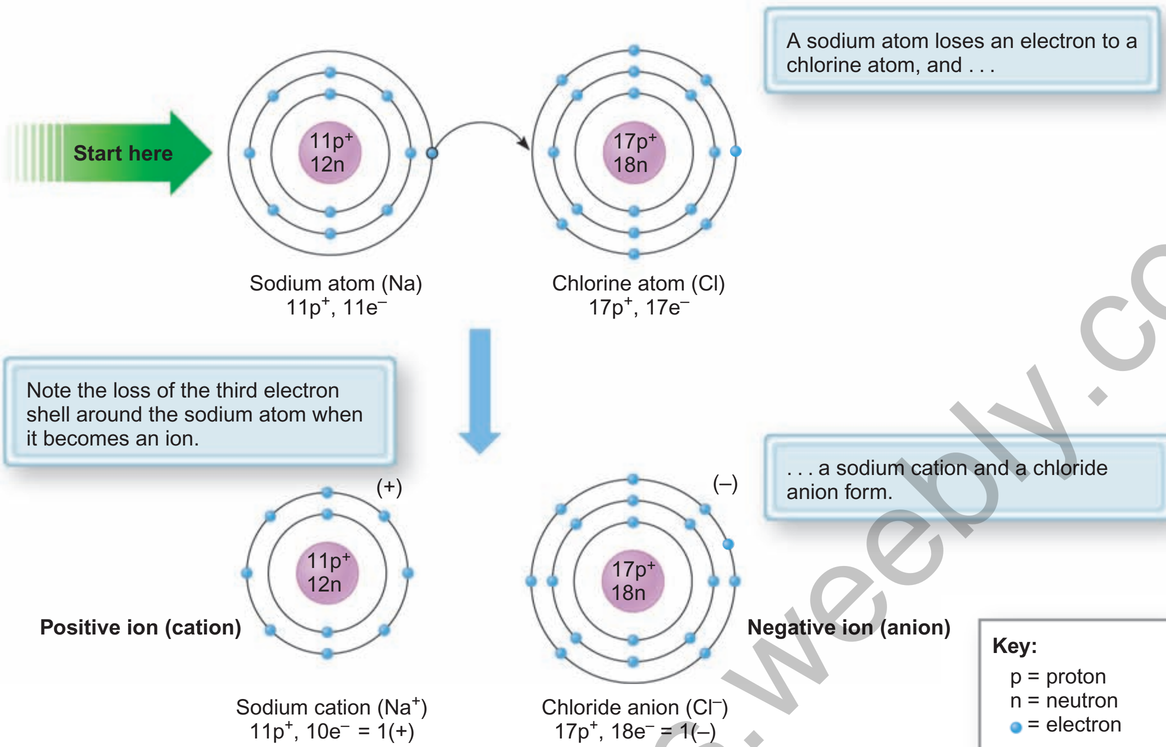


FIGURE 2.8 Ion Formation
A sodium atom has 2 electrons in the first energy level, 8 in the second energy level, and 1 in the third level. When it loses its 1 outer electron, it becomes a sodium cation.

energy level, it becomes a negative ion. All positively charged ions are called *cations* and all negative charged ions are called *anions* (figure 2.8). When these oppositely charged ions are close to one another, the attractive force between them forms an ionic bond. Ionic crystals form by the addition of ions to the outer surface of a small cluster of starter ions or seeds (figure 2.9). The dots in the following diagram represent the electrons in the outermost energy levels of each atom. This kind of diagram is called an electron dot formula.

$$Na\cdot + \cdot\ddot{\underset{..}{Cl}}: \longrightarrow Na^{+}Cl^{-}$$

When many ionic compounds (crystals) are dissolved in water, the ionic bonds are broken and the ions separate, or *dissociate,* from one another. For example, solid sodium chloride dissociates in water to become ions in solution:

$$NaCl \rightarrow Na^{+} + Cl^{-}$$

Any substance that dissociates into ions in water and allows the conduction of electric current is called an *electrolyte.*

Covalent Bonds

Most substances do not have the properties of ionic compounds, because they are not composed of ions. Most substances are composed of electrically neutral groups of atoms that are tightly bound together. As noted earlier, many gases are diatomic, occurring naturally as two of the same kinds of atoms bound together as an electrically neutral molecule. Hydrogen, for example, occurs as molecules of H_2 and no ions are involved. The hydrogen atoms are held together by a **covalent bond,** a chemical bond formed by the sharing of a pair of electrons. In the diatomic hydrogen molecule, each hydrogen atom contributes a single electron to the shared pair. Hydrogen atoms both share one pair of electrons, but other elements might share more than one pair.

Consider how the covalent bond forms between two hydrogen atoms by imagining two hydrogen atoms moving toward one another. Each atom has a single electron. As the atoms move closer and closer together, their outer energy levels begin to overlap. Each electron is attracted to the oppositely charged nucleus of the other atom and the overlap tightens. Then, the repulsive forces from the like-charged nuclei stop the merger. A state of stability is reached between the 2 nuclei and 2 electrons, because the outermost energy level is full and an H_2 molecule has been formed. The electron pair is now shared by both atoms, and the attraction of each nucleus for the electron of the other holds the atoms together (figure 2.10).

Dots can be used to represent the electrons in the outer energy levels of atoms. If each atom shares one of its electrons with the other, the two dots represent the bonding pair of electrons shared by the two atoms. Bonding pairs of electrons

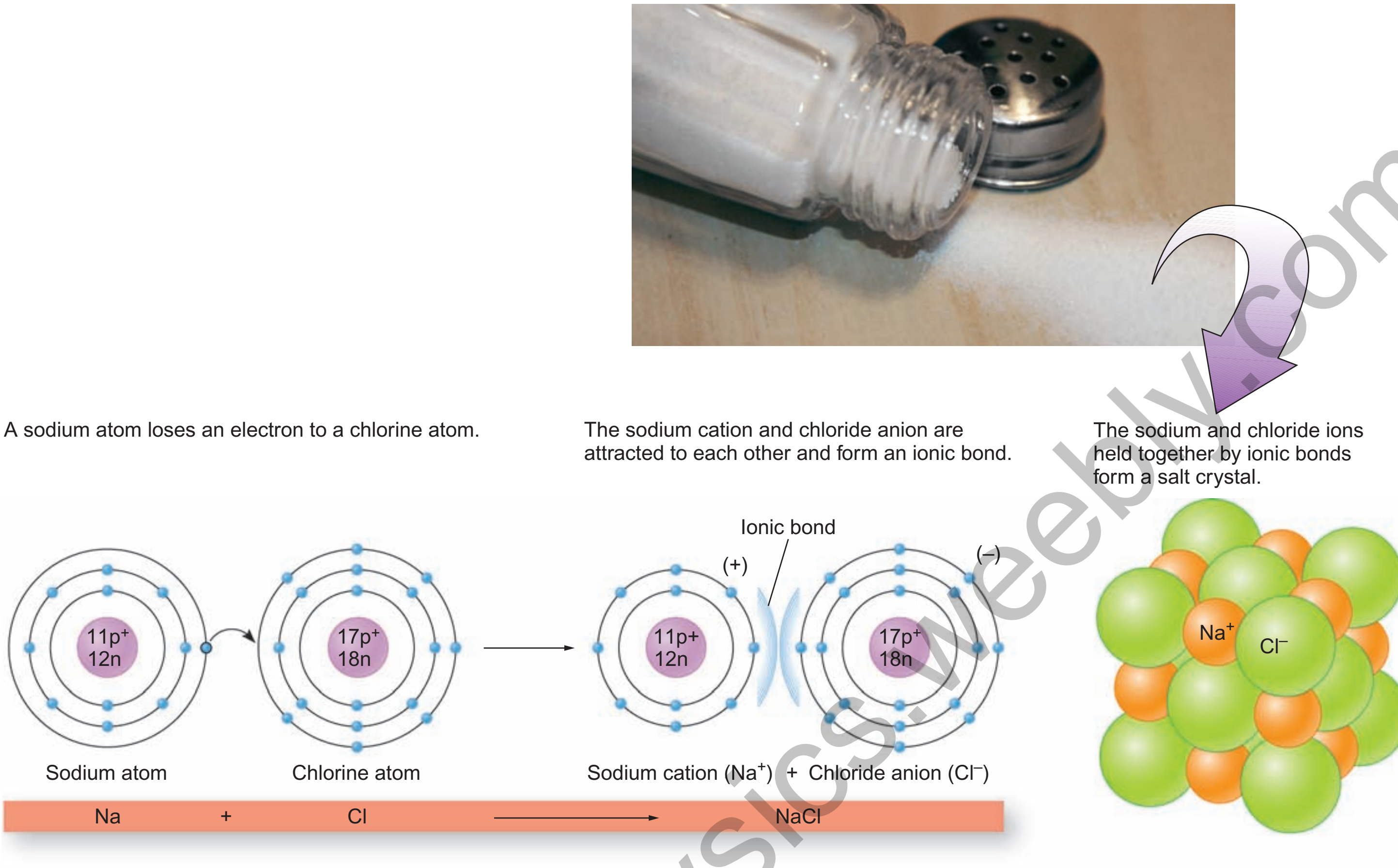


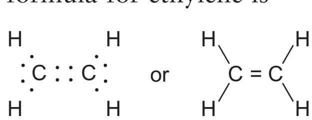
FIGURE 2.9 Crystals
A crystal is composed of ions that are bonded together and form a three-dimensional structure. Crystals grow with the addition of atoms to their outside surface.

are often represented by a simple line between two atoms, as in the following example:

H : H is shown as H – H

and

A covalent bond in which a single pair of electrons is shared by two atoms is called a *single covalent bond* or, simply, a single bond. Some atoms can share more than one electron pair. A double bond is a covalent bond formed when *two pairs* of electrons are shared by two atoms. This happens mostly in compounds involving atoms of the elements C, N, O, and S. For example, ethylene, a gas given off by ripening fruit, has a double bond between the two carbons (figure 2.11). The electron dot formula for ethylene is



A triple bond is a covalent bond formed when *three pairs* of electrons are shared by two atoms. Triple bonds occur mostly in compounds with atoms of the elements C and N. Atmospheric nitrogen gas, for example, forms a triple covalent bond:

$:N \vdots\vdots N:$ or $N \equiv N$

2.6 CONCEPT REVIEW

15. Why are the outermost electrons of an atom important?
16. Name two kinds of chemical bonds that hold atoms together. How do these bonds differ from one another?

2.7 Water: The Essence of Life

Water seems to be a simple molecule, but it has several special properties that make it particularly important for living things. A water molecule is composed of two atoms of hydrogen and

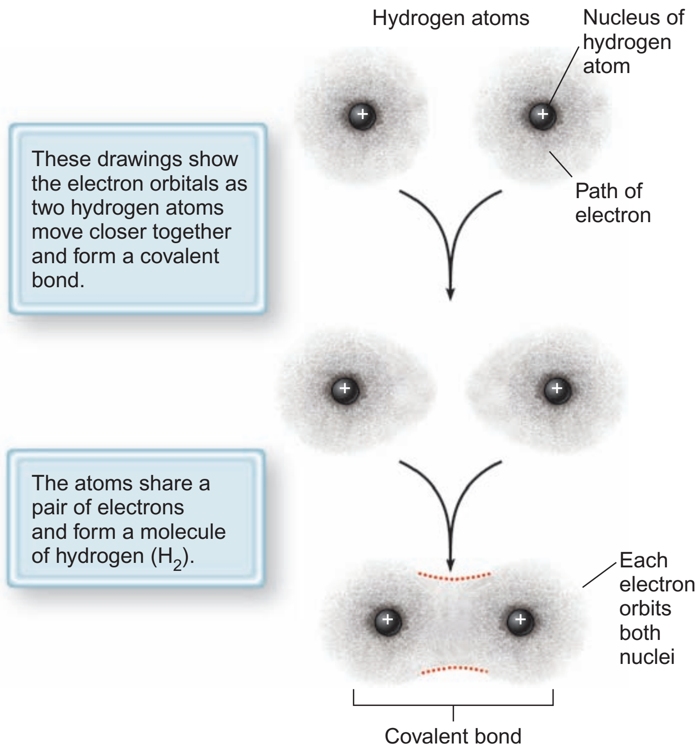
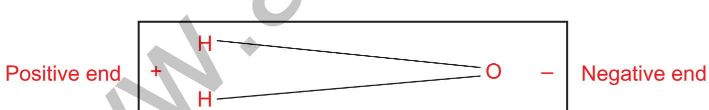


FIGURE 2.10 Covalent Bond Between Atoms
When two hydrogen atoms come so close to each other that the locations of the outermost electrons overlap, an electron from each one can be shared to "fill" the outermost energy levels. After the hydrogen atoms have bonded, a new electron distribution pattern forms around the entire molecule, and both electrons share the outermost molecular energy level.

FIGURE 2.11 Ethylene and the Ripening Process
The ancient Chinese knew from observation that fruit would ripen faster if placed in a container of burning incense, but they did not realize the incense released ethylene. We now know that ethylene stimulates the ripening process; it is used commercially to ripen fruits that are picked green.

one atom of oxygen joined by covalent bonds. However, the electrons in these covalent bonds are not shared equally. Oxygen, with 8 protons, has a greater attraction for the shared electrons than does hydrogen, with its single proton. Therefore, the shared electrons spend more time around the oxygen part of the molecule than they do around the hydrogen. As a result, the oxygen end of the molecule is more negative than the hydrogen end.

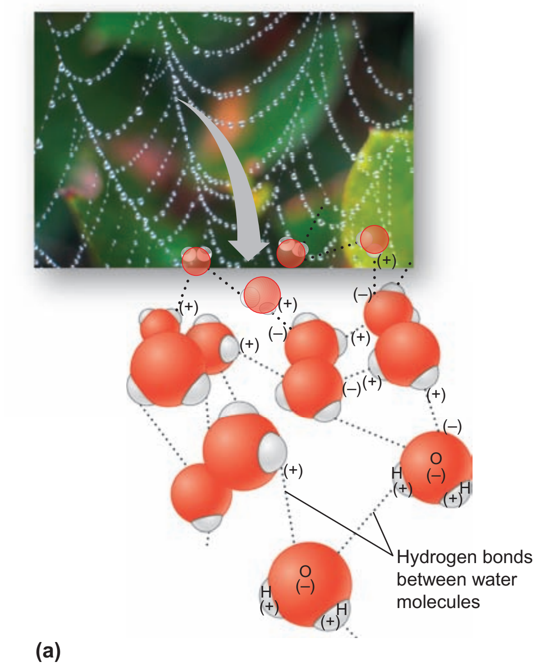


When the electrons in a covalent bond are not equally shared, the molecule is said to be *polar* and the covalent bonds are called *polar covalent bonds*.

When the negative end of a polar molecule is attracted to the positive end of another polar molecule, the hydrogen is located between the two molecules. Because in polar molecules the positive hydrogen end of one molecule is attracted to the negative end of another molecule, these attractive forces are often called *hydrogen bonds*. **Hydrogen bonds** can be intermolecular (between molecules) or intramolecular (within molecules) forces of attraction. They occur only between hydrogen and oxygen or hydrogen and nitrogen. As intramolecular forces, *hydrogen bonds hold molecules together. Because they do not bond atoms together, they are not considered true chemical bonds.* This attraction is usually represented as three dots between the attracted regions. This weak force of attraction is not responsible for forming molecules, but it is important in determining the three-dimensional shape of a molecule. For example, when a very large molecule, such as a protein, has some regions that are slightly positive and others that are slightly negative, these areas attract each other and result in the coiling or folding of these threadlike molecules (figure 2.12). Because water is a polar covalent compound (it has slightly + and – ends), it has several significant physical and biological properties (Outlooks 2.1).

Mixtures and Solutions

A **mixture** is matter that contains two or more substances that are not in set proportions (figure 2.13). A **solution** is a liquid mixture of ions or molecules of two or more substances. For example, salt water can be composed of varying amounts of NaCl and H_2O. If the components of the mixture are distributed equally throughout, the mixture is homogeneous. The process of making a solution is called *dissolving*. The amounts of the component parts of a solution are identified by the terms *solvent* and *solute*. The **solvent** is the component present in the larger amount. The **solute** is the component that dissolves in the solvent. Many combinations of solutes and solvents are



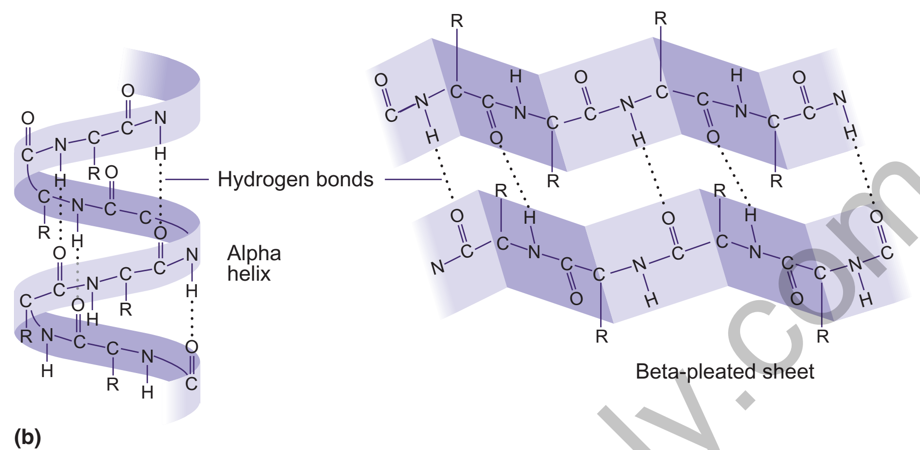


FIGURE 2.12 Hydrogen Bonds
(a) Water molecules arrange themselves so that their positive portions are near the negative portions of other water molecules. When enough gather together, water droplets form. It is this kind of intermolecular bonding that accounts for water's unique chemical and physical properties. Without such bonds, life as we know it on Earth would be impossible. *(b)* The large protein molecules here also have polar areas. When the molecules are folded so that the partially positive areas are near the partially negative areas, a slight attraction forms and tends to keep them folded or twisted.

possible. If one of the components of a solution is a liquid, it is usually identified as the solvent. An *aqueous solution* is a solution of a solid, liquid, or gas in water. When sugar dissolves in water, sugar molecules separate from one another. The molecules become uniformly dispersed throughout the molecules of water. In an aqueous salt solution, however, the salt dissociates into sodium and chlorine ions.

The relative amounts of solute and solvent are described by the *concentration* of a solution. In general, a solution with a large amount of solute is "concentrated," and a solution with much less solute is "dilute," although these are somewhat arbitrary terms.

2.7 CONCEPT REVIEW

17. What is the difference between a polar molecule and a nonpolar molecule?
18. What is different about a hydrogen bond in comparison with covalent and ionic bonds?
19. What is the difference between a solute and a solvent?
20. What relationship does kinetic energy have to homogeneous solutions?

2.8 Chemical Reactions

When compounds are broken or formed, new materials with new properties are produced. This kind of a change in matter is called a *chemical change,* and the process is called a *chemical reaction.* In a chemical reaction, the elements stay the same but the compounds and their properties change when the atoms are bonded in new combinations. All living things use energy and matter. In other words, they are constantly performing chemical reactions.

Chemical reactions produce new chemical substances with greater or smaller amounts of potential energy. Energy is absorbed to produce new chemical substances with more potential energy. Energy is released when the new chemical substances produced have less potential energy. For example, new chemical substances are produced in green plants through the process of *photosynthesis.* A green plant uses radiant energy (sunlight), carbon dioxide, and water to produce new chemical materials and oxygen. These new chemical materials, the stuff that makes up leaves, roots, and wood, contain more chemical energy than the carbon dioxide and water from which they were formed.

A **chemical equation** is a way of describing what happens in a chemical reaction. For example, the chemical reaction of photosynthesis is described by the equation

$$\text{Light} + 6\,CO_2 + 6\,H_2O \rightarrow C_6H_{12}O_6 + 6\,O_2$$

energy (sunlight) + carbon dioxide molecules + water molecules → plant material molecules (ex., sugar) + oxygen molecules

In chemical reactions, **reactants** are the substances that are changed (in photosynthesis, the carbon dioxide molecules and water molecules); they appear on the left side of the equation. The equation also indicates that energy is absorbed; the term *energy* appears on the left side. The arrow indicates

OUTLOOKS 2.1

Water and Life—The Most Common Compound of Living Things

1. **Water has a high surface tension.** Because water molecules are polar, hydrogen bonds form between water molecules, and they stick more to one another than to air molecules. Thus, water tends to pull together to form a smooth surface where water meets air. This layer can be surprisingly strong. For instance, some insects can walk on the surface of a pond. The tendency of water molecules to stick to each other and to some other materials explains why water can make things wet. It also explains why water climbs through narrow tubes, called capillary tubes. This *capillary* action also helps water move through soil, up the vessels in plants' stems, and through the capillaries (tiny blood vessels) in animals.

2. **Water has unusually high heats of vaporization and fusion.** Because polar water molecules stick to one another, an unusually large amount of heat energy is required to separate them. Water resists changes in temperature. It takes 540 calories of heat energy to convert 1 gram of liquid water to its gaseous state, water vapor. This means that large bodies of water, such as lakes and rivers, must absorb enormous amounts of energy before they will evaporate and leave the life within them high and dry. This also means that humans can get rid of excess body heat by sweating because, when the water evaporates, it removes heat from the skin. On the other hand, a high heat of fusion means that this large amount of heat energy must be removed from liquid water before it changes from a liquid to its solid state, ice. Therefore, water can remain liquid and a suitable home for countless organisms long after the atmospheric temperature has reached the freezing point, 0°C (32°F).
3. **Water has unusual density characteristics.** Water is most dense at 4°C. As heat energy is lost from a body of water and its temperature falls below 4°C, its density decreases and this less dense, colder water is left on top. As the surface water reaches the freezing point and changes from its liquid to its solid phase, the molecules form new arrangements, which resemble a honeycomb. The spaces between the water molecules make the solid phase, ice, less dense than the water beneath and the ice floats. It is the surface water that freezes to a solid, covering the denser, liquid water and the living things in it.
4. **Water's specific gravity is also an important property.** Water has a density of 1 gram/cubic centimeter at 4°C. Anything with a higher density sinks in water, and anything with a lower density floats. *Specific gravity* is the ratio of the density of a substance to the density of water. Therefore, the specific gravity of water is 1.00. Any substance with a specific gravity less than 1.00 floats. If you mix water and gasoline, the gasoline (specific gravity of 0.75) floats to the top. People also vary in the specific gravity of their bodies. Some persons find it very easy to float in water, whereas others find it impossible. This is directly related to each person's specific gravity, which is a measure of the person's ratio of body fat to muscle and bone.
5. **Water is considered the universal solvent,** because most other chemicals can be dissolved in water. This means that wherever water goes—through the ground, in the air, or through an organism—it carries chemicals. Water in its purest form is even capable of acting as a solvent for oils.
6. **Water comprises 50–60% of the bodies of most living things.** This is important, because the chemical reactions of all living things occur in water.
7. **Water vapor in the atmosphere is known as humidity, which changes with environmental conditions.** The ratio of how much water vapor is in the air to how much water vapor could be in the air at a certain temperature is called *relative humidity.* Relative humidity is closely associated with your comfort. When the relative humidity and temperature are high, it is difficult to evaporate water from your skin, so it is more difficult to cool yourself and you are uncomfortably warm.
8. **Water's specific gravity changes with its physical phase. Ice is also more likely to change from a solid to a liquid (melt) as conditions warm.** If the specific gravity of water did not decrease when it freezes, then the ice would likely sink and never thaw. Our life-giving water would be trapped in ocean-sized icebergs. Ice also provides a protective layer for the life under the ice sheet.

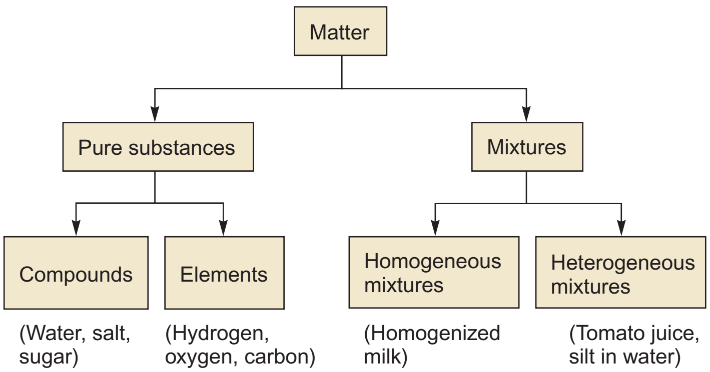


FIGURE 2.13 How Do Mixtures Compare?
Matter can be a pure substance or a mixture. The term *homogeneous* means "the same throughout." Homogenized milk has the same composition throughout the container. Before milk was homogenized (i.e., vigorously shaken to break fat into small globules), it was a heterogeneous mixture and it would "separate." The cream (which floats to the top) could be skimmed off the milk leaving skimmed milk. A heterogeneous mixture does not have the same composition throughout.

the direction in which the chemical reaction is occurring; it means "yields." The new chemical substances are on the right side and are called **products.** Reading the photosynthesis reaction as a sentence, you would say, "Carbon dioxide and water use energy to react, yielding plant materials and oxygen."

Notice in the photosynthesis reaction that there are numbers preceding some of the chemical formulas and subscripts within each chemical formula. The number preceding each of the chemical formulas indicates the number of each kind of molecule involved in the reaction. The subscripts indicate the number of each kind of element in a single molecule of that compound. Chemical reactions always take place in whole number ratios. That is, only whole molecules can be involved in a chemical reaction. It is not possible to have half a molecule of water serve as a reactant or become a product. Half a molecule of water is not water. Furthermore, the numbers of atoms of each element on the reactant side must equal the numbers on the product side. Because the preceding equation has equal numbers of each element (C, H, O) on both sides, the equation is said to be "balanced."

Five of the most important chemical reactions that occur in organisms are (1) oxidation-reduction, (2) dehydration synthesis, (3) hydrolysis, (4) phosphorylation, and (5) acid-base reactions.

