

did you know?

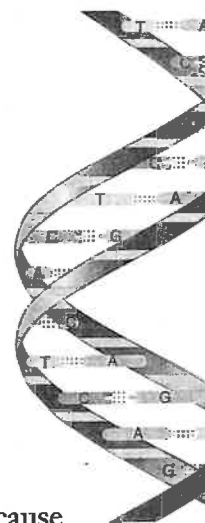
**H**ow often have you heard people talk about dietary fat? You have probably heard many debates regarding the health benefits of monounsaturated and polyunsaturated versus saturated fats (fatty acids). The chemistry of fatty acids is responsible for the physiological roles they play. A great deal of research has focused on the behavior of the various kinds of fatty acids in the body. At one time many scientists thought that total fat intake should be kept low to prevent heart disease. Now scientists believe that certain types of unsaturated fatty acids, such as those found in fish oils, may actually reduce heart disease risk.



Focus on Wellness, page 36

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**M**any common substances we eat and drink—water, sugar, table salt, proteins, starches, fats—play vital roles in keeping us alive. In this chapter, you will learn how these substances function in your body. Because your body is composed of chemicals and all body activities are chemical in nature, it is important to become familiar with the language and basic ideas of chemistry to understand human anatomy and physiology.



looking back to move ahead . . .

• Levels of Organization and Body Systems (p. 2)

# INTRODUCTION TO CHEMISTRY

**OBJECTIVES** • Define a chemical element, atom, ion, molecule, and compound.

- Explain how chemical bonds form.
- Describe what happens in a chemical reaction and explain why it is important to the human body.

**Chemistry** (KEM-is-trē) is the science of the structure and interactions of *matter*, which is anything that occupies space and has mass. *Mass* is the amount of matter in any living organism or nonliving thing.

## Chemical Elements and Atoms

All forms of matter are made up of a limited number of building blocks called *chemical elements*, substances that cannot be broken down into a simpler form by ordinary chemical means. At present, scientists recognize 112 different elements. Each element is designated by a *chemical symbol*, one or two letters of the element's name in English, Latin, or

another language. Examples are H for hydrogen, C for carbon, O for oxygen, N for nitrogen, K for potassium, Na for sodium, Fe for iron, and Ca for calcium.

Twenty-six different elements normally are present in your body. Just four elements, called the *major elements*, constitute about 96% of the body's mass: oxygen, carbon, hydrogen, and nitrogen. Eight others, the *lesser elements*, contribute 3.8% of the body's mass: calcium (Ca), phosphorus (P), potassium (K), sulfur (S), sodium (Na), chlorine (Cl), magnesium (Mg), and iron (Fe). An additional 14 elements, the *trace elements*—are present in tiny amounts. Together they account for the remaining 0.2% of the body's mass. Several trace elements have important functions in the body. For example, iodine (I) is needed to make thyroid hormones. The functions of some trace elements are unknown. Table 2.1 lists the main chemical elements of the human body.

Each element is made up of *atoms*, the smallest units of matter that retain the properties and characteristics of the element. A sample of the element carbon, such as pure carbon, contains only carbon atoms, and a tank of helium gas contains only helium atoms.

Table 2.1 Main Chemical Elements in the Body




Chemical Element (Symbol)	% of Total Body Mass	Significance
<b>MAJOR ELEMENTS</b>		
Oxygen (O)	65.0	Part of water and many organic (carbon-containing) molecules; used to generate ATP, a molecule used by cells to temporarily store chemical energy.
Carbon (C)	18.5	Forms backbone chains and rings of all organic molecules: carbohydrates, lipids (fats), proteins, and nucleic acids (DNA and RNA).
Hydrogen (H)	9.5	Constituent of water and most organic molecules; ionized form ( $H^+$ ) makes body fluids more acidic.
Nitrogen (N)	3.2	Component of all proteins and nucleic acids.
<b>LESSER ELEMENTS</b>		
Calcium (Ca)	1.5	Contributes to hardness of bones and teeth; ionized form ( $Ca^{2+}$ ) needed for blood clotting, release of hormones, contraction of muscle, and many other processes.
Phosphorus (P)	1.0	Component of nucleic acids and ATP; required for normal bone and tooth structure.
Potassium (K)	0.35	Ionized form ( $K^+$ ) is the most plentiful cation (positively charged particle) in intracellular fluid; needed to generate action potentials.
Sulfur (S)	0.25	Component of some vitamins and many proteins.
Sodium (Na)	0.2	Ionized form ( $Na^+$ ) is the most plentiful cation in extracellular fluid; essential for maintaining water balance; needed to generate action potentials.
Chlorine (Cl)	0.2	Ionized form ( $Cl^-$ ) is the most plentiful anion (negatively charged particle) in extracellular fluid; essential for maintaining water balance.
Magnesium (Mg)	0.1	Ionized form ( $Mg^{2+}$ ) needed for action of many enzymes, molecules that increase the rate of chemical reactions in organisms.
Iron (Fe)	0.005	Ionized forms ( $Fe^{2+}$ and $Fe^{3+}$ ) are part of hemoglobin (oxygen-carrying protein in red blood cells) and some enzymes (proteins that catalyze chemical reactions in living cells).
<b>TRACE ELEMENTS</b>		
	0.2	Aluminum (Al), Boron (B), Chromium (Cr), Cobalt (Co), Copper (Cu), Fluorine (F), Iodine (I), Manganese (Mn), Molybdenum (Mo), Selenium (Se), Silicon (Si), Tin (Sn), Vanadium (V), and Zinc (Zn).

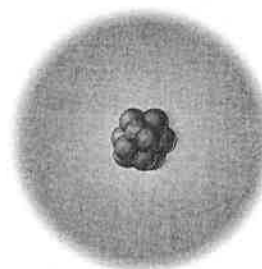
**Figure 2.1** Two representations of the structure of an atom.

Electrons move about the nucleus, which contains neutrons and protons. (a) In the electron cloud model of an atom, the shading represents the chance of finding an electron in regions outside the nucleus. (b) In the electron shell model, filled circles represent individual electrons, which are grouped into concentric circles according to the shells they occupy. Both models depict a carbon atom, with six protons, six neutrons, and six electrons.

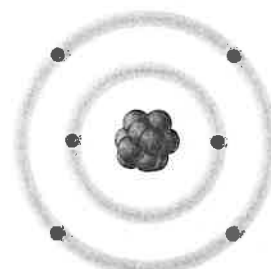


An atom is the smallest unit of matter that retains the properties and characteristics of its element.

-  Protons ( $p^+$ )
  -  Neutrons ( $n^0$ )
  -  Electrons ( $e^-$ )
- } Nucleus



(a) Electron cloud model



(b) Electron shell model



What is the atomic number of carbon?

An atom consists of two basic parts: a nucleus and one or more electrons (Figure 2.1). The centrally located **nucleus** contains positively charged **protons** ( $p^+$ ) and uncharged (neutral) **neutrons** ( $n^0$ ). Because each proton has one positive charge, the nucleus is positively charged. The **electrons** ( $e^-$ ) are tiny, negatively charged particles that move about in a large space surrounding the nucleus. They do not follow a fixed path or orbit but instead form a negatively charged “cloud” that surrounds the nucleus (Figure 2.1a). The number of electrons in an atom equals the number of protons. Because each electron carries one negative charge, the negatively charged electrons and the positively charged protons balance each other. As a result, each atom is electrically neutral, meaning its total charge is zero.

The number of protons in the nucleus of an atom is called the atom's **atomic number**. The atoms of each differ-

ent kind of element have a different number of protons in the nucleus: A hydrogen atom has 1 proton, a carbon atom has 6 protons, a sodium atom has 11 protons, a chlorine atom has 17 protons, and so on (Figure 2.2). Thus, each type of atom or element, has a different atomic number. The total number

**Figure 2.2** Atomic structures of several atoms that have important roles in the human body.

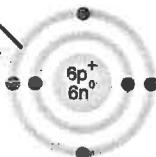
The atoms of different elements have different atomic numbers because they have different numbers of protons.

First  
electron  
shell



**Hydrogen (H)**  
Atomic number = 1  
Mass number = 1

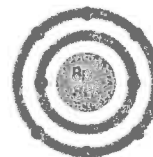
Second  
electron  
shell



**Carbon (C)**  
Atomic number = 6  
Mass number = 12

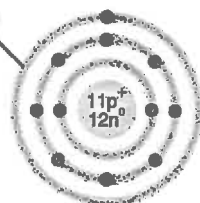


**Nitrogen (N)**  
Atomic number = 7  
Mass number = 14

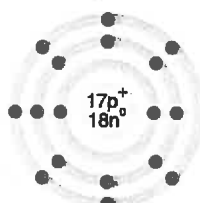


**Oxygen (O)**  
Atomic number = 8  
Mass number = 16

Third  
electron  
shell

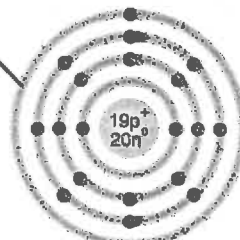


**Sodium (Na)**  
Atomic number = 11  
Mass number = 23



**Chlorine (Cl)**  
Atomic number = 17  
Mass number = 35

Fourth  
electron  
shell



**Potassium (K)**  
Atomic number = 19  
Mass number = 39

**Atomic number** = number of protons in an atom  
**Mass number** = number of protons and neutrons in an atom



Which four of these elements are most abundant in living organisms?

of protons plus neutrons in an atom is its **mass number**. For instance, an atom of sodium, with 11 protons and 12 neutrons in its nucleus, has a mass number of 23.

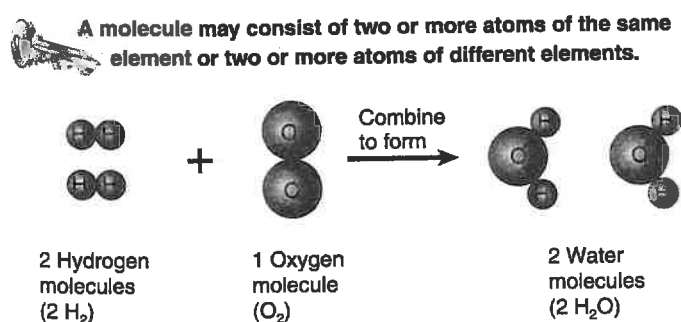
Even though their exact positions cannot be predicted, specific groups of electrons are most likely to move about within certain regions around the nucleus. These regions are called **electron shells**, which are depicted as circles in Figures 2.1b and 2.2 even though some of their shapes are not spherical. The electron shell nearest the nucleus—the first electron shell—can hold a maximum of 2 electrons. The second electron shell can hold a maximum of 8 electrons, and the third can hold up to 18 electrons. Higher electron shells (there are as many as seven) can contain many more electrons. The electron shells are filled with electrons in a specific order, beginning with the first shell.

## Ions, Molecules, and Compounds

The atoms of each element have a characteristic way of losing, gaining, or sharing their electrons when interacting with other atoms. If an atom either *gives up* or *gains* electrons, it becomes an **ion** (Ī-on), an atom that has a positive or negative charge due to unequal numbers of protons and electrons. An ion of an atom is symbolized by writing its chemical symbol followed by the number of its positive (+) or negative (−) charges. For example,  $\text{Ca}^{2+}$  stands for a calcium ion that has two positive charges because it has given up two electrons. Refer to Table 2.1 on page 23 for the important functions of several ions in the body.

In contrast, when two or more atoms *share* electrons, the resulting combination of atoms is called a **molecule** (MOL-e-kūl). A **molecular formula** indicates the number and type of atoms that make up a molecule. A molecule may consist of two or more atoms of the same element, such as an oxygen molecule or a hydrogen molecule, or two or more atoms of different elements, such as a water molecule (Figure 2.3). The molecular formula for a molecule of oxygen is  $\text{O}_2$ . The subscript 2 indicates there are two atoms of oxygen in the oxygen molecule. In the water molecule,  $\text{H}_2\text{O}$ , one atom of oxygen shares electrons with two atoms of hydrogen. Notice

Figure 2.3 Molecules.



