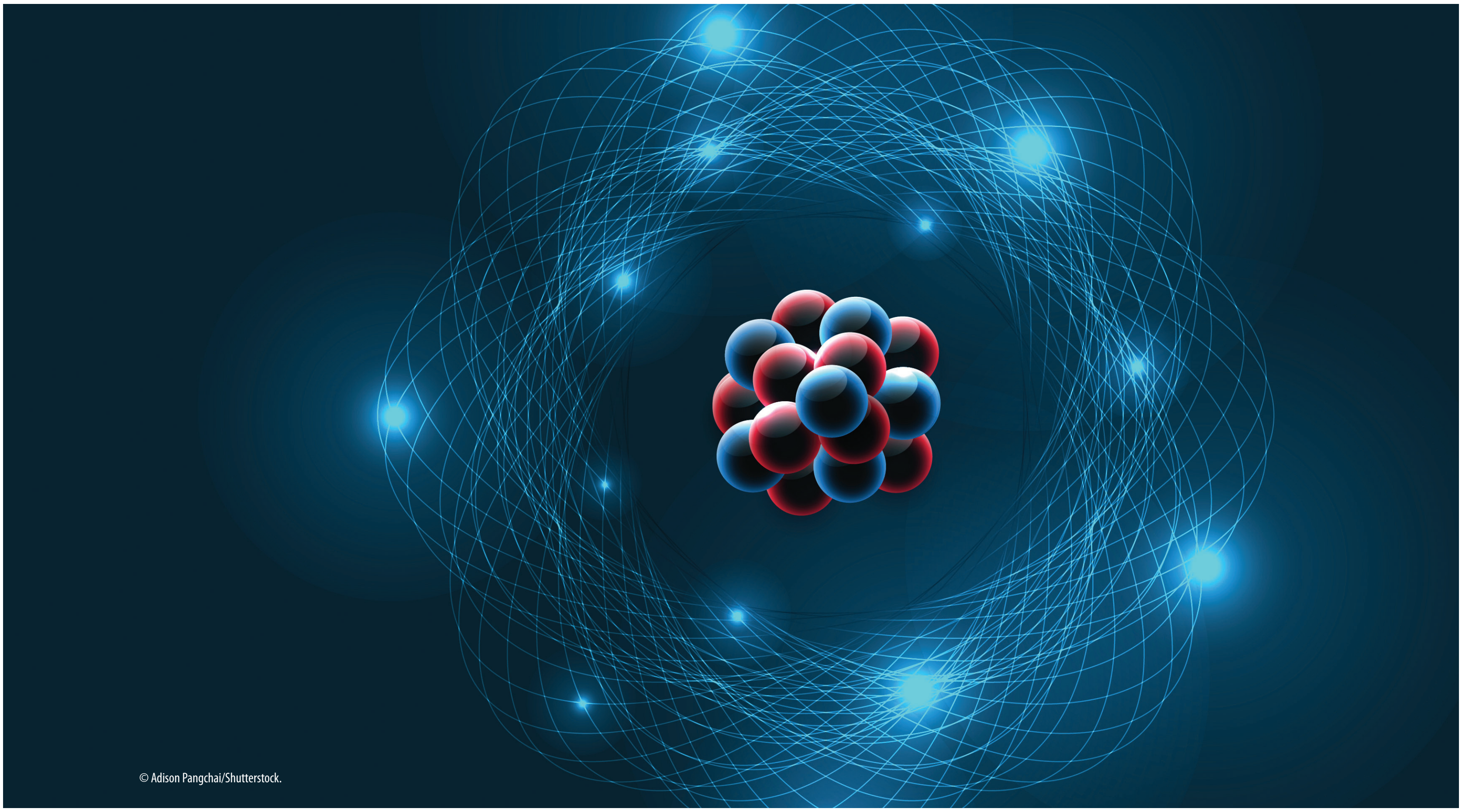
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CHAPTER 2

Chemical Basics of Life

OUTLINE

OBJECTIVES

After studying this chapter, readers should be able to

1. Describe the relationships between atoms and molecules.
2. Explain chemical bonds.
3. Describe how an atomic number is determined.
4. List the major groups of inorganic chemicals common in cells.
5. Explain acids, bases, and buffers.
6. Define the characteristics of lipids and proteins.
7. Define pH.
8. Describe the functions of various types of organic chemicals in cells.
9. List four examples of steroid molecules.
10. Explain nucleic acids.

Overview

Chemistry is the science that deals with the structure of matter, and the study of the human body begins with chemistry. It is essential for other sciences, including physiology, pathology, pharmacology, and microbiology. Life is based on atomic, molecular, and chemical interactions. Each cell of the body contains organelles made up of macromolecules, and the cells then compose tissues and organs. The chemical basics of life require the interactions of all these components.

Basic Chemistry

Studying basic chemistry and its relation to anatomy and physiology is important as the entire human body is made up of chemicals. Basic chemistry takes into account matter, the states of matter, and **energy** in all its various types. This chapter focuses on both basic chemistry and biochemistry.

Matter is a term that describes all things occupying space and having *mass*. Most types of matter can be sensed in various forms. Mass is not exactly the same as *weight*. An object's mass is equal to its actual amount of matter. Mass remains constant regardless of where the object is located. Weight is different because it varies with gravity. For example, because of differences in gravitational pull, your body weighs slightly more at extremely low sea levels and slightly less at extremely high sea levels. However, your body's mass is exactly the same at both levels. Chemistry studies the nature of matter and how chemical building blocks interact and how they are constructed.

The various *states* of matter are *gaseous, liquid*, and *solid*. The human body contains examples of all three states. Gases have no shape or definite volume. An example is the air that we breathe. *Liquids* have definite volume but are "shaped" by the structure containing them. An example is blood plasma, which assumes the shape of the blood vessels. *Solids* have a definite shape and volume. Examples include teeth and bones.

Atoms, Molecules, and Chemical Bonds

The composition of matter and changes in its composition are the focuses of the study of chemistry. If you understand chemistry, your understanding of anatomy and physiology improves. Chemical changes within cells influence body functions and the status of the body's structures. Chemicals of the body include water, proteins, carbohydrates, lipids, nucleic acids, and salts as well as foods, drinks, and medications.

Elements are fundamental substances that compose matter. Copper, iron, gold, silver, aluminum, carbon, hydrogen, and oxygen are all examples of elements. Most living organisms need about 20 elements to survive. **TABLE 2-1** lists the major and trace elements required by the human body. The *periodic table of elements* is a tabular arrangement of the chemical elements, and organized on the basis of atomic numbers, electron configurations, and recurring chemical properties. The elements are presented in order of increasing atomic number, which is the number of protons in the nucleus (**FIGURE 2-1**).

Atoms are tiny particles that compose elements, and are the smallest complete units of an element that retain its properties and vary in size, weight, and

TABLE 2-1 Elements of the Human Body

Element	Percentage in the Body
Major elements (totaling 99.9%)	
Oxygen (O)	65
Carbon (C)	18.5
Hydrogen (H)	9.5
Nitrogen (N)	3.2
Calcium (Ca)	1.5
Phosphorus (P)	1
Potassium (K)	0.4
Sulfur (S)	0.3
Chlorine (Cl)	0.2
Sodium (Na)	0.2
Magnesium (Mg)	0.1
Trace elements (totaling 0.1%)	
Chromium (Cr)	—
Cobalt (Co)	—
Copper (Cu)	—
Fluorine (F)	—
Iodine (I)	—
Iron (Fe)	—
Manganese (Mn)	—
Zinc (Zn)	—

interaction with other atoms. The characteristics of living and nonliving objects result from the atoms they contain and how those atoms combine and interact. Thus, by forming chemical bonds, atoms can combine with other atoms that are not similar to them.

Atomic Structure

Atoms are composed of subatomic particles and each atom consists of protons, neutrons, and electrons. Protons and neutrons are similar in size and mass; however, **protons** bear a positive electrical charge, whereas **neutrons** are electrically neutral (uncharged). **Electrons** bear a negative electrical charge. An atom's mass is determined mostly by the number of protons and neutrons in its **nucleus**. The nucleus contains approximately the entire mass (99.9%) of the atom. The mass of a larger object, such as the human body, is the sum of the masses of all its atoms. **FIGURE 2-2** shows the components of an atom and its nucleus.