Oxidation-Reduction Reactions

An **oxidation-reduction reaction** is a chemical change in which electrons are transferred from one atom to another and, with it, the energy contained in its electrons. As implied by the name, such a reaction has two parts and each part tells what happens to the electrons. *Oxidation* describes what happens to the atom or molecule that loses an electron. *Reduction* describes what happens to the atom or molecule that gains an electron. When the term *oxidation* was first used, it specifically meant reactions involving the combination of oxygen with other atoms. But fluorine, chlorine, and other elements were soon recognized to participate in similar reactions, so the definition was changed to describe the shifts of electrons in the reaction. The name also implies that, in any reaction in which oxidation occurs, reduction must also take place. One cannot take place without the other. Cellular respiration is an oxidation-reduction reaction that occurs in all cells:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ H_2O + 6\ CO_2 + \text{energy}$$

$$\text{sugar} + \text{oxygen} \rightarrow \text{water} + \text{carbon dioxide} + \text{energy}$$

In this cellular respiration reaction, sugar is being oxidized (losing its electrons) and oxygen is being reduced (gaining the electrons from sugar). The high chemical potential energy in the sugar molecule is released, and the organism uses some of this energy to perform work. In the previously mentioned photosynthesis reaction, water is oxidized (loses its electrons) and carbon dioxide is reduced (gains the electrons from water). The energy required to carry out this reaction comes from the sunlight and is stored in the product, sugar.

Dehydration Synthesis Reactions

Dehydration synthesis reactions are chemical changes in which water is released and a larger, more complex molecule is made (synthesized) from smaller, less complex parts. The water is a product formed from its component parts (H and OH), which are removed from the reactants. Proteins, for example, consist of a large number of amino acid subunits joined together by dehydration synthesis:

$$\underbrace{NH_2CH_2CO{-}OH}_{\text{amino acid 1}} + \underbrace{H{-}NHCH_2CO{-}OH}_{\text{amino acid 2}}$$

$$\downarrow$$

$$\underbrace{NH_2CH_2CO{-}NHCH_2CO{-}OH}_{\text{Protein}} + \underbrace{H{-}OH}_{\text{water } (H_2O)}$$

The building blocks of protein (amino acids) are bonded to one another to synthesize larger, more complex product molecules (i.e., protein). In dehydration synthesis reactions, water is produced as smaller reactants become chemically bonded to one another, forming fewer but larger product molecules.

Hydrolysis Reactions

Hydrolysis reactions are the opposite of dehydration synthesis reactions. In a hydrolysis reaction, water is used to break the reactants into smaller, less complex products:

$$\underbrace{NH_2CH_2CO{-}NH\ CH_2CO{-}OH}_{\text{Protein}} + \underbrace{H{-}OH}_{\text{water } (H_2O)}$$

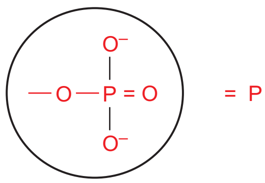
$$\downarrow$$

$$\underbrace{NH_2CH_2CO{-}OH}_{\text{amino acid 1}} + \underbrace{H{-}NH\ CH_2CO{-}OH}_{\text{amino acid 2}}$$

A more familiar name for this chemical reaction is *digestion*. This is the kind of chemical reaction that occurs when a protein food, such as meat, is digested. Notice in the previous example that the H and OH component parts of the reactant water become parts of the building block products.

Phosphorylation Reactions

A **phosphorylation reaction** takes place when a cluster of atoms known as a *phosphate group*



is added to another molecule. This cluster is abbreviated in many chemical formulas in a shorthand form as P, and only the P is shown when a phosphate is transferred from one molecule to another. This is a very important reaction, because the bond between a phosphate group and another atom contains the potential energy that is used by all cells to power numerous activities. Phosphorylation reactions result in the transfer of their potential energy to other molecules to power the activities of all organisms (figure 2.14).

FIGURE 2.14 Phosphorylation and Muscle Contractions
When the phosphate group is transferred between molecules, energy is released which powers muscle contractions.

high potential energy		low potential energy		low potential energy		high potential energy
Q–P	+	Z	→	Q	+	Z–P

This type of reaction is commonly involved in providing the kinetic energy needed by all organisms. It can also take place in reverse. When this occurs, energy must be added from the environment (sunlight or another phosphorylated molecule) and is stored in the newly phosphorylated molecule.

Acid-Base Reactions

Acid-base reactions take place when the ions of an acid interact with the ions of a base, forming a salt and water (see section 2.9). An aqueous solution containing dissolved acid is a solution containing hydrogen ions. If a solution containing a second ionic basic compound is added, a mixture of ions results. While they are mixed together, a reaction can take place—for example,

$H^+ Cl^-$	+	$Na^+ OH^-$	→	$Na^+ Cl^-$	+	HOH
hydrochloric acid	+	sodium hydroxide	→	sodium chloride	+	water (H_2O)

In an acid-base reaction, the H from the acid becomes chemically bonded to the OH of the base. This type of reaction frequently occurs in organisms and their environment. Because acids and bases can be very harmful, reactions in which they neutralize one another protect organisms from damage.

2.8 CONCEPT REVIEW

21. Give an example of an ion exchange reaction.
22. What happens during an oxidation-reduction reaction?
23. Explain the difference between a reactant and a product.

2.9 Acids, Bases, and Salts

Acids, bases, and salts are three classes of biologically important compounds (table 2.3). Their characteristics are determined by the nature of their chemical bonds. **Acids** are ionic compounds that release hydrogen ions in solution. A hydrogen atom without its electron is a proton. You can think of an acid, then, as a substance able to donate a proton to a solution. Acids have a sour taste, such as that of citrus fruits. However, tasting chemicals to see if they are acids can be very hazardous, because many are highly corrosive. An example of a common acid is the phosphoric acid—H_3PO_4—in cola soft drinks. It is a dilute solution of this acid that

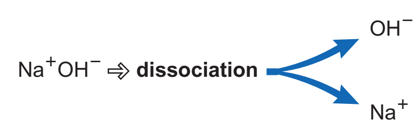
TABLE 2.3 Some Common Acids, Bases, and Salts

Acids		
Acetic acid	CH_3COOH	Weak acid found in vinegar
Carbonic acid	H_2CO_3	Weak acid of carbonated beverages that provides bubbles or fizz
Lactic acid	$CH_3CHOHCOOH$	Weak acid found in sour milk, sauerkraut, and pickles
Phosphoric acid	H_3PO_4	Weak acid used in cleaning solutions, added to carbonated cola beverages for taste
Sulfuric acid	H_2SO_4	Strong acid used in batteries
Bases		
Sodium hydroxide	$NaOH$	Strong base also called lye or caustic soda; used in oven cleaners
Potassium hydroxide	KOH	Strong base also known as caustic potash; used in drain cleaners
Magnesium hydroxide	$Mg(OH)_2$	Weak base also known as milk of magnesia; used in antacids and laxatives
Salts		
Alum	$Al(SO_4)_2$	Found in medicine, canning, and baking powder
Baking soda	$NaHCO_3$	Used in fire extinguishers, antacids, baking powder, and sodium bicarbonate
Chalk	$CaCO_3$	Used in antacid tablets
Epsom salts	$MgSO_4 \cdot H_2O$	Used in laxatives and skin care
Trisodium phosphate (TSP)	Na_3PO_4	Used in water softeners, fertilizers, and cleaning agents

gives cola drinks their typical flavor. Hydrochloric acid is another example:

Acids are ionically bonded molecules, which when placed in water dissociate, releasing hydrogen (H^+) ions.

A **base** is the opposite of an acid, in that it is an ionic compound, which, when dissolved in water, removes hydrogen ions from solution. Bases, or *alkaline* substances, have a slippery feel on the skin. They have a caustic action on living tissue by converting the fats in living tissue into a water-soluble substance. A similar reaction is used to make soap by mixing a strong base with fat. This chemical reaction gives soap its slippery feeling. Bases are also used in alkaline batteries. Weak bases have a bitter taste—for example, the taste of broccoli, turnip, and cabbage. Many kinds of bases release a group of hydrogen ions known as a **hydroxide ions,** or an OH^- group. This group is composed of an oxygen atom and a hydrogen atom bonded together, but with an additional electron. The hydroxide ion is negatively charged; therefore, it will remove positively charged hydrogen ions from solution. A very strong base used in oven cleaners is sodium hydroxide, NaOH. Notice that ions that are free in solution are always written with the type and number of their electrical charge as a superscript.



Basic (alkaline) substances are ionically bonded molecules, which when placed in water dissociate, releasing hydroxide (OH^-) ions.

Acids and bases are also spoken of as being strong or weak (Outlooks 2.2). Strong acids (e.g., hydrochloric acid) are those that dissociate nearly all of their hydrogens when in solution. Weak acids (e.g., phosphoric acid) dissociate only a small percentage of their hydrogens. Strong bases dissociate nearly all of their hydroxides (NaOH); weak bases, only a small percentage. The weak base sodium bicarbonate, $NaHCO_3$, will react with acids in the following manner:

$$NaHCO_3 + HCl \rightarrow NaCl + CO_2 + H_2O$$

Notice that sodium bicarbonate does not contain a hydroxide ion but it is still a base, because it removes hydrogen ions from solution.

The degree to which a solution is acidic or basic is represented by a quantity known as **pH**. The pH scale is a measure of hydrogen ion concentration (figure 2.15). A pH of 7 indicates that the solution is neutral and has an equal number of H^+ ions and OH^- ions to balance each other. As the pH number gets smaller, the number of hydrogen ions in the solution increases. A number higher than 7 indicates that the solution has more OH^- than H^+. Pure water has a pH of 7. As the pH number gets larger, the number of hydroxide ions increases.

OUTLOOKS 2.2

Maintaining Your pH—How Buffers Work

Acids, bases, and salts are called *electrolytes,* because, when these compounds are dissolved in water, the solution of ions allows an electrical current to pass through it. Salts provide a variety of ions essential to the human body. Small changes in the levels of some ions can have major effects on the functioning of the body. The respiratory system and kidneys regulate many of the body's ions. Because many kinds of chemical activities are sensitive to changes in the pH of the surroundings, it is important to regulate the pH of the blood and other body fluids within very narrow ranges. Normal blood pH is about 7.4. Although the respiratory system and kidneys are involved in regulating the pH of the blood, there are several systems in the blood that prevent wide fluctuations in pH.

Buffers are mixtures of *weak acids* and the *salts of weak acids* that tend to maintain constant pH, because the mixture can either accept or release hydrogen ions (H^+). The weak acid can release hydrogen ions (H^+) if a base is added to the solution, and the negatively charged ion of the salt can accept hydrogen ions (H^+) if an acid is added to the solution.

One example of a buffer system in the body is a phosphate buffer system, which consists of the weak acid dihydrogen phosphate ($H_2PO_4^-$) and the salt of the weak acid monohydrogen phosphate ($HPO_4^=$).

$H_2PO_4^-$	$\rightleftharpoons$	H^+	$+$	$HPO_4^=$
weak acid		hydrogen ion	+	salt of weak acid

(The two arrows indicate that this is in balance, with equal reactions in both directions.) The addition of an acid to the mixture causes the equilibrium to shift to the left.

$$H_2PO_4^- \leftharpoondown\!\!\!\rightharpoonup \; + \; HPO_4^= + \text{added } H^+$$

Notice that the arrow pointing to the right is shorter than the arrow pointing to the left. This indicates that H^+ is combining with $HPO_4^=$ and additional $H_2PO_4^-$ is being formed. This removes the additional hydrogen ions from solution and ties them up in the $H_2PO_4^-$, so that the amount of free hydrogen ions in the solution remains constant.

Similarly, if a base is added to the mixture, the equilibrium shifts to the right, additional hydrogen ions are released to tie up the hydroxyl ions, and the pH remains unchanged.

$$H_2PO_4^- + \text{added } OH^- \rightleftharpoons HPO_4^= + H^+OH^-$$

Seawater is a buffer solution that maintains a pH of about 8.2. Buffers are also added to medicines and to foods. Many lemon-lime carbonated beverages, for example, contain citric acid and sodium citrate (salt of the weak acid), which forms a buffer in the acid range. The beverage label may say that these chemicals are to impart and regulate "tartness." In this case, the tart taste comes from the citric acid, and the addition of sodium citrate makes it a buffered solution.

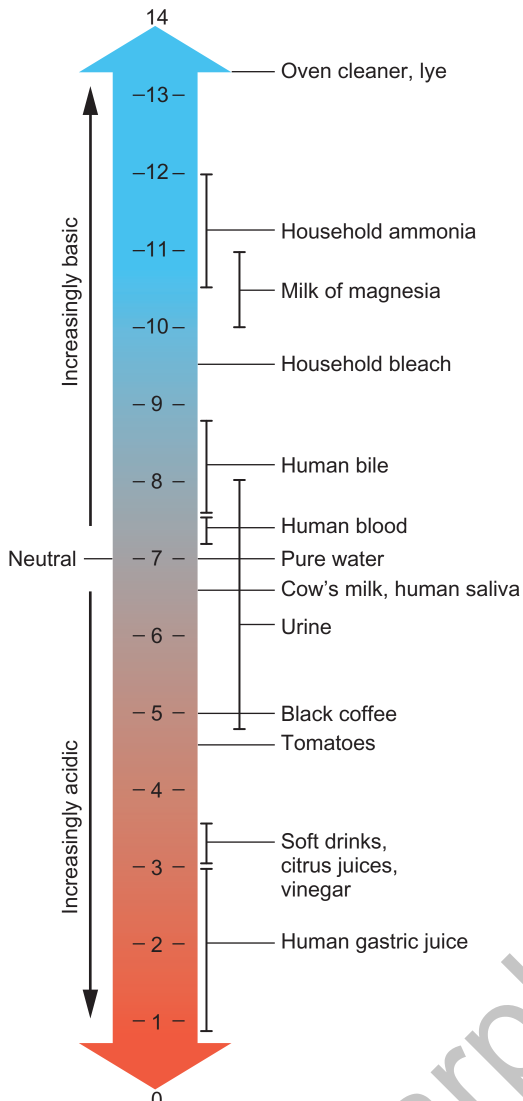
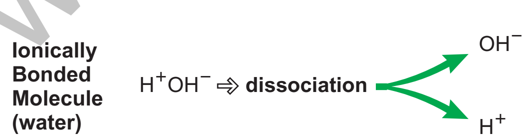


FIGURE 2.15 The pH Scale
The concentration of acid (proton donor or electron acceptor) is greatest when the pH number is lowest. As the pH number increases, the concentration of base (proton acceptor or electron donor) increases. At a pH of 7, the concentrations of H^+ and OH^- are equal. As the pH number gets smaller, the solution becomes more acidic. As the pH number gets larger, the solution becomes more basic, or alkaline.

It is important to note that the pH scale is logarithmic—that is, a change in one pH number is actually a 10-fold change in real numbers of OH^- or H^+. For example, there is 10 times more H^+



When water dissociates, it releases both hydrogen (H^+) and hydroxide (OH^-) ions. It is neither a base nor an acid. Its pH is 7, neutral.

in a solution of pH 5 than in a solution of pH 6 and 100 times more H^+ in a solution of pH 4 than in a solution of pH 6.

Salts are ionic compounds that do not release either H^+ or OH^- when dissolved in water; thus, they are neither acids nor bases. However, they are generally the result of the reaction between an acid and a base in a solution. For example, when an acid, such as HCl, is mixed with NaOH in water, the H^+ and the OH^- combine with each other to form pure water, H_2O. The remaining ions (Na^+ and Cl^-) join to form the salt NaCl:

$$HCl + NaOH \rightarrow Na^+ + Cl^- + H^+ + OH^- \rightarrow NaCl + H_2O$$

The chemical reaction that occurs when acids and bases react with each other is called *neutralization*. The acid no longer acts as an acid (it has been neutralized) and the base no longer acts as a base.

As you can see from figure 2.15, not all acids or bases produce the same pH. Some compounds release hydrogen ions very easily, cause low pHs, and are called strong acids. Hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) are strong acids (figure 2.16a). Many other compounds give up their hydrogen ions grudgingly and therefore do not change pH very much. They are known as weak acids. Carbonic acid (H_2CO_3) and many organic acids found in living things are weak acids. Similarly, there are strong bases, such as sodium hydroxide (NaOH) and weak bases, such as sodium bicarbonate—$Na^+(HCO_3)^-$.

(a) (b)

FIGURE 2.16 Strong Acid and Strong Base
(a) Hydrochloric acid (HCl) has the common name of muriatic acid. It is a strong acid used in low concentrations to clean swimming pools and brick surfaces. It is important that you wear protective equipment when working with a solution of muriatic acid. *(b)* Liquid-Plumr® is a good example of a drain cleaner with a strong base. The active ingredient is NaOH.

2.9 CONCEPT REVIEW

24. What does it mean if a solution has a pH of 3, 12, 2, 7, or 9?
25. If the pH of a solution changes from 8 to 9, what happens to the hydroxide ion concentration?

Summary

The study of life involves learning about the structure and function of organisms. All organisms display the chemical and physical properties typical of all matter and energy. The two kinds of energy used by organisms are potential and kinetic. The kinetic molecular theory states that all matter is made up of tiny particles, which are in constant motion.

Energy can be neither created nor destroyed, but it can be converted from one form to another. Potential energy and kinetic energy can be interconverted. The amount of kinetic energy that the molecules of various substances contain determines whether they are solids, liquids, or gases. Temperature is a measure of the average kinetic energy of the molecules making up a substance. Heat is the total internal kinetic energy of molecules. The random motion of molecules, which is due to their kinetic energy, results in their being distributed throughout available space, forming mixtures.

There are many kinds of atoms, whose symbols and traits are described by the periodic table of the elements. These atoms differ from one another by the number of protons and electrons they contain. Each is given an atomic number, based on the number of protons in the nucleus, and an atomic weight, an average of all the isotopes of a particular element. The mass number is the sum of the number of protons and neutrons in the nucleus of an atom.

All matter is composed of atoms, which are composed of an atomic nucleus and electrons. The atomic nucleus can contain protons and neutrons, whereas the electrons encircle the nucleus at different energy levels. Atoms tend to seek their most stable configuration and follow the octet rule, which states that they all seek a filled outermost energy level.

Atoms may be combined by chemical reactions into larger units called molecules. There are many kinds of molecules. Two kinds of chemical bonds allow molecules to form—ionic bonds and covalent bonds. A third bond, the hydrogen bond, is a weaker bond that holds molecules together and may help large molecules maintain a specific shape. Molecules are described by their chemical formulas, which state the number and kinds of components of which they are composed.

An ion is an atom that is electrically unbalanced. Ions interact to form ionic compounds, such as acids, bases, and salts. Compounds that release hydrogen ions when mixed in water are called acids; those that remove hydrogen ions are called bases. A measure of the hydrogen ions present in a solution is the pH of the solution.

Water is one of the most important compounds required by all organisms. This polar molecule has many unique properties, which allow organisms to survive and reproduce. Without water, life as we know it on Earth would not be possible.

How atoms achieve stability is the nature of chemical reactions. Five of the most important chemical reactions that occur in organisms are (1) oxidation-reduction, (2) dehydration synthesis, (3) hydrolysis, (4) phosphorylation, and (5) acid-base reactions.

Acids, bases, and salts are three classes of biologically important molecules. The hydrogen ion releasing or acquiring properties of acids and bases make them valuable in all organisms.

Salts are a source of many essential ions. Although acids and bases may be potentially harmful, buffer systems help in maintain pH levels.

Key Terms

*Use the interactive flash cards on the **Concepts in Biology**, 14/e website to help you learn the meaning of these terms.*

acid-base reactions 39
acids 39
atomic mass unit 25
atomic nucleus 25
atomic number 25
atomic weight 25
bases 40
calorie 30
chemical bonds 29
chemical equation 36
chemical reaction 28
chemicals 24
chemistry 24
compound 29
covalent bond 33
dehydration synthesis reactions 38
electron 25
elements 25
energy 24
energy level 25
formula 29
gas 31
heat 30
hydrogen bonds 35
hydrolysis reactions 38
hydroxide ions 40
ion 32
ionic bonds 32
isotope 25
kinetic energy 24
kinetic molecular theory 29
law of conservation of energy 24
liquid 31
mass number 25
matter 24
mixture 35
molecule 29
neutron 25
oxidation-reduction reaction 38
pH 40
phases of matter 31
phosphorylation reaction 39
potential energy 24
products 38
proton 25
reactants 36
salts 42
solid 31
solute 35
solution 35
solvent 35
temperature 29

Basic Review

1. _____ is the total internal kinetic energy of molecules.
2. The atomic weight of the element sodium is
   a. 22.989.
   b. 11.
   c. 10.252.
   d. 11 + 22.989.
3. Which is *not* a pure substance?
   a. the compound sugar
   b. the element oxygen
   c. a mixture of milk and honey
   d. the compound table salt
4. When a covalent bond forms between two kinds of atoms that are the same, the result is known as a
   a. mixture.
   b. crystal.
   c. dehydration chemical reaction.
   d. diatomic molecule.
5. In this kind of chemical reaction, two molecules interact, resulting in the formation of a molecule of water and a new, larger end product.
   a. hydrolysis
   b. dehydration synthesis
   c. phosphorylation
   d. acid-base reaction
6. Which of the following is an acid?
   a. HCl
   b. NaOH
   c. KOH
   d. $CaCO_3$
7. Salts are compounds that do not release either _____ or _____ ions when dissolved in water.
8. This intramolecular force under the right conditions can result in a molecule that is coiled or twisted into a complex, three-dimensional shape.
   a. covalent bond
   b. ionic bond
   c. hydrogen bond
   d. cement bond
9. A triple covalent bond is represented by which of the following?
   a. a single, fat, straight line
   b. a single, thin, straight line
   c. three separate, thin lines
   d. three thin, curved lines
10. Electron clouds, or routes, traveled by electrons are sometimes drawn as spherical or _____ shapes.
11. Atoms of the same element differ from ions of that element because
    a. they have different numbers of electrons.
    b. their proton numbers are not the same.
    c. their neutrons numbers are not the same.
    d. there is no difference between an atom and an ion of the same element.
12. When someone uses the expression "you're full of hot air," he is referring to which phase of matter?
    a. solid
    b. liquid
    c. gas
    d. hydrogen
13. When a person is "running a fever," she is experiencing an increase in her body's _____.
14. Ions that are bonded together and form a three-dimensional structure are called a _____.
15. A bottle of soda or pop is best described as
    a. a heterogeneous mixture.
    b. a compound.
    c. a homogeneous mixture.
    d. a pure substance.

Answers
1. Heat 2. a 3. c 4. d 5. b 6. a 7. H^+, OH^- 8. c 9. c 10. hourglass 11. a 12. c 13. temperature 14. crystal 15. c

Thinking Critically

Chemicals Around the House
Sodium bicarbonate ($NaHCO_3$) is a common household chemical known as baking soda, bicarbonate of soda, or bicarb. It has many uses and is a component of many products, including toothpaste and antacids, swimming pool chemicals, and headache remedies. When baking soda comes in contact with hydrochloric acid, the following reaction occurs:

$$HCl + NaHCO_3 \rightarrow NaCl + CO_2 + H_2O$$

What happens to the atoms in this reaction? In your description, include changes in chemical bonds, pH, and kinetic energy. Why is baking soda such an effective chemical in the previously mentioned products? Try this at home: Place a pinch of sodium bicarbonate ($NaHCO_3$) on a plate. Add two drops of vinegar. Observe the reaction. Based on the previous reaction, can you explain chemically what has happened?

CHAPTER 3

Organic Molecules—The Molecules of Life

Down the Toilet—But Then What?

Scientists Increasingly Concerned About the Water We Drink.

It has been reported that a vast array of pharmaceuticals have been found in the drinking water supplies of at least 41 million Americans. Many of these are organic compounds and include antibiotics, anti-convulsants, mood stabilizers, and sex hormones. Organic compounds can be very complex and long-lasting molecules. How do these drugs get into the water? One way is by unmetabolized drugs that are excreted in urine. Also, healthcare providers recommend that unused medications be flushed down the toilet. In addition, these compounds get into the water supply on occasion by accidental spills that can result in contamination of our water. One U.S. Environmental Protection Agency (EPA) administrator stated that this problem is a growing concern. The EPA is taking this issue seriously because neither sewage treatment nor water purification can remove all drugs.

As scientists learn from their research, more specific questions are formulated that relate to long-term health effects of pharmaceutical contamination of our water. For example, a popular osteoporosis drug, Fosamax, has been linked to severe musculoskeletal pain and a serious bone disease called osteonecrosis of the jaw (ONJ), also known as "dead jaw" and "fossy jaw." Microbial biofilms, a mix of bacteria and sticky organic compounds, appear to be the cause of this side effect. If the drugs reach high enough levels of contamination in our water supply, will we see an increase in ONJ in people who don't even take this medication?

Some dentists are observing the eruption of second molar teeth in children as young as 8 years old. Normally these do not appear until a person is about 12 or 13 years old. Might there be a cause-and-effect relationship with some pharmaceutical contaminant in our water supply?

- **What makes organic molecules different from other molecules?**
- **What is the structure of various organic compounds?**
- **Is there a point at which the cure is worse than the disease?**

CHAPTER OUTLINE

Background Check

Concepts you should already know to get the most out of this chapter:

- The nature of matter (chapter 2)
- Chemical changes that can occur in matter (chapter 2)
- The key characteristics of water (chapter 2)
- The different types of chemical reactions (chapter 2)

3.1 Molecules Containing Carbon

The principles and concepts discussed in chapter 2 apply to all types of matter—nonliving as well as living. Living systems are composed of various types of molecules. Most of the chemicals described in chapter 2 do not contain carbon atoms and, so, are classified as **inorganic molecules.** This chapter is mainly concerned with more complex structures, **organic molecules,** which contain carbon atoms arranged in rings or chains. The words *organic, organism, organ,* and *organize* are all related. Organized objects have parts that fit together in a meaningful way. Organisms are living things that are organized. Animals, for example, have organ systems within their bodies, and their organs are composed of unique kinds of molecules that are *organic.*

The original meanings of the terms *inorganic* and *organic* came from the fact that organic materials were thought either to be alive or to be produced only by living things. A very strong link exists between organic chemistry and the chemistry of living things, which is called **biochemistry** or biological chemistry. Modern chemistry has considerably altered the original meanings of the terms *organic* and *inorganic,* because it is now possible to manufacture unique organic molecules that cannot be produced by living things. Many of the materials we use daily are the result of the organic chemist's art. Nylon, aspirin, polyurethane varnish, silicones, Plexiglas, food wrap, Teflon, and insecticides are just a few of the unique synthetic molecules that have been invented by organic chemists (figure 3.1). Plastics such as low-density polyethylene (LDPE) used to make garbage bags are extremely stable molecules that require hundreds of years to break down.

Many organic chemists have taken their lead from living organisms and have been able to produce organic molecules more efficiently, or in forms that are slightly different from the original natural molecules. Some examples of these are rubber, penicillin, certain vitamins, insulin, and alcohol (figure 3.2).

FIGURE 3.1 Some Common Synthetic Organic Materials
These are only a few examples of products containing useful organic compounds invented and manufactured by chemists.