? Which of the molecules shown here is a compound?

that two hydrogen molecules can combine with one oxygen molecule to form two water molecules (Figure 2.3).

A **compound** is a substance containing atoms of two or more different elements. Most of the atoms in your body are joined into compounds, for example, water ( $\text{H}_2\text{O}$ ). A molecule of oxygen ( $\text{O}_2$ ) is *not* a compound because it consists of atoms of only one element.

A **free radical** is an electrically charged ion or molecule that has an unpaired electron in its outermost shell. (Most of an atom's electrons associate in pairs.) A common example of a free radical is **superoxide**, which is formed by the addition of an electron to an oxygen molecule. Having an unpaired electron makes a free radical unstable and destructive to nearby molecules. Free radicals break apart important body molecules by either giving up their unpaired electron to or taking on an electron from another molecule.

In our bodies, several processes can generate free radicals. They may result from exposure to ultraviolet radiation in sunlight or to x-rays. Some reactions that occur during normal metabolic processes produce free radicals. Moreover, certain harmful substances, such as carbon tetrachloride (a solvent used in dry cleaning), give rise to free radicals when they participate in metabolic reactions in the body. Among the many disorders and diseases linked to oxygen-derived free radicals are cancer, the buildup of fatty materials in blood vessels (atherosclerosis), Alzheimer disease, emphysema, diabetes mellitus, cataracts, macular degeneration, rheumatoid arthritis, and deterioration associated with aging. Consuming more **antioxidants**—substances that inactivate oxygen-derived free radicals—is thought to slow the pace of damage caused by free radicals. Important dietary antioxidants include selenium, zinc, beta-carotene, and vitamins C and E.

## Chemical Bonds

The forces that bind the atoms of molecules and compounds together, resisting their separation, are **chemical bonds**. The chance that an atom will form a chemical bond with another atom depends on the number of electrons in its outermost shell, also called the **valence shell**. An atom with an outer shell holding eight electrons is **chemically stable**, which means it is unlikely to form chemical bonds with other atoms. Neon, for example, has eight electrons in its outer shell, and for this reason it rarely forms bonds with other atoms.

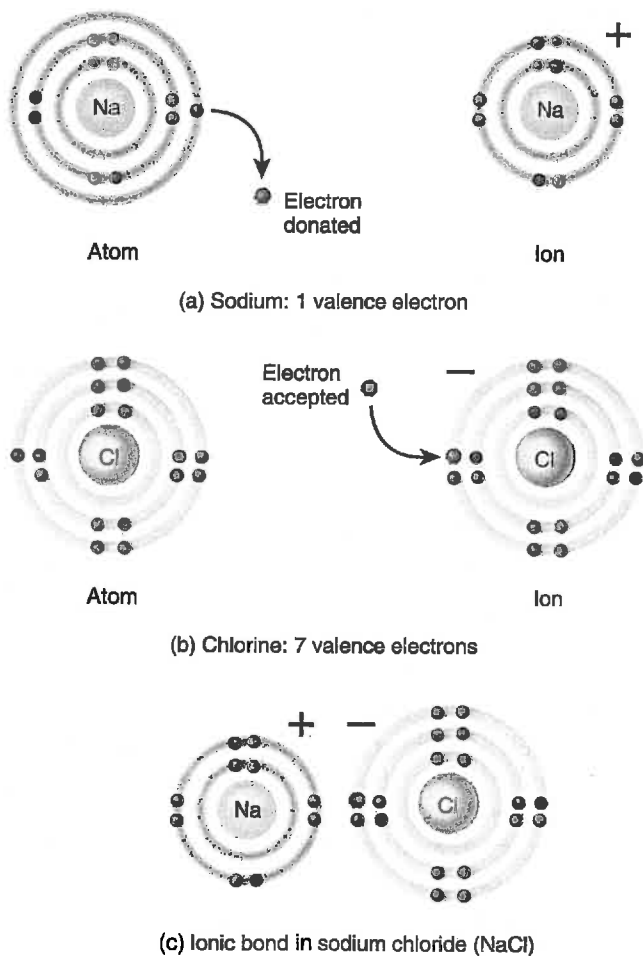
The atoms of most biologically important elements do not have eight electrons in their outer shells. Given the right conditions, two or more such atoms can interact or bond in ways that produce a chemically stable arrangement of eight electrons in the outer shell of each atom (**octet rule**). Three general types of chemical bonds are ionic bonds, covalent bonds, and hydrogen bonds.


### Ionic Bonds

Positively charged ions and negatively charged ions are attracted to one another. This force of attraction between ions of opposite charges is called an **ionic bond**. Consider sodium and chlorine atoms to see how an ionic bond forms (Figure 2.4). Sodium has one outer shell electron (Figure 2.4a). If a sodium atom *loses* this electron, it is left with the eight electrons in its second shell. However, the total number of protons (11) now exceeds the number of electrons (10). As

**Figure 2.4 Ions and ionic bond formation.** (a) A sodium atom can attain the stability of eight electrons in its outermost shell by losing its one valence electron; it then becomes a sodium ion,  $\text{Na}^+$ . (b) A chlorine atom can attain the stability of eight electrons in its outermost shell by accepting one electron; it then becomes a chloride ion,  $\text{Cl}^-$ . (c) An ionic bond holds  $\text{Na}^+$  and  $\text{Cl}^-$  together in the ionic compound sodium chloride,  $\text{NaCl}$ . The electron that is donated or accepted is colored red.

 An ionic bond is the force of attraction that holds together oppositely charged ions.



 Will the element potassium (K) be more likely to form an anion or a cation? Why? (Hint: Look back to Figure 2.2 for the atomic structure of K.)

a result, the sodium atom becomes a **cation** (KAT-i-on), positively charged ion. A sodium ion has a charge of  $1+$  and is written  $\text{Na}^+$ . On the other hand, chlorine has seven outer shell electrons (Figure 2.4b), too many to lose. But if chlorine *accepts* one electron from a neighboring atom, it will have eight electrons in its third electron shell. When this happens, the total number of electrons (18) exceeds the number of protons (17), and the chlorine atom becomes an **anion** (AN-i-on), a negatively charged ion. The ionic form of chlorine is called a chloride ion. It has a charge of  $1-$  and is written  $\text{Cl}^-$ . When an atom of sodium donates its sole outer shell electron to an atom of chlorine, the resulting positive and negative charges attract each other to form an ionic bond (Figure 2.4c). The resulting ionic compound is sodium chloride, written  $\text{NaCl}$ .

In the body, ionic bonds are found mainly in teeth and bones, where they give great strength to the tissue. Many other ions in the body are dissolved in body fluids. An ionic compound that breaks apart into cations and anions when dissolved is called an **electrolyte** (e-LEK-trō-līt) because the solution can conduct an electric current. As you will see in later chapters, electrolytes have many important functions. For example, they are critical for controlling water movement within the body, maintaining acid-base balance, and producing nerve impulses.

### Covalent Bonds

When a **covalent bond** forms, neither of the combining atoms loses or gains electrons. Instead, the atoms form a molecule by *sharing* one, two, or three pairs of their outer shell electrons. The greater the number of electron pairs shared between two atoms, the stronger the covalent bond. Covalent bonds are the most common chemical bonds in the body, and the compounds that result from them form most of the body's structures. Unlike ionic bonds, most covalent bonds do not break apart when the molecule is dissolved in water.

It is easiest to understand the nature of covalent bonds by considering those that form between atoms of the same element (Figure 2.5). A **single covalent bond** results when two atoms share one electron pair. For example, a molecule of hydrogen forms when two hydrogen atoms share their single valence electrons (Figure 2.5a), which allows both atoms to have a full valence shell. (Recall that the first electron shell holds only two electrons.) A **double covalent bond** (Figure 2.5b) or a **triple covalent bond** (Figure 2.5c) results when two atoms share two or three pairs of electrons. Notice the **structural formulas** for covalently bonded molecules in Figure 2.5. The number of lines between the chemical symbols for two atoms indicates whether the bond is a single (—), double (=), or triple ( $\equiv$ ) covalent bond.

The same principles of covalent bonding that apply to atoms of the same element also apply to covalent bonds between atoms of different elements. Methane ( $\text{CH}_4$ ), a gas

**Figure 2.5 Covalent bond formation.** The red electrons are shared equally in (a)-(d) and unequally in (e). To the right are simpler ways to represent these molecules. In a structural formula, each covalent bond is denoted by a straight line between the chemical symbols for two atoms. In a molecular formula, the number of atoms in each molecule is noted by subscripts.

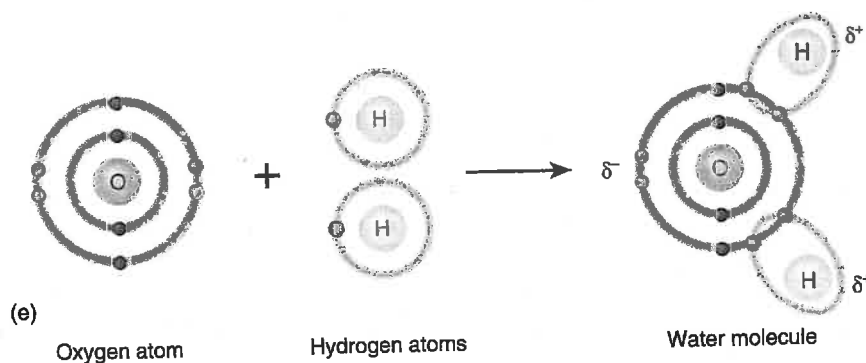
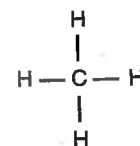
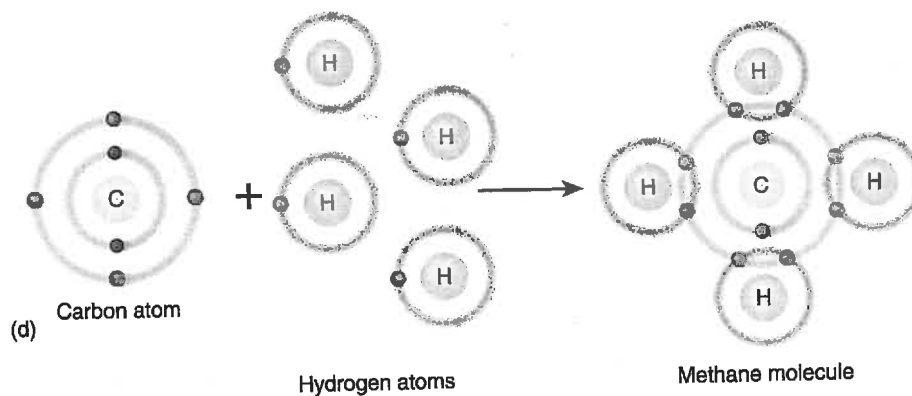
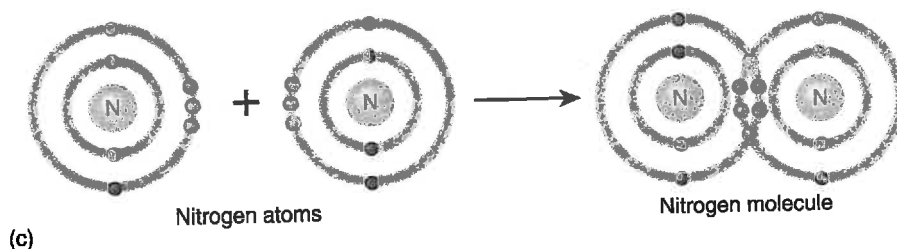
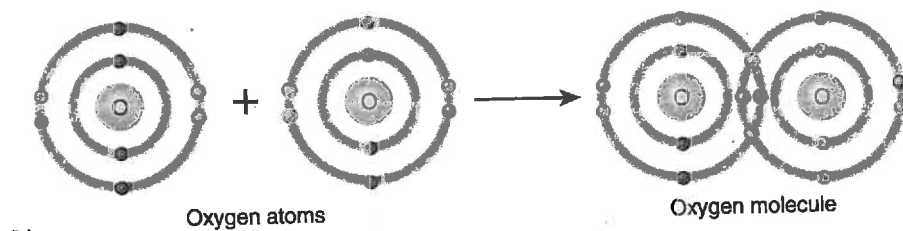
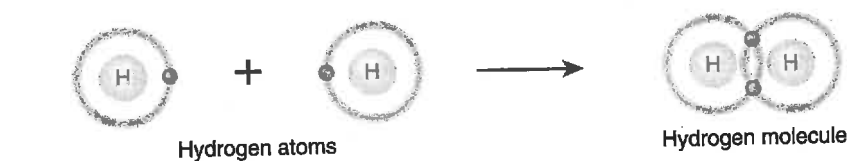
In a covalent bond, two atoms share one, two, or three pairs of electrons in the outer shell.