Electrons orbit an atom's nucleus at high speed, forming a spherical electron cloud. Atoms normally contain equal numbers of protons and electrons. The number of protons in an atom is known as its **atomic number**. Thus, hydrogen (H), the simplest atom, has one proton, giving it the atomic number 1, whereas magnesium, with 12 protons, has the atomic number 12.

The **atomic weight** of an element's atom equals the number of protons and neutrons in its nucleus. For example, oxygen has eight protons and eight neutrons, so its atomic weight is 16. An **isotope** is defined as when an element's atoms have nuclei containing the same number of protons but different number of neutrons. Isotopes may or may not be radioactive. Radioactivity is the emission of energetic particles known as *radiation*, which occurs because of instability of the atomic nuclei.

The nuclei of certain isotopes (**radioisotopes**) spontaneously emit subatomic particles or radiation in measurable amounts. The process of emitting radiation is called *radioactive decay.* Strong radioactive isotopes are dangerous because their emissions can destroy molecules, cells, and living tissue. For diagnostic procedures, weak radioactive isotopes are used to diagnose structural and functional characteristics of internal organs. Radiation is basically identified as one of three common forms: alpha (α), beta (β), or gamma (γ). Gamma radiation is the most penetrating type and is similar to X-ray radiation.

Health professionals and researchers use radioactive isotopes for clinical applications because they are easily detected and measured. All isotopes of a certain element have the same atomic number. For example, two types of iodine, 125-iodine and 131-iodine, can substitute for 126-iodine in chemical reactions. Iodine may be used in diagnostic procedures involving the thyroid gland to detect thyroid cancer.

	Group IA	Group IIA	Group IIIA	Group IVA	Group VA	Group VIA	Group VIIA	Group VIII	Group VIII	Group VIII	Group IB	Group IIB	Group IIIB	Group IVB	Group VB	Group VIB	Group VIIB	Group 0
Period 1	1 H 1.008																	2 He 4.003
Period 2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
Period 3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
Period 4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.70	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
Period 5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
Period 6	55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)
Period 7	87 Fr (223)	88 Ra (226.0)	89 Ac (227)	104 Unq	105 Unp	106 Unh	107 Uns		109 Une									

Lanthanides (rare earth metals)

58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0

Actinides

90 Th 232.0	91 Pa (231)	92 U 238.0	93 Np (244)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

KEY

16	Atomic number
S	Symbol of element
32.06	Atomic mass

Metals · Metalloids · Nonmetals · Noble Gases

FIGURE 2-1 Periodic table of elements.

TEST YOUR UNDERSTANDING

1. Define the term "atom" and explain its structure.
2. Differentiate between atomic weight and atomic number.
3. Describe the locations of electrons, protons, and neutrons.
4. Define the terms "atomic number" and "radioisotopes."

Molecules and Compounds

The term **molecule** is defined as any chemical structure that consists of atoms held together by covalent bonds (involving the sharing of electrons between atoms). When two atoms of the same element bond, they produce molecules of that element such as hydrogen, oxygen, or nitrogen molecules. Most atoms are chemically combined with other atoms. For example, when two oxygen atoms combine, a molecule of O_2 (oxygen gas) is formed.

When two different kinds of atoms combine, they form molecules of a *compound* (see "Covalent Bonds" later in this chapter). **Compounds** are chemically

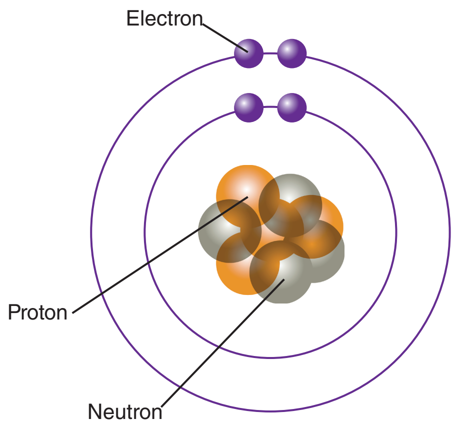

FIGURE 2-2 The components of an atom.

pure, with identical molecules. A molecule is the smallest particle of a compound that still has the specific characteristics of that compound. Examples of compounds include water (a compound of hydrogen and oxygen), dry ice (frozen carbon dioxide), table sugar, baking soda, alcohol (as used in beverages), natural gas, and most medicinal drugs. A molecule of a compound has specific types and amounts of atoms (see "Hydrogen Bonds" later in this chapter).

Mixtures

Mixtures are substances containing two or more components that are physically *intermixed*. They do not chemically combine and may not occur in fixed (specific) proportions. An example is the various powders combined together in a capsule with an active drug. The individual characteristics of the components of a mixture are not lost. They may be separated from each other if this is required. The three basic types of mixtures are colloids, solutions, and suspensions. In nature, most matter exists in the form of mixtures. Colloids, solutions, and suspensions are each found in both living and nonliving systems. Living material is the most complex mixture of all, containing colloids, solutions, and suspensions—all of which interact with each other.

Colloids

Colloids are also known as *emulsions*. Their composition differs in various areas of their mixtures, meaning they are referred to as *heterogeneous mixtures*. Colloids have solute particles that are larger than the particles in true solutions and do not settle. The appearance of a colloid is often milky or translucent. Light is scattered when shown through a colloid, meaning the path of the light beam is visible.

Colloids often have the ability to undergo *sol–gel transformations*. This means they can change (reversibly) from a sol (fluid) state to a gel (more solid) state. An example of a nonliving colloid that undergoes a sol–gel transformation (when refrigerated) is a gelatin product such as Jell-O. Also, the reverse process occurs when these products are heated, such as by sunlight, with their state returning to a liquid. In living cells, the semifluid material known as cytosol undergoes sol–gel transformations. **Cytosol** has many dispersed proteins, and these transformations are the basis for cell division, cell shape changes, and other important activities.

Solutions

Solutions may be gases, liquids, or solids that are homogeneous mixtures of these components. This means the mixture has exactly the same composition throughout in terms of the atoms or molecules it contains. One sample of any part of the mixture will reveal an identical composition to any other sample of the mixture. Examples include ocean water (which is a mixture of water and salts) and environmental air (which is a mixture of gases). In a mixture, the **solvent** is the substance that is present in the largest amount. A solvent is also known as a *dissolving medium* and is usually a liquid. The substances present in a mixture in smaller amounts are called **solutes**.

In the human body, water is the primary solvent. Most body solutions are called *true solutions*, which are usually transparent. They contain gases, liquids, or solids dissolved in water. True solutions are exemplified by mineral water, glucose/water, and saline solution (which is a mixture of sodium chloride and water). In true solutions, the solutes are minute, usually consisting of individual atoms and molecules. These microscopic solutes do not scatter light (allow a beam of light to pass through) or settle.

True solutions are described by their *concentration*, which is often described in parts per 100% of the solute in the total solution. Water is usually assumed to be the solvent. True solutions may also be described in *milligrams per deciliter* (mg/dL). Another way to describe true solutions is **molarity** (M), which is defined as *moles per liter*. This is a complicated but more chemically useful method. A **mole** is equal to an element or compound's atomic weight or **molecular weight**, in grams. For example, glucose is written as a combination of 6 carbon atoms, 12 hydrogen atoms, and 6 oxygen atoms ($C_6H_{12}O_6$). To find its molecular weight, you must multiply the number of atoms of each component by its atomic weight. Then, you must add the total atomic weights of the three components to find the total atomic weight of glucose. In this example, carbon's 6 atoms multiplied by its atomic weight of 12.011 equals a total atomic weight of 72.066. Using the same formula, the total atomic weights of hydrogen (12.096) and oxygen (95.994) are added together to find that the total atomic weight of glucose is 180.156. Overall, it is important to understand that 1 mole of any substance always contains exactly the same number of solute particles. This is referred to as *Avogadro's number*, and is calculated in molecules of the substance as 6.02×10^{23}. In body fluids, because solute concentrations are very low, their values are usually described in terms of *millimoles* (Mmol or 1/1,000 mole).