FIGURE 3.2 Natural and Synthetic Organic Compounds
(a) This researcher is testing antibiotics produced by microbes isolated from the environment. Each paper disk, containing a different antibiotic, is placed on the surface of a Petri dish with growing, disease-causing bacteria. The presence of a "dead zone" around a disk indicates that the antibiotic has spread through the gel and is able to inhibit or kill the bacteria. *(b)* Certain types of chrysanthemums produce the insecticide Pyrethrin. *(c)* It can be found as an "active ingredient" in many commercially available ant- and cockroach-killing products.

Another example is the insecticide Pyrethrin. It is based on a natural insecticide and is widely used for agricultural and domestic purposes. It is derived from a certain type of chrysanthemum plant, *Pyrethrum cinerariaefolium*.

Carbon: The Central Atom

All organic molecules, whether natural or synthetic, have certain common characteristics. The carbon atom, which is the central atom in all organic molecules, has some unusual properties that contribute to the nature of an organic compound. Carbon is unique in that it can combine with other carbon atoms to form long chains. In many cases, the ends of these chains may join together to form rings (figure 3.3).

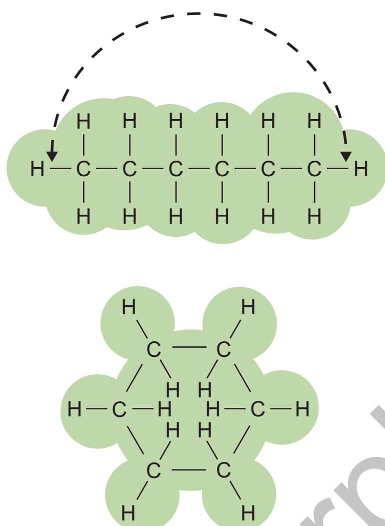
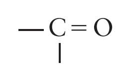


FIGURE 3.3 Chain and Ring Structures
The ring structure shown on the bottom is formed by joining the two ends of a chain of carbon atoms.

Also unusual is that these bonding sites are all located at equal distances from one another because the 4 outer-most electrons do not stay in the standard positions described in chapter 2. They distribute themselves differently, enabling them to be as far apart as possible (figure 3.4). Carbon atoms are usually involved in covalent bonds. Because carbon has four places it can bond, the carbon atom can combine with four other atoms by forming four separate, *single covalent bonds* with other atoms. This is the case with the methane molecule, which has four hydrogen atoms attached to a single carbon atom (review figure 3.4). Pure methane is a colorless, odorless gas that makes up 95% of natural gas. The aroma of natural gas is the result of mercaptan and trimethyl disulfide added for safety to let people know when a leak occurs.

Some atoms may be bonded to a single atom more than once. This results in a slightly different arrangement of bonds around the carbon atom. An example of this type of bonding occurs when oxygen is attracted to a carbon. An atom of oxygen has 2 electrons in its outermost energy level. If it shares 1 of these with a carbon and then shares the other with the same carbon, it forms a *double covalent bond*. A **double bond** is two covalent bonds formed between two atoms that share two pairs of electrons. Oxygen is not the only atom that can form double bonds, but double bonds are common between oxygen and carbon. The double bond is denoted by two lines between the two atoms:



Since carbon has 4 electrons in its outer energy level, two carbon atoms might form double bonds between each other and then bond to other atoms at the remaining bonding sites. Figure 3.5 shows several compounds that contain double bonds.

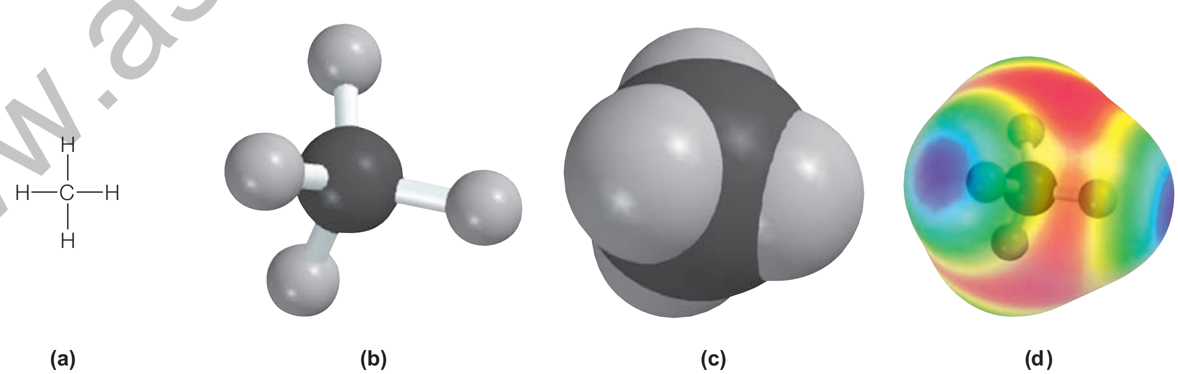


FIGURE 3.4 Models of a Methane Molecule
The structures of molecules can be modeled in many ways. For the sake of simplicity, diagrams of molecules such as the gas methane can be *(a)* two-dimensional drawings, although in reality they are three-dimensional molecules and take up space. The model shown in *(b)* is called a ball-and-stick model. Part *(c)* is a space-filling model, while *(d)* is a computer-generated model. Each time you see the various ways in which molecules are displayed, try to imagine how much space they actually occupy.

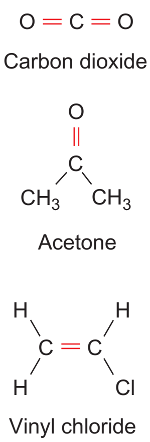


FIGURE 3.5 Double Bonds
These diagrams show several molecules that contain double bonds in red. A double bond is formed when two atoms share two pairs of electrons with each other.

Some organic molecules contain *triple covalent bonds;* the flammable gas acetylene, HC≡CH, is one example. Others—such as hydrogen cyanide HC≡N—have biological significance. This molecule inhibits the production of energy and can cause death as can other organic molecules. (How Science Works 3.1).

The Complexity of Organic Molecules

Although many kinds of atoms can be part of an organic molecule, only a few are commonly found. Hydrogen (H) and oxygen (O) are almost always present. Nitrogen (N), sulfur (S), and phosphorus (P) are also very important in specific types of organic molecules.

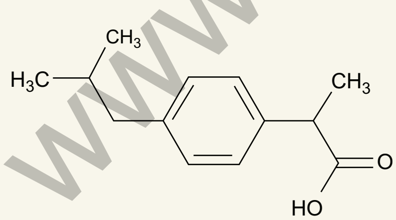
An enormous variety of organic molecules is possible, because carbon is able to (1) bond at four different places, (2) form long chains and rings, and (3) combine with many other kinds of atoms. The types of atoms in the molecule are important in determining the properties of the molecule. The

HOW SCIENCE WORKS 3.1

Organic Compounds: Poisons to Your Pets!

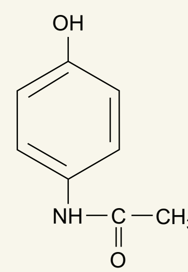
The opening vignette concerning the pharmaceutical contamination of our water supply has far-reaching health implications to humans. However, we should not forget our pets, whose metabolism is not necessarily the same as that of humans. Organic compounds can affect them differently—most people have organic compounds around the house or garage that are toxic to dogs.

Ibuprofen—This nonsteroidal, anti-inflammatory (NSAID) might help relieve the pain of a person's headache, but if ingested by a dog, it can cause stomach and kidney problems in the animal. It can also alter the dog's nervous system, resulting in depression and seizures.



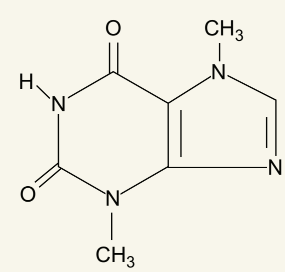
Ibuprofen

Acetaminophen—While a common pain medication for people, this drug can cause liver failure, swelling of the face and paws, and a problem with oxygen transport in the blood in a dog. If a dog ingests acetaminophen, it will probably need to be hospitalized.

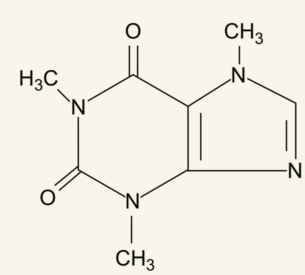


Acetaminophen

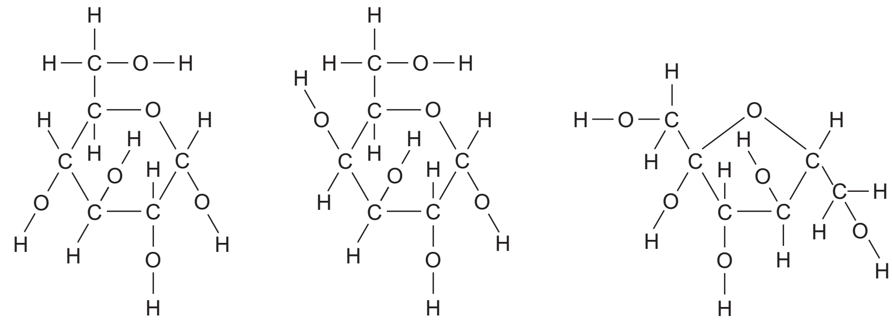
Chocolate—Two toxic compounds in chocolate are theobromine and caffeine. **Theobromine** is found in candy, tea, and cola beverages. Since dogs and kittens metabolize this compound very slowly, it can remain in their bodies long enough to cause nausea, vomiting, diarrhea, and increased urination. Depending on the amount of chocolate the pet has ingested, it can also cause seizures, internal bleeding, heart attacks, and eventually death. **Caffeine** in coffee, tea, and cola drinks can result in vomiting, diarrhea, tremors, heart arrhythmias, and seizures in pets. Notice how similar the molecular structure of theobromine is to caffeine.



Theobromine



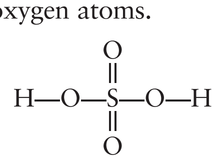
Caffeine



Glucose $C_6H_{12}O_6$ | Galactose $C_6H_{12}O_6$ | Fructose $C_6H_{12}O_6$

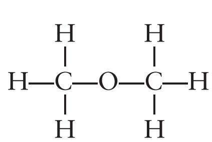
FIGURE 3.6 Structural Formulas for Several Hexoses
Three 6-carbon sugars—hexoses (*hex* = 6; *-ose* = sugar)—are represented here. All have the same empirical formula ($C_6H_{12}O_6$), but each has a different structural formula. These three are called *structural isomers*. Structural isomers have different chemical properties from one another.

three-dimensional arrangement of the atoms within the molecule is also important. Because most inorganic molecules are small and involve few atoms, a group of atoms can be usually arranged in only one way to form a molecule. There is only one arrangement for a single oxygen atom and two hydrogen atoms in a molecule of water. In a molecule of sulfuric acid, there is only one arrangement for the sulfur atom, the two hydrogen atoms, and the four oxygen atoms.

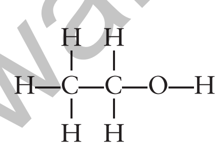


Sulfuric (battery) acid

However, consider these two organic molecules:



Dimethyl ether



Ethyl alcohol (as found in alcohol beverages)

Both the dimethyl ether and the ethyl alcohol contain two carbon atoms, six hydrogen atoms, and one oxygen atom, but they are quite different in their arrangement of atoms and in the chemical properties of the molecules. The first is an ether; the second is an alcohol. Because the ether and the alcohol have the same number and kinds of atoms, they are said to have the same *empirical formula,* which in this case can be written C_2H_6O. An empirical formula simply indicates the number of each kind of atom within the molecule. The arrangement of the atoms and their bonding within the molecule are indicated in a *structural formula*. Figure 3.6 shows several structural formulas for the empirical formula $C_6H_{12}O_6$. Molecules that have the same empirical formula but different structural formulas are called *isomers*.

The Carbon Skeleton and Functional Groups

At the core of all organic molecules is a **carbon skeleton,** which is composed of rings or chains (sometimes branched) of carbon. It is this carbon skeleton that determines the overall shape of the molecule. The differences among various kinds of organic molecules are determined by three factors: (1) the length and arrangement of the carbon skeleton, (2) the kinds and location of the atoms attached to it, and (3) the way these attached atoms are combined. These specific combinations of atoms, called **functional groups,** are frequently found on organic molecules. The kind of functional groups attached to a carbon skeleton determine the specific chemical properties of that molecule. By learning to recognize some of the functional groups, you can identify an organic molecule and predict something about its activity. Figure 3.7 shows some of the functional groups that are important in biological activity. Remember that a functional group does not exist by itself; it is part of an organic molecule. Outlooks 3.1 explains how chemists and biologists diagram the kinds of bonds formed in organic molecules.

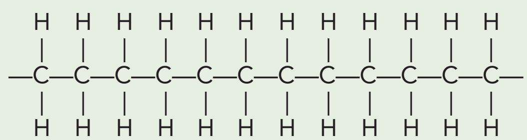
Macromolecules of Life

Macromolecules (*macro* = large) are very large organic molecules. We will look at four important kinds of macromolecules: carbohydrates, proteins, nucleic acids, and lipids. Carbohydrates, proteins, and nucleic acids are all *polymers* (*poly* = many; *mer* = segments). **Polymers** are combinations

OUTLOOKS 3.1

Chemical Shorthand

You have probably noticed that sketching the entire structural formula of a large organic molecule takes a great deal of time. If you know the structure of the major functional groups, you can use several shortcuts to more quickly describe chemical structures. When multiple carbons with 2 hydrogens are bonded to each other in a chain, it is sometimes written as follows:



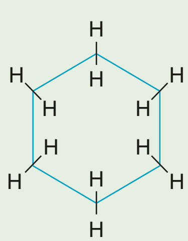
It can also be written:

$$—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—$$

More simply, it can be written$(—CH_2—)_{12}$. If the 12 carbons were in a pair of two rings, we probably would not label the carbons or hydrogens unless we wished to focus on a particular group or point. We would probably draw the two 6-carbon rings with only hydrogen attached as follows:

$$(—CH_2—)_{12}$$

Don't let these shortcuts throw you. You will soon find that you will be putting a —H group onto a carbon skeleton and neglecting to show the bond between the oxygen and hydrogen. Structural formulas are regularly included in the package insert information of most medications.



or

of many smaller, similar building blocks called *monomers* (*mono* = single) bonded together (figure 3.8).

Although lipids are macromolecules, they are not polymers. A polymer is similar to a pearl necklace or a boat's anchor chain. All polymers are constructed of similar segments (pearls or links) hooked together to form one large product (necklace or anchor chain).

The monomers in a polymer are usually combined by a dehydration synthesis reaction (*de* = remove; *hydro* = water; *synthesis* = combine). This reaction occurs when two smaller molecules come close enough to have an —OH removed from one and an —H removed from the other. These are combined to form a new water molecule (H_2O), and the remaining two segments are combined to form the macromolecule. Figure 3.9a shows the removal of water from between two monomers. Notice that, in this case, the structural formulas are used to help identify where this is occurring. The chemical equation also indicates the removal of water. You can easily recognize a dehydration synthesis reaction, because the reactant side of the equation shows numerous, small molecules, whereas the product side lists fewer, larger products and water.

The reverse of a dehydration synthesis reaction is known as hydrolysis (*hydro* = water; *lyse* = to split or break). Hydrolysis is the process of splitting a larger organic molecule into two or more component parts by adding water (figure 3.9b). The digestion of food molecules in the stomach is an example of hydrolysis.

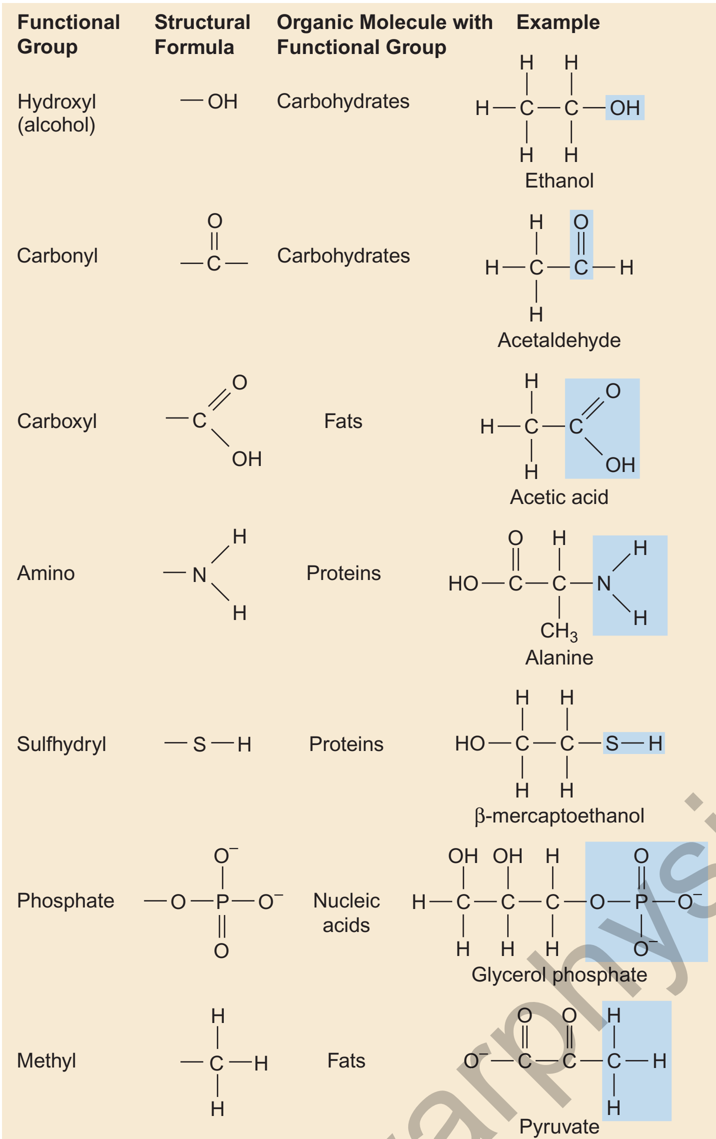


FIGURE 3.7 Functional Groups
These are some of the groups of atoms that frequently attach to a carbon skeleton. The nature of the organic compound changes as the nature of the functional group changes from one molecule to another.

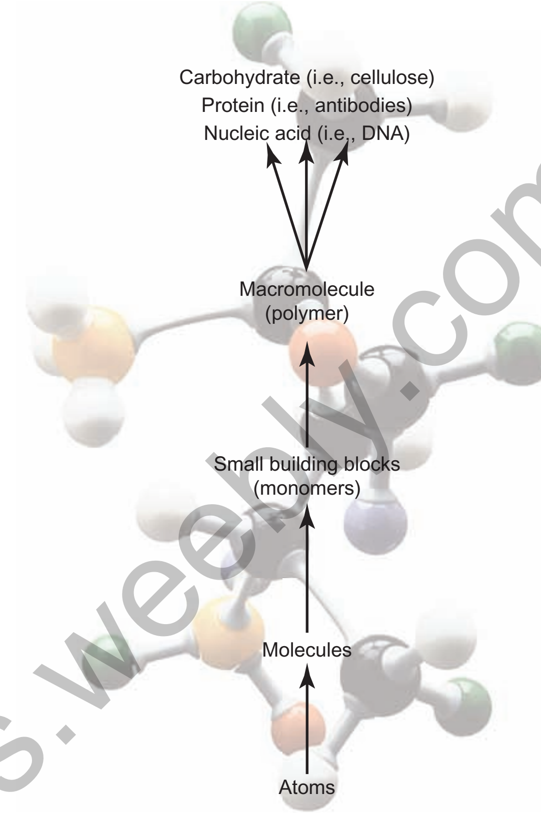


FIGURE 3.8 Levels of Chemical Organization
As a result of bonding specific units of matter in specific ways, molecules of enormous size and complexity are created.

3.1 CONCEPT REVIEW

1. What is the difference between inorganic and organic molecules?
2. What two characteristics of the carbon molecule make it unique?
3. Diagram an example of the following functional groups: amino, alcohol, carboxyl.
4. Describe five functional groups.
5. List three monomers and the polymers that can be constructed from them.

3.2 Carbohydrates

Carbohydrates are composed of carbon, hydrogen, and oxygen atoms linked together to form monomers called *simple sugars* or *monosaccharides* (*mono* = single; *saccharine* = sweet, sugar). Carbohydrates play a number of roles in living things. They are an immediate source of energy (sugars), provide shape to certain cells (cellulose in plant cell walls), and are the components of many antibiotics and coenzymes. They are also an essential part of the nucleic acids, DNA and RNA. The ability to taste sweetness is a genetic trait. Geneticists have found two forms of a gene that are known to encode for the sweet taste receptors, and people whose ancestors are from Europe have the keenest sensitivity to sweets.

Simple Sugars

The empirical formula for a simple sugar is easy to recognize, because there are equal numbers of carbons and oxygens and twice as many hydrogens—for example, $C_3H_6O_3$ or $C_5H_{10}O_5$. The ending *-ose* indicates that you are dealing with a carbohydrate. Simple sugars are usually described by the number of carbons in the molecule. A tri*ose* has 3 carbons, a pent*ose* has 5, and a hex*ose* has 6. If you remember that the number of carbons equals the number of oxygen atoms and that the number of hydrogens is double that number, these names tell you the empirical formula for the simple sugar.

Simple sugars, such as glucose, fructose, and galactose, provide the chemical energy necessary to keep organisms alive. *Glucose*, $C_6H_{12}O_6$, is the most abundant simple sugar; it serves as a food and a basic building block for other carbohydrates. Glucose (also called *dextrose*) is found in the sap of plants; in the human bloodstream, it is called *blood sugar.* Corn syrup, which is often used as a sweetener, is mostly glucose. Fructose, as its name implies, is the sugar that occurs in fruits *(fruit sugar),* and you also see it on food labels as high fructose corn syrup. Glucose and fructose have the same empirical formula but have different structural formulas—that is, they are isomers (refer to figure 3.6). Honey is a mixture of glucose and fructose. This mixture of glucose and fructose is also formed when table sugar (sucrose) is reacted with water in the presence of an acid, a reaction that takes place in the preparation of canned fruit and candies. The mixture of glucose and fructose is called *invert sugar.* Thanks to fructose, invert sugar is about twice as sweet to the taste as the same amount of sucrose. Invert sugar also attracts water (is hygroscopic). Brown sugar feels moister than white, granulated sugar because it contains more invert sugar. Therefore, baked goods made with brown sugar are moist and chewy.


Brown-sugar Cookies

Cells can use simple sugars as building blocks of other more complex molecules such as the genetic material, DNA, and the important energy transfer molecule, ATP. DNA contains the simple sugar deoxyribose, and ATP contains the simple sugar ribose.

TABLE 3.1 Relative Sweetness of Various Sugars and Sugar Substitutes

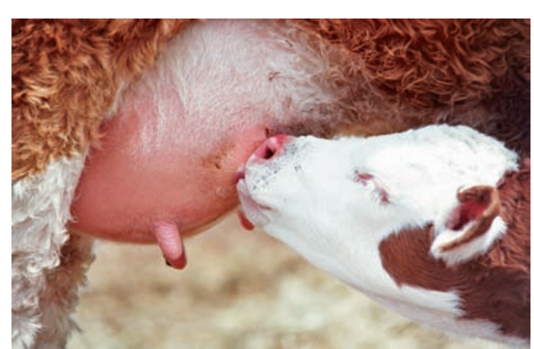
Type of Sugar or Artificial Sweetener	Relative Sweetness
Lactose (milk sugar)	0.16
Maltose (malt sugar)	0.33
Glucose	0.75
Sucrose (table sugar)	**1.00**
Fructose (fruit sugar)	1.75
Cyclamate	30.00
Aspartame	150.00
Stevia	300.00
Saccharin	350.00
Sucralose	600.00

Complex Carbohydrates

Simple sugars can be combined with each other to form **complex carbohydrates** (figure 3.10). When two simple sugars bond to each other, a *disaccharide* (*di* = two) is formed; when three bond together, a *trisaccharide* (*tri* = three) is formed. Generally, a complex carbohydrate that is larger than this is called a *polysaccharide* (*poly* = many). For example, when glucose and fructose are joined together, they form a disaccharide, with the loss of a water molecule (review figure 3.9).

Sucrose (table sugar) is the most common disaccharide. Sucrose occurs in high concentrations in sugarcane and sugar beets. It is extracted by crushing the plant materials, then dissolving the sucrose with water. The water is evaporated and the crystallized sugar is decolorized with charcoal to produce white sugar. Other common disaccharides are *lactose* (milk sugar) and *maltose* (malt sugar). All three of these disaccharides have similar properties, but maltose tastes only about one-third as sweet as sucrose. Lactose tastes only about one-sixth as sweet as sucrose (Table 3.1).

All the complex carbohydrates are polysaccharides and formed by dehydration synthesis reactions. Some common examples of polysaccharides are starch and glycogen. Cellulose is an important polysaccharide used in constructing the cell walls of plant cells. Humans cannot digest (hydrolyze) this complex carbohydrate, so we are not able to use it as an energy source. On the other hand, animals known as ruminants (e.g., cows and sheep) and termites have microorganisms within their digestive tracts that digest cellulose, making it an energy source for them. Plant cell walls add bulk or fiber to our diet, but no calories. Fiber is an important addition to the diet, because it helps control weight and reduces the risk of colon cancer. It also controls constipation and diarrhea, because these large, water-holding molecules make these conditions less of a problem.