# DIAGRAMS OF ATOMIC AND MOLECULAR STRUCTURE

STRUCTURAL  
FORMULA

MOLECULAR  
FORMULA



What is the main difference between an ionic bond and a covalent bond?

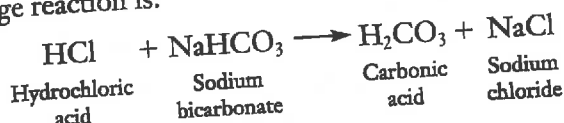
tions. Some of the energy released is temporarily stored in a special molecule called **adenosine triphosphate (ATP)**, which will be discussed more fully later in this chapter. The energy transferred to the ATP molecules is then used to drive the energy-requiring synthesis reactions that lead to the building of body structures such as muscles and bones.

### Exchange Reactions

Many reactions in the body are **exchange reactions**; they consist of both synthesis and decomposition reactions. One type of exchange reaction works like this:



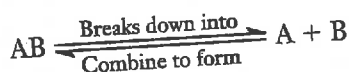
The bonds between A and B and between C and D break (decomposition), and new bonds then form (synthesis) between A and D and between B and C. An example of an exchange reaction is:



Notice that the ions in both compounds have “switched partners”: The hydrogen ion (H<sup>+</sup>) from HCl has combined with the bicarbonate ion (HCO<sub>3</sub><sup>-</sup>) from NaHCO<sub>3</sub>, and the sodium ion (Na<sup>+</sup>) from NaHCO<sub>3</sub> has combined with the chloride ion (Cl<sup>-</sup>) from HCl.

### Reversible Reactions

Some chemical reactions proceed in only one direction, as previously indicated by the single arrows. Other chemical reactions may be reversible. **Reversible reactions** can go in either direction under different conditions and are indicated by two half arrows pointing in opposite directions:



Some reactions are reversible only under special conditions:



Whatever is written above or below the arrows indicates the condition needed for the reaction to occur. In these reactions, AB breaks down into A and B only when water is added, and A and B react to produce AB only when heat is applied.

### CHECKPOINT

1. Compare the meanings of atomic number, mass number, ion, and molecule.
2. What is the significance of the valence (outer) electron shell of an atom?
3. Distinguish among ionic, covalent, and hydrogen bonds.
4. Explain the difference between anabolism and catabolism. Which involves synthesis reactions?

## CHEMICAL COMPOUNDS AND LIFE PROCESSES

**OBJECTIVES** • Discuss the functions of water and inorganic acids, bases, and salts.

- Define pH and explain how the body attempts to keep pH within the limits of homeostasis.
- Discuss the functions of carbohydrates, lipids, and proteins.
- Explain the importance of deoxyribonucleic acid (DNA), ribonucleic acid (RNA), and adenosine triphosphate (ATP).

Chemicals in the body can be divided into two main classes of compounds: inorganic and organic. **Inorganic compounds** usually lack carbon, are structurally simple, and are held together by ionic or covalent bonds. They include water, many salts, acids, and bases. Two inorganic compounds that contain carbon are carbon dioxide (CO<sub>2</sub>) and bicarbonate ion (HCO<sub>3</sub><sup>-</sup>). **Organic compounds**, by contrast, always contain carbon, usually contain hydrogen, and always have covalent bonds. Examples include carbohydrates, lipids, proteins, nucleic acids, and adenosine triphosphate (ATP). Organic compounds are discussed in detail in Chapters 19 and 20. Large organic molecules called **macromolecules** are formed by covalent bonding of many identical or similar building-block subunits termed **monomers**.

### Inorganic Compounds

#### Water

**Water** is the most important and most abundant inorganic compound in all living systems, making up 55% to 60% of body mass in lean adults. With few exceptions, most of the volume of cells and body fluids is water. Several of its properties explain why water is such a vital compound for life.

1. **Water is an excellent solvent.** A **solvent** is a liquid gas in which some other material, called a **solute**, has been dissolved. The combination of solvent plus solute is called a **solution**. Water is the solvent that carries nutrients, oxygen, and wastes throughout the body. The versatility of water as a solvent is due to its polar covalent bonds and its “bent” shape (see Figure 2.5e), which allows each water molecule to interact with several neighboring ions or molecules. Solutes that are charged or contain polar covalent bonds are **hydrophilic** (*hydro-* = water, *-philic* = loving), which means they dissolve easily in water. Common examples of hydrophilic solutes are sugar and salt. Molecules that contain mainly nonpolar covalent bonds, by contrast, are **hydrophobic** (*-phobos* = fearing). They are not very water soluble. Examples of hydrophobic compounds include animal fats and vegetable oils.

contains four separate single covalent bonds; each hydrogen atom shares one pair of electrons with the carbon atom (Figure 2.5d).

In some covalent bonds, atoms share the electrons equally—one atom does not attract the shared electrons more strongly than the other atom. This is called a *nonpolar covalent bond*. The bonds between two identical atoms always are nonpolar covalent bonds (Figure 2.5a–c). Another example of a nonpolar covalent bond is the single covalent bond that forms between carbon and each atom of hydrogen in a methane molecule (Figure 2.5d).

In a *polar covalent bond*, the sharing of electrons between atoms is unequal—one atom attracts the shared electrons more strongly than the other. The partial charges are indicated by a lowercase Greek delta ( $\delta$ ) with a minus or plus sign. For example, when polar covalent bonds form, the resulting molecule has a partial negative charge, written  $\delta^-$ , near the atom that attracts electrons more strongly. At least one other atom in the molecule then will have a partial positive charge, written  $\delta^+$ . A very important example of a polar covalent bond in living systems is the bond between oxygen and hydrogen in a molecule of water (Figure 2.5e).

### Hydrogen Bonds

The polar covalent bonds that form between hydrogen atoms and other atoms can give rise to a third type of chemical bond, a hydrogen bond. A *hydrogen bond* forms when a hydrogen atom with a partial positive charge ( $\delta^+$ ) attracts the partial negative charge ( $\delta^-$ ) of neighboring electronegative atoms, most often oxygen or nitrogen. Thus, hydrogen bonds result from attraction of oppositely charged parts of molecules rather than from sharing of electrons as in covalent bonds. Hydrogen bonds are weak when compared to ionic and covalent bonds. Thus, they cannot bind atoms into molecules. However, hydrogen bonds do establish important links between molecules or between different parts of a large molecule, such as deoxyribonucleic acid (DNA). See Figure 2.15.

## Chemical Reactions

A *chemical reaction* occurs when new bonds form and/or old bonds break between atoms. Through chemical reactions, body structures are built and body functions are carried out, processes that involve transfers of energy.

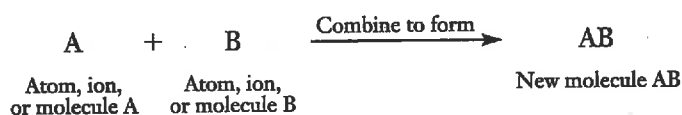
### Forms of Energy and Chemical Reactions

**Energy** (*en-* = in; *-ergy* = work) is the capacity to do work. The two main forms of energy are *potential energy*, energy stored by matter due to its *position*, and *kinetic energy*, the energy of matter *in motion*. For example, the energy stored in a battery or in a person poised to jump down some steps is potential energy. When the battery is used to run a clock or the person jumps, potential energy is converted into kinetic energy. **Chemical energy** is a form of potential energy that is stored in the bonds of molecules. In your body, chemical en-

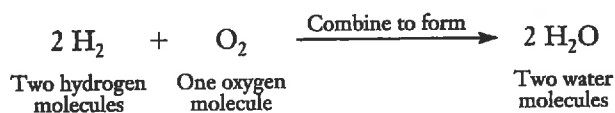
ergy in the foods you eat is eventually converted into various forms of kinetic energy, such as mechanical energy, used to walk and talk, and heat energy, used to maintain body temperature. In chemical reactions, breaking old bonds requires an input of energy and forming new bonds releases energy. Because most chemical reactions involve both breaking old bonds and forming new bonds, the *overall reaction* may either release energy or require energy.

### Synthesis Reactions

When two or more atoms, ions, or molecules combine to form new and larger molecules, the process is a *synthesis reaction*. The word *synthesis* means “to put together.” Synthesis reactions can be expressed as follows:



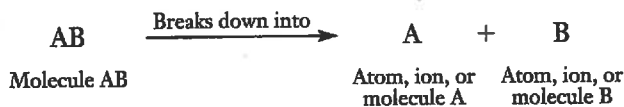
An example of a synthesis reaction is the synthesis of water from hydrogen and oxygen molecules (see Figure 2.3):



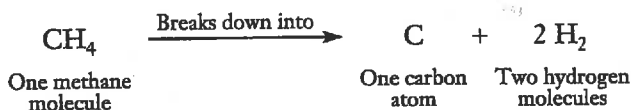
All the synthesis reactions that occur in your body are collectively referred to as *anabolism* (a-NAB-ō-lizm). Combining simple molecules like amino acids (discussed shortly) to form large molecules such as proteins is an example of anabolism.

### Decomposition Reactions

In a *decomposition reaction*, a molecule is split apart. The word *decompose* means to break down into smaller parts. Large molecules are split into smaller molecules, ions, or atoms. A decomposition reaction occurs in this way:



For example, under the proper conditions, a methane molecule can decompose into one carbon atom and two hydrogen molecules:



The decomposition reactions that occur in your body are collectively referred to as *catabolism* (ka-TAB-ō-lizm). The breakdown of large starch molecules into many small glucose molecules during digestion is an example of catabolism.

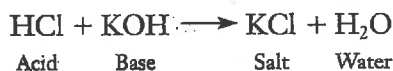
In general, energy-releasing reactions occur as nutrients, such as glucose, are broken down via decomposition reac-

2. **Water participates in chemical reactions.** Because water can dissolve so many different substances, it is an ideal medium for chemical reactions. Water also is an active participant in some decomposition and synthesis reactions. During digestion, for example, decomposition reactions break down large nutrient molecules into smaller molecules by the addition of water molecules. This type of reaction is called *hydrolysis* (hī-DROL-i-sis; *-lysis* = to loosen or break apart) (see Figure 2.8). Hydrolysis reactions enable dietary nutrients to be absorbed into the body.
3. **Water absorbs and releases heat very slowly.** In comparison to most other substances, water can absorb or release a relatively large amount of heat with only a slight change in its own temperature. The large amount of water in the body thus moderates the effect of changes in the environmental temperature, thereby helping maintain the homeostasis of body temperature.
4. **Water requires a large amount of heat to change from a liquid to a gas.** When the water in sweat evaporates from the skin surface, it takes with it large quantities of heat and provides an excellent cooling mechanism.
5. **Water serves as a lubricant.** Water is a major part of saliva, mucus, and other lubricating fluids. Lubrication is especially necessary in the thoracic and abdominal cavities, where internal organs touch and slide over one another. It is also needed at joints, where bones, ligaments, and tendons rub against one another.

### Inorganic Acids, Bases, and Salts

Many inorganic compounds can be classified as acids, bases, or salts. An **acid** is a substance that breaks apart or *dissociates* (dis-SŌ-sē-āts) into one or more *hydrogen ions* ( $H^+$ ) when it dissolves in water (Figure 2.6a). A **base**, by contrast, usually dissociates into one or more *hydroxide ions* ( $OH^-$ ) when it dissolves in water (Figure 2.6b). A **salt**, when dissolved in water, dissociates into cations and anions, neither of which is  $H^+$  or  $OH^-$  (Figure 2.6c).