Suspensions

Suspensions, known as *heterogeneous mixtures*, have large, often visible solutes that usually settle. In the blood, living blood cells are *suspended* in the fluid portion of the blood (the blood plasma). When a blood sample is left still for a period of time, the suspended cells settle unless they are mixed or shaken. In the body, they do not settle because of blood circulation.

TEST YOUR UNDERSTANDING

1. Define the terms molecule, compound, and mixture.
2. List examples of true solutions in the body.
3. Define the terms mole, molarity, and molecular weight.

Chemical Bonds

Atoms can bond with other atoms by using chemical bonds that result from interactions between their electrons. During this process, the atoms may gain, lose, or share electrons. Chemically inactive atoms are known as *inert* atoms. An example of a chemical that is made up of inert atoms is helium. Atoms that either gain or lose electrons are called **ions**. These atoms are electrically charged. An example of an electrically charged atom or ion is sodium. The three important types of chemical bonds are ionic, covalent, and hydrogen.

Ionic Bonds

Ionic bonds form between ions. They are chemical bonds between atoms that form because of the transfer of electrons. The atom gaining one or more electrons is referred to as the *electron acceptor*. Ions that acquire a net positive charge are called **cations** and those that acquire a net negative charge are called **anions**.

Oppositely charged ions attract each other to form an *ionic bond*, which is a chemical bond that forms arrays (indiscreet molecules) such as crystals. An example is when sodium forms an ionic bond with chloride to create sodium chloride (or table salt). An ionic bond is shown in **FIGURE 2-3**. Sodium has an atomic number of 11 and only has one electron inside its valence shell (its outermost energy level that contains electrons). If this electron is lost, the second shell (with eight electrons) becomes the valence shell. The loss of the single electron in the third (outer) shell causes sodium to become stable, meaning it is then a cation. Oppositely, chlorine (with an atomic number of 17) needs only one electron to fill its valence shell. When it gains one electron, it becomes stable and is then an anion.

The interaction of sodium and chlorine involves sodium donating one electron to chlorine. Oppositely charged ions then attract each other to form sodium chloride. Examples of ionic bonds include atoms that have one or two valence shell electrons and atoms that have seven valence shell electrons. Those with one or two valence shell electrons include calcium, potassium, and sodium (all are metallic elements) and those with seven valence shell electrons include chlorine, fluorine, and iodine.

In this category, most ionic compounds are referred to as *salts*. They do not exist as individual molecules in their dry state, but instead form **crystals**. These are large collections of cations and anions held together by ionic bonds. Sodium chloride gives us an example of a compound that is very different from the atoms that make it up individually. Separately, sodium is a metal that is silver white in color. Chlorine is a green-colored gas. Mixed together to become sodium chloride, the result is a white crystalline solid (table salt).

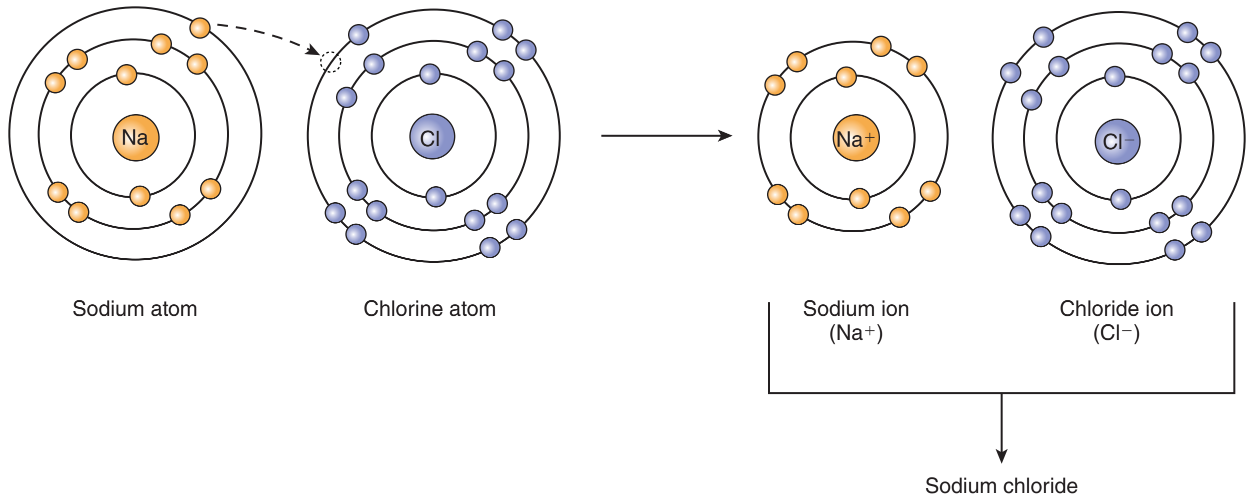

FIGURE 2-3 Ionic bond.

Covalent Bonds

For atoms to achieve stability, electrons do not have to be completely transferred. They may be shared, meaning each atom can fill its outer electron shell for part of the time. When electrons are shared, this produces molecules in which the shared electrons are located in a single orbital that is common to both atoms, which makes up a **covalent bond**. Hydrogen has only one electron. It can fill its only shell, labeled as *Shell 1*, when a pair of electrons from another atom is shared. If a hydrogen atom shares with another hydrogen atom, a molecule of hydrogen gas is formed. Therefore, the shared electron pair orbits around the molecule *as a whole* to make each atom achieve stability. An example of a covalent bond is when two hydrogen atoms bond to form a hydrogen molecule (**FIGURE 2-4**).

Each atom has different needs in terms of bonding to achieve stability. Shared electrons orbit and become part of the whole molecule, which ensures the stability of each atom. Hydrogen has only its one electron but needs two. Carbon has four electrons in its outer shell but needs eight for stability. For a methane molecule (CH_4), carbon shares four pairs of electrons with four hydrogen atoms, meaning one pair with each hydrogen atom. A single covalent bond is formed when two atoms share one pair of electrons. A double covalent bond occurs when two electron pairs are shared. Likewise, a triple covalent bond occurs when three electron pairs are shared. When written, the amount of covalent bonds present are signified by using single, double, or triple horizontal lines, as (using oxygen as the example): O—O, O═O or O≡O.

Polar and Nonpolar Molecules

In covalent bonds, molecules may be either polar or nonpolar. **Nonpolar molecules** are electrically balanced. They do not have separate positive and negative poles of charge. However, this does not always occur. Covalent bonds always have a specific three-dimensional shape to their molecules. The bonds are formed at definite angles. The shape helps to determine other atoms or molecules with which the original molecule can interact. However, it may also cause unequal electron pair sharing.

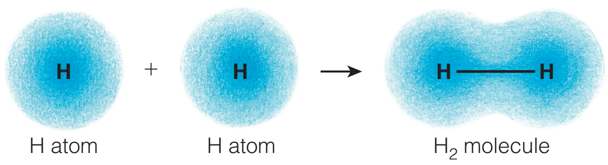

FIGURE 2-4 Covalent bond.

This creates a **polar** molecule. This is common in nonsymmetric molecules that contain atoms with different electron-attracting abilities.

Oxygen, nitrogen, and chlorine are examples of electro-hungry atoms that attract electrons strongly. This is a capability of atoms known as **electronegativity**. These small atoms have six or seven valence shell electrons. However, most atoms that have only one or two valence shell electrons are **electropositive**. Their ability to attract electrons is so low that, most often, they lose their own valence shell electrons to other atoms. Potassium and sodium each have one valence shell electron and are examples of electropositive atoms.

Whether a covalently bonded molecule will be polar or nonpolar is determined by the molecular shape and related electron-attracting ability of each atom. For example, in the carbon dioxide molecule, four electron pairs of carbon are shared with two oxygen atoms, meaning two pairs are shared with each oxygen. Because oxygen is extremely electronegative, it attracts the shared electrons more strongly than carbon is able to. Even so, because the carbon dioxide molecule is symmetric and linear, the ability of one oxygen atom to pull electrons is offset by the other oxygen atom. Therefore, the shared electrons continue to orbit the entire molecule, and carbon dioxide is a nonpolar compound.