Source of Milk Sugar

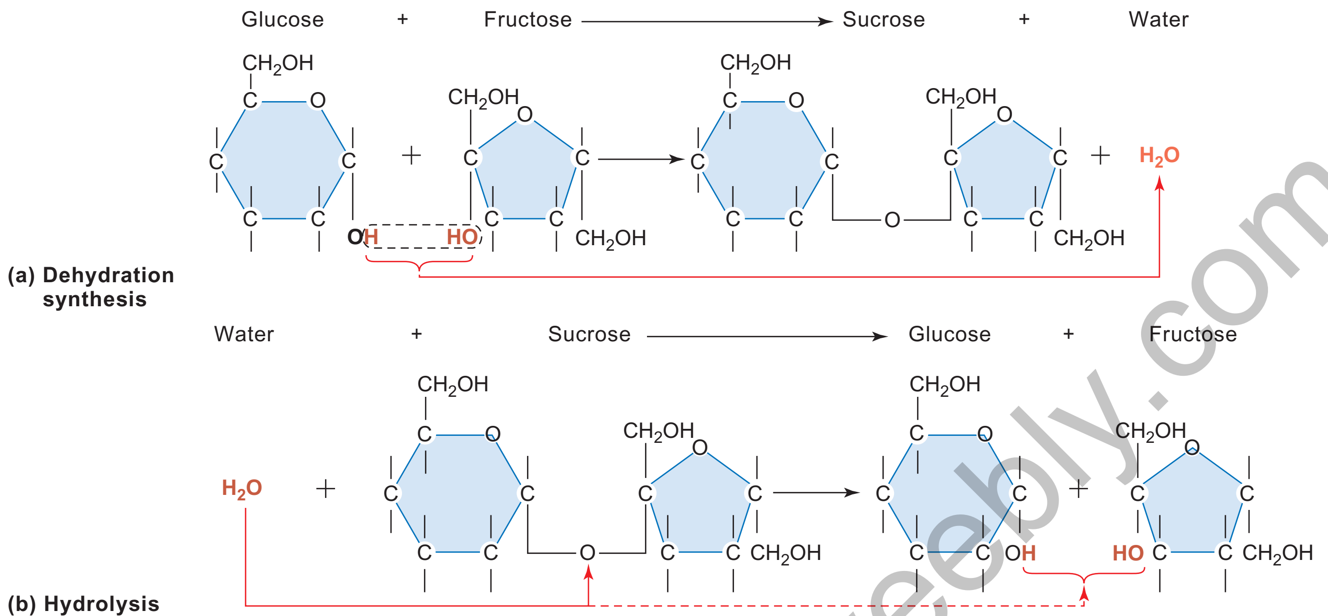


FIGURE 3.9 Polymer Formation and Breakdown
(a) In the dehydration synthesis reaction illustrated here, the two —OH groups line up next to each other, so that an —OH group can be broken from one of the molecules and an —H can be removed from the other. The H— and the —OH are then combined to form water, and the oxygen that remains acts as a connection between the two sugar molecules. *(b)* A hydrolysis reaction is the opposite of a dehydration synthesis reaction. Carefully compare the two.

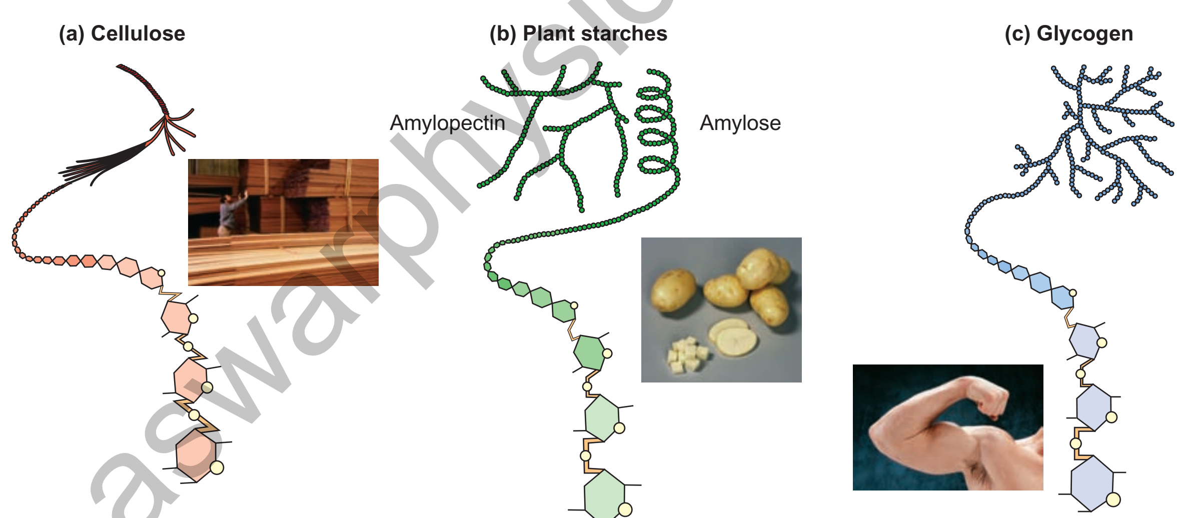


FIGURE 3.10 Complex Carbohydrates
Three common complex carbohydrates are *(a)* cellulose (wood fibers), *(b)* amylose and amylopectin (plant starches), and *(c)* glycogen (sometimes called animal starch). Glycogen is found in muscle cells. Notice how all are similar in that they are all polymers of simple sugars, but they differ in how they are joined together. Although many organisms are capable of digesting (hydrolyzing) the bonds that are found in glycogen and plant starch molecules, few are able to break those that link the monosaccharides of cellulose.

3.2 CONCEPT REVIEW

6. Give two examples of simple sugars and two examples of complex sugars.
7. What are the primary characteristics used to identify a compound as a carbohydrate?

3.3 Proteins

Proteins are polymers made up of monomers known as *amino acids*. An **amino acid** is a short carbon skeleton that contains an amino functional group (nitrogen and two hydrogens) attached on one end of the skeleton and a carboxylic acid group at the other end. In addition, the carbon

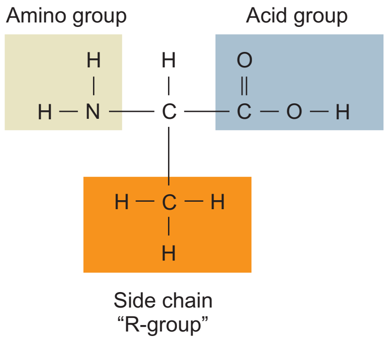


FIGURE 3.11 The Structure of an Amino Acid
An amino acid is composed of a short carbon skeleton with three functional groups attached: an amino group, a carboxylic acid group (acid group), and an additional group, the side chain that is different for each kind of amino acid.

skeleton may have one of several different "side chains" on it (figure 3.11). There are about 20 naturally occurring amino acids (Outlooks 3.2).

The Structure of Proteins

Amino acids can bond together by dehydration synthesis reactions. When two amino acids undergo dehydration synthesis, the nitrogen of the amino group of one is bonded to the carbon of the acid group of another. This covalent bond is termed a *peptide bond* (figure 3.12).

You can imagine that, by using 20 different amino acids as building blocks, you can construct millions of combinations. Each of these combinations is termed a **polypeptide** chain. A specific polypeptide is composed of a specific sequence of amino acids bonded end to end. Protein molecules are composed of individual polypeptide chains or groups of chains forming a particular configuration. There are four levels, or degrees, of protein structure: primary, secondary, tertiary, and quaternary structure.

Primary Structure

A listing of the amino acids in their proper order within a particular polypeptide is its *primary structure* (figure 3.13a). The specific sequence of amino acids in a polypeptide is controlled by the genetic information of an organism. **Genes** *are specific portions of DNA that serve as messages that tell the cell to link particular amino acids in a specific order; that is, they determine a polypeptide's primary structure. The kinds of side chains on these amino acids influence the shape that the polypeptide forms, as well as its function.*

OUTLOOKS 3.2

So You Don't Eat Meat! How to Stay Healthy

Humans require nine amino acids in their diet: threonine, tryptophan, methionine, lysine, phenylalanine, isoleucine, valine, histidine, and leucine. They are called *essential amino acids* because the body is not able to manufacture them. The body uses these essential amino acids in the synthesis of the proteins required for good health. For example, the sulfur-containing amino acid methionine is essential for the absorption and transportation of the elements selenium and potassium. It also prevents excess fat buildup in the liver, and it traps heavy metals, such as lead, cadmium, and mercury, bonding with them so that they can be excreted from the body. Because essential amino acids are not readily available in most plant proteins, they are most easily acquired through meat, fish, and dairy products.

If this is the case, how do people avoid nutritional deficiency if for economic or personal reasons do not eat meat, poultry, fish, meat products, dairy products, and honey? People who exclude all animal products from their diet are called *vegans*. Those who include only milk are called *lacto-vegetarians*; those who include eggs are *ovo-vegetarians*, and those who include both eggs and milk are *lacto-ovo vegetarians*. For anyone but a true vegan, the essential amino acids can be provided in even a small amount of milk and eggs. True vegans can get all their essential amino acids by eating certain combinations of plants or plant products. Even though there are certain plants that contain all of these amino acids (*soy*, lupin, *hempseed*, *chia seed*, *amaranth*, *buckwheat*, and *quinoa*) most plants contain one or more of the essential amino acids. However, by eating the right combination of different plants, it is possible to get all the essential amino acids in one meal. These combinations are known as *complementary foods*.

Vegetarian Meal

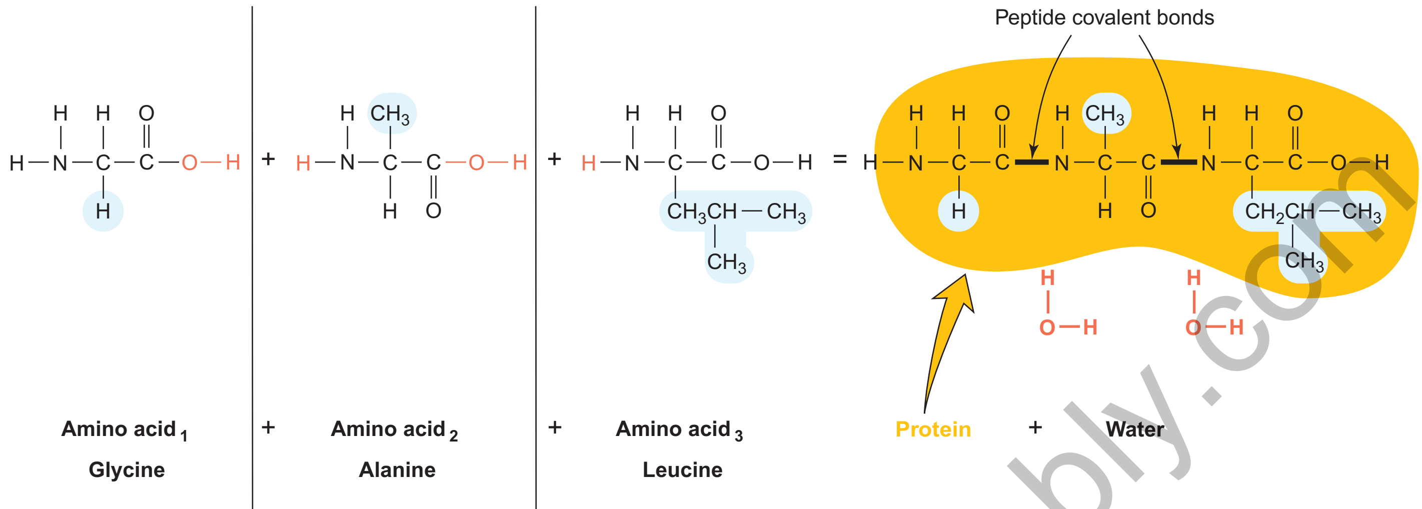


FIGURE 3.12 Peptide Covalent Bonds
The bond that results from a dehydration synthesis reaction between amino acids is called a peptide bond. This bond forms as a result of the removal of the hydrogen and hydroxide groups. In the formation of this bond, the nitrogen is bonded directly to the carbon. This tripeptide is made up of the amino acids glycine, alanine, and leucine. The side chain unique to each amino acid is shown in color.

Many polypeptides fold into globular shapes after they have been made as the molecule bends. Some of the amino acids in the chain can form bonds with their neighbors.

Secondary Structure

Some sequences of amino acids in a polypeptide are likely to twist, whereas other sequences remain straight. These twisted forms are referred to as the *secondary structure* of polypeptides (figure 3.13b). For example, at this secondary level some proteins (e.g., hair) take the form of an *alpha helix:* a shape like that of a coiled spring. Like most forms of secondary structure, the shape of the alpha helix is maintained by hydrogen bonds formed between different amino acid side chains at different locations within the polypeptide. Remember from chapter 2 that these forces of attraction do not form molecules but result in the orientation of one part of a molecule to another part within the same molecule. Other polypeptides form hydrogen bonds that cause them to make several flat folds that resemble a pleated skirt. This is called a *beta-pleated sheet.*

Tertiary Structure

It is possible for a single polypeptide to contain one or more coils and pleated sheets along its length. As a result, these different portions of the molecule can interact to form an even more complex globular structure. This occurs when the coils and pleated sheets twist and combine with each other. The complex, three-dimensional structure formed in this manner is the polypeptide's *tertiary* (third-degree) *structure* (figure 3.13c). A good example of tertiary structure can be seen when a coiled electric cord becomes so twisted that it folds around and back on itself in several places. The oxygen-holding protein found in muscle cells, myoglobin, displays tertiary structure. It is composed of a single (153 amino acids) helical molecule folded back and bonded to itself in several places.

Quaternary Structure

Frequently, several different polypeptides, each with its own tertiary structure, twist around each other and chemically combine. The larger globular structure formed by these interacting polypeptides is referred to as the protein's *quaternary* (fourth-degree) *structure.* The individual polypeptide chains are bonded to each other by the interactions of certain side chains, which can form disulfide covalent bonds (figure 3.13d). One group of proteins that form quaternary structure are *immunoglobulins*, also known as *antibodies*. They are involved in fighting infectious diseases such as the flu, the mumps, and chicken pox.

The Form and Function of Proteins

If a protein is to do its job effectively, it is vital that it has a particular three-dimensional shape. The protein's shape can be altered by changing the order of the amino acids, which causes different cross-linkages to form. Figure 3.14 shows the importance of the protein's three-dimensional shape, another emergent property.

For example, normal hemoglobin found in red blood cells consists of two kinds of polypeptide chains, called the alpha and beta chains. The beta chain is 146 amino acids long. If just one of these amino acids is replaced by a different one, the hemoglobin molecule may not function properly. A classic example of this results in a condition known as *sickle-cell anemia.* In this case, the sixth amino acid in the beta chain,

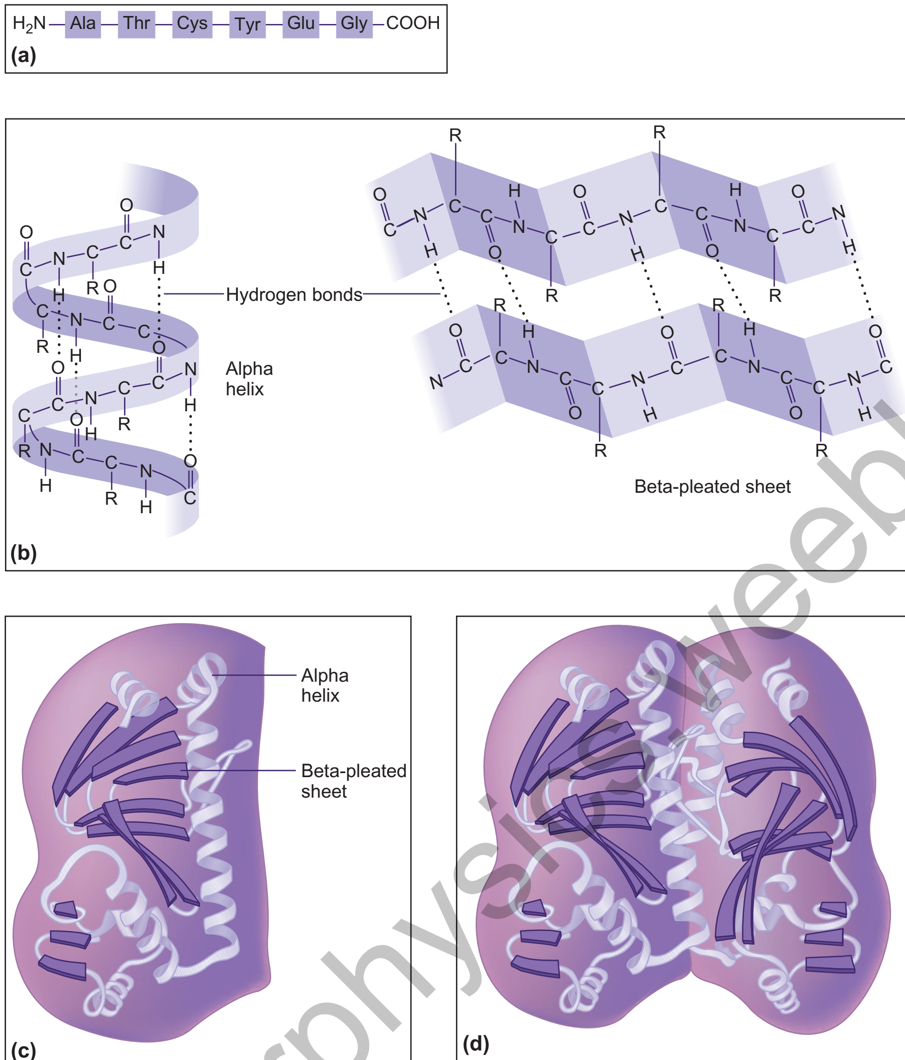


FIGURE 3.13 Levels of Protein Structure
(a) The primary structure of a protein molecule is simply a list of its amino acids in the order in which they occur. *(b)* This shows the secondary structure of protein molecules or how one part of the molecule is attached to another part of the same molecule. *(c)* If already folded parts of a single molecule attach at other places, the molecule is said to display tertiary (third-degree) structure. *(d)* Quaternary (fourth-degree) structure is displayed by molecules that are the result of two separate molecules (each with its own tertiary structure) combining into one large macromolecule.

which is normally glutamic acid, is replaced by valine. What might seem like a minor change causes the hemoglobin to fold differently. The red blood cells that contain this altered hemoglobin assume a sickle shape when the body is deprived of an adequate supply of oxygen.

In other situations, two proteins may have the same amino acid sequence but they do not have the same three-dimensional form. The difference in shape affects how they function. Mad cow disease (bovine spongiform encephalopathy—BSE), chronic wasting disease in deer and Creutzfeldt-Jakob disease (CJD) in humans are caused by rogue proteins called *prions*. The prions that cause these diseases have an amino acid sequence identical to a normal brain protein but are folded differently. The normal brain protein contains helical segments, whereas the corresponding segments of the prion protein are pleated sheets. When these malformed proteins enter the body, they cause normal proteins to fold differently. This causes the death of brain cells which causes loss of brain function and eventually death.

Denatured Egg White

Changing environmental conditions also influence the shape of proteins. Energy in the form of heat or light may break the hydrogen bonds within protein molecules. When this occurs, the chemical and physical properties of the protein are changed and the protein is said to be **denatured.** (Keep in mind that a protein is a molecule, not a living thing, and therefore cannot be "killed.") A common

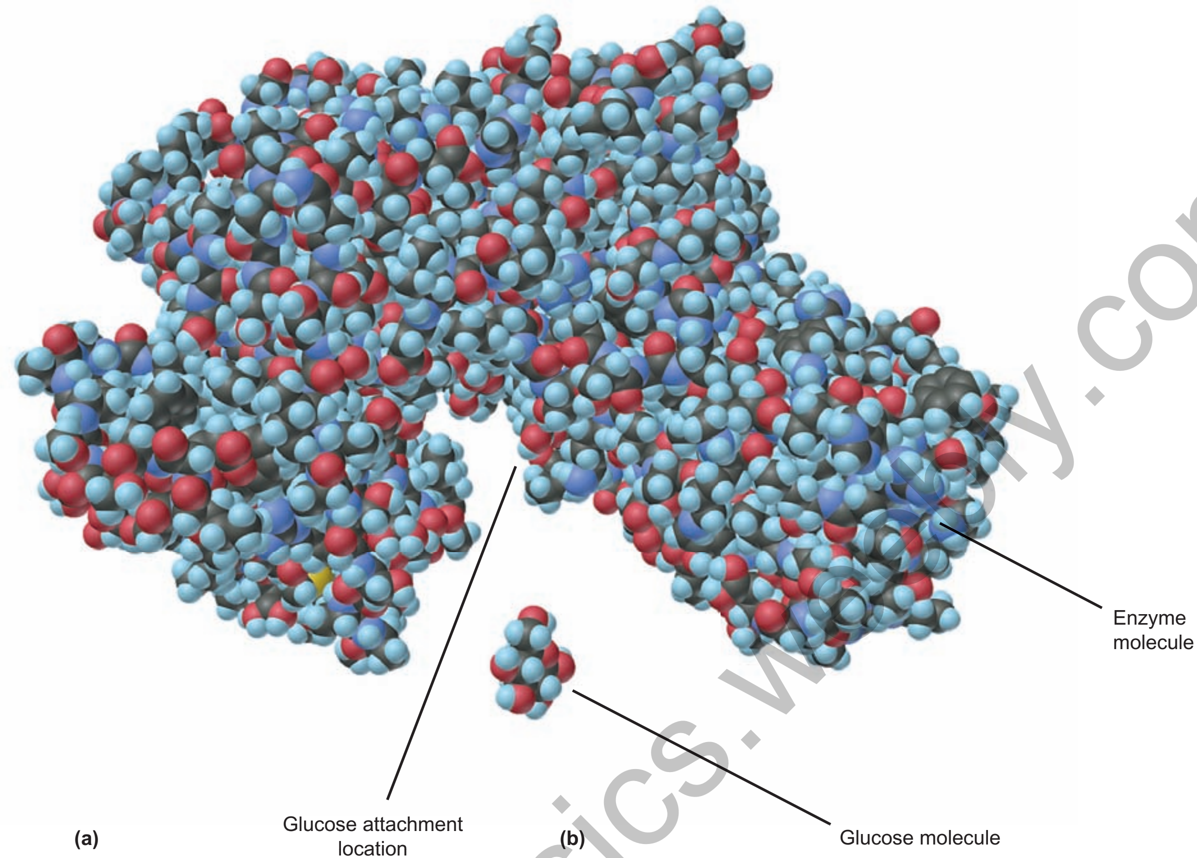


FIGURE 3.14 The Three-Dimensional Shape of Proteins
(a) The specific arrangement of amino acids in a polypeptide allows the amino acid side chains to bond with other amino acids. These stabilizing interactions result in a protein with a specific surface geometry. The large molecule pictured is an enzyme, a protein molecule that acts as a tool to speed the rate of a chemical reaction. Without having this specific shape, this protein would not be able to attach to the smaller *(b)* glucose molecule and chemically change the glucose molecule.

example of this occurs when the gelatinous, clear portion of an egg is cooked and the protein changes to a white solid. Some medications, such as insulin, are proteins and must be protected from denaturation so as not to lose their effectiveness. For protection, such medications may be stored in brown bottles to protect them from light or may be kept under refrigeration to protect them from heat.

What Do Proteins Do?

There are thousands of kinds of proteins in living things, and they can be placed into three categories based on the functions they serve. **Structural proteins** are important for maintaining the shape of cells and organisms. The proteins that make up cell membranes, muscle cells, tendons, and blood cells are examples of structural proteins. The protein collagen, found throughout the human body, gives tissues shape, support, and strength.

Regulator proteins, the second category of proteins, help determine what activities will occur in the organism. Regulator proteins include *enzymes*, *chaperones*, and some *hormones*. These molecules help control the chemical activities of cells and organisms. Enzymes speed the rate of chemical reactions and will be discussed in detail in chapter 5. Some examples of enzymes are the digestive enzymes in the intestinal tract. The job of a chaperone is to help other proteins fold into their proper shape. For example, some chaperones act as heat shock proteins—that is, they help repair heat-damaged proteins. Three hormones that are regulator proteins are insulin, glucagon, and oxytocin. Insulin and glucagon, produced by different cells of your pancreas, control the amount of glucose in the blood. If insulin production is too low, or if the molecules are improperly constructed, glucose molecules are not removed from the bloodstream at a fast enough rate. The excess sugar is then eliminated in the urine. Other symptoms of excess "sugar" in the blood include excessive thirst and even loss of consciousness. When blood sugar is low, glucagon is released from the pancreas to stimulate the breakdown of glycogen. The disease caused by improperly functioning insulin is known as *diabetes*. Oxytocin, a third protein hormone, stimulates the contraction of the uterus during childbirth. It is an organic molecule that has been produced artificially (e.g., Pitocin), and used by physicians to induce labor.

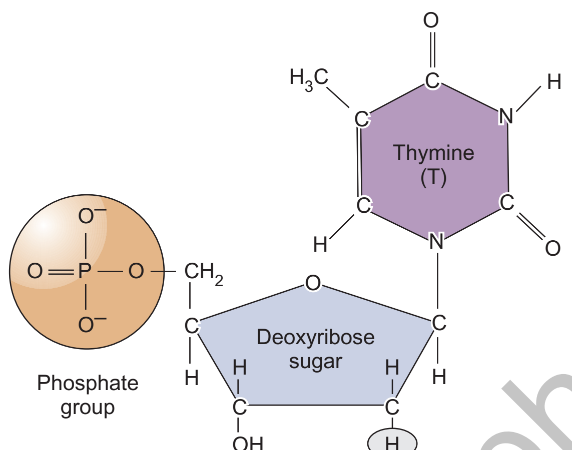
Carrier proteins are the third category. These pick up molecules at one place and transport them to another. For example, proteins from your food attach to cholesterol circulating in your blood to form *lipoproteins*, which are carried from the digestive system throughout the body.

3.3 CONCEPT REVIEW

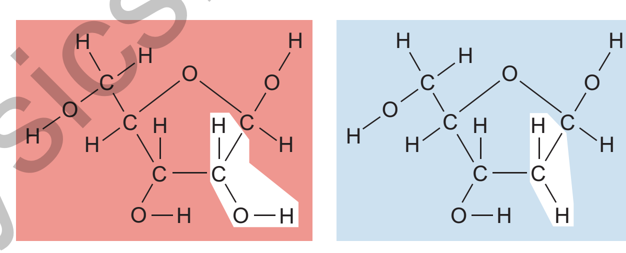
8. How do the primary, secondary, tertiary, and quaternary structures of proteins differ?
9. List the three categories of proteins and describe their functions.

3.4 Nucleic Acids

Nucleic acids are complex organic polymers that store and transfer genetic information within a cell. There are two types of nucleic acids: deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). DNA serves as genetic material, whereas RNA plays a vital role in using genetic information to manufacture proteins. All nucleic acids are constructed of monomers known as **nucleotides.** Each nucleotide is composed of three parts: (1) a 5-carbon simple sugar molecule, which may be ribose or deoxyribose, (2) a phosphate group, and (3) a nitrogenous base. The nitrogenous base may be one of five types. Two of the types are the larger, double-ring molecules adenine and guanine. The smaller bases are the single-ring bases thymine, cytosine, and uracil (i.e., A, G, T, C, and U) (figure 3.15). Nucleotides (monomers) are linked together in long sequences (polymers), so that the sugar and phosphate sequence forms a "backbone" and the nitrogenous bases stick out to the side. DNA has deoxyribose sugar and the bases A, T, G, and C, whereas RNA has ribose sugar and the bases A, U, G, and C (figure 3.16).