Acids and bases react with one another to form salts. For example, the reaction of hydrochloric acid (HCl) and potassium hydroxide (KOH), a base, produces the salt potassium chloride (KCl), along with water ( $H_2O$ ). This exchange reaction can be written as follows:

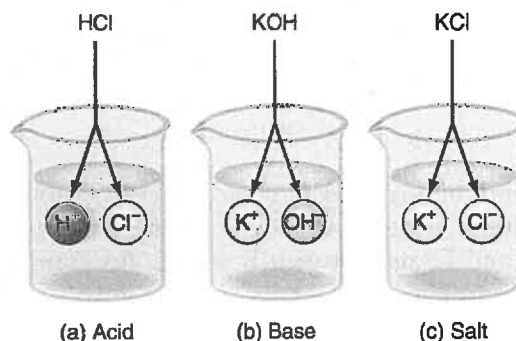


### Acid-Base Balance: The Concept of pH

To ensure homeostasis, body fluids must contain almost balanced quantities of acids and bases. The more hydrogen ions ( $H^+$ ) dissolved in a solution, the more acidic the solution; conversely, the more hydroxide ions ( $OH^-$ ), the more basic (alkaline) the solution. The chemical reactions that take place in the body are very sensitive to even small changes in the

**Figure 2.6 Acids, bases, and salts.** (a) When placed in water, hydrochloric acid (HCl) ionizes into  $H^+$  and  $Cl^-$ . (b) When the base potassium hydroxide (KOH) is placed in water, it ionizes into  $OH^-$  and  $K^+$ . (c) When the salt potassium chloride (KCl) is placed in water, it ionizes into positive and negative ions ( $K^+$  and  $Cl^-$ ), neither of which is  $H^+$  or  $OH^-$ .

 **Ionization is the separation of inorganic acids, bases, and salts into ions in a solution.**



? The compound  $CaCO_3$  (calcium carbonate) dissociates into a calcium ion ( $Ca^{2+}$ ) and a carbonate ion ( $CO_3^{2-}$ ). Is it an acid, a base, or a salt? What about  $H_2SO_4$ , which dissociates into two  $H^+$  and one  $SO_4^{2-}$ ?

acidity or alkalinity of the body fluids in which they occur. Any departure from the narrow limits of normal  $H^+$  and  $OH^-$  concentrations greatly disrupts body functions.

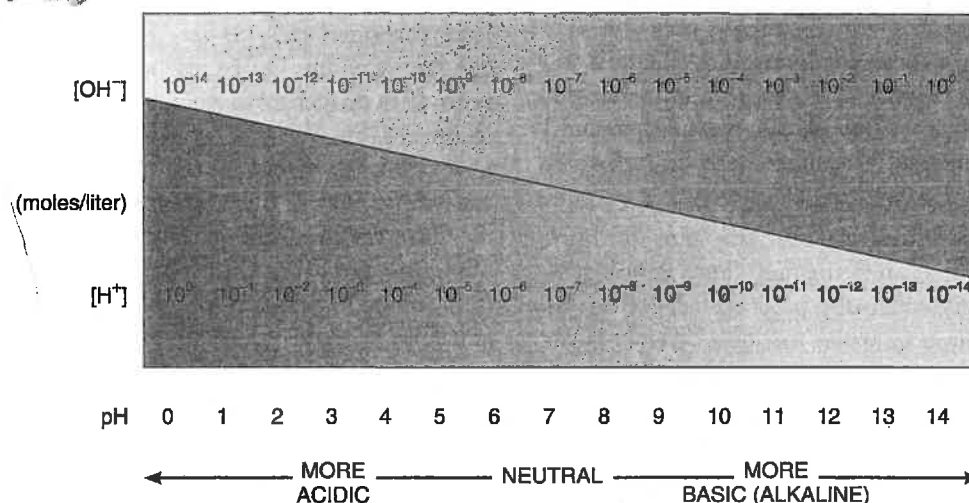
A solution's acidity or alkalinity is expressed on the **pH scale**, which extends from 0 to 14 (Figure 2.7). This scale is based on the number of hydrogen ions in a solution. The midpoint of the pH scale is 7, where the numbers of  $H^+$  and  $OH^-$  are equal. A solution with a pH of 7, such as pure water, is **neutral**—neither acidic nor alkaline. A solution that has more  $H^+$  than  $OH^-$  is **acidic** and has a pH below 7. A solution that has more  $OH^-$  than  $H^+$  is **basic (alkaline)** and has a pH above 7. A change of one whole number on the pH scale represents a **10-fold** change in the number of  $H^+$ . At a pH of 6, there are 10 times more  $H^+$  than at a pH of 7. Put another way, a pH of 6 is 10 times more acidic than a pH of 7, and a pH of 9 is 100 times more alkaline than a pH of 7.

### Maintaining pH: Buffer Systems

Although the pH of various body fluids may differ, the normal limits for each are quite narrow. Table 2.2 shows the pH values for certain body fluids compared with those of common household substances. Homeostatic mechanisms maintain the pH of blood between 7.35 and 7.45, so that it is slightly more basic than pure water. Even though strong acids and bases may be taken into the body or be formed by body cells, the pH of fluids inside and outside cells remains almost constant. One important reason is the presence of **buffer systems**, in which chemical compounds called **buffers** convert strong acids or bases into weak acids or bases. (More will be said about buffers in Chapter 22.)

**Figure 2.7 The pH scale.** A pH below 7 indicates an acidic solution, or more  $H^+$  than  $OH^-$ . The lower the numerical value of the pH, the more acidic the solution because the  $H^+$  concentration becomes progressively greater. A pH above 7 indicates a basic (alkaline) solution; that is, there are more  $OH^-$  than  $H^+$ . The higher the pH, the more basic the solution.

At pH 7 (neutrality), the concentrations of  $H^+$  and  $OH^-$  are equal.



Which pH is more acidic, 6.82 or 6.91? Which pH is closer to neutral, 8.41 or 5.59?

## Organic Compounds

### Carbohydrates

**Carbohydrates** include sugars, glycogen, starches, and cellulose. The elements present in carbohydrates are carbon, hydrogen, and oxygen. The ratio of hydrogen to oxygen atoms is usually 2:1, as in water ( $H_2O$ ), and the number of carbon and oxygen atoms is the same or nearly the same. For example, the molecular formula for the small carbohydrate glucose is  $C_6H_{12}O_6$ . Carbohydrates are divided into three major groups based on their size: monosaccharides, disaccharides, and polysaccharides. Monosaccharides and disaccharides are termed *simple sugars*, and polysaccharides are also known as *complex carbohydrates*.

1. **Monosaccharides** (mon'-ō-SAK-a-rīds; *mono-* = one; *sacchar-* = sugar) are the building blocks of carbohydrates. In your body, the principal function of the monosaccharide glucose is to serve as a source of chemical energy for generating the ATP that fuels metabolic reactions. Ribose and deoxyribose are monosaccharides used to make ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), which are described on pages 38-39.
2. **Disaccharides** (dī-SAK-a-rīds; *di-* = two) are simple sugars that consist of two monosaccharides joined by a covalent bond. When two monosaccharides (smaller molecules) combine to form a disaccharide (a larger molecule), a molecule of water is formed and removed. Such a reaction is called *dehydration synthesis*.

Table 2.2 pH Values of Selected Substances

Substance*	pH Val
Gastric juice (digestive juice of the stomach)	1.2-3
Lemon juice	2.3
Grapefruit juice, vinegar, wine	3.0
Carbonated soft drink	3.0-3
Orange juice	3.5
Vaginal fluid	3.5-4
Tomato juice	4.2
Coffee	5.0
Urine	4.6-8
Saliva	6.35-6
Cow's milk	6.8
Distilled (pure) water	7.0
Blood	7.35-7
Semen (fluid containing sperm)	7.20-7
Cerebrospinal fluid (fluid associated with the nervous system)	7.4
Pancreatic juice (digestive juice of the pancreas)	7.1-8
Bile (liver secretion that aids fat digestion)	7.6-8
Milk of magnesia	10.5
Lye	14.0

\*Substances in the human body are highlighted in gold.

(*de-* = from, down; or out; *hydra-* = water). Such reactions occur during synthesis of large molecules. For example, the monosaccharides glucose and fructose combine to form the disaccharide sucrose (table sugar) as shown in Figure 2.8. Disaccharides can be split into monosaccharides by adding a molecule of water, a hydrolysis reaction. Sucrose, for example, may be hydrolyzed into its components of glucose and fructose by the addition of water (Figure 2.8). Other disaccharides include maltose (glucose + glucose), or malt sugar, and lactose (glucose + galactose), the sugar in milk.

3. **Polysaccharides** (pol'-ē-SAK-a-rīds; *poly-* = many) are large, complex carbohydrates that contain tens or hundreds of monosaccharides joined through dehydration synthesis reactions. Like disaccharides, polysaccharides can be broken down into monosaccharides through hydrolysis reactions. The main polysaccharide in the human body is *glycogen*, which is made entirely of glucose units joined together in branching chains (Figure 2.9). Glycogen is stored in cells of the liver and in skeletal muscles. If energy demands of the body are high, glycogen is broken down into glucose; when energy demands are low, glucose is built back up into glycogen. *Starches* are also made of glucose units and are polysaccharides made mostly by plants. We digest starches to glucose as another energy source. *Cellulose* is a polysaccharide found in plant cell walls. Although

humans cannot digest cellulose, it does provide bulk (roughage or fiber) that helps move feces through the large intestine. Unlike simple sugars, polysaccharides usually are not soluble in water and do not taste sweet.

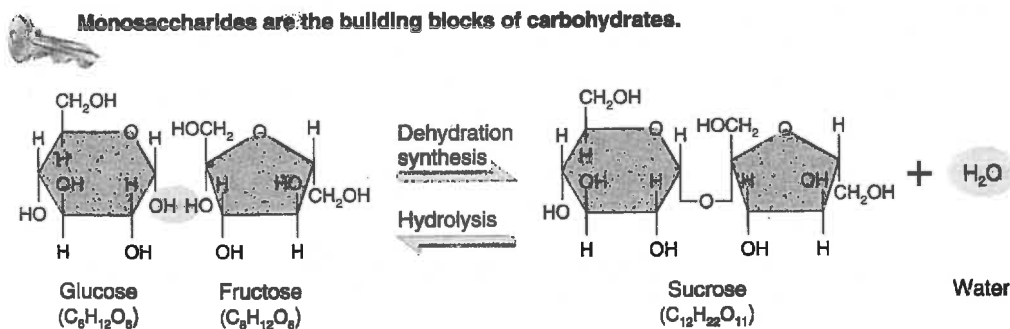
### Lipids

Like carbohydrates, **lipids** (*lip-* = fat) contain carbon, hydrogen, and oxygen. Unlike carbohydrates, they do not have a 2:1 ratio of hydrogen to oxygen. The proportion of oxygen atoms in lipids is usually smaller than in carbohydrates, so there are fewer polar covalent bonds. As a result, most lipids are hydrophobic; that is, they are insoluble in water (see page 29).

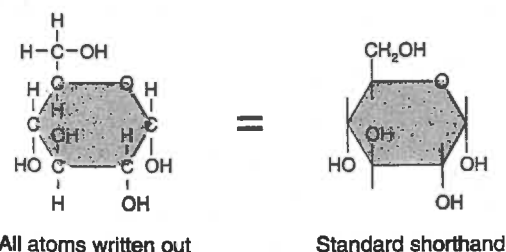
The diverse lipid family includes triglycerides (fats and oils), phospholipids (lipids that contain phosphorus), steroids, fatty acids, and fat-soluble vitamins (vitamins A, D, E, and K).

The most plentiful lipids in your body and in your diet are the **triglycerides** (tri-GLI-cer-īds; *tri-* = three). At room temperature, triglycerides may be either solids (fats) or liquids (oils). They are the body's most highly concentrated form of chemical energy, storing more than twice as much chemical energy per gram as carbohydrates or proteins. Our capacity to store triglycerides in fat tissue, called adipose tissue, for all practical purposes, is unlimited. Excess dietary carbohydrates, proteins, fats, and oils all have the same fate: They are deposited in adipose tissue as triglycerides.