A different example exists in the water molecule, which is V-shaped or bent. On the same end of this molecule, there are two electropositive hydrogen atoms located. The most electronegative oxygen atom is at the opposite end. Therefore, oxygen can pull the shared electrons away from the two hydrogen atoms. The electron pairs are not shared equally; instead, they are closer to the oxygen for most of the time. Because of the negative charges of electrons, the oxygen end is slightly more negative and the hydrogen end slightly more positive. Water is a polar molecule with two poles of charge, which is also called a **dipole**.

Polar molecules are essential for chemical reactions in body cells. They orient themselves toward charged particles (ions, certain proteins, etc.) or other dipoles. Various molecules have different degrees of polarity. There is a gradual change from ionic to nonpolar covalent bonding. Complete electron transfer is referred to as an *ionic bond*. Equal electron sharing is known as a **nonpolar covalent bond**. These are extreme compared with each other. There are various degrees of unequal electron sharing in between these two extremes. Nonpolar covalent bonds are very common and involve carbon atoms that make up most structural components of the human body.

Hydrogen Bonds

When the positive hydrogen end of a polar molecule is attracted to the negative nitrogen or oxygen end of another polar molecule, the attraction is called a **hydrogen bond** (**FIGURE 2-5**). Hydrogen atoms already covalently linked to one electronegative atom (such as oxygen or nitrogen) are attracted by an atom requiring electrons, forming a "bridge." These bonds are weak at body temperature. In environmental extremes, they may change form, from water to ice and back again. Hydrogen bonds are important in protein and nucleic acid structure, forming between polar regions of different parts of a single, large molecule. Hydrogen bonding commonly occurs between *dipoles*, an example of which is the water molecule. It occurs because the (slightly) negative oxygen atoms of a certain molecule attract the (slightly) positive hydrogen atoms of another molecule. Therefore, because of hydrogen bonding, water molecules usually cling together. They form *films*, and this formation process is referred to as **surface tension**. As a result, water beads into spheres when it is on a hard surface such as a countertop. This is also the reason that certain small insects are able to walk on the surface of a body of water.

Hydrogen bonds are too weak to bind atoms together and form molecules. However, they are important *intramolecular bonds*, holding different parts of one large molecule in a specific three-dimensional shape. Proteins and DNA are examples of large biologic molecules that have many hydrogen bonds helping to maintain and stabilize their structures. The water molecule is one excellent example of a hydrogen bond. It consists of two hydrogen atoms and one oxygen atom. Another example occurs when two hydrogen atoms bind with two oxygen atoms, forming hydrogen peroxide.

Because the properties of compounds are usually different from the properties of their contained atoms, it is difficult to tell which atoms are contained without a chemical analysis (e.g., water, which is made up of hydrogen and oxygen). The numbers and types of atoms in a molecule are represented by a *molecular formula*. The molecular formula for water is H_2O, signifying the two atoms of hydrogen and the one atom of oxygen. *Structural formulas* are used to signify how atoms are joined and arranged inside molecules. Single bonds are represented by single lines and double bonds are represented by double lines. When structural formulas are represented in three-dimensional models, different colors are used to show different types of atoms.

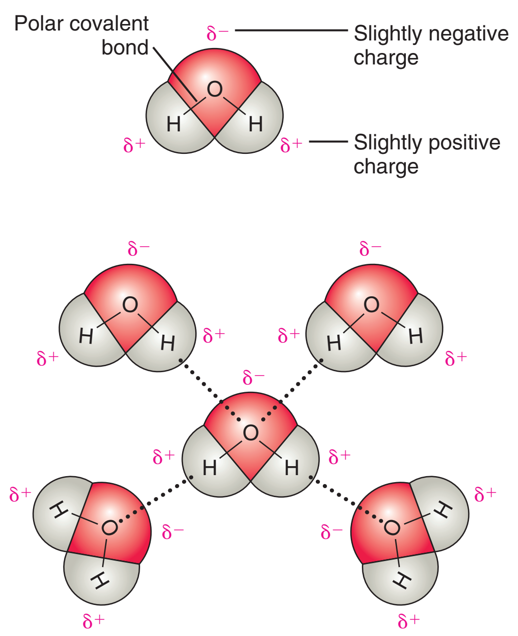

FIGURE 2-5 Hydrogen bonding between polar water molecules.

TEST YOUR UNDERSTANDING

1. Distinguish between ionic bonds and covalent bonds.
2. Which kind of bond holds together atoms in a water molecule?
3. Describe polar and nonpolar molecules.

Chemical Reactions

A **chemical reaction** occurs when a chemical bond is formed, broken, or rearranged. Chemical reactions are written using symbols, which are known as *chemical equations*. Any number that is written in a smaller letter that appears below the level of the main text (a subscript) indicates the atoms are joined by chemical bonds. A number written as a prefix shows the number of unjoined atoms or molecules. For example, for H_2O, the number "2" indicates that two hydrogen atoms are bonded together with one oxygen atom to form the water molecule. If an equation used the term "2H," it would mean there were two unjoined hydrogen atoms. A chemical equation contains the kinds and number of reacting substances (**reactants**), the chemical composition of the results (**products**), and, if the equation is *balanced*, the relative proportion of each reactant and each product. Four types of chemical reactions are important to the study of physiology: synthesis, decomposition, exchange, and reversible.

Synthesis Reactions

Chemical reactions change the bonds between atoms, molecules, and ions to generate new chemical combinations. **Synthesis** is a reaction that occurs when two or more reactants (atoms) bond to form a more complex product or structure. The formation of water from hydrogen and oxygen molecules is a synthesis reaction. Synthesis always involves the formation of new chemical bonds, whether the reactants are atoms or molecules. Synthesis requires energy, important for growth and repair of tissues. Synthesis is symbolized as: $A + B \rightarrow AB$.

Decomposition Reactions

Decomposition is a reaction that occurs when bonds within a reactant molecule break, forming simpler atoms, molecules, or ions. For example, a typical meal contains molecules of sugars, proteins, and fats that are too large and too complex to be absorbed and used by the body. Decomposition reactions in the digestive tract break these molecules down into smaller fragments before absorption begins. Decomposition is symbolized as: $AB \rightarrow A + B$.

Exchange Reactions

In an **exchange reaction**, parts of the reacting molecules are shuffled around to produce new products. For example, an exchange reaction is the reaction of an acid with a base, which forms water and a salt. Exchange reactions are symbolized as: $AB + CD \rightarrow AD + CB$.

Reversible Reactions

A **reversible reaction** is one where the products of the reaction can change back into the reactants they originally were. These reactions can proceed in opposite directions, depending on the relative proportions of reactants and products as well as how much energy is available.

So, if $A + B \rightarrow AB$, then $AB \rightarrow A + B$. Many important biological reactions are freely reversible. Such reactions can be represented as the equation $A + B \rightarrow AB$.

TEST YOUR UNDERSTANDING

1. Describe four kinds of chemical reactions.
2. What are the structural formulas for synthesis reactions and exchange reactions?
3. Explain decomposition reactions.

Acids, Bases, and the pH Scale

Acids are **electrolytes** that release **hydrogen ions** (H^+) in water. An example of an acid is hydrochloric acid, made up of hydrogen and chloride ions. **Bases** are electrolytes that release hydroxide (OH^-) ions that bond with hydrogen ions. An example of a base is sodium hydroxide (NaOH), made up of sodium, oxygen, and hydrogen ions. In body fluids, the concentrations of hydrogen and hydroxide ions affect chemical reactions by a considerable amount. These reactions control certain physiological functions such as blood pressure and breathing rates.