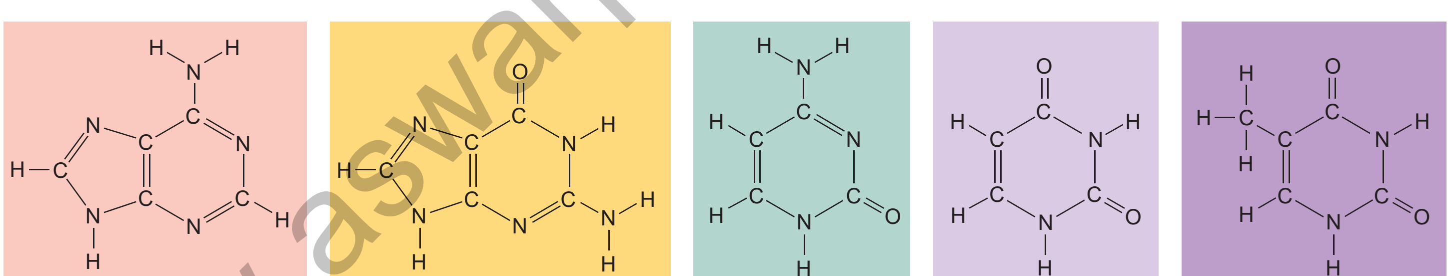


(a) Nucleotide



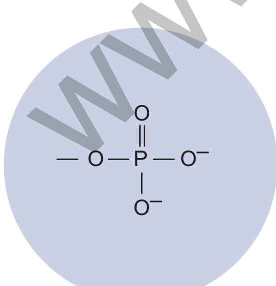
(1) Ribose
(2) Deoxyribose

(b) Sugars:



(1) Adenine
(2) Guanine
(3) Cytosine
(4) Uracil
(5) Thymine

(c) Nitrogenous bases:



(d) A phosphate group

FIGURE 3.15 The Building Blocks of Nucleic Acids
(a) A complete DNA nucleotide composed of a sugar, phosphate, and a nitrogenous base. *(b)* The two possible sugars used in nucleic acids, ribose and deoxyribose. *(c)* The five possible nitrogenous bases: adenine (A), guanine (G), cytosine (C), uracil (U), and thymine (T). *(d)* A phosphate group.

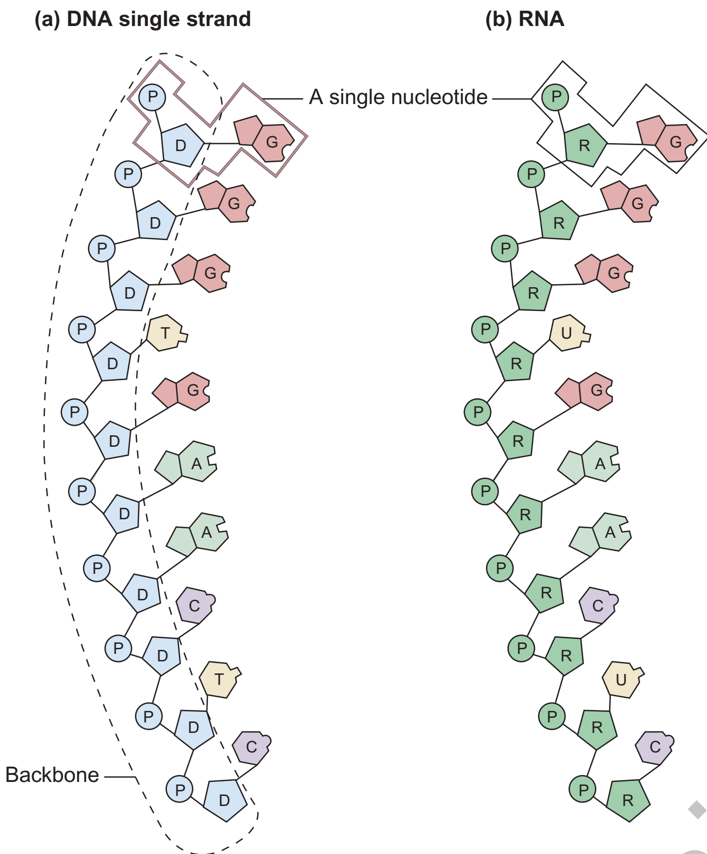


FIGURE 3.16 DNA and RNA
(a) A single strand of DNA is a polymer composed of nucleotides. Each nucleotide consists of deoxyribose sugar, phosphate, and one of four nitrogenous bases: A, T, G, or C. Notice the backbone of sugar and phosphate. *(b)* RNA is also a polymer, but each nucleotide is composed of ribose sugar, phosphate, and one of four nitrogenous bases: A, U, G, or C.

DNA

***D**eoxyribo**n**ucleic **a**cid* **(DNA)** is composed of two strands, which form a twisted, ladderlike structure thousands of nucleotides long (figure 3.17). The two strands are attached by hydrogen bonds between their bases according to the base-pair rule. *The base-pairing rule states that adenine always pairs with thymine, A with T (in the case of RNA, adenine always pairs with uracil—A with U) and guanine always pairs with cytosine—G with C.*

A T (or A U) and G C

A meaningful genetic message, a gene, is written using the nitrogenous bases as letters along a section of a strand of DNA, such as the base sequence CATTAGACT. The strand that contains this message is called the *coding strand,* from which comes the term *genetic code.* To make a protein, the cell reads the coding strand and uses sets of 3 bases. In the example sequence, sets of three bases are CAT, TAG, and ACT. This system is the basis of the genetic code for all organisms. Directly opposite the coding strand is a sequence of nitrogenous bases that are called *non-coding,* because the sequence of letters make no "sense," but this strand protects the coding strand from chemical and physical damage. Both strands are twisted into a helix—that is, a molecule turned around a tubular space, like a twisted ladder.

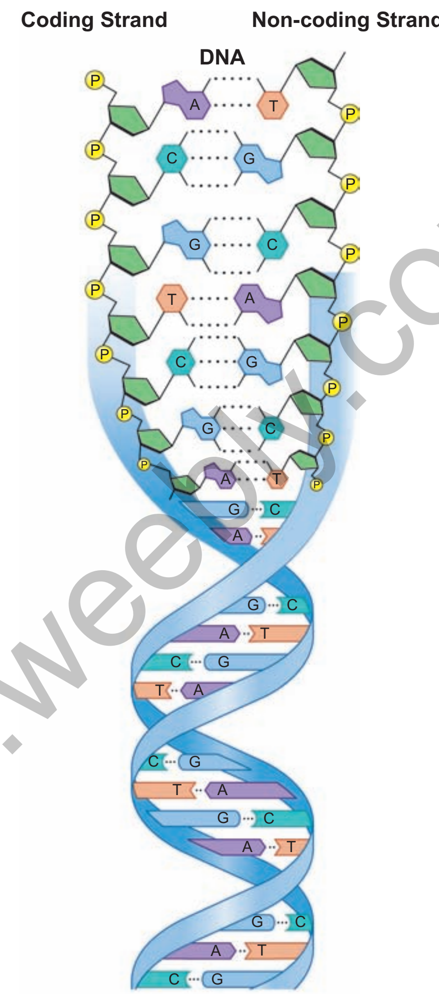


FIGURE 3.17 DNA
The genetic material is really double-stranded DNA molecules comprised of sequences of nucleotides that spell out an organism's genetic code. The coding strand of the double molecule is the side that can be translated by the cell into meaningful information. The genetic code has the information for telling the cell what proteins to make, which in turn become the major structural and functional components of the cell. The non-coding strand is unable to code for such proteins.

The information carried by DNA can be compared to the information in a textbook. Books are composed of words (constructed from individual letters) in particular combinations, organized into chapters. In the same way, DNA is composed of tens of thousands of nucleotides (letters) in specific three letter sequences (words) organized into genes (chapters). Each chapter gene carries the information for producing a protein, just as the chapter of a book carries information relating to one idea. The

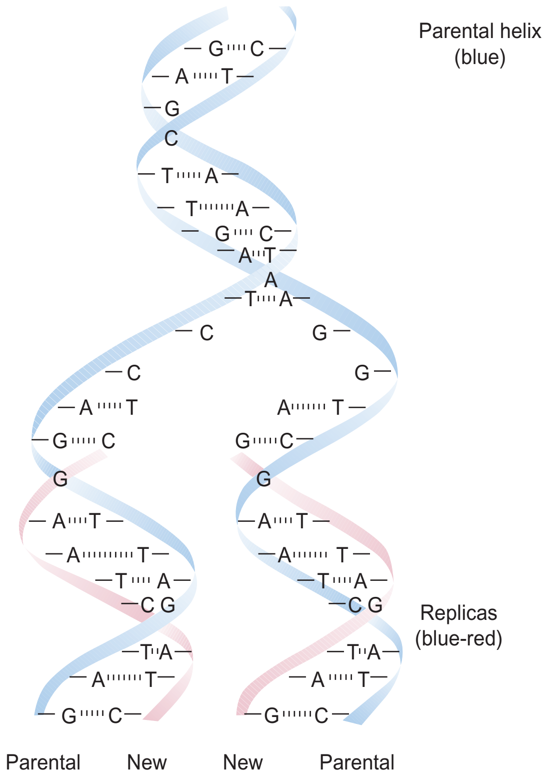


FIGURE 3.18 Passing on Information to the Next Generation
This is a generalized illustration of DNA replication. Each daughter cell receives a copy of the double helix. The helices are identical to each other and identical to the original double strands of the parent cell.

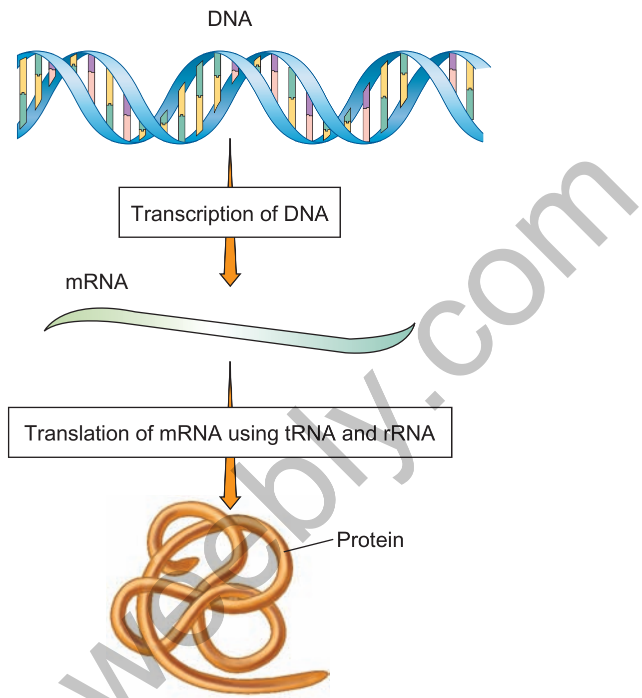


FIGURE 3.19 The Role of RNA
The entire process of protein synthesis begins with DNA. All forms of RNA (messenger, transfer, and ribosomal) are copies of different sequences of coding strand DNA and each plays a different role in protein synthesis. When the protein synthesis process is complete, the RNA can be reused to make more of the same protein coded for by the mRNA.

order of nucleotides in a gene is directly related to the order of amino acids in the protein for which it codes. Just as chapters in a book are identified by beginning and ending statements, different genes along a DNA strand have beginning and ending signals. They tell when to start and when to stop reading the gene. Human body cells contain 46 strands (books) of helical DNA, each containing many genes (chapters). These strands are called **chromosomes** when they become super-coiled in preparation for cellular reproduction. Before cellular reproduction, the DNA makes copies of the coding and non-coding strands, ensuring that the offspring, or *daughter* cells, will receive a full complement of the genes required for their survival (figure 3.18). A gene is a segment of DNA that is able to (1) replicate by directing the manufacture of copies of itself; (2) mutate, or chemically change, and transmit these changes to future generations; (3) store information that determines the characteristics of cells and organisms; and (4) use this information to direct the synthesis of structural, carrier, and regulator proteins.

RNA

***Ribo**nucleic **a**cid* (**RNA**) is found in three basic forms. **Messenger RNA (mRNA)** is a single-strand copy of a portion of the coding strand of DNA for a specific gene. When mRNA is formed on the surface of the DNA, the base-pair rule applies. However, because RNA does not contain thymine, it pairs U with A instead of T with A. After mRNA is formed and peeled off, it links with a cellular structure called the *ribosome,* where the genetic message can be translated into a protein molecule. Ribosomes contain another type of RNA, **ribosomal RNA (rRNA).** rRNA is also an RNA copy of DNA, but after being formed it becomes twisted and covered in protein to form a ribosome. The third form of RNA, **transfer RNA (tRNA),** is also a copy of different segments of DNA, but when peeled off the surface each segment takes the form of a cloverleaf. tRNA molecules are responsible for transferring or carrying specific amino acids to the ribosome, where all three forms of RNA come together and cooperate in the manufacture of protein molecules (figure 3.19).

Whereas the specific sequence of nitrogenous bases correlates with the coding of genetic information, the energy transfer function of nucleic acids is correlated with the number of phosphates each contains. A nucleotide with 3 phosphates has more energy than a nucleotide with only 1 or 2 phosphates. All of the different nucleotides are involved in transferring energy in phosphorylation reactions. One of the most important, ATP (*a*denosine *tri*phosphate) and its role in metabolism will be discussed in chapter 6.

3.4 CONCEPT REVIEW

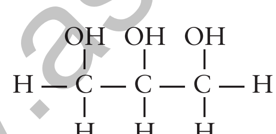
10. Describe how DNA differs from and is similar to RNA both structurally and functionally.
11. List the nitrogenous bases that base-pair in DNA and in RNA.

3.5 Lipids

There are three main types of **lipids:** *true fats* (e.g., olive oil), *phospholipids* (the primary component of cell membranes), and *steroids* (some hormones). In general, lipids are large, nonpolar (do not have a positive end and a negative end), organic molecules that do not dissolve easily in polar solvents, such as water. For example, nonpolar vegetable oil molecules do not dissolve in polar water molecules; they separate. Molecules in this group are generally called **fats.** They are not polymers, as are carbohydrates, proteins, and nucleic acids. Fats are soluble in nonpolar substances, such as ether or acetone. Just like carbohydrates, lipids are composed of carbon, hydrogen, and oxygen. They do not, however, have the same ratio of carbon, hydrogen, and oxygen in their empirical formulas. Lipids generally have very small amounts of oxygen, compared with the amounts of carbon and hydrogen. *Simple lipids* are not able to be broken down into smaller, similar subunits. *Complex lipids* can be hydrolyzed into smaller, similar units.

True (Neutral) Fats

True (neutral) fats are important, complex organic molecules that are used to provide energy, among other things. The building blocks of a fat are a *glycerol* molecule and *fatty acids*. **Glycerol** is a carbon skeleton that has three alcohol groups attached to it. Its chemical formula is $C_3H_5(OH)_3$. At room temperature, glycerol looks like clear, lightweight oil. It is used under the name *glycerin* as an additive to many cosmetics to make them smooth and easy to spread.



Glycerol

A **fatty acid** is a long-chain carbon skeleton that has a carboxyl functional group. True (neutral) fat molecules that form from a glycerol molecule and 3 attached fatty acids are called *triglycerides*; those with 2 fatty acids are *diglycerides*; those with 1 fatty acid are *monoglyceride* (figure 3.20). Triglycerides account for about 95% of the fat stored in human tissue.

If the carbon skeleton of a fatty acid molecule has as much hydrogen bonded to it as possible, it is called **saturated.** The saturated fatty acid shown in figure 3.21a is stearic acid, a component of solid meat fats, such as bacon fat. Notice

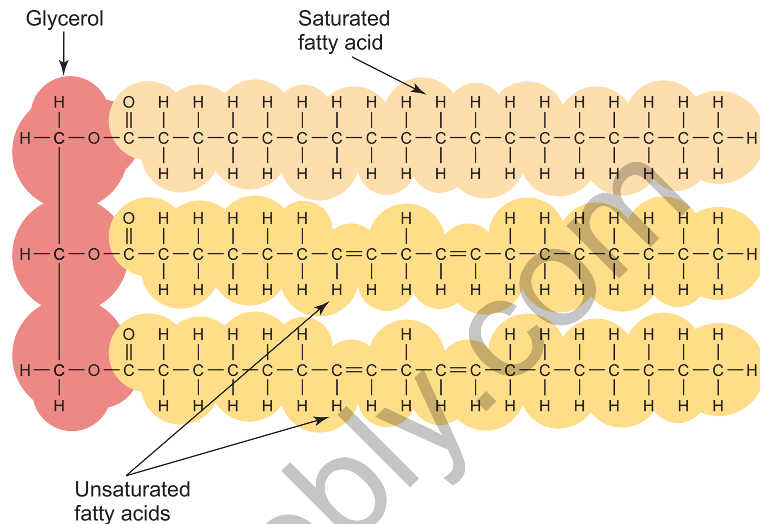
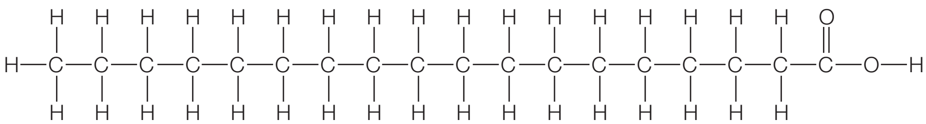


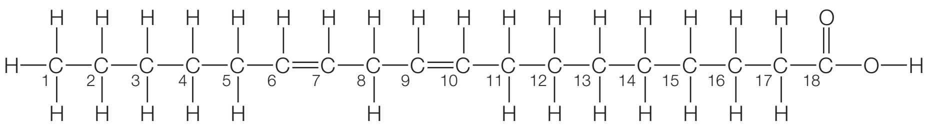
FIGURE 3.20 A Triglyceride Molecule
The arrangement of the 3 fatty acids (yellow) attached to a glycerol molecule (red) is typical of the formation of a fat. The structural formula of the fat appears to be very cluttered until you dissect the fatty acids from the glycerol; then, it becomes much more manageable. This example of a triglyceride contains a glycerol molecule, 2 unsaturated fatty acids (linoleic acid), and a third saturated fatty acid (stearic acid).

that, at every point in this structure, the carbon has as much hydrogen as it can hold. Saturated fats are generally found in animal tissues—they tend to be solids at room temperatures. Some other examples of saturated fats are butter, whale blubber, suet, lard, and fats associated with such meats as steak and pork chops.

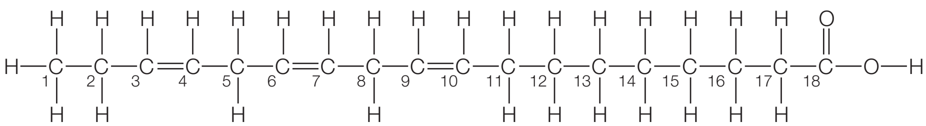
A fatty acid is said to be **unsaturated** if the carbons are double-bonded to each other at one or more points. The occurrence of a double bond in a fatty acid is indicated by the Greek letter ω (omega), followed by a number indicating the location of the first double bond in the molecule. Counting begins from the omega end, that is the end farthest from the carboxylic acid functional group. Oleic acid, one of the fatty acids found in olive oil, is comprised of 18 carbons with a single double bond between carbons 9 and 10. Therefore, it is chemically designated C18:1ω9 and is a monounsaturated fatty acid. This fatty acid is commonly referred to as an omega-9 fatty acid. The unsaturated fatty acid in figure 3.21b is linoleic acid, a component of sunflower and safflower oils. Notice that there are two double bonds between the carbons and fewer hydrogens than in the saturated fatty acid. Linoleic acid is chemically a polyunsaturated fatty acid with two double bonds and is designated C18:2ω6, an omega-6 fatty acid. This indicates that the first double bond of this 18-carbon molecule is between carbons 6 and 7. Because the human body cannot make this fatty acid and must be taken in as a part of the diet, it is called an *essential fatty acid.* The other essential fatty acid, linolenic acid (figure 3.21c), is C18:3ω3; it has three double bonds. This fatty acid is commonly



(a) Stearic acid



(b) Linoleic acid (omega-6)



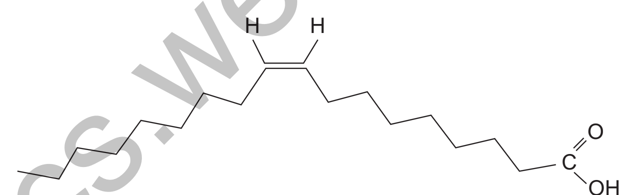
(c) Alpha-linolenic acid (omega-3)

FIGURE 3.21 Structure of Saturated and Unsaturated Fatty Acids
(a) Stearic acid is an example of a saturated fatty acid. *(b)* Linoleic acid is an example of an unsaturated fatty acid. It is technically an omega-6 fatty acid, because the first double bond occurs at carbon number 6. *(c)* An omega-3 fatty acid, linolenic acid. Both linoleic and linolenic acids are essential fatty acids for humans.

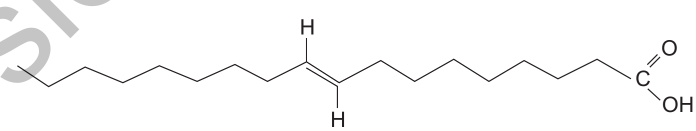
referred to as an omega-3 fatty acid. One key function of these essential fatty acids is the synthesis of the prostaglandin hormones that are necessary in controlling cell growth and specialization. Many food manufacturers are now adding omega-3 fatty acids to their products, based on evidence that these reduce the risk of cardiovascular disease.

Sources of Omega-3 Fatty Acids	Sources of Omega-6 Fatty Acids
Certain fish oils (salmon, sardines, herring)	Corn oil
	Peanut oil
Flaxseed oil	Cottonseed oil
Soybeans	Soybean oil
Soybean oil	Sesame oil
Walnuts	Sunflower oil
Canola oil	Safflower oil
Green, leafy vegetables	

Many unsaturated fat molecules are plant fats or oils—they are usually liquids at room temperatures. Peanut, corn, and olive oils are mixtures of true fats and are considered unsaturated because they have double bonds between the carbons of the carbon skeleton (Outlooks 3.3). A polyunsaturated fatty acid is one that has several double bonds in the carbon skeleton. When glycerol and 3 fatty acids are combined by three dehydration synthesis reactions, a fat is formed. That dehydration synthesis is almost exactly the same as the reaction that causes simple sugars to bond.



cis double bond: oleic acid



trans double bond: elaidic acid

In nature, most unsaturated fatty acids have hydrogen atoms that are on the same side of the double-bonded carbons. These are called *cis* fatty acids. If the hydrogens are on opposite sides of the double bonds, they are called *trans* fatty acids. *Trans* fatty acids are found naturally in grazing animals, such as cattle and sheep. Therefore, humans acquire them in their diets in the form of meat and dairy products. *Trans* fatty acids are also formed during the *hydrogenation* of either vegetable or fish oils. The hydrogenation process breaks the double bonds in the fatty acid chain and adds more hydrogen atoms. This can change the liquid to a solid. Many product labels list the term *hydrogenated*. This process extends shelf life and allows producers to convert oils to other solids, such as margarine.

Clinical studies have shown that *trans* fatty acids tend to raise total blood cholesterol levels, but less than the more

OUTLOOKS 3.3

What Happens When You Deep-Fry Food?

You have probably noticed that deep-fried foods are covered with some sort of breading or batter. The coating forms a barrier and protects the underlying food (e.g., chicken or cheese) from being burned when it is placed in the hot oil. This means that your food is being cooked indirectly, not directly, as you would cook a hot dog on a grill. Deep-fried foods cook quickly because fats and oils can be heated to higher temperatures before they boil. Cooking at these higher temperatures keeps the cooking fats and oils from getting inside the food. If the fat or oil is not hot enough, the food will be greasy. If the oil is too hot, the coating will burn before the food inside can be cooked the way you like it. Even though there is some variation in oil temperature due to the thickness and kind of food being deep-fried, the general rule is to have your oil at 375°F (190°C). The best oils to use for stir-frying are those that can be heated to a high temperature without smoking (e.g., canola, peanut, or grapeseed oil).

saturated fatty acids. Dietary *trans* fatty acids also tend to raise the so-called bad fats (low-density lipoproteins, LDLs) and lower the so-called good fats (high-density lipoproteins, HDLs) when consumed instead of *cis* fatty acids. Scientific evidence indicates that this increases the risk for heart disease (Outlooks 3.4). Because of the importance of *trans* fatty acids in cardiovascular health, the U.S. Department of Health and Human Services (HHS) requires that the amount of *trans* fatty acids in foods be stated under the listed amount of saturated fat. The HHS suggests that a person eat no more than 20 grams of saturated fat a day (about 10% of total calories), including *trans* fatty acids.

Fats are important molecules for storing energy. There is more than twice as much energy in a gram of fat as in a gram of sugar—9 Calories versus 4 Calories. This is important to an organism, because fats can be stored in a relatively small space yet yield a high amount of energy. Fats in animals also provide protection from heat loss; some animals have an insulating layer of fat under the skin. The thick layer of blubber in whales, walruses, and seals prevents the loss of internal body heat to the cold, watery environment in which they live. The same layer of fat and the fat deposits around some organs (such as the eyes, kidneys and heart) cushion the organs from physical damage.

Phospholipids

Phospholipids are a class of complex, water-insoluble organic molecules that resemble neutral fats but have a phosphate-containing group (PO_4) in their structure (figure 3.22). Phospholipids are important because they are a major component of cell membranes. Without these lipids, the cell contents would not be separated from the exterior environment. Some

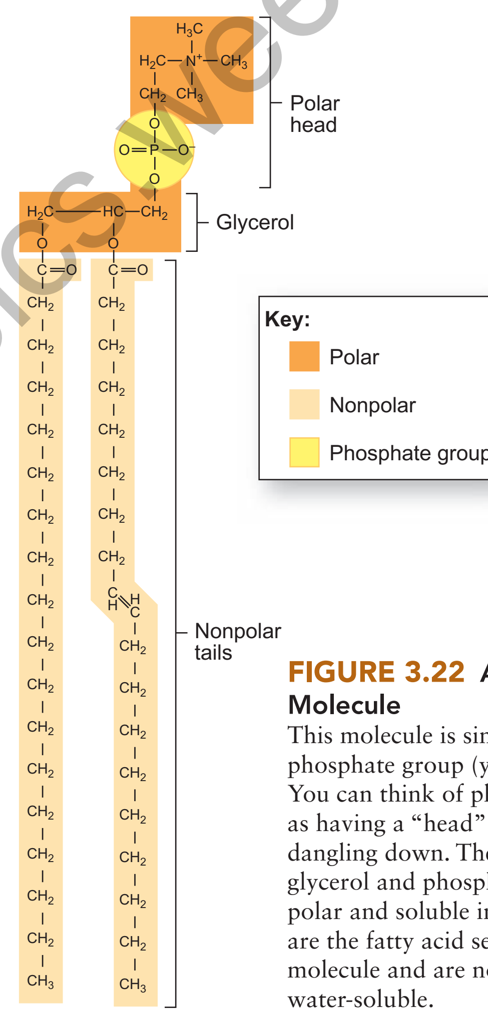


FIGURE 3.22 A Phospholipid Molecule
This molecule is similar to a fat but has a phosphate group (yellow) in its structure. You can think of phospholipid molecules as having a "head" with two strings dangling down. The head portion is the glycerol and phosphate group, which is polar and soluble in water. The strings are the fatty acid segments of the molecule and are nonpolar and not water-soluble.