**Figure 2.8 Dehydration synthesis and hydrolysis of a molecule of sucrose.** In the dehydration synthesis reaction (read from left to right), two smaller molecules, glucose and fructose, are joined to form a larger molecule of sucrose. Note the loss of a water molecule. In the hydrolysis reaction (read from right to left), the larger sucrose molecule is broken down into two smaller molecules, glucose and fructose. Here, a molecule of water is added to sucrose for the reaction to occur.



(a) Dehydration synthesis and hydrolysis of sucrose



(b) Alternate chemical structures of organic molecules (shown here is glucose)

? How many carbons are there in fructose? in sucrose?

**Figure 2.9** Part of a glycogen molecule, the main polysaccharide in the human body.

Glycogen is made up of glucose units and is the storage form of carbohydrate in the human body.



? Which body cells store glycogen?

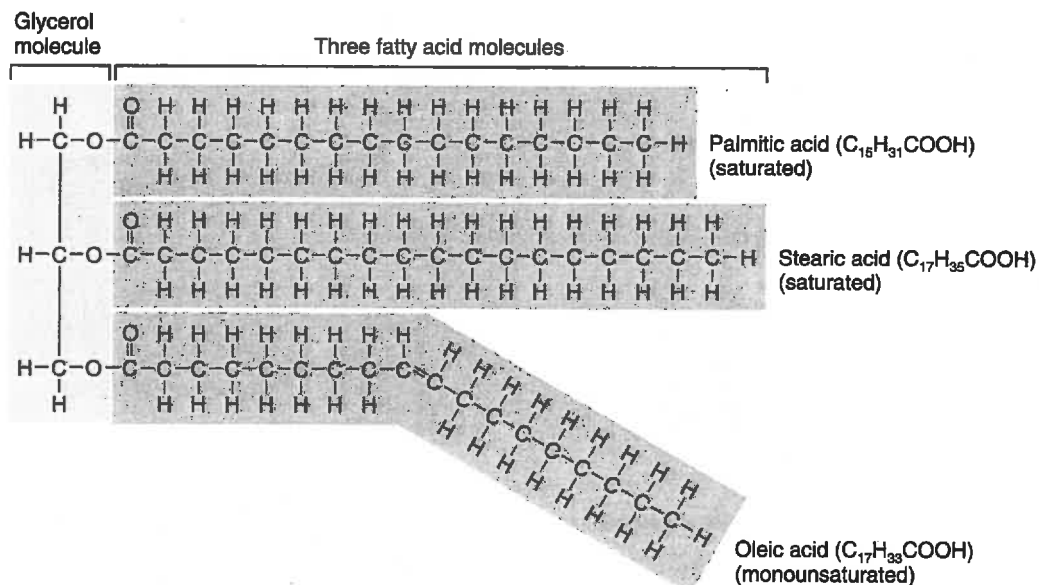
A triglyceride consists of two types of building blocks: a single glycerol molecule and three fatty acid molecules. A three-carbon **glycerol** molecule forms the backbone of a triglyceride (Figure 2.10). Three **fatty acids** are attached, by dehydration synthesis reactions, one to each carbon of the glycerol backbone. The fatty acid chains of a triglyceride may be saturated, monounsaturated, or polyunsaturated.

**Saturated fats** contain only *single covalent bonds* between fatty acid carbon atoms. Because they do not contain any double bonds between fatty acid carbon atoms, each carbon atom is *saturated with hydrogen atoms* (see palmitic acid and stearic acid in Figure 2.10). Triglycerides with mainly saturated fatty acids are solid at room temperature and occur mostly in meats (especially red meats) and nonskim dairy products (whole milk, cheese, and butter). They also occur in a few tropical plants, such as cocoa, palm, and coconut. Diets that contain large amounts of saturated fats are associated with disorders such as heart disease and colorectal cancer. **Monounsaturated fats** (*mono-* = one) contain fatty acids with *one double covalent bond* between two fatty acid carbon atoms and thus are not completely saturated with hydrogen atoms (see oleic acid in Figure 2.10). Olive oil, peanut oil, canola oil, most nuts, and avocados are rich in triglycerides with monounsaturated fatty acids. Monounsaturated fats are thought to decrease the risk of heart disease. **Polyunsaturated fats** (*poly-* = many) contain *more than one double covalent bond* between fatty acid carbon atoms. Corn oil, safflower oil, sunflower oil, soybean oil, and fatty fish (salmon, tuna, and mackerel) contain a high percentage of polyunsaturated fatty acids. Polyunsaturated fats are also believed to decrease the risk of heart disease. However, when products such as margarine and vegetable shortening are made from polyunsaturated fats, compounds called *trans* fatty acids are produced. Trans fatty acids, like saturated fats, increase the risk of cardiovascular disease.

A group of fatty acids called **essential fatty acids (EFAs)** are essential to human health. However, they cannot be made by the human body and must be obtained from foods or

**Figure 2.10** Triglycerides consist of three fatty acids attached to a glycerol backbone. The fatty acids vary in length and the number and location of double bonds between carbon atoms ( $C=C$ ). Shown here is a triglyceride molecule that contains two saturated fatty acids and one monounsaturated fatty acid.

A triglyceride consists of two types of building blocks: a single glycerol molecule and three fatty acid molecules.



? How many double bonds are there in a monounsaturated fatty acid?

supplements. Among the more important EFAs are *omega-3 fatty acids*, *omega-6 fatty acids*, and *cis-fatty acids*.

Omega-3 and omega-6 fatty acids are polyunsaturated fatty acids that may have a protective effect against heart disease and stroke by lowering total cholesterol, raising HDL (high-density lipoproteins or "good cholesterol") and lowering LDL (low-density lipoproteins or "bad cholesterol"). In addition, they decrease bone loss; reduce symptoms of arthritis due to inflammation; promote wound healing; improve certain skin disorders (psoriasis, eczema, and acne); and improve mental functions. Primary sources of omega-3 fatty acids include flaxseed, fatty fish, oils that have large amounts of polyunsaturated fats, fish oils, and walnuts. Primary sources of omega-6 fatty acids include most processed foods (cereals, breads, white rice), eggs, baked goods, oils with large amounts of polyunsaturated fats, and meats (especially organ meats, such as liver).

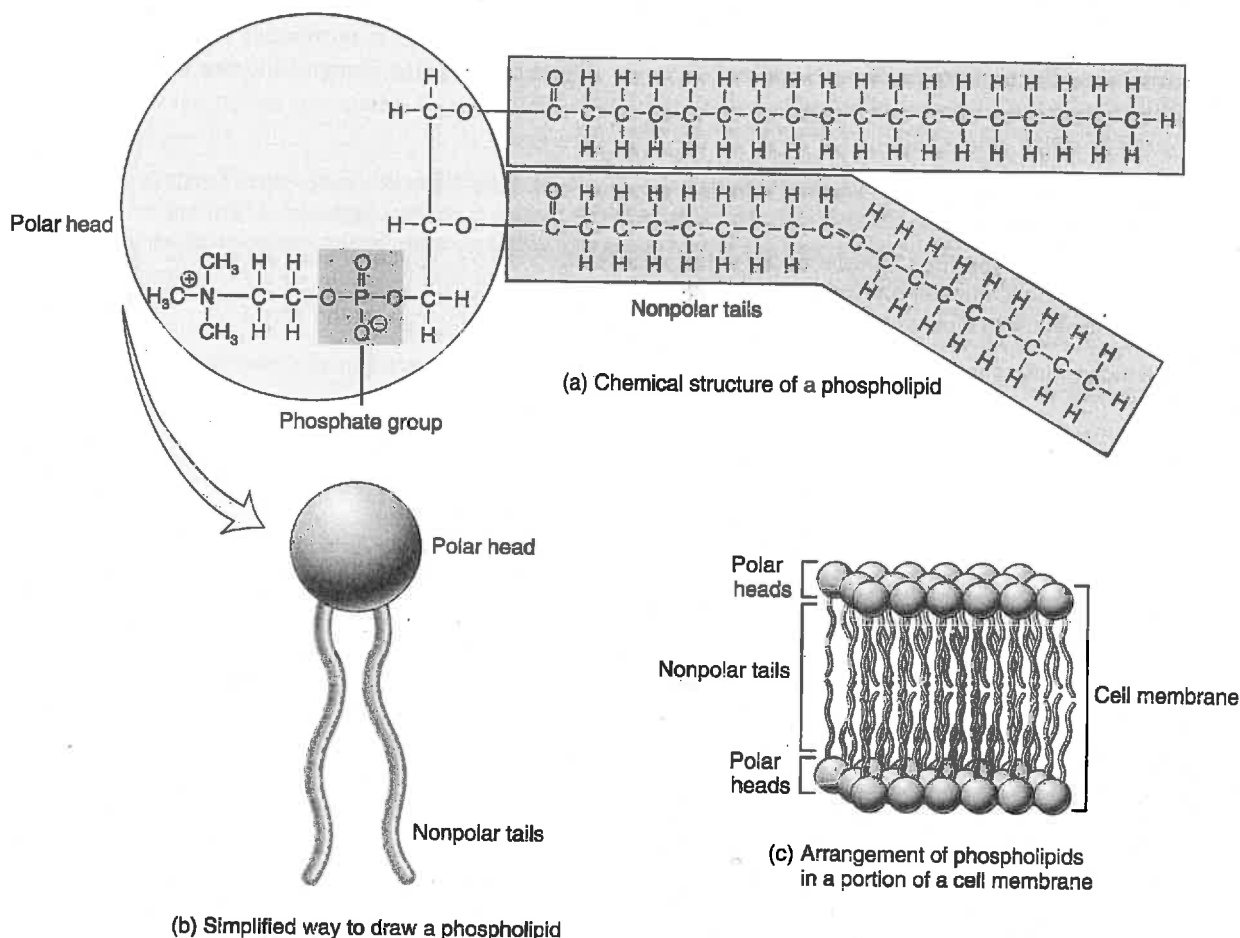
*Cis*-fatty acids are nutritionally beneficial monosaturated fatty acids that are used by the body to produce hormone-like

regulators and cell membranes. However, when *cis*-fatty acids are heated, pressurized, and combined with a catalyst (usually nickel) in a process called *hydrogenation*, they are changed to unhealthy *trans* fatty acids. Hydrogenation is used by manufacturers to make vegetable oils solid at room temperature and less likely to turn rancid. Hydrogenated or *trans* fatty acids are common in commercially baked goods (crackers, cakes, and cookies), salty snack foods, some margarine, and fried foods (donuts and french fries). If a product label contains the words hydrogenated or partially hydrogenated, then the product contains *trans* fatty acids. Among the adverse effects of *trans* fatty acids are an increase in total cholesterol, a decrease in HDL, an increase in LDL, and an increase in triglycerides. These effects, which can increase the risk of heart disease and other cardiovascular diseases, are similar to those caused by saturated fats.

Like triglycerides, **phospholipids** have a glycerol backbone and two fatty acids attached to the first two carbons (Figure 2.11a). Attached to the third carbon is a phosphate

**Figure 2.11 Phospholipids.** (a) In the synthesis of phospholipids, two fatty acids attach to the first two carbons of the glycerol backbone. A phosphate group links a small charged group to the third carbon in glycerol. In (b), the circle represents the polar head region, and the two wavy lines represent the two nonpolar tails.

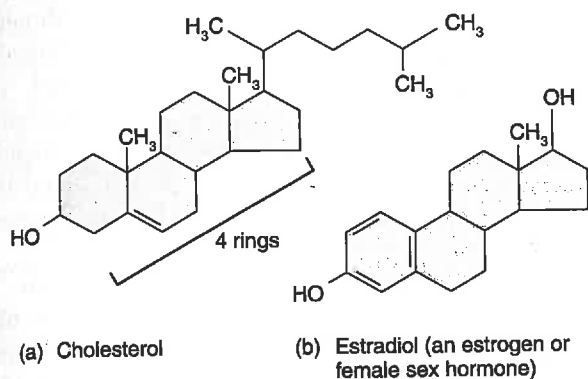
Phospholipids are the main lipids in cell membranes.