The **bicarbonate ion** (HCO_3^-) is important in the human body, and found in large amounts in the blood. **Ammonia** (NH_3) is a base that is also a waste product of the body's breakdown of protein. Ammonia has one pair of unshared electrons that have a strong ability to attract protons. When a proton is accepted, ammonia becomes an ammonium ion (NH_4^+) in the following process:

$$NH_3 + H^+ \rightarrow NH_4^+$$

Hydrogen ion concentrations in body fluids are vital, and can be measured by the value **pH**. It is expressed in a type of mathematical shorthand based on concentrations calculated in moles per liter (with a mole representing an amount of solute in a solution). The pH of a solution is defined as the level of acidity or basicity. The pH scale ranges from 0 to 14, with 7 being the midpoint (meaning it has equal numbers of hydrogen and hydroxide ions). Pure water has a pH of 7, and this midpoint is considered to be neutral (neither acidic nor basic). Therefore, a solution contains an equal number of hydrogen ions and hydroxide ions are neutral. Measurements of less than 7 pH are considered acidic, meaning there are more hydrogen ions than hydroxide ions. Measurements of more than 7 pH are considered basic, also known as alkaline, meaning there are more hydroxide ions than hydrogen ions.

The pH of blood usually ranges from 7.35 to 7.45. Abnormal fluctuations in pH can damage cells and tissues, change the shapes of proteins, and alter cellular functions. *Acidosis* is an abnormal physiological state caused by blood pH that is lower than 7.35. If pH falls below 7, coma may occur. The two different types of acidosis are *metabolic* and *respiratory*. Metabolic acidosis is a condition in which the kidneys are not able to remove ketone bodies, which are metabolites of fats. In patients with type 1 diabetes, the body may be producing too many ketone bodies. Respiratory acidosis occurs in patients suffering from chronic lung diseases such as emphysema or chronic bronchitis.

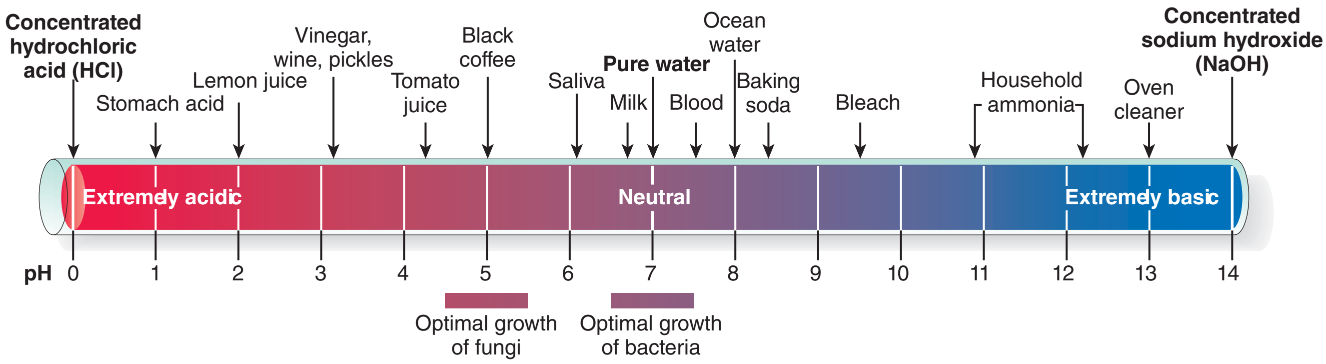

FIGURE 2-6 pH scale.

Higher carbon dioxide concentrations in the blood results in blood pH decreasing.

Alkalosis results from blood pH that is higher than 7.45. If pH rises above 7.8, it generally causes uncontrollable and sustained skeletal muscle contractions. Alkalosis also may be metabolic or respiratory. Metabolic alkalosis involves elevations of tissue pH, either as a result of decreased hydrogen ion concentration or a direct result of increased bicarbonate concentrations. Respiratory alkalosis is caused by increased respiration, which elevates the blood pH. It may be caused by pneumonia, stroke, meningitis, fever, and pregnancy.

Chemicals that resist pH changes are called *buffers*. They combine with hydrogen ions when these ions are excessive and contribute hydrogen ions when these ions are reduced. **FIGURE 2-6** shows the pH values of acids and bases. An example of a buffer that is important in body fluids is *sodium bicarbonate*.

TEST YOUR UNDERSTANDING

1. Define electrolytes, acids, and bases.
2. What does pH measure?
3. Define the pH of a solution.

FOCUS ON PATHOLOGY

Metabolic acidosis is a decrease in plasma pH that is not caused by a respiratory disorder. Chronic renal disease leads to metabolic acidosis, as a result of reduced H^+ excretion, as well as altered bicarbonate reabsorption. The most common causes of metabolic acidosis include accumulation of ketones and lactic acid, renal failure, and ingestion of drugs or toxins.

Biochemistry

Biochemistry, also known as *biological chemistry*, is the study of chemical processes within and relating to living organisms. Chemicals can basically be divided into two main groups: organic and inorganic. **Organic** chemicals are those that always contain the elements carbon and hydrogen and generally oxygen as well. **Inorganic** chemicals are any chemicals that do not contain any elements. Inorganic substances release ions in water and are also called electrolytes. Although many organic substances dissolve in water, they dissolve to great effect in alcohol or ether. Organic substances that dissolve in water usually do not release ions and are known as *nonelectrolytes*.

Inorganic Substances

Inorganic substances in body cells include water, salts, and acids/bases.

Water

The most abundant compound in the human body is water, accounting for nearly two-thirds of the body weight. Any substance that dissolves in water is called a *solute*. Because solutes dissolved in water are more likely to react with each other as they break down into smaller particles, most metabolic reactions occur in water. There are five major properties of water:

- *Cushioning*: Protection of certain organs from physical trauma (e.g., cerebrospinal fluid that cushions the brain)
- *High heat capacity*: Ability to absorb and release large amounts of heat before water itself actually changes temperature to any large degree; this prevents sudden temperature changes from external factors such as exposure to sun or wind or from internal conditions that quickly release heat such

as vigorous muscle activity; in the blood, water redistributes heat among tissues, maintaining homeostasis

- *High vaporization heat*: Water changes from liquid to gas (water vapor), which requires large amounts of heat to be absorbed in order to break hydrogen bonds that keep water molecules together; this is valuable as part of sweating—since mostly water evaporates from the skin, the body is efficiently cooled
- *Polar solvent properties*: Water is referred to as the **universal solvent**, since nearly all chemical reactions in the body require its solvent properties. As a result, biochemistry is called *wet chemistry*. Biological molecules only react chemically when they are in a solution. Water molecules are polar, and their slightly negative ends are oriented toward the positive ends of solutes, The reverse is also true. Solute molecules are attracted and then surrounded. This is why acids, bases, other small reactive molecules, and ionic compounds *dissociate* in water. Their ions separate from each other and scatter throughout the water, forming true solutions.
    - Water also forms **hydration layers** of its molecules around large charged molecules such as proteins. Hydration layers shield the molecules from other nearby charged substances, preventing them from settling out of the solution. These protein-water mixtures are known as *biological colloids*. Examples include blood plasma and cerebrospinal fluid.
    - The solvent properties of water make it the body's major transport system. Metabolic wastes, nutrients, and respiratory gases are carried to be dissolved in the blood plasma. Many metabolic wastes are excreted as urine. Lubricants such as mucus use water to dissolve other substances.
- *Reactivity*: For many chemical reactions, water is an important reactant; an example is when foods are broken down to their components by adding a water molecule to each bond.

Salts

Salts are compounds of oppositely charged ions that are abundant in tissue fluids. A salt is an ionic compound that contains cations other than hydrogen ions and anions other than the hydroxyl ion. When salts are dissolved in water, they dissociate into their component ions. One example is when sodium sulfate (Na_2SO_4) dissociates into two sodium ions and one SO_4^{2-} ion. It dissociates easily since its ions are already formed. Water then easily overcomes the attraction between the oppositely charged ions.