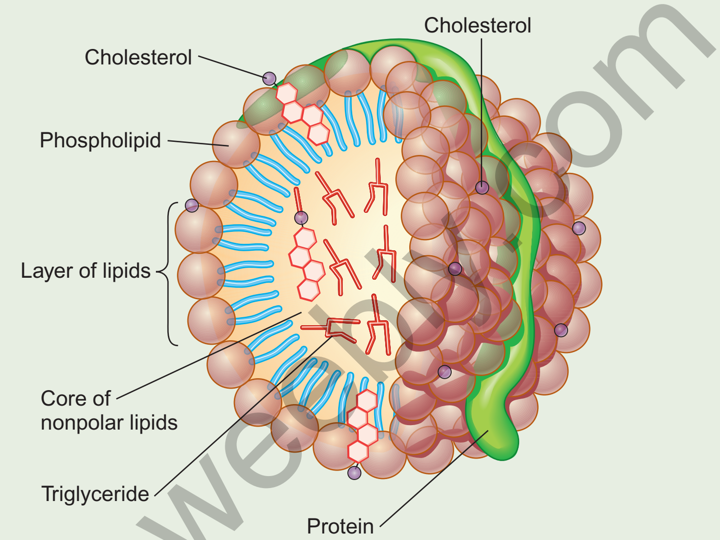
OUTLOOKS 3.4

Fat and Your Diet

When triglycerides are eaten in fat-containing foods, digestive enzymes hydrolyze them into glycerol and fatty acids. These molecules are absorbed by the intestinal tract and coated with protein to form lipoprotein, as shown in the accompanying diagram. The combination allows the fat to dissolve better in the blood, so that it can move throughout the body in the circulatory system.

Five types of lipoproteins found in the body are

1. Chylomicrons
2. Very-low-density lipoproteins (VLDLs)
3. Low-density lipoproteins (LDLs)
4. High-density lipoproteins (HDLs)
5. Lipoprotein a [Lp(a)]



Chylomicrons are very large particles formed in the intestine; they are 80–95% triglycerides. As the chylomicrons circulate through the body, cells remove the triglycerides in order to make sex hormones, store energy, and build new cell parts. When most of the triglycerides have been removed, the remaining portions of the chylomicrons are harmlessly destroyed.

The VLDLs and LDLs are formed in the liver. VLDLs contain all types of lipid, protein, and 10–15% cholesterol, whereas the LDLs are about 50% cholesterol. As with the chylomicrons, the body uses these molecules for the fats they contain. However, in some people, high levels of LDL and lipoprotein a [Lp(a)] in the blood are associated with atherosclerosis, stroke, and heart attack. It appears that saturated fat disrupts the clearance of LDLs from the bloodstream. Thus, while in the blood, LDLs may stick to the insides of the vessels, forming deposits, which restrict blood flow and contribute to high blood pressure, strokes, and heart attacks. Even though they are 30% cholesterol, a high level of HDLs (made in the intestine), compared with LDLs and [Lp(a)], is associated with a lower risk for atherosclerosis. One way to reduce the risk of this disease is to lower your intake of LDLs and [Lp(a)]. This can be done by reducing your consumption of saturated fats. An easy way to remember the association between LDLs and HDLs is "L = Lethal" and "H = Healthy" or "Low = Bad" and "High = Good." The federal government's cholesterol guidelines recommend that all adults get a full lipoprotein profile (total cholesterol, HDL, LDL, and triglycerides) once every five years.

They also recommend a sliding scale for desirable LDL levels; however, recent studies suggest that one's LDL level should be as low as possible.

Taking certain drugs is one way to control the level of lipoproteins in the body. Statins are a group of medicines (e.g., simvastatin, atorvastatin) that work by blocking the action of enzymes that control the rate of cholesterol production in the body. Their use can lower cholesterol 20–60%. They also increase the liver's ability to remove low-density lipoproteins. An additional benefit is a slight increase in high-density lipoproteins and a decrease in triglycerides.

Total cholesterol goal values:

- 75–169 mg/dL (milligram per deciliter) for those age 20 and younger
- 100–199 mg/dL for those over age 21

Low-density lipoprotein (LDL) goal values:

- Less than 70 mg/dL for those with heart or blood vessel disease and for other patients at very high risk of heart disease (those with metabolic syndrome)
- Less than 100 mg/dL for high-risk patients (for example, some patients who have diabetes or multiple heart disease risk factors)
- Less than 130 mg/dL otherwise

Very-low-density lipoprotein (VLDL) goal values:

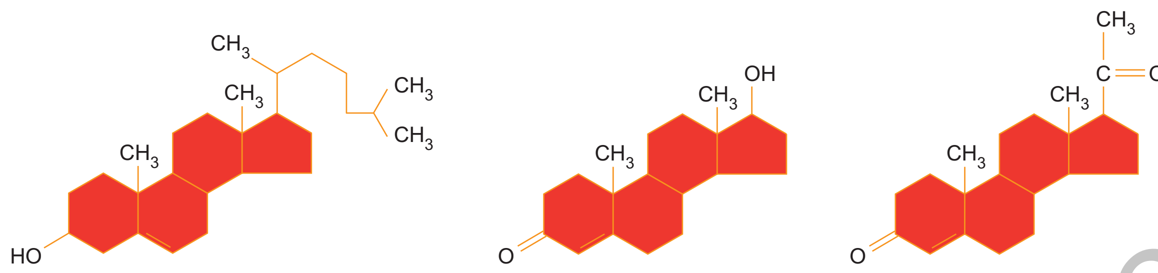
- Less than 40 mg/dL

High-density lipoprotein (HDL) goal value:

- Greater than 45 mg/dL (the higher the better)

Triglyceride goal value:

- Less than 150 mg/dL



(a) **Cholesterol** (b) **Testosterone** (c) **Progesterone**

FIGURE 3.23 Steroids
(a) Cholesterol is produced by the human body and is found in cell membranes. *(b)* Testosterone increases during puberty, causing the male sex organs to mature. *(c)* Progesterone is a female sex hormone produced by the ovaries and placenta. Notice the slight structural differences among these molecules.

of the phospholipids are better known as *lecithins*. Found in cell membranes, lecithins help in the emulsification of fats—that is, they help separate large portions of fat into smaller units. This allows the fat to mix with other materials. Lecithins are added to many types of food for this purpose (chocolate bars, for example). Some people take lecithin as nutritional supplements because they believe it leads to healthier hair and better reasoning ability. But once inside the intestines, lecithins are destroyed by enzymes, just as any other phospholipid is. Because phospholipids are essential components of the membranes of all cells, they will also be examined in chapter 4.

Steroids

Steroids, another group of lipid molecules, are characterized by their arrangement of interlocking rings of carbon. Many steroid molecules are sex hormones. Some of them regulate reproductive processes, such as egg and sperm production (see chapter 27); others regulate such things as salt concentration in the blood. Figure 3.23 illustrates some of the steroid compounds, such as testosterone and progesterone, that are typically manufactured by organisms and also in the laboratory as pharmaceuticals. We have already mentioned one steroid molecule: cholesterol. Serum cholesterol (the kind found in your blood and associated with lipoproteins) has been implicated in many cases of atherosclerosis. However, your body makes this steroid for use as a component of cell membranes. Cholesterol is necessary for the manufacture of vitamin D, which assists in the proper development of bones and teeth. Cholesterol molecules in your skin react with ultraviolet light to produce vitamin D. The body also uses it to make bile acids. These products of the liver are channeled into your intestine to emulsify fats.

Regulating the amount of cholesterol in the body to prevent its negative effects can be difficult, because we consume it in our diet. Recall that diets high in saturated fats increase the risk for diseases such as atherosclerosis. By watching your diet, you can reduce the amount of cholesterol in your blood serum by about 20%, as much as taking a cholesterol-lowering drug. Therefore, it is best to eat foods that are low in cholesterol. Because many foods that claim to be low- or no-cholesterol have high levels of saturated fats, they should also be avoided in order to control serum cholesterol levels.

3.5 CONCEPT REVIEW

12. Describe three kinds of lipids.
13. What is meant by HDL, LDL, and VLDL? Where are they found? How do they relate to disease?

Summary

The chemistry of living things involves a variety of large and complex molecules. This chemistry is based on the carbon atom and the fact that carbon atoms can connect to form long chains or rings. This results in a vast array of molecules. The structure of each molecule is related to its function. Changes in the structure may result in abnormal functions, called disease. Some of the most common types of organic molecules found in living things are carbohydrates, lipids, proteins, and nucleic acids. Table 3.2 summarizes the major types of biologically important organic molecules and how they function in living things.

TABLE 3.2 Types of Organic Molecules Found in Living Things

Type of Organic Molecule	Basic Subunit	Function	Examples
Carbohydrates	Simple sugar/monosaccharides	Provide energy	Glucose Cellulose, starch, glycogen
Proteins	Amino acid	Maintain the shape of cells and parts of organisms	Cell membrane Hair Antibodies Clotting factors Enzymes Muscle
		As enzymes, regulate the rate of cell reactions	Ptyalin in the mouth
		As hormones, affect physiological activity, such as growth or metabolism	Insulin
		Serve as molecules that carry other molecules to distant places in the body	Lipoproteins, hemoglobin
Nucleic acids	Nucleotide	Store and transfer genetic information that controls the cell	DNA
		Are involved in protein synthesis	RNA
Lipids			
1. Fats	Glycerol and fatty acids	Provide energy Provide insulation Serve as shock absorbers	Lard Olive oil Linseed oil Tallow
2. Phospholipids	Glycerol, fatty acids, and phosphate group	Form a major component of the structure of the cell membrane	Cell membrane
3. Steroids and prostaglandins	Structure of interlocking carbon rings	Often serve as hormones that control the body processes	Testosterone Vitamin D Cholesterol

Key Terms

Use the interactive flash cards on the ***Concepts in Biology,*** *14/e website to help you learn the meaning of these terms.*

amino acid 53
biochemistry 46
carbohydrates 51
carbon skeleton 49
carrier proteins 58
chromosomes 60
complex carbohydrates 52
denatured 56
deoxyribonucleic acid (DNA) 58
double bond 47
fats 61
fatty acid 61
functional groups 49
genes 54
glycerol 61
inorganic molecules 46
lipids 61
macromolecules 49
messenger RNA (mRNA) 60
nucleic acids 58
nucleotides 58
organic molecules 46
phospholipids 63
polymers 49
polypeptide 54
proteins 53
regulator proteins 57
ribonucleic acid (RNA) 58
ribosomal RNA (rRNA) 60
saturated 61
steroids 65
structural proteins 57
transfer RNA (tRNA) 60
true (neutral) fats 61
unsaturated 61

Basic Review

1. A(n) _____ formula indicates the number of each kind of atom within a molecule.
2. The name of this functional group, $-NH_2$, is
   a. amino. c. carboxylic acid.
   b. alcohol. d. aldehyde.
3. Molecules that have the same empirical formula but different structural formulas are called
   a. ions. c. icons.
   b. isomers. d. radicals.
4. Which is *not* a macromolecule?
   a. carbohydrate c. sulfuric acid
   b. protein d. steroid
5. Which is *not* a polymer?
   a. insulin c. fatty acid
   b. DNA d. RNA
6. The monomer of a complex carbohydrate is
   a. an amino acid. c. a nucleotide.
   b. a monosaccharide. d. a fatty acid.
7. When blood sugar is low, this protein hormone is released from the pancreas to stimulate the breakdown of glycogen.
   a. glucagon c. oxytocin
   b. estrogen d. glycine
8. Mad cow disease is caused by a
   a. virus. c. prion.
   b. bacteria. d. hormone.
9. _____ occurs when the shape of a macromolecule altered as a result of exposure to excess heat or light.
10. By watching your diet it is possible to reduce the amount of cholesterol in your blood serum by about _____%.
11. Organic compounds that do not have their proper _____ are not likely to function properly in a cell.
12. The genetic material of many organisms belongs to which major category of organic compounds?
    a. carbohydrate b. protein
    c. nucleic acid d. lipid
13. "Oh no! The doctor said my cholesterol was too high." I guess I'll have to keep an eye on the amount of _____ I eat.
14. Many types of birth control pills contain compounds called _____, one of which is estrogen.
15. Beta-pleated sheets found in protein molecules is an example of _____ structures.

Answers
1. empirical 2. a 3. b 4. c 5. c 6. b 7. a 8. c 9. Denaturation 10. 20% 11. 3-D shape 12. c 13. lipids 14. steroids 15. secondary

Thinking Critically

Archaeologists, anthropologists, chemists, biologists, and healthcare professionals agree that the drinking of alcohol dates back thousands of years. Evidence also exists that this practice has occurred in most cultures around the world. Use the Internet to search out answers to the following questions:

1. What is the earliest date for which there is evidence for the production of ethyl alcohol?
2. In which culture did alcohol drinking first occur?
3. What is the molecular formula and structure of ethanol?
4. Do alcohol and water mix?
5. How much ethanol is consumed in the form of beverages in the United States each year?
6. What is the legal limit to be considered intoxicated in your state?
7. How is the legal limit in your state measured?
8. Why is there a tax on alcoholic beverages?
9. How do the negative effects of drinking alcohol compare for men and women?
10. Have researchers demonstrated any beneficial effects of drinking alcohol?

Compare what you thought you knew to what you can now support with scientific evidence.

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CHAPTER 4

Cell Structure and Function

CHAPTER OUTLINE

Cadavers Source of Healing Power

Is there a risk?

Most people think that bones are lifeless; however, they are actually living, growing tissues. Bone is composed of many kinds of living cells surrounded by a bone matrix made of minerals and proteins. Certain bone cells are a source of *red* and *white blood cells* while others are engaged in a process known as *bone remodeling*—much like the process a sculptor uses when creating a piece of art from clay. Remodeling occurs throughout life and is the result of the absorption of bone followed by the formation of new bone. Cells known as *osteoblasts* are responsible for adding new bone matrix, whereas *osteoclasts* remove old matrix. Remodeling takes place as a result of bone loss due to stress, disease or breakage.

Following certain accidents or diseases, bone cells are unable to remodel the damage. However, researchers have discovered that healing can be promoted by using protein bone matrix from cadavers—dead bodies. This tissue is rich in growth factors that signal bone cells to multiply and promote repair. Are there drawbacks? There is only a limited supply of this matrix because it comes from human donors, and there is a risk of transmitting viruses to the recipient.

- **What is the basic makeup of a cell?**
- **How do growth factors signal cells?**
- **In order to become a bone matrix organ donor, should a person undergo screening to check for hidden viruses?**

Background Check

Concepts you should already know to get the most out of this chapter:

- The atomic and molecular nature of matter (chapter 2)
- Some molecules can be very large (chapter 3)
- There are millions of different kinds of molecules and that each kind of molecule has specific physical properties (chapter 2)
- Kinetic molecular theory (chapter 2)

4.1 The Development of the Cell Theory

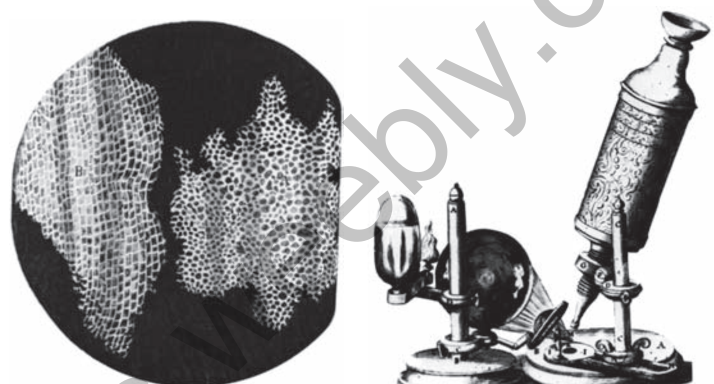
The **cell theory** states that all living things are made of cells. The **cell** is the basic structural and functional unit of living things and is the smallest unit that displays the characteristics of life. However, the concept of a cell did not emerge all at once but, rather, was developed and modified over several centuries. It is still being modified today. The ideas of hundreds of people were important in the development of the cell theory, but certain key people can be identified.

Some History

The first person to use the term *cell* was Robert Hooke (1635–1703) of England. He used a simple kind of microscope to study thin slices of cork from the bark of a cork oak tree (figure 4.1). He saw many cubicles fitting neatly together, which reminded him of the barren rooms (cells) in a monastery. He used the term *cell* when he described his observations in 1665 in the publication *Micrographia*, the first picture book of science to come off the press, with 38 beautiful engravings. The book became a best-seller. The tiny cork boxes Hooke saw, and described in his book were, in fact, only the cell walls that surrounded the once living portions of these plant cells.

We now know that the **cell wall** of a plant cell is produced on the outside of the cell and is composed of the complex carbohydrate called cellulose. It provides strength and protection to the living contents of the cell. Although the cell wall appears to be a rigid, solid layer of material, it is actually composed of many interwoven strands of cellulose molecules. Thus, most kinds of molecules pass easily through it.

Anton van Leeuwenhoek (1632–1723), a Dutch merchant who sold cloth, was one of the first individuals to carefully study magnified cells. He apparently saw a copy of Hooke's *Micrographia* and began to make his own microscopes, so that he could study biological specimens. He was interested in magnifying glasses, because magnifiers were used to count the number of threads in cloth. He used a very simple kind of microscope that had only one lens. Basically, it was a very powerful magnifying glass (figure 4.2). What made his microscope better than others of the time was his ability to grind very high-quality lenses. He used his skill at lens grinding to make about 400 lenses during his lifetime. One of his lenses was able to magnify 270 times. Van Leeuwenhoek made thousands of observations of many kinds of microscopic objects. He also made very detailed sketches of the things he viewed with his simple microscopes and communicated his findings to



(a) (b)

FIGURE 4.1 Hooke's Observations
(a) The concept of a cell has changed considerably over the past 300 years. Robert Hooke's idea of a cell was based on his observation of slices of cork (cell walls of the bark of the cork oak tree). *(b)* Hooke constructed his own simple microscope to be able to make these observations.

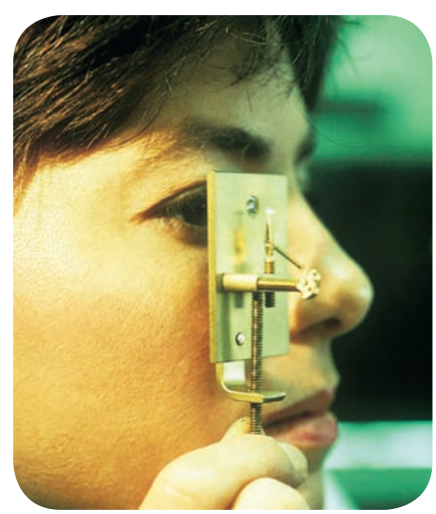


FIGURE 4.2 Anton van Leeuwenhoek's Microscope
Although van Leeuwenhoek's microscope had only one lens, the lens quality was so good that he was able to see cells clearly. This replica of his microscope shows that it is a small, simple apparatus.

Robert Hooke and the Royal Society of London. His work stimulated further investigation of magnification techniques and descriptions of cell structures.

When van Leeuwenhoek discovered that he could see things moving in pond water using his microscope, his curiosity stimulated him to look at a variety of other things. He studied many things such as blood, semen, feces, and pepper, for example. He was the first to see individual cells and recognize them as living units, but he did not call them cells. The name he gave to the "little animals" he saw moving around in the pond water was *animicules*.

Although Hooke, van Leeuwenhoek, and others continued to make observations, nearly 200 years passed before it was generally recognized that all living things are made of cells and that these cells can reproduce themselves. In 1838, Mathias Jakob Schleiden of Germany stated that all plants are made up of smaller cellular units. In 1839, Theodor Schwann, another German, published the idea that all animals are composed of cells.

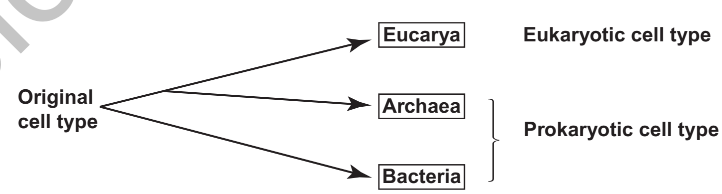
Soon after the term *cell* caught on, it was recognized that the cell wall of plant cells was essentially lifeless and that it was really the contents of the cell that had "life." This living material was termed **protoplasm,** which means *first-formed substance*. Scientists used the term *protoplasm* to distinguish between the living portion of the cell and the nonliving cell wall. As better microscopes were developed, people began to distinguish two different regions of protoplasm. One region, called the *nucleus*, appeared as a central body within a more fluid material surrounding it. Today, we know the **nucleus** is the part of a cell that contains the genetic information. **Cytoplasm** was the name given to the fluid portion of the protoplasm surrounding the nucleus. Although the term *protoplasm* is seldom used today, the term *cytoplasm* is still common.

The development of special staining techniques, better light microscopes, and ultimately powerful electron microscopes revealed that the cytoplasm contains many structures, called **organelles** *(little organs)*. Further research has shown that each kind of organelle has certain functions related to its structure.

Basic Cell Types

All living things are cells or composed of cells, and all cells share three basic traits: They all have an *outer membrane, cytoplasm*, and *genetic material*. However, about 400 years of research has revealed a variety of differences among cells. For example, we know that while all the cells in your body have been derived from one, single, fertilized egg cell, bone cells show structural differences in comparison to brain cells. They not only look different under the microscope, but perform very different metabolically. As scientists studied the cells of even more diverse organisms such as bacteria, plants, animals, fungi, algae, and protozoans, it became clear that there were even greater differences. Some of these differences were structural; others only became evident by doing chemical analysis. As a result of these investigations, biologists have categorized cells into two general types: **eukaryotic** and **prokaryotic (noneukaryotic) cells** (figure 4.3). The cells of plants, animals, fungi, protozoa, and algae are eukaryotic, and are placed in a category called **Eucarya.** All eukaryotic cells have their genetic material surrounded by a nuclear membrane forming the cellular nucleus. They also have a large number and variety of complex organelles, each specialized in the metabolic function it performs. In general, they are large in comparison to noneukaryotic cells. There are two categories of prokaryotic cells: **Bacteria** and **Archaea.** Neither of these cell types has a nuclear membrane; therefore they lack a cellular nucleus. In addition, they display unique chemical and metabolic characteristics but do not have the variety and number of organelles seen in eukaryotes. Bacteria and Archaea are classified into a group referred to as the **Prokaryotes.** From studying a vast amount of data, biologists have tried to understand the evolutionary relationship among these cell types. The previous hypothesized evolutionary relationship among these cell types was:

However, current data points to a different evolutionary pattern:



The fossil record shows evidence of prokaryotes 3.5 billion years ago. Eucarya show up in the fossil record about 1.8 billion years ago.

4.1 CONCEPT REVIEW

1. Describe how the concept of the cell has changed over the past 200 years.
2. What features do all cell types have in common?

4.2 Cell Size

Cells of different kinds vary greatly in size (figure 4.4). In general, the cells of Bacteria and Archaea are much smaller than those of eukaryotic organisms. Prokaryotic cells are typically 1–2 micrometers in diameter, whereas eukaryotic cells are typically 10–100 times larger.

Some basic physical principles determine how large a cell can be. A cell must transport all of its nutrients and all of its wastes through its outer membrane to stay alive. Cells are

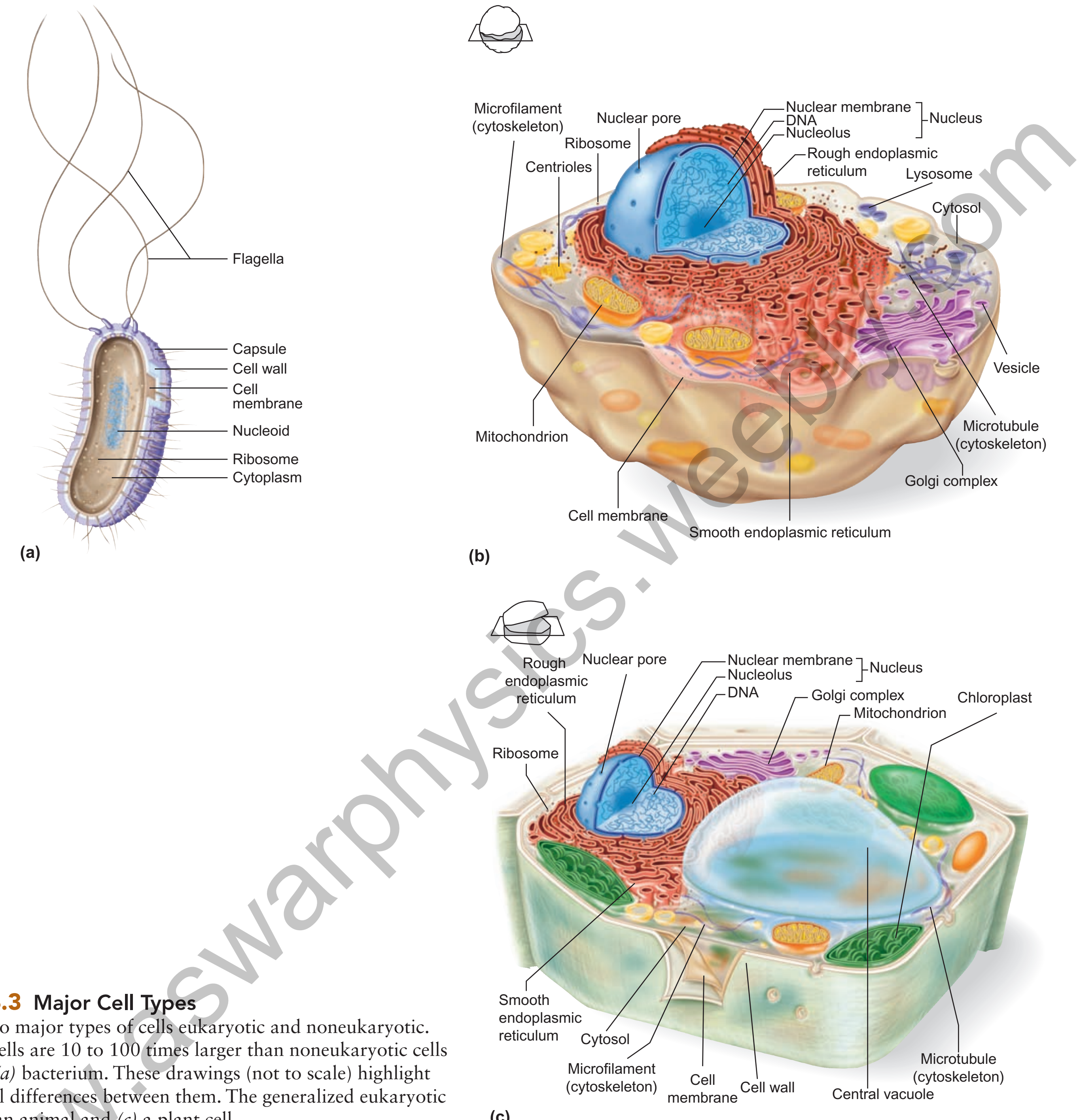


FIGURE 4.3 Major Cell Types
There are two major types of cells eukaryotic and noneukaryotic. Eukaryotic cells are 10 to 100 times larger than noneukaryotic cells such as this *(a)* bacterium. These drawings (not to scale) highlight the structural differences between them. The generalized eukaryotic cells are *(b)* an animal and *(c)* a plant cell.

limited in size because, as a cell becomes larger, adequate transport of materials through the membrane becomes more difficult. The difficulty arises because, as the size of a cell increases, the amount of living material (the cell's volume) increases more quickly than the size of the outer membrane (the cell's surface area). As cells grow, the amount of surface area increases by the square (X^2) but volume increases by the cube (X^3). This mathematical relationship between the surface area and volume is called the *surface area-to-volume ratio* and is shown for a cube in figure 4.5. Notice that, as the cell becomes larger, both surface area and volume increase. Most important, volume increases *more* quickly than surface area, causing the surface area-to-volume ratio to decrease. As the cell's volume increases, the cell's metabolic requirements increase but its ability to satisfy those requirements is limited by the surface area through which the needed materials must pass. Consequently, most cells are very small.