How does a phospholipid differ from a triglyceride?

**Figure 2.12 Steroids.** All steroids have four rings of carbon atoms.

Cholesterol is the starting material for synthesis of other steroids in the body.



? Which dietary lipids are thought to contribute to atherosclerosis?

group ( $\text{PO}_4^{3-}$ ) that links a small charged group to the glycerol backbone. Whereas the nonpolar fatty acids form the hydrophobic “tails” of a phospholipid, the polar phosphate group and charged group form the hydrophilic “head” (Figure 2.11b). Phospholipids line up tails-to-tails in a double row to make up much of the membrane that surrounds each cell (Figure 2.11c).

The structure of **steroids**, with their four rings of carbon atoms, differs considerably from that of the triglycerides and

phospholipids. Cholesterol (Figure 2.12a), which is needed for membrane structure, is the steroid from which other steroids may be synthesized by body cells. For example, cells in the ovaries of females synthesize estradiol (Figure 2.12b), which is one of the estrogens or female sex hormones. Estrogens regulate sexual functions. Other steroids include testosterone (the main male sex hormone), which also regulates sexual functions; cortisol, which is necessary for maintaining normal blood sugar levels; bile salts, which are needed for lipid digestion and absorption; and vitamin D, which is related to bone growth.

### Proteins

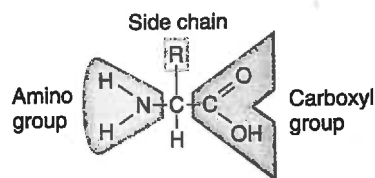
**Proteins** are large molecules that contain carbon, hydrogen, oxygen, and nitrogen; some proteins also contain sulfur. Much more complex in structure than carbohydrates or lipids, proteins have many roles in the body and are largely responsible for the structure of body cells. For example, proteins termed enzymes speed up particular chemical reactions, other proteins are responsible for contraction of muscles, proteins called antibodies help defend the body against invading microbes, and some hormones are proteins.

**Amino acids** (a-MĒ-nō) are the building blocks of proteins. All amino acids have an **amino group** ( $-\text{NH}_2$ ) at one end and a **carboxyl group** ( $-\text{COOH}$ ) at the other end. Each of the 20 different amino acids has a different **side chain** (R group) (Figure 2.13a). The covalent bonds that join amino acids together to form more complex molecules are called **peptide bonds** (Figure 2.13b).

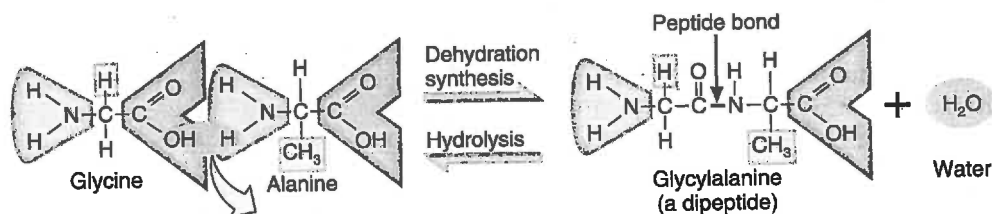
**Figure 2.13 Amino acids.** (a) In keeping with their name, amino acids have an amino group (shaded blue) and a carboxyl (acid) group (shaded red). The side chain (R group) is shaded gold and is different in each type of amino acid. (b) When two amino acids are chemically united by dehydration synthesis (read from left to right), the resulting covalent bond between them is called a peptide bond. The peptide bond is formed at the point where water is lost. Here, the amino acids glycine and alanine are joined to form the dipeptide glycylalanine. Breaking a peptide bond occurs by hydrolysis (read from right to left).



Amino acids are the building blocks of proteins.



(a) Structure of an amino acid



(b) Protein formation



How many peptide bonds would there be in a tripeptide?

## FOCUS ON WELLNESS

### Herbal Supplements — They're Natural but Are They Safe?

**S**ales of herbal supplements are booming. Preparations of ginseng and echinacea stand next to bottles of vitamin C and aspirin in medicine cabinets across North America. But beware: Although some herbal supplements are helpful for specific problems, others are a waste of money, and many can be harmful to your health.

#### Does Natural Mean Safe?

Herbal supplements are preparations made from the leaves, flowers, bark, berries, or roots of plants. Herbal preparations have been used throughout the ages in cultures around the world to relieve pain, heal wounds, chase away evil spirits, and even to kill. Many of the active ingredients in drugs we use today were originally isolated from herbs. For example, the heart drug digitalis comes from the foxglove plant.

Anyone who knows some chemistry can understand why "natural" does not necessarily mean "safe." Natural chemicals are still chemicals. They participate in chemical reactions in your body. They have chemical ef-

fects in the same way that manufactured drugs do.

Herbal products can't be effective and harmless at the same time because anything that has a physiological effect can be harmful at some dose. All drugs become toxic if you take too much of them.

#### Handle with Care

If you want to use herbal supplements, you must also use your head. Because regulation of these supplements is currently fairly loose in most countries, you can't believe everything the manufacturer says on the label or in advertising literature. If a product sounds too good to be true, beware!

Health-care professionals are especially concerned about the lack of data on the long-term safety of many herbal products. Scientists are just beginning to investigate the use of herbs, and our understanding of these remedies is still in its infancy.

#### Talk to Your Doctor

If you decide to try herbal supplements for an ailment, talk to your health-care

provider to be sure you are not overlooking beneficial medical treatments. If you are taking any medications, ask your pharmacist whether you should be concerned about possible interactions between the supplement and your drugs. For example, it is dangerous to take ginkgo biloba and aspirin together, because both have potent blood-thinning effects that can lead to dangerous bleeding.

Women who are pregnant, intending to become pregnant, or nursing a baby should avoid supplements in the same way that they avoid drugs.



#### ► THINK IT OVER . . .

► *Your Aunt Mary tells you she is taking an herbal weight-loss supplement. "It's natural, so it's safe," she says. In fact, it's not working as well as it was two weeks ago, so she is now taking double the recommended dose. What would you say to her?*

The union of two or more amino acids produces a **peptide** (PEP-tid). When two amino acids combine, the molecule is called a **dipeptide** (Figure 2.13b). Adding another amino acid to a dipeptide produces a **tripeptide**. A **polypeptide** contains a large number of amino acids. Proteins are polypeptides that contain as few as 50 or as many as 2000 amino acids. Because each variation in the number and sequence of amino acids produces a different protein, a great variety of proteins is possible. The situation is similar to using an alphabet of 20 letters to form words. Each letter would be equivalent to an amino acid, and each word would be a different protein.

An alteration in the sequence of amino acids can have serious consequences. For example, a single substitution of an amino acid in hemoglobin, a blood protein, can result in a deformed molecule that produces **sickle-cell disease** (page 360).

A protein may consist of only one polypeptide or several intertwined polypeptides. A given type of protein has a unique three-dimensional shape because of the ways that each individual polypeptide twists and folds as associated polypeptides come together. If a protein encounters a hos-

the environment in which temperature, pH, or ion concentration is significantly altered, it may unravel and lose its characteristic shape. This process is called **denaturation** (dē-nā'-chur-Ā-shun). Denatured proteins are no longer functional. A common example of denaturation is seen in frying an egg. In a raw egg, the egg-white protein (albumin) is soluble and the egg white appears as a clear, viscous fluid. When heat is applied to the egg, however, the albumin denatures; it changes shape, becomes insoluble, and turns white.

### Enzymes

As we have seen, chemical reactions occur when chemical bonds are made or broken as atoms, ions, or molecules collide with one another. At normal body temperature, such collisions occur too infrequently to maintain life. **Enzymes** (EN-zīms) are the living cell's solution to this problem, because they speed up chemical reactions by increasing the frequency of collisions and by properly orienting the colliding molecules. Substances such as enzymes that can speed up chemical reactions without themselves being altered are called **catalysts** (KAT-a-lists). In living cells, most enzymes are proteins. The names of enzymes usually end in **-ase**. All enzymes can be grouped according to the types of chemical reactions they catalyze. For example, *oxidases* add oxygen, *kinases* add phosphate, *dehydrogenases* remove hydrogen, *anhydrases* remove water, *ATPases* split ATP, *proteases* break down proteins, and *lipases* break down lipids.

Enzymes catalyze selected reactions with great efficiency and with many built-in controls. Three important properties of enzymes are their specificity, efficiency, and control.

**Specificity.** Enzymes are highly specific. Each particular enzyme catalyzes a particular chemical reaction that involves specific **substrates**, the molecules on which the enzyme acts, and that gives rise to specific **products**, the molecules produced by the reaction. In some cases, the enzyme fits the substrate like a key fits in a lock. In other cases, the enzyme changes its shape to fit snugly around the substrate once the substrate and enzyme come together. Each of the more than 1000 known enzymes in your body has a characteristic three-dimensional shape with a specific surface configuration that allows it to fit specific substrates.

**Efficiency.** Under optimal conditions, enzymes can catalyze reactions at rates that are millions to billions of times more rapid than those of similar reactions occurring without enzymes. A single enzyme molecule can convert substrate molecules to product molecules at rates as high as 600,000 per second.

**Control.** Enzymes are subject to a variety of cellular controls. Their rate of synthesis and their concentration at any given time are under the control of a cell's genes. Substances within the cell may either enhance or inhibit

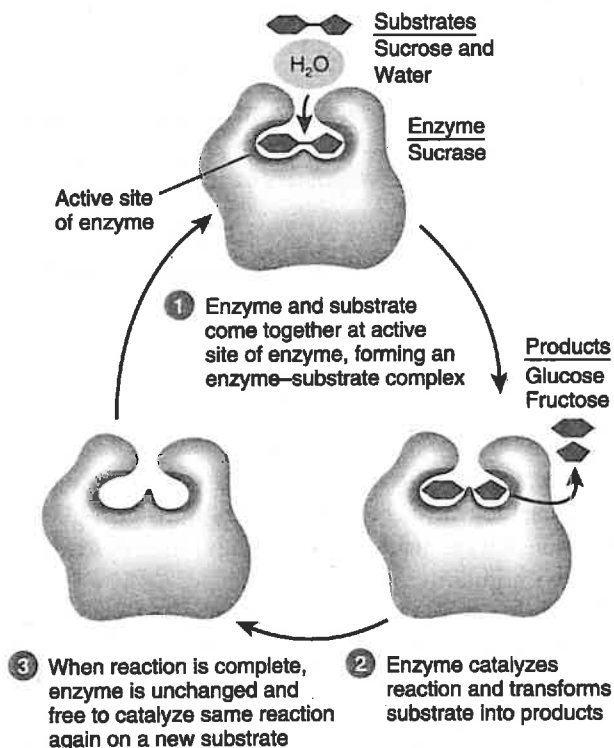
activity of a given enzyme. Many enzymes exist in both active and inactive forms within the cell. The rate at which the inactive form becomes active or vice versa is determined by the chemical environment inside the cell. Many enzymes require a nonprotein substance, known as a **cofactor** or **coenzyme**, to operate properly. Ions of iron, zinc, magnesium, or calcium are cofactors; niacin or riboflavin, derivatives of B vitamins, act as coenzymes.

Figure 2.14 illustrates the actions of an enzyme.

- 1 The substrates attach to the **active site** of the enzyme molecule, the specific part of the enzyme that catalyzes the reaction, forming a temporary compound called the **enzyme-substrate complex**. In this reaction, the substrates are the disaccharide sucrose and a molecule of water.
- 2 The substrate molecules are transformed by the rearrangement of existing atoms, the breakdown of the substrate molecule, or the combination of several substrate molecules into products of the reaction. Here the products are two monosaccharides: glucose and fructose.
- 3 After the reaction is completed and the reaction products move away from the enzyme, the unchanged enzyme is free to attach to another substrate molecule.

Figure 2.14 How an enzyme works.