All ions are electrolytes, which conduct electrical currents when in solution. Electrolytes release ions in water. As they dissolve in water, the negative and positive ends of water molecules cause ions to separate and interact with water molecules instead of each other. The resulting solution contains electrically charged particles (ions) that conduct electricity. Groups of atoms that have an overall charge, such as sulfate, are known as *polyatomic ions.*

In the body, common salts include sodium chloride (NaCl), calcium carbonate ($CaCO_3$), and potassium chloride (KCl). The most plentiful salts are the calcium phosphates, which are utilized to harden the bones and teeth. The ionized form of salts is used for vital body functions. Salt ions are important for transporting substances to and from the cells, muscle contractions, and nerve impulse conduction. Ionic iron makes up part of the hemoglobin molecules transporting oxygen inside red blood cells. Certain enzymes require zinc and copper ions. Other important functions of elements from body salts include:

- *Calcium*: Found as a salt in bones and teeth, its ionic form is needed for blood clotting, conduction of nerve impulses, and muscle contraction
- *Chlorine*: Its ion, chloride, is the most abundant anion in extracellular fluids
- *Iron*: A component of hemoglobin and some enzymes
- *Phosphorus*: Part of calcium phosphate salts in bones and teeth, also in nucleic acids, and is a part of adenosine triphosphate (ATP)
- *Potassium*: Its ion is the major positive cation in cells; vital for conduction nerve impulses and muscle contraction
- *Sodium*: Its ion is the major positive ion in extracellular fluids; important for conduction of nerve impulses, muscle contraction, and water balance

TEST YOUR UNDERSTANDING

1. Distinguish between organic and inorganic chemicals.
2. Define the term "biochemistry" and list its other descriptive title.
3. What are the five major properties of water?

Organic Substances

Organic substances include carbohydrates, lipids, proteins, and nucleic acids. Many organic molecules are made up of long chains of carbon atoms linked by

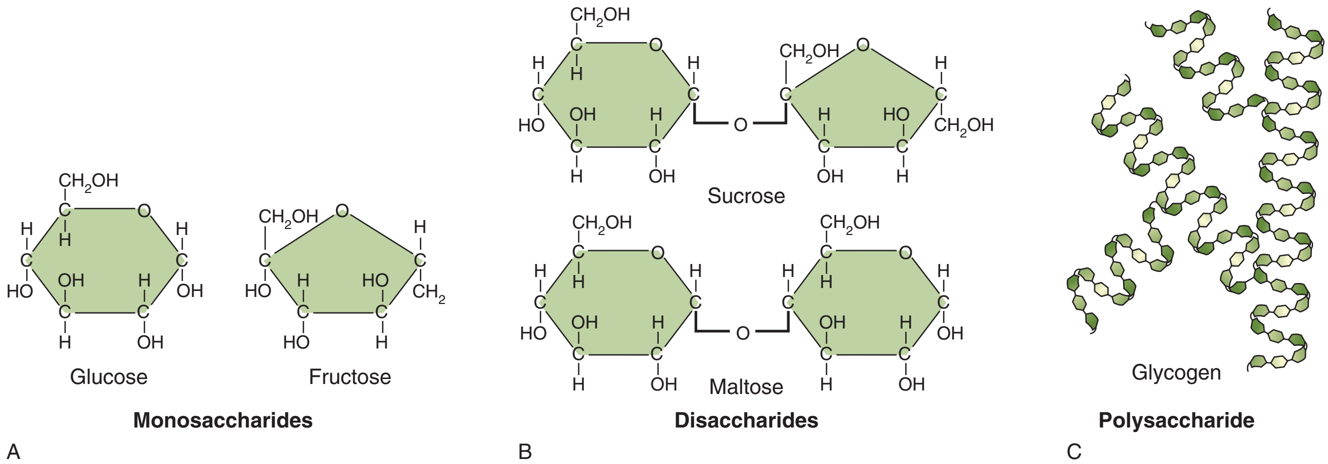

FIGURE 2-7 (**A**) Monosaccharide, (**B**) disaccharide, and (**C**) polysaccharide.

covalent bonds. The carbon atoms usually form additional covalent bonds with hydrogen or oxygen atoms and less commonly with nitrogen, phosphorus, sulfur, or other elements.

Carbohydrates

Carbohydrates provide much of the energy required by the body's cells and help to build cell structures. Carbohydrate molecules consist of carbon, hydrogen, and oxygen molecules. The carbon atoms they contain join in chains that vary with the type of carbohydrate. The hydrogen and oxygen atoms usually occur in a 2:1 ratio, which is the same as in water. In most cases, the overall carbon to hydrogen to oxygen ratio is 1:2:1. Carbohydrates with shorter chains are called *sugars*. Carbohydrates also include *starches*. Collectively, carbohydrates represent 1% to 2% of cell mass in the body. The term *carbohydrate* actually means "hydrated carbon." Usually, the larger the carbohydrate molecule, the less soluble it is in water. Carbohydrate molecules are the body's most readily available source of energy.

Monosaccharides

Simple sugars have 6 carbon atoms, 12 hydrogen atoms, and 6 oxygen atoms ($C_6H_{12}O_6$). They are also known as **monosaccharides**. Simple sugars include glucose, fructose, galactose, ribose, and deoxyribose. Ribose and deoxyribose differ from the others in that they each contain five atoms of carbon. The most important metabolic fuel molecule in the body is glucose. Monosaccharides are single chain or single ring structures. They may contain between three and seven carbon atoms. Monosaccharides are generally named based on the number of carbon atoms they contain. In the human body, the most important ones are the pentose (five-carbon) and hexose (six-carbon) sugars (**FIGURE 2-7**).

Disaccharides

Complex carbohydrates include sucrose (table sugar) and lactose (milk sugar). Some of these carbohydrates are double sugars or **disaccharides** and are formed when two monosaccharides are joined by *dehydration synthesis*. A water molecule is lost as the bond is made. Another important disaccharide is *maltose* (malt sugar). Disaccharides cannot pass through cell membranes because of their size, so instead are digested to simple sugar units for absorption from the digestive tract. They decompose via *hydrolysis*, which is basically the reverse process of dehydration synthesis. A water molecule is added, which breaks the bond and releases the simple sugar units.

Polysaccharides

Other types of complex carbohydrates contain many simple joined sugar units such as plant starch, and are known as **polysaccharides**. They are polymers of simple sugars, linked together via dehydration synthesis, and function as storage products because they are large and fairly insoluble. They are less sweet than the simple and double sugars. Humans and other animals synthesize a polysaccharide called glycogen.

In all animal tissues, *glycogen* is the storage carbohydrate. It is mostly stored in the skeletal muscle and liver, and is highly branched (like starch) and made up of large molecules. When the blood sugar level drops quickly, the liver cells break down glycogen releasing its glucose units into the blood. Because of many branch ends that can release glucose at the same time, body cells can have almost immediate stores of glucose to use as fuel.

Only glycogen and starch are of major importance in the human body. They are glucose polymers with different forms of *branching*. *Starch* is the storage carbohydrate that is formed by plants, with high and variable amounts of glucose units. Starches include potatoes and grain products. Starches must be digested for absorption. Humans cannot digest **cellulose**, which is another polysaccharide found in plants, but it functions as *bulk*, a form of fiber, which aids in peristalsis of feces.

Carbohydrates are primarily used by the body for ever-ready, easy-to-use cellular fuel. Glucose is the primary form of fuel used by most cells, which in general can only use a few types of other simple sugars. Remember that glucose is broken down and oxidized inside cells, during which time electrons are transferred. This releases the bond energy that is stored in the glucose, and ATP can be synthesized. When ATP is sufficiently present, carbohydrates from the diet can be converted to glycogen (or fat) and stored in the body. For structural needs, only tiny amounts of carbohydrates are used. There are some sugars in human genes, whereas others are attached to external cell surfaces and used to guide interactions between cells.