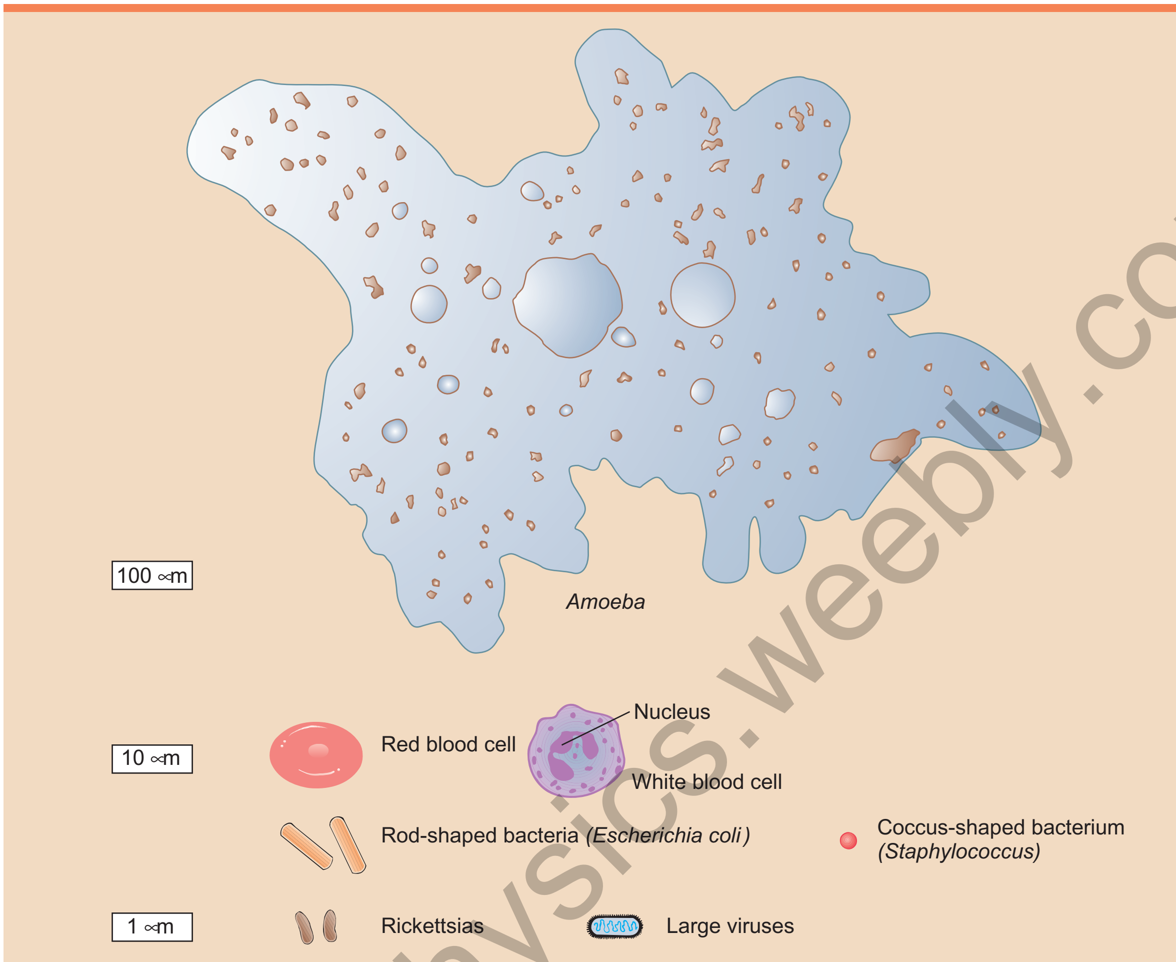


FIGURE 4.4 Comparing Cell Sizes
Most cells are too small to be seen with the naked eye. Bacteria and Archaea cells are generally about 1–2 micrometers in diameter. Eukaryotic cells are much larger and generally range between 10 and 100 micrometers. A micrometer is 1/1,000 of a millimeter. A sheet of paper is about 1/10 of a millimeter thick, which is about 100 micrometers. Therefore, some of the largest eukaryotic cells are just visible to the naked eye.

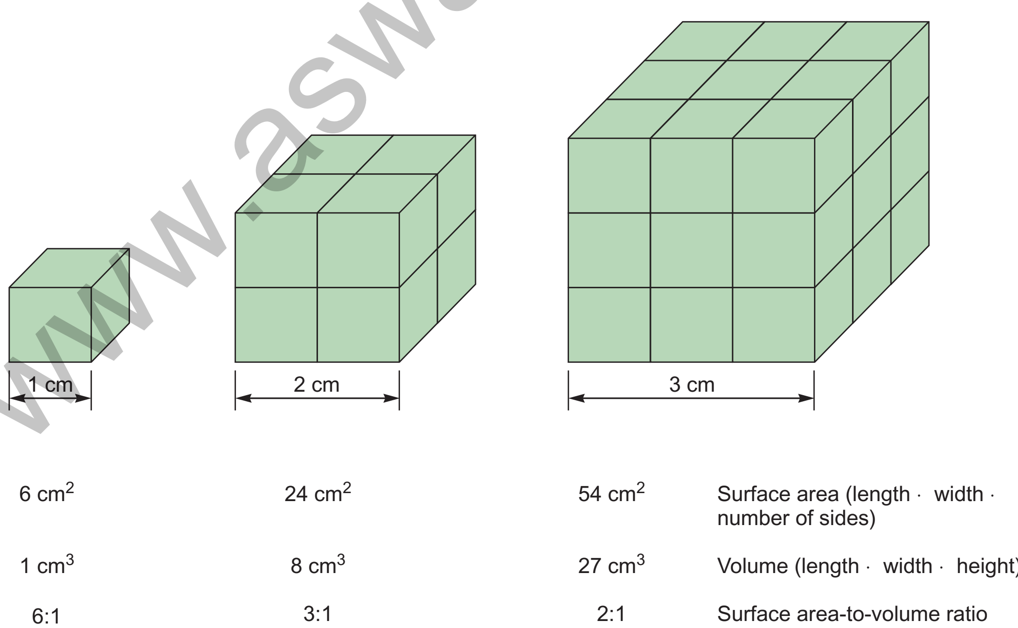


FIGURE 4.5 Surface Area-to-Volume Ratio
As the size of an object increases, its volume increases faster than its surface area. Therefore, the surface area-to-volume ratio decreases.

There are a few exceptions to this general rule, but they are easily explained. For example, what we call the yolk of a chicken's egg cell is a single cell. However, the only part of an egg cell that is metabolically active is a small spot on its surface. The largest portion of the egg cell is simply inactive stored food called *yolk*. Similarly, some plant cells are very large but consist of a large, centrally located region filled with water. Again, the metabolically active portion of the cell is at the surface, where exchange of materials with the surroundings is possible.

4.2 CONCEPT REVIEW

3. On the basis of surface area-to-volume ratio, why do cells tend to remain small?
4. What happens to the surface-to-volume ratio when folds are made in a cell's outer membrane?

4.3 The Structure of Cellular Membranes

One feature common to all cells is the presence of **cellular membranes,** thin sheets composed primarily of phospholipids and proteins. The current model of how cellular membranes are constructed is known as the *fluid-mosaic model.* The **fluid-mosaic model,** considers cellular membranes to consist of two layers of phospholipid molecules and that the individual phospholipid molecules are able to move about within the structure of the membrane (How Science Works 4.1). Many kinds of proteins and some other molecules are found among the phospholipid molecules within the membrane and on the membrane surface. The individual molecules of the membrane remain associated with one another because of the physical interaction of its molecules with its surroundings. The phospholipid molecules of the membrane have two ends, which differ chemically. One end, which contains phosphate, is soluble in water and is therefore called **hydrophilic** (*hydro* = water; *phile* = loving). The other end of the phospholipid molecule consists of fatty acids, which are not soluble in water, and is called **hydrophobic** (*phobia* = fear).

In diagrams, phospholipid molecules are commonly represented as a balloon with two strings (figure 4.6). The balloon represents the water-soluble phosphate portion of the molecule and the two strings represent the 2 fatty acids. Consequently, when phospholipid molecules are placed in water, they form a double-layered sheet, with the water-soluble (hydrophilic) portions of the molecules facing away from each other. This is commonly referred to as a *phospholipid bilayer* (figure 4.7). If phospholipid molecules are shaken in a glass of water, the molecules automatically form double-layered membranes. It is important to understand that the membranes formed are not rigid but, rather, resemble a heavy olive oil in consistency. The component phospholipid molecules are in constant motion as they move with the surrounding water molecules and slide past one another. Other molecules found in cell membranes are cholesterol, proteins, and carbohydrates.

Because cholesterol is not water-soluble, it is found in the middle of the membrane, in the hydrophobic region. It appears to play a role in stabilizing the membrane and keeping it flexible. There are many different proteins associated with the membrane. Some are found on the surface, some are partially submerged in the membrane, and others traverse the

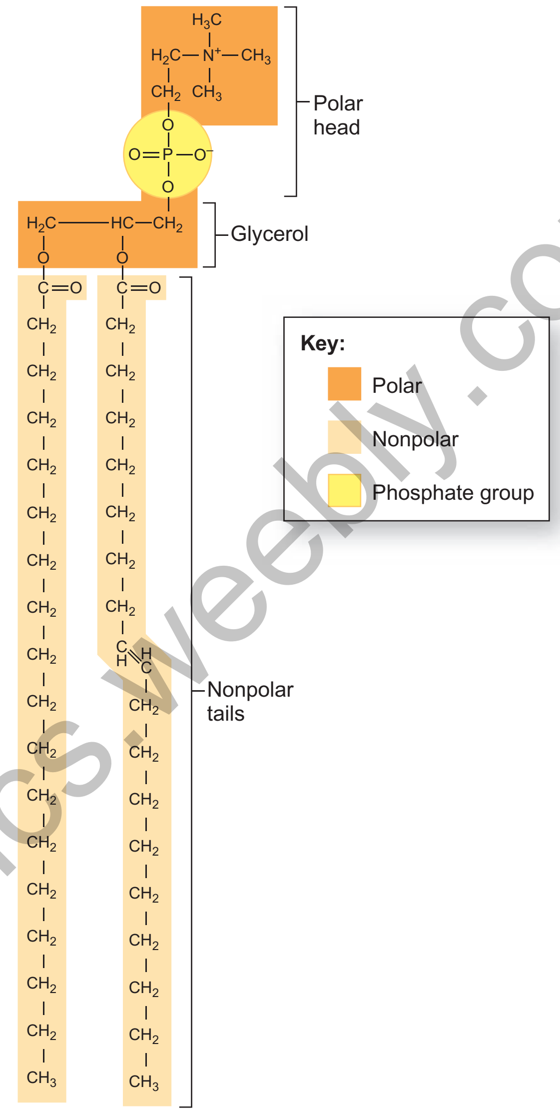


FIGURE 4.6 A Phospholipid Molecule
Phospholipids have a hydrophobic (water-insoluble) portion and a hydrophilic (water-soluble) portion. The hydrophilic portion contains phosphate and is represented as a balloon in many diagrams. The fatty acids are represented as two strings on the balloon.

HOW SCIENCE WORKS 4.1

Developing the Fluid-Mosaic Model

The fluid-mosaic model describes the current understanding of how cellular membranes are organized and function. As is typical during the development of most scientific understandings, the fluid-mosaic model was formed as a result of the analysis of data from many experiments. We will look at three characteristics of cellular membranes and how certain experiments and observations about these characteristics led scientists to develop the fluid-mosaic model.

1. *What is the chemical nature of cellular membranes and how do they provide a barrier between the contents of the cell and the cell's environment?*

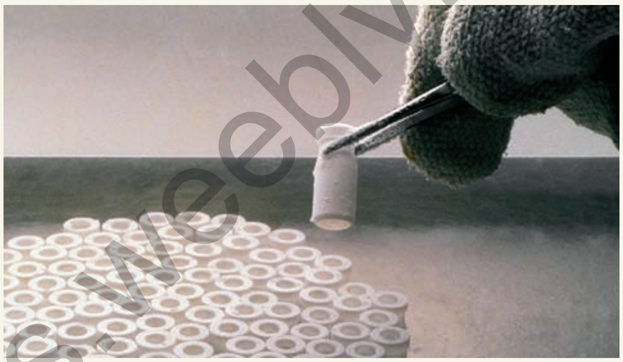
   In 1915, scientists isolated cellular membranes from other cellular materials and chemically determined that they consisted primarily of lipids and proteins. The scientists recognized that, because lipids do not mix with water, a layer of lipid could serve as a barrier between the watery contents of a cell and its watery surroundings.
2. *How are the molecules arranged within the membrane?*

   Nearly 10 years after it became known that cellular membranes consist of lipids and proteins, two scientists reasoned from the chemical properties of lipids and proteins that cellular membranes probably consist of two layers of lipid. This arrangement became known as a bilayer. They were able to make this deduction because they understood the chemical nature of lipids and how they behave in water. But this model did not account for the proteins, which were known to be an important part of cellular membranes because proteins were usually isolated from cellular membranes along with lipids. Also, artificial cellular membranes—made only of lipids—did not have the same chemical properties as living cellular membranes.

   The first model to incorporate proteins into the cellular membrane was incorrect. It was called the sandwich model, because it placed the lipid layers of the cellular membrane between two layers of protein, which were exposed to the cell's watery environment and cytoplasm. Although incorrect, the sandwich model was very popular into the 1960s, because it was supported by images from electron microscopes, which showed two dark lines, with a lighter area between them.

   One of the biggest problems with the sandwich model was that the kinds of proteins isolated from the cellular membrane were strongly hydrophobic. A sandwich model with the proteins on the outside required these hydrophobic proteins to be exposed to water, which would have been an unstable arrangement.

   In 1972, two scientists proposed that the hydrophobic proteins are actually made stable because they are submerged in the hydrophobic portion of the lipid bilayer. This hypothesis was supported by an experimental technique called freeze-fracture.



   Freeze-fracture experiments split a frozen lipid bilayer, so that the surface between the two lipid layers could be examined by electron microscopy. These experiments showed large objects (proteins) sitting in a smooth background (phospholipids), similar to the way nuts are suspended in the chocolate of a flat chocolate bar. These experiments supported the hypothesis that the proteins are not on the surface but, rather, are incorporated into the lipid bilayer.
3. *How do these protein and lipid molecules interact with one another within the cellular membrane?*

   The answer to this question was provided by a series of hybrid-cell experiments. In these experiments, proteins in a mouse cell and proteins in a human cell were labeled differently. The two cells were fused, so that their cellular membranes were connected. At first, one-half of the new hybrid cell contained all mouse proteins. The other half of the new hybrid cell contained all human proteins. However, over several hours, the labeled proteins were seen to mix until the mouse and human proteins were evenly dispersed. Seeing this dispersion demonstrated that molecules in cellular membranes move. Cellular membranes consist of a mosaic of protein and lipid molecules, which move about in a fluid manner.

membrane and protrude from both surfaces. These proteins serve a variety of functions, including:

1. helping transport molecules across the membrane,
2. acting as attachment points for other molecules, and
3. functioning as identity tags for cells.

Carbohydrates are typically attached to the membranes on the outside of cells. They appear to play a role in cell-to-cell interactions and are involved in binding with regulatory molecules.

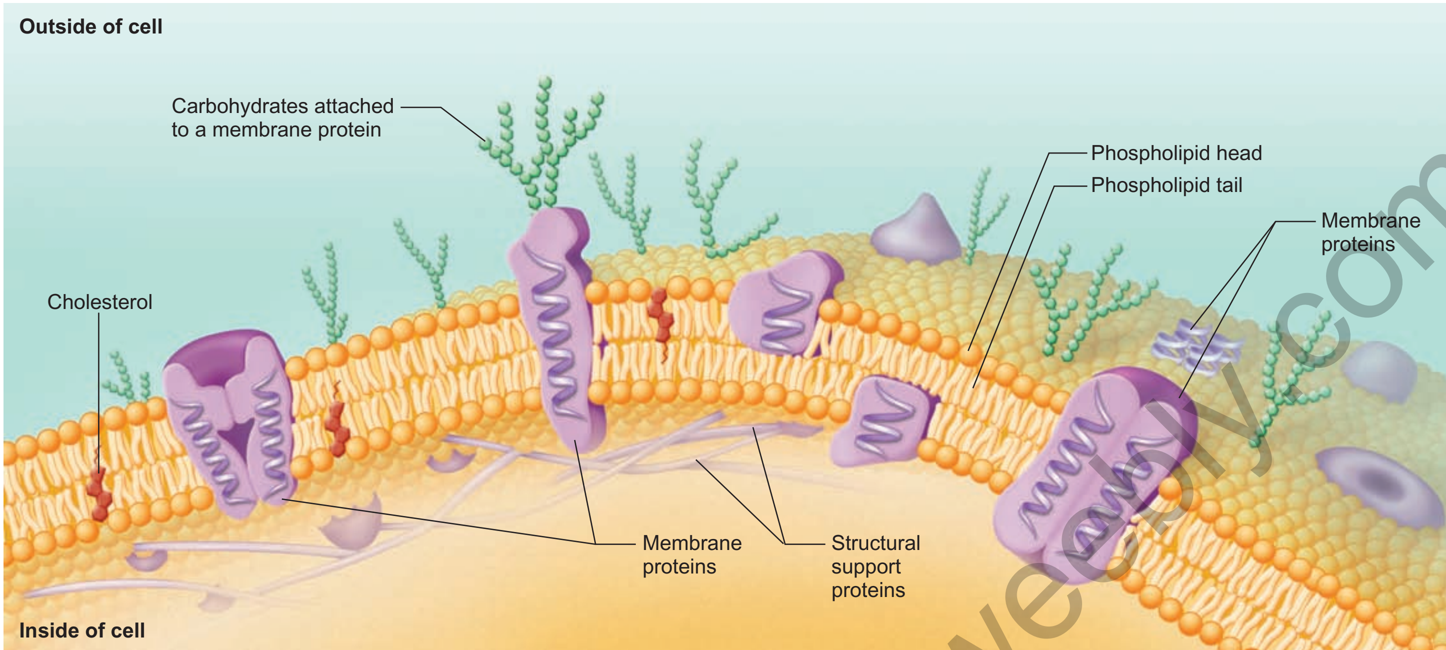


FIGURE 4.7 The Nature of Cellular Membranes
The membranes in all cells are composed primarily of protein and phospholipids. Two layers of phospholipid are oriented so that the hydrophobic fatty acid tails extend toward each other and the hydrophilic phosphate-containing heads are on the outside. Proteins are found buried within the phospholipid layer and are found on both surfaces of the membrane. Cholesterol molecules are also found among the phospholipid molecules. Carbohydrates are often attached to one surface of the membrane.

4.3 CONCEPT REVIEW

5. What are the prime molecules that make up cell membranes?
6. Describe the structure of cellular membranes based on the fluid-mosaic model.

4.4 Organelles Composed of Membranes

Although all cells have membranes, eukaryotic cells have many more organelles composed of membranes than do Bacteria and Archaea. Organelles are involved in specialized metabolic activities, the movement of molecules from one side of the membrane to the other, the identification of molecules, and many other activities. In the following section about the plasma membrane, many of these special properties will be discussed in detail.

Plasma Membrane

The outer limiting boundary of all cells is known as the **plasma membrane,** or **cell membrane.** It is composed of a phospholipid bilayer and serves as a barrier between the cell contents and the external environment. However, it is not just a physical barrier. The plasma membrane has many different functions. In many ways, it acts in a manner analogous to a border between countries, separating but also allowing controlled movement from one side to the other. The plasma membrane performs several important activities.

Metabolic Activities

Because the plasma membrane is part of a living unit, it is metabolically active. Many important chemical reactions take place within the membrane or on its inside or outside surface. Many of these chemical reactions involve transport of molecules.

Movement of Molecules Across the Membrane

Cells must continuously receive nutrients and rid themselves of waste products—one of the characteristics of life. There is constant traffic of molecules from the external *matrix,* or environment, across the plasma membrane. The surrounding matrix is rich in many kinds of important compounds including nutrients, growth factors, and hormones. See section 4.7 for a detailed discussion of the many ways by which molecules enter and leave cells. Many of the proteins that are associated with the plasma membrane are involved in moving molecules across the membrane. Some proteins are capable of moving from one side of the plasma membrane to the other and shuttle certain molecules across the membrane. Others extend from one side of the membrane to the other and form channels through which substances can travel. Some of these channels operate like border checkpoints, which open and close when circumstances dictate. Some molecules pass through the membrane passively, whereas others are assisted by metabolic activities within the membrane.

Inside and Outside

The inside of the plasma membrane is different from its outside. The carbohydrates that are associated with the plasma membrane are usually found on the outside of the membrane, where they are bound to proteins or lipids. Many important activities take place on only one of the surfaces of the plasma membrane because of the way the two sides differ.

Identification

The outside surface of the plasma membrane has many proteins, which act as recognition molecules. Each organism has a unique combination of these molecules. Thus, the presence of these molecules enables one cell or one organism to recognize cells that are like it and those that are different. For example, if a disease organism enters your body, the cells of your immune system use the proteins on the invader's surface to identify it as being foreign. Immune system cells can then destroy the invader (How Science Works 4.2).

Attachment Sites

Some molecules on the outside surface of the plasma membrane serve as attachment sites for specific chemicals, bacteria, protozoa, white blood cells, and viruses. Many dangerous agents cannot stick to the surface of cells and therefore do not cause harm. For this reason, cell biologists explore the exact structure and function of these cell surface molecules. They are also attempting to identify molecules that can interfere with the binding of viruses and bacteria to cells in the hope of controlling infections. For example, human immunodeficiency virus (HIV) attaches to specific molecules on the surface of certain immune system cells and nerve cells. If these attachment sites could be masked, the virus would not be able to attach to the cells and cause disease. Drugs that function this way are called "blockers."

Signal Transduction

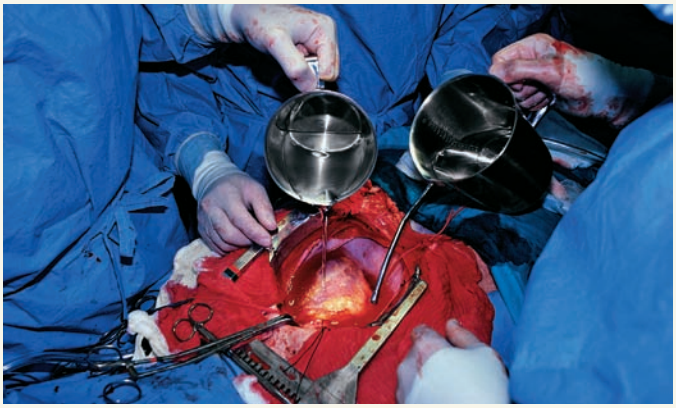
Another way in which attachment sites are important is in signal transduction. **Signal transduction** is the process by which cells detect specific signals from the surrounding intercellular matrix and transmit these signals to the cell's interior. These signals can be physical (electrical or heat) or chemical. Some chemicals are capable of passing directly through the membrane of specific target cells. Once inside, they can pass on their message to regulator proteins. These proteins then enter into chemical reactions, which result in a change in the cell's behavior. For example, estrogen produced in one part of the body travels through the bloodstream and passes through the tissue to make direct contact with specific target cells. Once the hormone passes through the plasma membrane of the target cells, the message is communicated to begin the process of female sex organ development. This is like a person smelling the cologne of his or her date through a curtain. The aroma molecules pass through the curtain to the person's nose and stimulate a response.

However, most signal molecules are not capable of entering cells in such a direct manner but remain in the external environment (i.e., outside their target cells). When they arrive at the cell, they attach to a receptor site molecule embedded in the membrane. The signal molecule is often

HOW SCIENCE WORKS 4.2

Cell Membrane Structure and Tissue Transplants

In humans, there is a group of protein molecules, collectively known as *histocompatibility antigens* (*histo* = tissue), that are located on the cell surface. Each person has a specific combination of these proteins. It is the presence of these antigens that is responsible for the rejection of transplanted tissues or organs from donors that are "incompatible." In large part, a person's pattern of histocompatibility antigens is hereditary; for instance, in identical twins, the cells of both individuals have a very high percentage of similar proteins. Therefore, in transplant situations, the cells of the immune system would see the cells of the donor twin to be the same as those on the cell surfaces of the recipient twin. When closely related donors are not available, physicians try to find donors whose histocompatability antigens are as similar as possible to those of recipients.



called the *primary messenger.* The receptor–signal molecule combination initiates a sequence of events within the membrane that transmits information through the membrane to the interior, generating internal signal molecules, called *secondary messengers*.

The secondary messengers are molecules or ions that begin a cascade of chemical reactions causing the target cell to change how it functions (figure 4.8). This is like your mother sending your little brother to tell you it is time for dinner. Your mother provides the primary message, your little brother provides the secondary message, and you respond by going home. In a cell, such signal transduction results in a change in the cell's chemical activity. Often, this is accomplished by turning genes on or off. For example, when a signal molecule called *epidermal growth factor (EGF)* attaches to the receptor protein of skin cells, it triggers a chain of events inside the plasma membrane of the cells. These changes within the plasma membrane produce secondary messengers, ultimately leading to gene action, which in turn causes cell growth and division.