 An enzyme speeds up a chemical reaction without being altered or consumed.



 What part of an enzyme combines with its substrate?

Enzyme deficiencies may lead to certain disorders. For example, some people do not produce enough lactase, an enzyme that breaks down the disaccharide lactose into the monosaccharides glucose and galactose. This deficiency causes a condition called **lactose intolerance**, in which undigested lactose retains fluid in the feces, and bacterial fermentation of lactose results in the production of gases. Symptoms of lactose intolerance include diarrhea, gas, bloating, and abdominal cramps after consumption of milk and other dairy products. The severity of symptoms varies from relatively minor to sufficiently serious to require medical attention. Persons with lactose intolerance can take dietary enzyme supplements to aid in the digestion of lactose.

### Nucleic Acids: Deoxyribonucleic Acid (DNA) and Ribonucleic Acid (RNA)

**Nucleic acids** (noo-KLĒ-ic), so named because they were first discovered in the nuclei of cells, are huge organic molecules that contain carbon, hydrogen, oxygen, nitrogen, and phosphorus. The two kinds of nucleic acids are **deoxyribonucleic acid (DNA)** (dē-ok'-sē-rī'-bō-noo-KLĒ-ik) and **ribonucleic acid (RNA)**.

A nucleic acid molecule is composed of repeating building blocks called **nucleotides**. Each nucleotide of DNA consists of three parts (Figure 2.15a):

- One of four different **nitrogenous bases**, ring-shaped molecules that contain atoms of C, H, O, and N.
- A five-carbon monosaccharide called **deoxyribose**.
- A **phosphate group** ( $\text{PO}_4^{3-}$ ).

In DNA, the four bases are adenine (A), thymine (T), cytosine (C), and guanine (G). Figure 2.15b shows the following structural characteristics of the DNA molecule:

1. The molecule consists of two strands, with crossbars. The strands twist about each other in the form of a **double helix** so that the shape resembles a twisted rope ladder.
2. The uprights (strands) of the DNA ladder consist of alternating phosphate groups and the deoxyribose portions of the nucleotides.
3. The rungs of the ladder contain paired nitrogenous bases, which are held together by hydrogen bonds. Adenine always pairs with thymine, and cytosine always pairs with guanine.

About 1000 rungs of DNA comprise a **gene**, a portion of a DNA strand that performs a specific function, for example, providing instructions to synthesize the hormone insulin. Humans have about 30,000 genes. Genes determine which traits we inherit, and they control all the activities that take

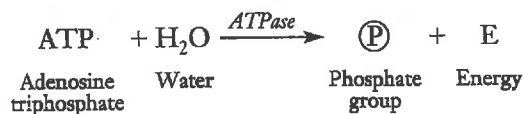
place in our cells throughout a lifetime. Any change that occurs in the sequence of nitrogenous bases of a gene is called a **mutation**. Some mutations can result in the death of a cell, cause cancer, or produce genetic defects in future generations.

RNA, the second kind of nucleic acid, is copied from DNA but differs from DNA in several respects. DNA is double-stranded, RNA is single-stranded. The sugar in the RNA nucleotide is ribose, and RNA contains the nitrogenous base uracil (U) rather than thymine. Cells contain three different kinds of RNA: messenger RNA, ribosomal RNA, and transfer RNA. Each has a specific role to perform in carrying out the instructions encoded in DNA, as will be described in Chapter 3.

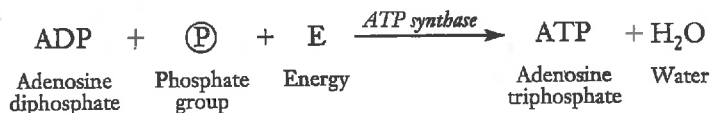
### Adenosine Triphosphate

**Adenosine triphosphate** (a-DEN-ō-sēn trī-FOS-fāt) or **ATP** is the “energy currency” of living organisms. As you learned earlier in the chapter, ATP transfers energy from energy-releasing reactions to energy-requiring reactions that maintain cellular activities. Among these cellular activities are contraction of muscles, movement of chromosomes during cell division, movement of structures within cells, transport of substances across cell membranes, and synthesis of larger molecules from smaller ones.

Structurally, ATP consists of three phosphate groups attached to adenosine, which is composed of adenine and ribose (Figure 2.16). The energy-transferring reaction occurs via hydrolysis: Removal of the last phosphate group ( $\text{PO}_4^{3-}$ ), symbolized by  $\text{P}$  in the following discussion, by addition of a water molecule liberates energy and leaves a molecule called **adenosine diphosphate (ADP)**. The enzyme that catalyzes the hydrolysis of ATP is called **ATPase**. This reaction may be represented as follows:



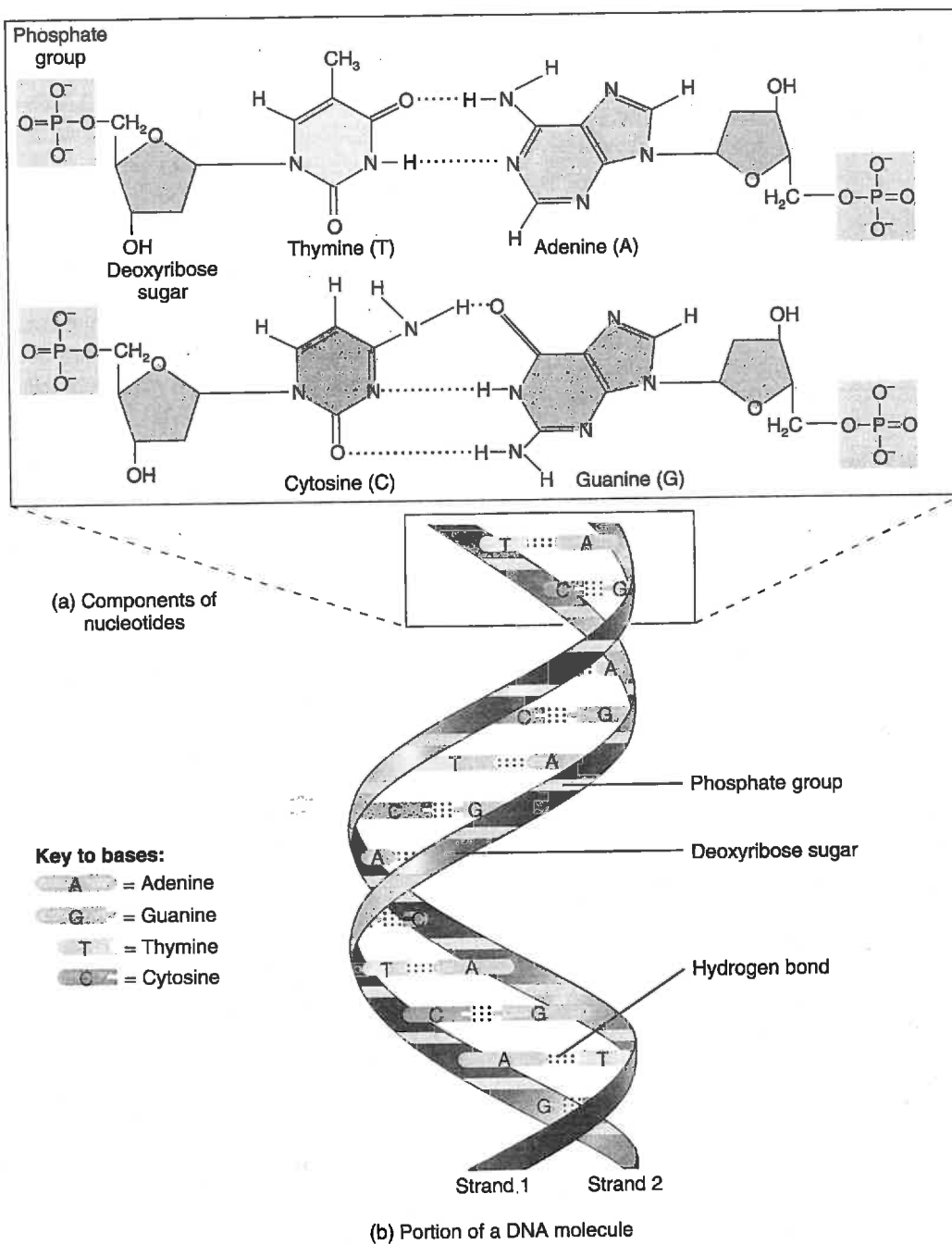
The energy released by the breakdown of ATP into ADP is constantly being used by the cell. As the supply of ATP at any given time is limited, a mechanism exists to replenish it: The enzyme **ATP synthase** promotes the addition of a phosphate group to ADP. The reaction may be represented as follows:



As you can see from this reaction, energy is required to produce ATP. The energy needed to attach a phosphate group to ADP is supplied mainly by the breakdown of glucose in a process called cellular respiration, which you will learn more about in Chapter 20.

**Figure 2.15 DNA molecule.** (a) A nucleotide consists of a nitrogenous base, a five-carbon sugar, and a phosphate group. (b) The paired nitrogenous bases project toward the center of the double helix. The structure is stabilized by hydrogen bonds (dotted lines) between each base pair. There are two hydrogen bonds between adenine and thymine and three between cytosine and guanine.

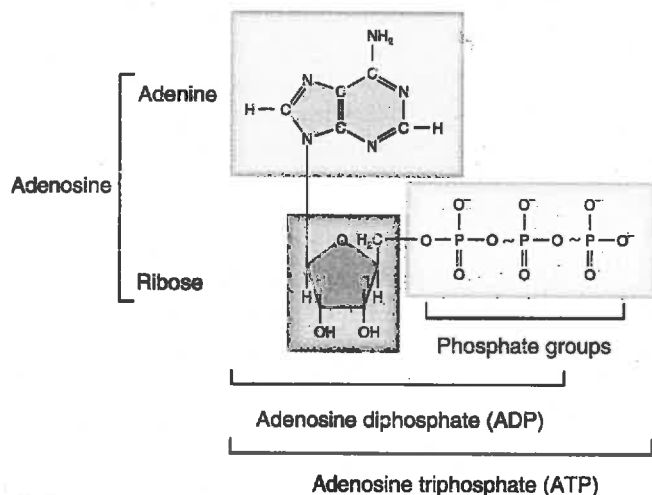
**Nucleotides are the building blocks of nucleic acids.**



? Which nitrogenous base is not present in RNA? Which nitrogenous base is not present in DNA?

**Figure 2.16 Structure of ATP and ADP.** The two phosphate bonds that can be used to transfer energy are indicated in red. Most often energy transfer involves hydrolysis of the terminal phosphate bond of ATP.

ATP transfers chemical energy to power cellular activities.



? What are some cellular activities that depend on energy supplied by ATP?

## CHECKPOINT

- How do inorganic compounds differ from organic compounds?
- What functions does water perform in the body?
- Distinguish among saturated, monounsaturated, and polyunsaturated fats.
- What are the important properties of enzymes?
- How do DNA and RNA differ?
- Why is ATP important?

• • •

In Chapter 1, you learned that the human body is comprised of various levels of organization and that the chemical level consists of atoms and molecules. Now that you have an understanding of the chemicals in the body, you will see in the next chapter how they are organized to form the structures of cells and perform the activities of cells that contribute to homeostasis.