Lipids

Lipids are insoluble in water, but may dissolve in other lipids, oils, ether, chloroform, or alcohol. Lipids include a variety of compounds such as triglycerides, phospholipids, and steroids with vital cell functions. Fats are the most common type of lipids. They provide roughly twice the energy of carbohydrates. Lipids help to maintain body temperature. Like carbohydrates, fat molecules also contain carbon, hydrogen, and oxygen but have far fewer oxygen atoms than do carbohydrates. Some complex lipids also contain phosphorus. **Lipoproteins** are complexes or compounds that contain lipids and proteins. Nearly all lipids in the plasma are present as lipoproteins. There are five types of lipoproteins:

- High-density lipoproteins (HDL): Good cholesterol
- Low-density lipoproteins (LDL): Bad cholesterol
- Very-high-density lipoproteins (VHDL)
- Very-low-density lipoproteins (VLDL)
- Intermediate-density lipoproteins (IDL)

Triglycerides

Fatty acids and glycerol are the building blocks of fat molecules. A single fat molecule consists of one glycerol molecule bonded to three fatty acid molecules. These fat molecules are known as **triglycerides**, also called *neutral fats*, a subcategory of lipids that includes fats (when solid) and oils (when liquid). These molecules are formed by the condensation of one molecule of glycerol, which is a three-carbon sugar alcohol (a modified simple sugar). A triglyceride contains three **fatty acid** molecules and glycerol. Triglycerides contain different saturated and unsaturated fatty acid combinations. Those with the most saturated fatty acids are called **saturated fats** and those with the most unsaturated fatty acids are called **unsaturated fats**. In general, the ratio of fatty acids to glycerol in a triglyceride is 3:1. Via dehydration synthesis, fat synthesis involves the attachment of three fatty acid chains to just one glycerol molecule. An E-shaped molecule is developed. The fatty acid chains vary, but the glycerol is always the same in all triglycerides.

Fatty acids are linear chains of carbon and hydrogen atoms known as *hydrocarbon chains*, with an organic acid group located at one end. They consist of a long hydrocarbon *tail* and a smaller area consisting of a carboxyl group known as the *head* (**FIGURE 2-8**). Triglycerides may be made up of hundreds of atoms. Fats and oils, after being consumed, must be broken down to their simpler building blocks before they can be absorbed. Nonpolar molecules are made from their hydrocarbon chains. Oils (fats) and water cannot mix because polar and nonpolar molecular molecules cannot interact. Triglycerides provide the body's best type of stored energy. Upon oxidizing, they release large amounts of energy. Deeper body tissues are protected from heat loss and mechanical trauma by triglycerides, which are mostly found beneath the skin. Women have a thicker subcutaneous fatty layer than men, which helps to insulate them from colder temperatures.

Saturated fat is defined as containing carbon atoms that are bound to as many hydrogen atoms as possible becoming saturated with them. The degree of saturation determines how solid the molecule is at various temperatures. Saturated fats have fatty acid changes with single covalent bonds between carbon atoms (**FIGURE 2-9**). These straight fatty acid chains have saturated fat molecules packed closely together at room temperature making them solid. Longer fatty

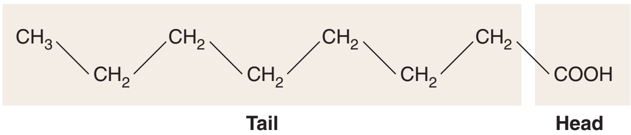

FIGURE 2-8 Parts of a fatty acid.

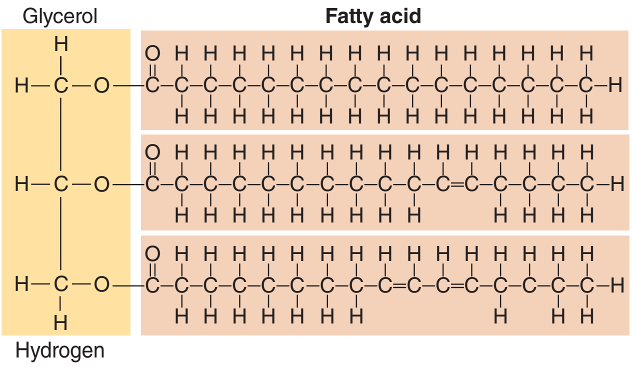

FIGURE 2-9 Saturated fats.

acid chains and fatty acids with more saturation are commonly found in animal fats and butterfat, which are solid at room temperature.

Fatty acid molecules with one double bond between carbon atoms are called *unsaturated*. Double bonds cause fatty acid chains to form "kinks," meaning they cannot be packed closely enough to solidify. Therefore, triglycerides with either short fatty acid chains or unsaturated fatty acids are oils. They are liquid at room temperature, a typical factor of plant lipids. Examples include oils from corn, olives, peanuts, safflowers, and soybeans. Unsaturated fats (especially olive oil) are healthier. Fatty acid molecules with many double-bonded carbon atoms are called *polyunsaturated*. **FIGURE 2-10** compares the differences between saturated and unsaturated fats.

Many types of margarines and baked products contain **trans fats**, which are oils solidified by adding hydrogen atoms at the sites of carbon double bonds. Trans fats are now known to increase risks for heart disease even more significantly than solid animal fats. Oppositely, the **omega-3 fatty acids** from coldwater fish are known to decrease the risk of heart disease and certain inflammatory diseases.

Phospholipids

Similar to a fat molecule, a **phospholipid** consists of a glycerol portion with fatty acid chains. They are structurally related to glycolipids and are actually modified triglycerides. Human cells can synthesize both types of lipids, primarily from fatty acids. A phospholipid includes a phosphate group that is soluble in water and two molecules of fatty acids. They are an important part of cell structures. The distinctive chemical properties of phospholipids come from the phosphorus-containing group. The tails of these

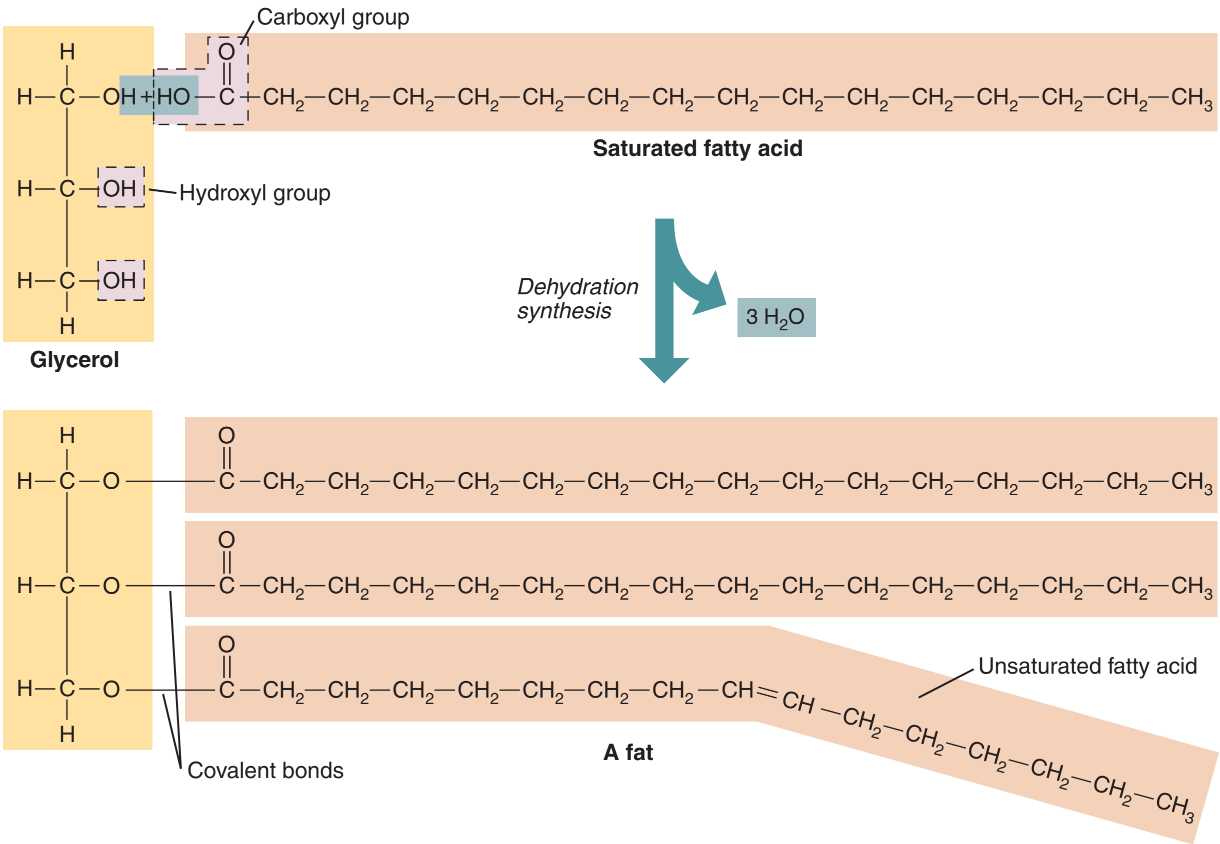

FIGURE 2-10 Saturated versus unsaturated fats.

molecules (the hydrocarbon portion) are nonpolar; they react only with nonpolar molecules. The heads of these molecules (the phosphorus-containing part) are polar, attracting other polar or charged particles (including ions or water). The unique phospholipids can be used as the primary material for the building of cell membranes.