Endoplasmic Reticulum

There are many other organelles in addition to the plasma membrane, that are composed of membranes. Each of these membranous organelles has a unique shape or structure associated with its particular functions. One of the most common organelles found in cells, the **endoplasmic reticulum (ER)**, consists of folded membranes and tubes throughout the cell (figure 4.9). This system of membranes provides a large surface on which chemical activities take place. Because the ER has an enormous surface area, many chemical reactions can be carried out in an extremely small space. Picture the vast surface area of a piece of newspaper crumpled into a tight little ball. The surface contains hundreds of thousands of tidbits of information in an orderly arrangement, yet it is packed into a very small volume.

Proteins on the surface of the ER are actively involved in controlling and encouraging chemical activities—whether they are reactions involving cell growth and development or reactions resulting in the accumulation of molecules from the environment. The arrangement of the proteins allows them to control the sequences of metabolic activities, so that chemical reactions can be carried out very rapidly and accurately.

On close examination with an electron microscope, it is apparent that there are two types of ER—rough and smooth. The rough ER appears rough because it has *ribosomes* attached to its surface. **Ribosomes** are nonmembranous organelles that are associated with the synthesis of proteins from amino acids. They are "protein-manufacturing machines." Therefore, cells with an extensive amount of rough ER—for example, human pancreas cells—are capable of synthesizing large quantities of proteins. Smooth ER lacks attached ribosomes but is the site of many other important cellular chemical activities. Fat metabolism and detoxification reactions involved in the destruction of toxic substances, such as alcohol and drugs occur on this surface. Human liver cells are responsible for detoxification reactions and contain extensive smooth ER.

In addition, the spaces between the folded membranes serve as canals for the movement of molecules within the cell. This system of membranes allows for the rapid distribution of molecules within a cell.

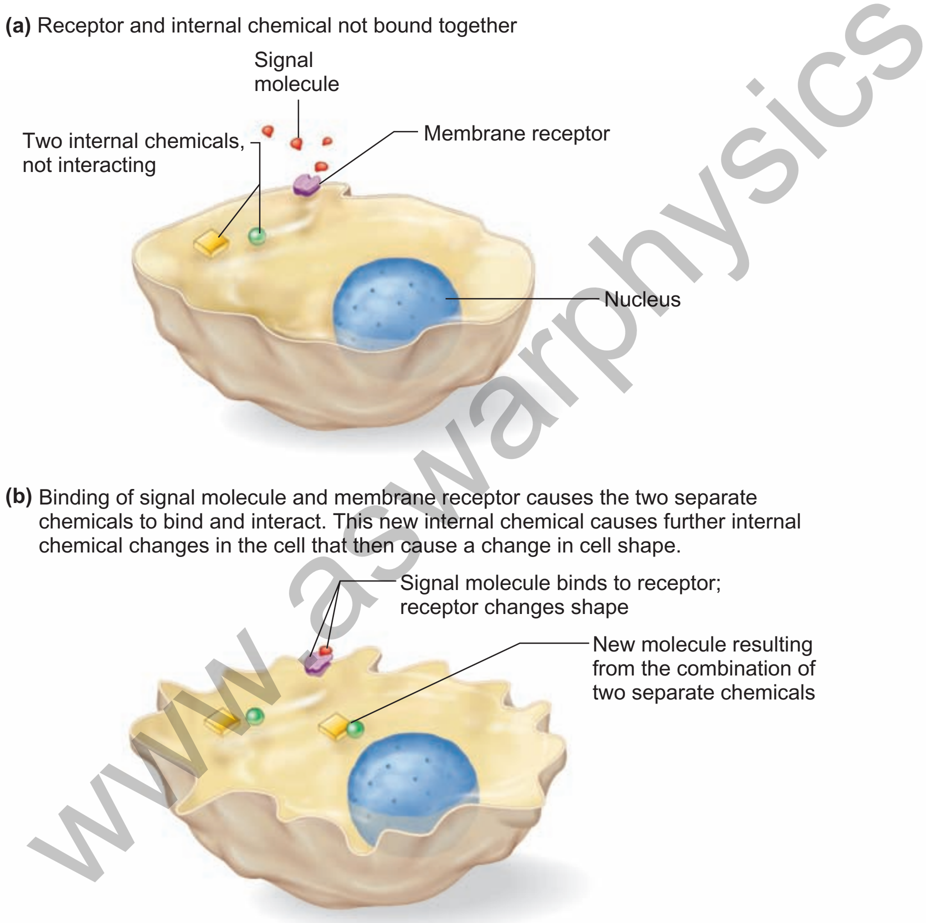


FIGURE 4.8 Signal Transduction and Secondary Messengers
Signal transduction results in chemical changes within the cell and is the result of cell membrane receptors binding with signal molecules from outside the cell. Secondary messengers inside the cell then communicate this information to appropriate molecules, sometimes to DNA.

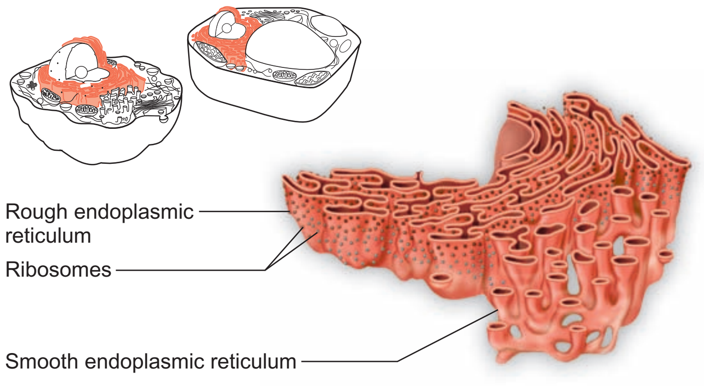


FIGURE 4.9 Endoplasmic Reticulum
The endoplasmic reticulum consists of folded membranes located throughout the cytoplasm of the cell. Some endoplasmic reticulum has ribosomes attached and appears rough. Many kinds of molecules are manufactured on the surfaces of endoplasmic reticulum.

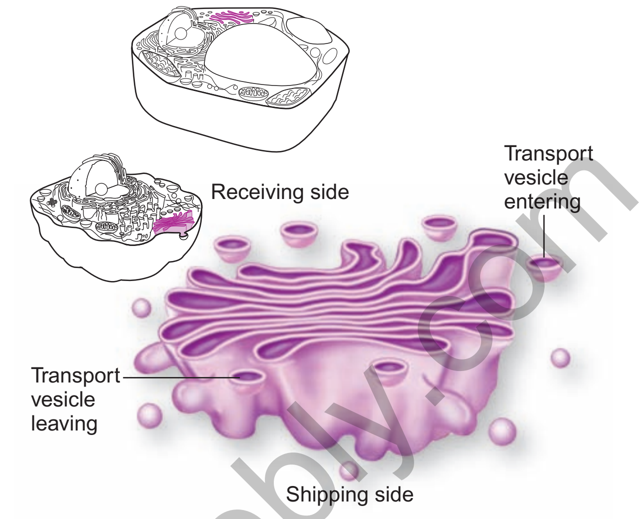


FIGURE 4.10 Golgi Apparatus
The Golgi apparatus is a series of membranous sacs that accept packages of materials and produce vesicles containing specific molecules. Some packages of materials are transported to other parts of the cell. Others are transported to the plasma membrane and release their contents to the exterior of the cell.

Golgi Apparatus

Another organelle composed of membrane is the **Golgi apparatus.** Animal cells contain several such structures and plant cells contain hundreds. The typical Golgi apparatus consists of 5 to 20 flattened, smooth membranous sacs, which resemble a stack of flattened balloons (figure 4.10). The Golgi apparatus has several functions:

1. it modifies molecules shipped to it from elsewhere in the cell,
2. it manufactures some polysaccharides and lipids, and
3. it packages molecules within sacs.

There is a constant traffic of molecules through the Golgi apparatus. Tiny, membranous sacs called *vesicles* deliver molecules to one surface of the Golgi apparatus. Many of these vesicles are formed by the endoplasmic reticulum and contain proteins. These vesicles combine with the sacs of the Golgi apparatus and release their contents into it. Many kinds of chemical reactions take place within the Golgi apparatus. Ultimately, new sacs, containing "finished products," are produced from the surface of the Golgi apparatus.

The Golgi apparatus produces many kinds of vesicles. Each has a different function. Some are transported within the cell and combine with other membrane structures, such as the endoplasmic reticulum. Some migrate to the plasma membrane and combine with it. These vesicles release molecules such as mucus, cellulose, glycoproteins, insulin, and enzymes to the outside of the cell. In plant cells, cellulose-containing vesicles are involved in producing new cell wall material. Finally, some of the vesicles produced by the Golgi apparatus contain enzymes that can break down the various molecules of the cell, causing its destruction. These vesicles are known as *lysosomes.*

Lysosomes

Lysosomes are tiny vesicles that contain enzymes capable of digesting carbohydrates, nucleic acids, proteins, and lipids. Because cells are composed of these molecules, these enzymes must be controlled in order to prevent the destruction of the cell. This control is accomplished very simply. The enzymes of lysosomes function best at a pH of about 5. The membrane, which is the outer covering of the lysosome, transports hydrogen ions into the lysosome and creates the acidic conditions these enzymes need. Since the pH of a cell is generally about 7, these enzymes will not function if released into the cell cytoplasm.

The functions of lysosomes are basically digestion and destruction. For example, in many kinds of protozoa, such as *Paramecium* and *Amoeba,* food is taken into the cell in the form of a membrane-enclosed food vacuole. Lysosomes combine with food vacuoles and break down the food particles into smaller molecules, which the cell can use.

In a similar fashion, lysosomes destroy disease-causing microorganisms, such as bacteria, viruses, and fungi. The microorganisms become surrounded by membranes from the endoplasmic reticulum. Lysosomes combine with the membranes surrounding these invaders and destroy them. This kind of activity is common in white blood cells that engulf and destroy disease-causing organisms.

Lysosomes are also involved in the breakdown of worn-out cell organelles by fusing with them and destroying them (figure 4.11).

Peroxisomes

Another organelle that consists of many kinds of enzymes surrounded by a membrane is the *peroxisome.* **Peroxisomes** were first identified by the presence of an enzyme, catalase, that breaks down hydrogen peroxide (H_2O_2). Peroxisomes

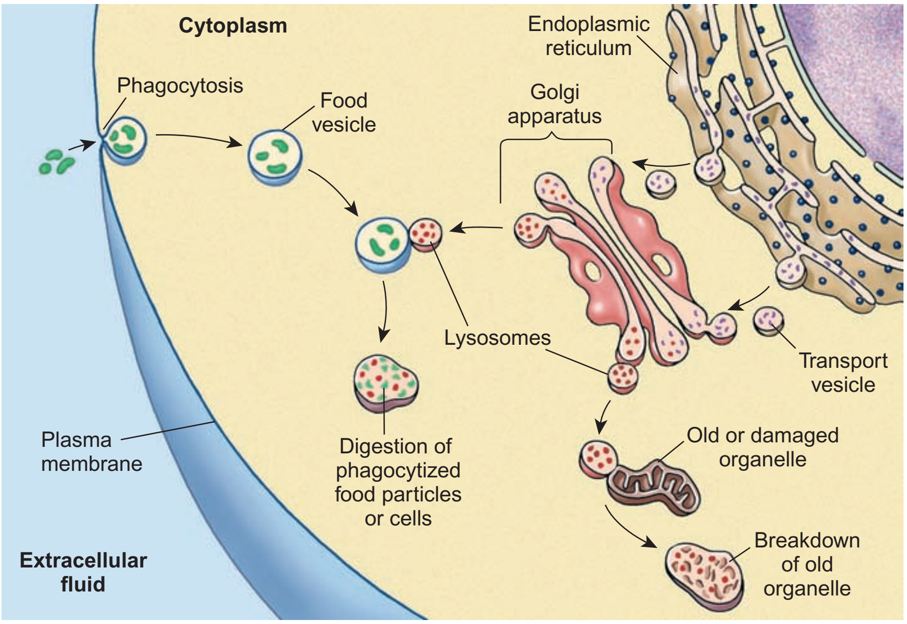


FIGURE 4.11 Lysosome Function
Lysosomes contain enzymes that are capable of digesting many kinds of materials. They are involved in the digestion of food vacuoles, harmful organisms, and damaged organelles.

differ from lysosomes in that peroxisomes are not formed by the Golgi apparatus and they contain different enzymes. It appears that the membrane surrounding peroxisomes is formed from the endoplasmic reticulum and the enzymes are imported into this saclike container. The enzymes of peroxisomes have been shown to be important in many kinds of chemical reactions. These include the breakdown of long-chain fatty acids, the synthesis of cholesterol, and the synthesis of plasma membrane lipids used in nerve cells.

Vacuoles and Vesicles

There are many kinds of membrane-enclosed containers in cells known as *vacuoles* and *vesicles*. **Vacuoles** are the larger structures and **vesicles** are the smaller ones. They are frequently described by their function. In most plants, there is one huge, centrally located, water-filled vacuole. Many kinds of protozoa have specialized water vacuoles called *contractile vacuoles* which are able to forcefully expel excess water that has accumulated in the cytoplasm. The contractile vacuole is a necessary organelle in cells that live (figure 4.12) in freshwater because water constantly diffuses into the cell. Animal cells typically have many small vacuoles and vesicles throughout the cytoplasm.

Nuclear Membrane

Just as a room is a place created by walls, a floor, and a ceiling, a cell's nucleus is a place created by the **nuclear membrane.** If the nuclear membrane were not formed around the cell's genetic material, the organelle called the cellular nucleus would not exist. This membrane separates the genetic material (DNA) from the cytoplasm. Because they are separated, the cytoplasm and the nuclear contents can maintain different chemical compositions. The nuclear membrane is composed

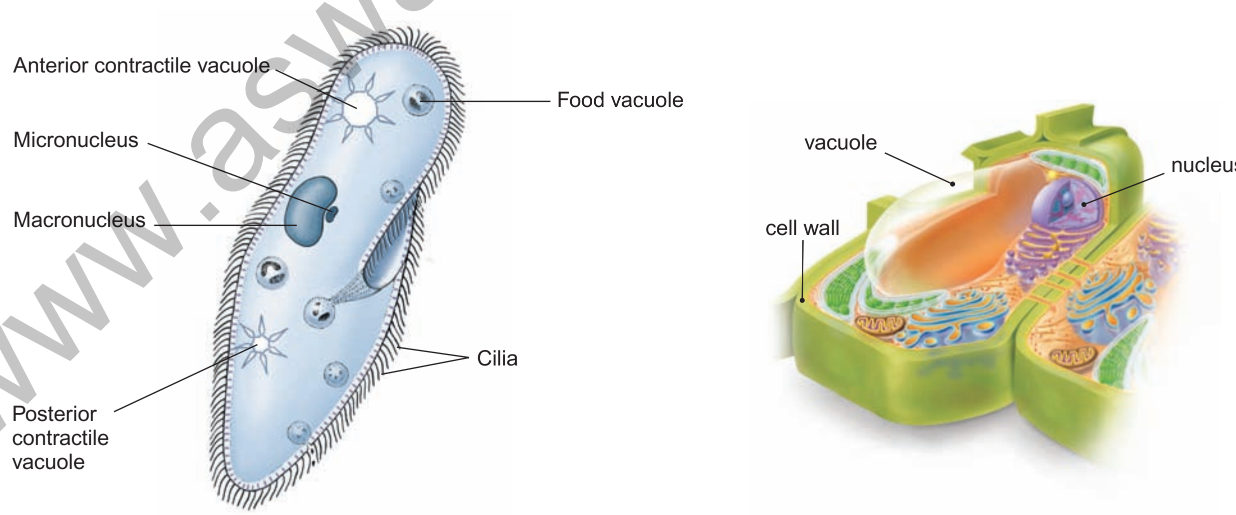


FIGURE 4.12 Vacuoles
Vacuoles are membrane-enclosed sacs that contain a variety of materials. Often, in many kinds of protozoa, food is found inside vacuoles. Plant cells have a large central vacuole filled with water. Some freshwater organisms have contractile vacuoles that expel water from the cell.

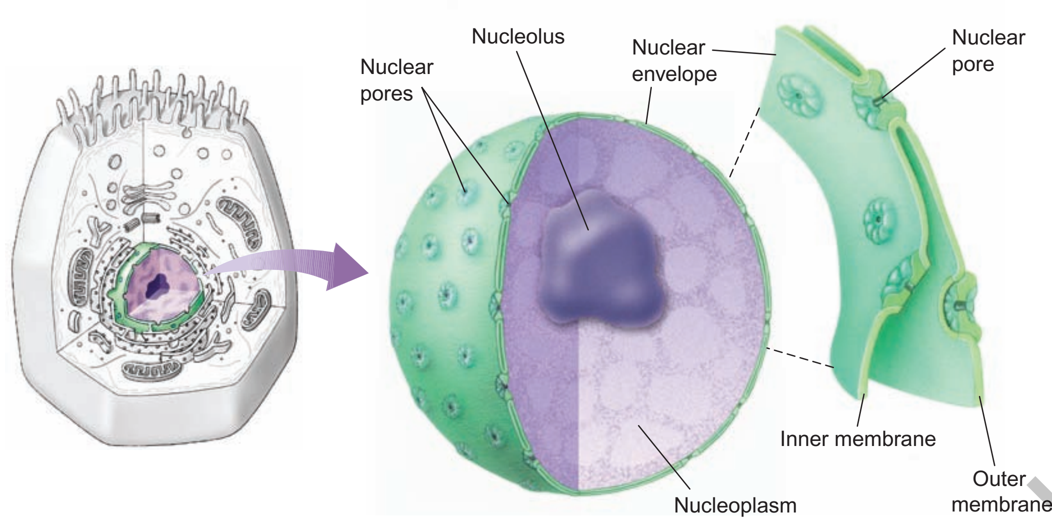


FIGURE 4.13 Nuclear Membrane
The nuclear membrane is a double membrane separating the nuclear contents from the cytoplasm. Pores in the nuclear membrane allow molecules as large as proteins to pass through.

of two layers and has openings called *nuclear pore complexes* (figure 4.13). The nuclear pore complexes consist of proteins, which collectively form barrel-shaped pores. These pores allow relatively large molecules, such as RNA, to pass through the nuclear membrane. Thousands of molecules move in and out through these pores each second.

The Endomembrane System—Interconversion of Membranes

It is important to remember that all membranous structures in cells are composed of two layers of phospholipid with associated proteins and other molecules. Furthermore, all of these membranous organelles can be converted from one form to another (figure 4.14). For example, the plasma membrane is continuous with the endoplasmic reticulum; as a cell becomes larger, some of the endoplasmic reticulum moves to the surface to become plasma membrane. Similarly, the nuclear membrane is connected to the endoplasmic reticulum. Remember also that the Golgi apparatus receives membrane-enclosed packages from the endoplasmic reticulum and produces lysosomes that combine with other membrane-enclosed structures and secretory vesicles that fuse with the plasma membrane. Thus, this entire set of membranes is constantly swapping pieces.

Energy Converters—Mitochondria and Chloroplasts

Two other organelles composed of membranes are *mitochondria* and *chloroplasts*. Both types of organelles are associated with energy conversion reactions in the cell. Mitochondria and chloroplasts are different from other kinds of membranous structures in four ways. First, their membranes are chemically different from those of other membranous organelles; second, they are composed of two layers of membrane—an inner and an outer membrane; third, both of these structures have ribosomes and DNA that are similar to those of bacteria; fourth, these two structures have a certain degree of independence from the rest of the cell—they have a limited ability to reproduce themselves but must rely on DNA from the cell nucleus for assistance. It is important to understand that cells cannot make mitochondria or chloroplasts by themselves. The DNA of the organelle is necessary for their reproduction.

Mitochondrion

The **mitochondrion** is an organelle that contains the enzymes responsible for aerobic cellular respiration. It consists of an outer membrane and an inner folded membrane. The individual folds of the inner membrane are known as **cristae** (figure 4.15a). **Aerobic cellular respiration** is the series of enzyme-controlled reactions involved in the release of energy from food molecules and requires the participation of oxygen molecules.

$$\begin{pmatrix}\text{Food} \\ \text{molecules}\end{pmatrix} + \text{Oxygen} \rightarrow \begin{matrix}\text{Carbon} \\ \text{dioxide}\end{matrix} + \text{Water} + \begin{pmatrix}\text{Energy for} \\ \text{cell activity}\end{pmatrix}$$

Some of the enzymes responsible for these reactions are dissolved in the fluid inside the mitochondrion and are made using DNA in the mitochondria (mDNA). Others are incorporated into the structure of the membranes and are arranged in an orderly sequence.

The number of mitochondria per cell varies from less than 10 to over 1,000 depending on the kind of cell. Cells involved in activities that require large amounts of energy, such as muscle cells, contain the most mitochondria. When cells are functioning aerobically, the mitochondria swell with activity. When this activity diminishes, though, they shrink and appear as threadlike structures. The details of the reactions involved in aerobic cellular respiration and their relationship to the structure of mitochondria will be discussed in chapter 6.

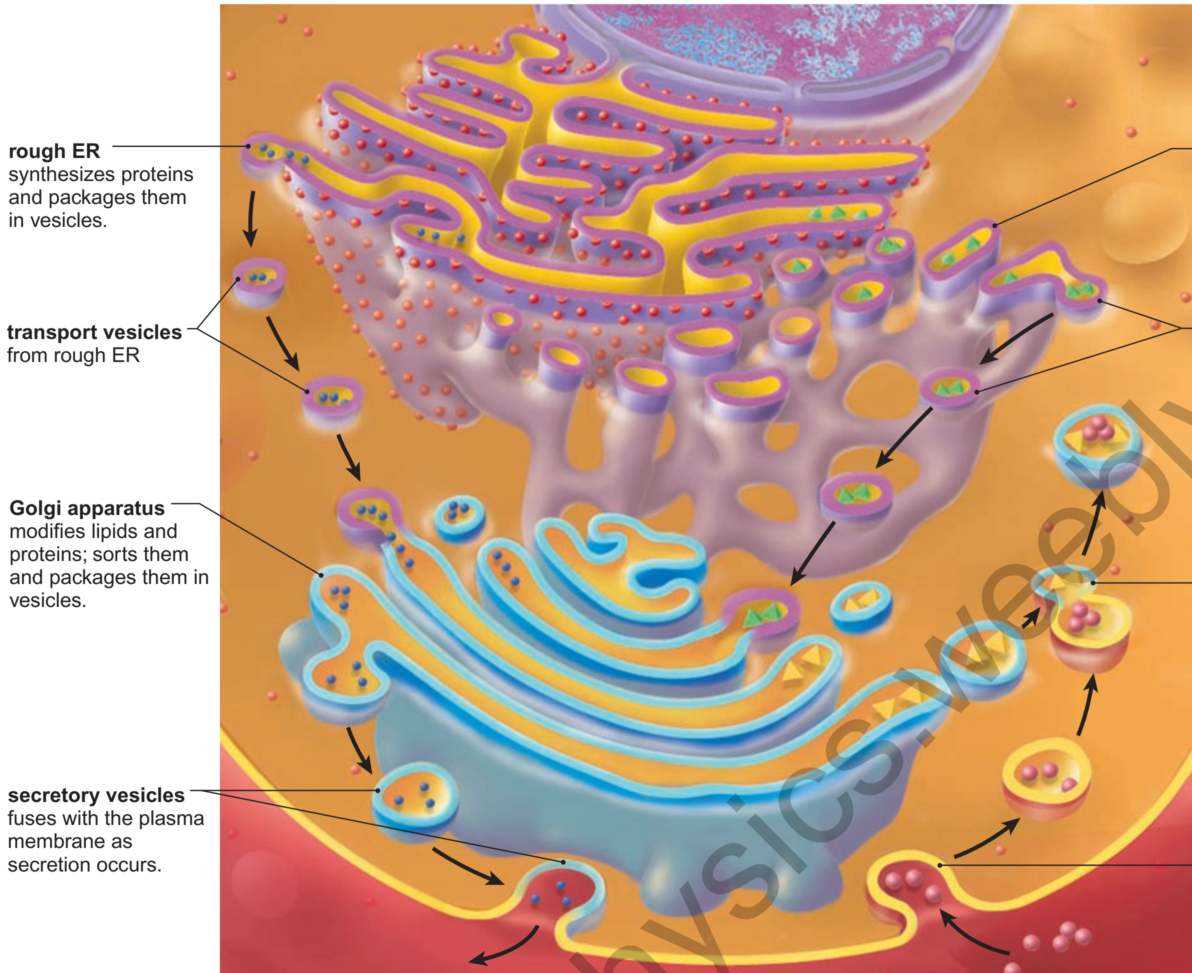


FIGURE 4.14 **The Endomembrane System**
Eukaryotic cells contain a variety of organelles composed of membranes that consist of two layers of phospholipids and associated proteins. Each organelle has a unique shape and function. Many of these organelles are interconverted from one to another as they perform their essential functions.

Chloroplast

The **chloroplast** is a membranous saclike organelle responsible for the process of photosynthesis. Chloroplasts contain the green pigment, **chlorophyll**, and are found in cells of plants and other eukaryotic organisms that carry out photosynthesis. The cells of some organisms contain one large chloroplast; others contain hundreds of smaller chloroplasts. **Photosynthesis** is a metabolic process in which light energy is converted to chemical bond energy. Chemical-bond energy is found in food molecules.

$$\left(\begin{matrix}\text{Carbon}\\ \text{dioxide}\end{matrix} + \text{Water} + \begin{matrix}\text{Light}\\ \text{energy}\end{matrix} \rightarrow \begin{matrix}\text{Organic}\\ \text{molecules}\end{matrix} + \text{Oxygen}\right)$$

A study of the ultrastructure—that is, the structures seen with an electron microscope—of a chloroplast shows that the entire organelle is enclosed by a membrane. Inside are other membranes throughout the chloroplast, forming networks and structures of folded membrane. As shown in figure 4.15b, in some areas, these membranes are stacked up or folded back on themselves. Chlorophyll molecules are attached to these membranes and are called **thylakoids.** Thylakoids that are stacked on top of one another form the **grana** of the chloroplast. The space between the grana, which has no chlorophyll, is known as the **stroma.** The details of how photosynthesis occurs and how this process is associated with the structure of the chloroplast will be discussed in chapter 7.

4.4 CONCEPT REVIEW

7. List the membranous organelles of a eukaryotic cell and describe the functions of each.
8. Define the following terms: stroma, grana, cristae.
9. Describe the functions of the plasma membrane.