## STUDY OUTLINE

### Introduction to Chemistry (p. 23)

- Chemistry is the science of the structure and interactions of matter, which is anything that occupies space and has mass. Matter is made up of chemical elements.
- The elements oxygen (O), carbon (C), hydrogen (H), and nitrogen (N) make up 96% of the body's mass.
- Each element is made up of units called atoms, which consist of a nucleus that contains protons and neutrons, and electrons that move about the nucleus in electron shells. The number of electrons is equal to the number of protons in an atom.
- The atomic number, the number of protons, distinguishes the atoms of one element from those of another element.
- The combined total of protons and neutrons in an atom is its mass number.
- An atom that *gives up* or *gains* electrons becomes an ion—an atom that has a positive or negative charge due to having unequal numbers of protons and electrons.
- A molecule is a substance that consists of two or more chemically combined atoms. The molecular formula indicates the number and type of atoms that make up a molecule.
- A compound is a substance that can be broken down into two or more different elements by ordinary chemical means.
- A free radical is a destructive, electrically charged ion or molecule that has an unpaired electron in its outermost shell.
- Chemical bonds hold the atoms of a molecule together.
- Electrons in the valence (outermost) shell are the parts of an atom that participate in chemical reactions.
- When outer shell electrons are transferred from one atom to another, the transfer forms ions, whose unlike charges attract each other and form ionic bonds. Positively charged ions are called cations; negatively charged ions are called anions.
- In a covalent bond, pairs of outer shell electrons are shared between two atoms.
- Hydrogen bonds are weak bonds between hydrogen and certain other atoms within large complex molecules such as proteins and nucleic acids. They add strength and stability and help determine the molecule's three-dimensional shape.
- Energy is the capacity to do work. Potential energy is energy stored by matter due to its position. Kinetic energy is the energy of matter in motion. Chemical energy is a form of potential energy stored in the bonds of molecules.
- In chemical reactions, breaking old bonds requires energy and forming new bonds releases energy.

In a synthesis (anabolic) reaction, two or more atoms, ions, or molecules combine to form a new and larger molecule. In a decomposition (catabolic) reaction, a molecule is split apart into smaller molecules, ions, or atoms.

When nutrients, such as glucose, are broken down via decomposition reactions, some of the energy released is temporarily stored in adenosine triphosphate (ATP) and then later used to drive energy-requiring synthesis reactions that build body structures, such as muscles and bones.

Exchange reactions are combination synthesis and decomposition reactions. Reversible reactions can proceed in both directions under different conditions.

### Inorganic Compounds and Life Processes (p. 29)

Organic compounds usually are structurally simple and lack carbon. Organic substances always contain carbon, usually combined with hydrogen, and always have covalent bonds.

Water is the most abundant substance in the body. It is an excellent solvent, participates in chemical reactions, absorbs and releases heat slowly, requires a large amount of heat to change from a liquid to a gas, and serves as a lubricant.

Organic acids, bases, and salts dissociate into ions in water. An acid ionizes into hydrogen ions ( $H^+$ ); a base usually ionizes into hydroxide ions ( $OH^-$ ). A salt ionizes into neither  $H^+$  nor  $OH^-$  ions.

The pH of body fluids must remain fairly constant for the body to maintain homeostasis. On the pH scale, 7 represents neutrality. Values below 7 indicate acidic solutions, and values above 7 indicate alkaline solutions.

Buffer systems help maintain pH by converting strong acids or bases into weak acids or bases.

- Carbohydrates include sugars, glycogen, and starches. They may be monosaccharides, disaccharides, or polysaccharides. Carbohydrates provide most of the chemical energy needed to generate ATP. Carbohydrates, and other large, organic molecules, are synthesized via dehydration synthesis reactions, in which a molecule of water is lost. In the reverse process, called hydrolysis, large molecules are broken down into smaller ones upon the addition of water.
- Lipids are a diverse group of compounds that include triglycerides (fats and oils), phospholipids, and steroids. Triglycerides protect, insulate, provide energy, and are stored in adipose tissue. Phospholipids are important membrane components. Steroids are synthesized from cholesterol.
- Proteins are constructed from amino acids. They give structure to the body, regulate processes, provide protection, help muscles to contract, transport substances, and serve as enzymes.
- Enzymes are molecules, usually proteins, that speed up chemical reactions and are subject to a variety of cellular controls.
- Deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) are nucleic acids consisting of nitrogenous bases, five-carbon sugars, and phosphate groups. DNA is a double helix and is the primary chemical in genes. RNA differs in structure and chemical composition from DNA; its main function is to carry out the instructions encoded in DNA.
- Adenosine triphosphate (ATP) is the principal energy-transferring molecule in living systems. When it transfers energy, ATP is decomposed by hydrolysis to adenosine diphosphate (ADP) and  $P_i$ . ATP is synthesized from ADP and  $P_i$  using primarily the energy supplied by the breakdown of glucose.

### SELF-QUIZ

A substance that dissociates in water to form  $H^+$  is called  
a. a base    b. a salt    c. a buffer    d. an acid    e. a nucleic acid

Covalent bonds are characterized by

a. sharing electrons between atoms

b. their ability to form strong, stable bonds

c. atoms giving away and taking electrons

d. the type of bonding formed in most organic compounds

e. the attraction between water molecules

If an atom has two electrons in its second electron shell and its first electron shell is filled, it will tend to

a. lose two electrons from its second electron shell

b. lose the electrons from its first electron shell

c. lose all of the electrons from its first and second electron shells

d. gain six electrons in its second electron shell

e. gain two electrons in its second electron shell

- Matter that cannot be broken down into simpler substances by chemical reactions is known as  
a. a molecule    b. an antioxidant  
c. a compound    d. a buffer    e. a chemical element
- Chlorine (Cl) has an atomic number of 17. An atom of chlorine may become a chloride ion ( $Cl^-$ ) by  
a. losing one electron    b. losing one neutron  
c. gaining one proton    d. gaining one electron  
e. gaining two electrons
- Which of the following is NOT true?  
a. A substance that separates in water to form some cation other than  $H^+$  and some anion other than  $OH^-$  is known as a salt.  
b. A solution that has a pH of 9.4 is acidic.  
c. A solution with a pH of 5 is 100 times more acidic than distilled water, which has a pH of 7.  
d. Buffers help to make the body's pH more stable.  
e. Amino acids are linked by peptide bonds.

7. Which of the following organic compounds are NOT paired with their correct subunits (building blocks)?
  - a. glycogen, glucose
  - b. proteins, monosaccharides
  - c. DNA, nucleotides
  - d. lipids, glycerol and fatty acids
  - e. ATP, ADP and P
8. The type of reaction by which a disaccharide is formed from two monosaccharides is known as a
  - a. decomposition reaction
  - b. hydrolysis reaction
  - c. dehydration synthesis reaction
  - d. reversible reaction
  - e. dissociation reaction
9. Which of the following contains the genetic code in human cells?
  - a. DNA
  - b. enzymes
  - c. RNA
  - d. glucose
  - e. ATP
10. What is the principal energy-transferring molecule in the body?
  - a. ADP
  - b. RNA
  - c. DNA
  - d. ATP
  - e. NAD
11. Which of the following statements about water is NOT true?
  - a. It is involved in many chemical reactions in the body.
  - b. It is an important solvent in the human body.
  - c. It helps lubricate a variety of structures in the body.
  - d. It can absorb a large amount of heat without changing its temperature.
  - e. It requires very little heat to change from a liquid to a gas.
12. The difference in  $H^+$  concentration between solutions with a pH of 3 and a pH of 5 is that the solution with the pH of 3 has \_\_\_\_  $H^+$ .
  - a. 2 times more
  - b. 5 times more
  - c. 10 times more
  - d. 100 times more
  - e. 200 times less
13. Which of the following is NOT a true statement about enzyme activity?
  - a. Enzymes form a temporary complex with their substrates
  - b. Enzymes are not permanently altered by the chemical reactions they catalyze.
  - c. All proteins are enzymes.
  - d. Enzymes are considered to be organic catalysts.
  - e. Enzymes are subject to cellular control.
14. For each item in the following list, place an R if it applies to RNA or a D if it refers to DNA; use R and D if it applies to both RNA and DNA.
  - \_\_\_\_ a. composed of nucleotides
  - \_\_\_\_ b. forms a double helix
  - \_\_\_\_ c. contains thymine
  - \_\_\_\_ d. contains the sugar ribose
  - \_\_\_\_ e. contains the nitrogenous base uracil
  - \_\_\_\_ f. is the hereditary material of cells
  - \_\_\_\_ g. contains the sugar deoxyribose
  - \_\_\_\_ h. is single-stranded
  - \_\_\_\_ i. contains adenine
  - \_\_\_\_ j. contains phosphate groups
15. An organic compound that consists of C, H, and O and that may be broken down into glycerol and fatty acids is a
  - a. triglyceride
  - b. nucleic acid
  - c. monosaccharide
  - d. carbohydrate
  - e. protein
16. Why is it important to consume foods that contain antioxidants?
  - a. They provide an energy source for the body.
  - b. They help inactivate damaging free radicals.
  - c. They make up the body's genes.
  - d. They act as buffers to help maintain the blood's pH.
  - e. They are important solvents in the body.
17. If an enzyme is exposed to an extremely high temperature, it will
  - a. divide
  - b. release energy
  - c. become an electrolyte
  - d. form hydrogen bonds
  - e. denature
18. In what form are lipids stored in the adipose (fat) tissue of the body?
  - a. triglycerides
  - b. glycogen
  - c. cholesterol
  - d. polypeptides
  - e. disaccharides
19. Approximately 96% of your body's mass is composed of which of the following elements? Place an X beside each correct answer.
 

____ calcium	____ iron	____ nitrogen
____ phosphorus	____ sodium	____ chlorine
____ carbon	____ oxygen	____ sulfur
____ hydrogen	____ potassium	____ magnesium
20. Match the following:
 

____ a. inorganic compound	A. glycogen
____ b. monosaccharide	B. enzyme
____ c. polysaccharide	C. glucose
____ d. component of triglycerides	D. water
____ e. lipase	E. glycerol

## CRITICAL THINKING APPLICATIONS

1. While having a tea party, your three-year-old cousin Sabrina added milk, lemon juice, and lots of sugar to her tea. The tea now has strange white lumps floating in it. What caused the milk to curdle?
2. Joy is very proud of her healthy diet. "I drink only pure spring water and eat organic foods. I have a chemical-free body." Sonia replied, "Ever hear of  $H_2O$ ?" Explain the error in Joy's reasoning.
3. Albert, Jr., was trying out the new Super Genius Home Chemistry Kit that he got for his birthday. He decided to check the

pH of his secret formula: lemon juice and diet cola. The pH was 2.5. Next he added tomato juice. Now he has a really disgusting mixture with a pH of 3.5. "Wow! That's twice as strong!" Does Albert, Jr., have the makings of a "Super Genius"? Explain.

4. During chemistry lab, Maria places sucrose (table sugar) in a glass beaker, adds water, and stirs. As the table sugar disappears, she loudly proclaims that she has chemically broken down the sucrose into fructose and glucose. Is Maria's chemical analysis correct?

## ANSWERS TO FIGURE QUESTIONS

- 2.1 The atomic number of carbon is 6.
- 2.2 The four most plentiful elements in living organisms are oxygen, carbon, hydrogen, and nitrogen.
- 2.3 Water is a compound because it contains atoms of both hydrogen and oxygen.
- 2.4 K is an electron donor; when it ionizes, it becomes a cation,  $K^+$ , because losing one electron from the fourth electron shell leaves eight electrons in the third shell.
- 2.5 An ionic bond involves the *loss* and *gain* of electrons; a covalent bond involves the *sharing* of pairs of electrons.
- 2.6  $CaCO_3$  is a salt, and  $H_2SO_4$  is an acid.
- 2.7 A pH of 6.82 is more acidic than a pH of 6.91. Both pH = 8.41 and pH = 5.59 are 1.41 pH units from neutral (pH = 7).
- 2.8 There are 6 carbons in fructose, 12 in sucrose.

- 2.9 Glycogen is stored in liver and skeletal muscle cells.
- 2.10 A monounsaturated fatty acid has one double bond.
- 2.11 A triglyceride has three fatty acid molecules attached to a glycerol backbone, and a phospholipid has two fatty acid tails and a phosphate group attached to a glycerol backbone.
- 2.12 The dietary lipids thought to contribute to atherosclerosis are cholesterol and saturated fats.
- 2.13 A tripeptide would have two peptide bonds, each linking two amino acids.
- 2.14 The enzyme's active site combines with the substrate.
- 2.15 Thymine is present in DNA but not in RNA, and uracil is present in RNA but not in DNA.
- 2.16 A few cellular activities that depend on energy supplied by ATP are muscular contractions, movement of chromosomes, transport of substances across cell membranes, and synthesis reactions.