Steroids

Steroid molecules are large, basically flat lipid molecules that share a distinctive carbon framework in comparison with fats or oils. Steroids have four connected rings of carbon atoms. All steroid molecules have the same basic structure: three six-carbon rings joined to one five-carbon ring. They include cholesterol, estrogen, progesterone, testosterone, cortisol, and estradiol (**FIGURE 2-11**). Steroids are also fat soluble and have little to no oxygen. Steroid hormones are vital for homeostasis. The sex hormones include the *sex steroids*, which are essential for reproduction. If no *corticosteroids* were produced by the adrenal glands, it would be fatal.

Cholesterol is the most important steroid and is ingested in animal foods such as cheese, eggs, and meat. The liver also produces certain amounts of cholesterol. Although essential for human life, excessive cholesterol participates in atherosclerosis and related disease. In the cell membranes, cholesterol is the raw material that helps to synthesize vitamin D, bile salts, and steroid hormones.

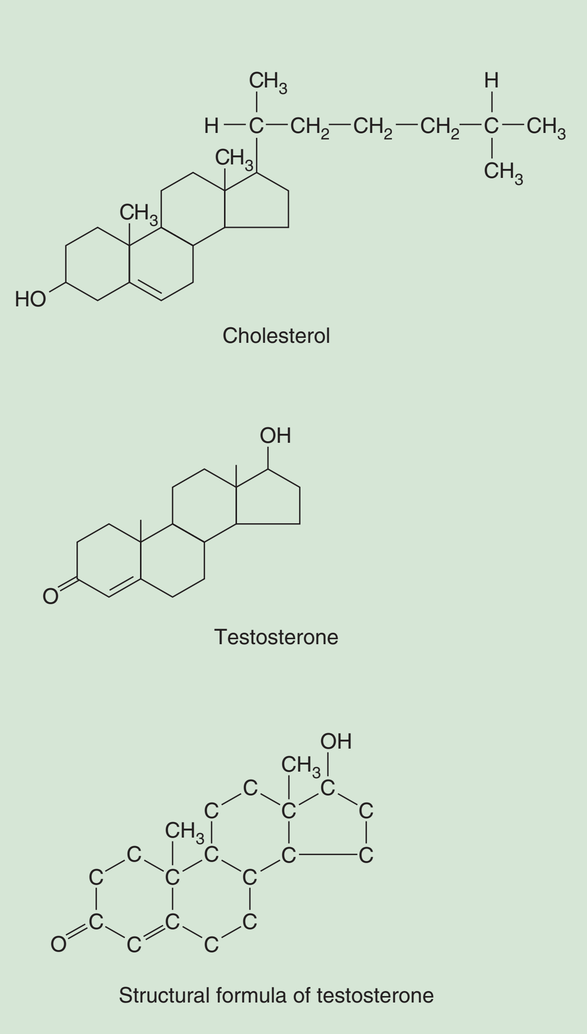

FIGURE 2-11 Various types of steroid molecules.

Eicosanoids

Eicosanoids are lipids that are mostly derived from **arachidonic acid**, a 20-carbon fatty acid existing in all cell membranes, the most important of which are the *prostaglandins* and related acids. Prostaglandins are important for blood clotting, inflammation, labor contractions, regulation of blood pressure, and many other body processes. Prostaglandin synthesis and inflammatory effects are blocked by medications such as the cyclooxygenase inhibitors and nonsteroidal anti-inflammatory drugs.

TEST YOUR UNDERSTANDING

1. Explain the most common type of lipids and list the components their molecules contain.
2. Distinguish between saturated and unsaturated fats.
3. Define the terms phospholipid and steroid.
4. What are the roles of prostaglandins?

FOCUS ON PATHOLOGY

Dyslipidemia is elevation of plasma cholesterol, triglycerides, or both. It may also be a low level of high-density lipoproteins, which contributes to the development of atherosclerosis.

Proteins

Proteins are the most abundant organic components of the human body and in many ways the most important. They make up between 10% and 30% of cell mass and are the basic structural materials of the body. Proteins are vital for many body functions. On cell surfaces, some proteins combine with carbohydrates to become glycoproteins. They allow cells to respond to certain molecules that bind to them. Proteins include biologic **catalysts** (enzymes), contractile proteins of muscles, and the hemoglobin of the blood.

There are more than 200,000 types of proteins in the human body, the full set known as the **proteome**. Antibodies are proteins that detect and destroy foreign substances. All proteins contain carbon, hydrogen, oxygen, and nitrogen atoms, with small quantities of sulfur also present. Proteins always contain nitrogen atoms. Twenty common **amino acids**, both essential and nonessential, make up the proteins that exist in humans and most other living organisms (**TABLE 2-2**). Amino acids are the building blocks of proteins, with two primary groups: *amines* and *organic acids*. Amino acids act as either bases (proton acceptors) or acids (proton donors). All amino acids are exactly the same except for one group of atoms, known as the amino acid's *R group*. Differences in the R group determine the chemical uniqueness of each amino acid (**FIGURE 2-12**).

TABLE 2-2 Essential and Nonessential Amino Acids	
Amino Acid	**Abbreviation**
Alanine	Ala
Arginine	Arg
Asparagine	Asn
Aspartic acid	Asp
Cysteine	Cys
Glutamic acid	Glu
Glutamine	Gln
Glycine	Gly
Histidine	His
Isoleucine	Ile
Leucine	Leu
Lysine	Lys
Methionine	Met
Phenylalanine	Phe
Proline	Pro
Serine	Ser
Threonine	Thr
Tryptophan	Trp
Tyrosine	Tyr
Valine	Val

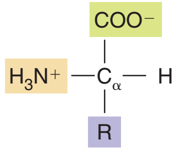

FIGURE 2-12 General amino acid.

Protein molecules consisting of amino acids held together by peptide bonds are called *peptides*, which are joined together via dehydration synthesis. The amine end of one amino acid is linked to the acid end of the next amino acid. This forms the characteristic atomic arrangement of a **peptide bond**. Each type of peptide is named for the amount of amino acids that are united: *dipeptide* (2), *tripeptide* (3), *polypeptide* (10 or more), and so on. Although most proteins are **macromolecules**, polypeptides that contain more than 50 amino acids are called proteins. *Macromolecules* are large and complex, with as few as 100 to over 10,000 amino acids.

Every type of amino acid has its own distinct properties. The way they bind determines how the proteins they produce are structured and how they function. A change in one amino acid that is linked to others produces an entirely unique function. Such a change can also make the protein become nonfunctional. Examples of proteins include insulin, oxytocin, and glucagon (**FIGURE 2-13**).

Types of Proteins

Proteins are generally classified as either fibrous or globular. **Fibrous proteins** are longer and resemble "strands" and are highly stable and insoluble in water. They provide mechanical support and tensile strength for body tissues. **Collagen**, the most abundant protein in the body, is a fibrous protein as are elastin, keratin, and some contractile proteins found in muscles. Because of their supporting functions, they are also called *structural proteins*.

Globular proteins are more compact than fibrous proteins and spherical in shape. They are chemically active and water-soluble. Globular proteins are important in almost all biologic processes and are therefore also referred to as *functional proteins*. Examples of globular proteins are antibodies, protein-based hormones, and enzymes. Antibodies function in immunity,

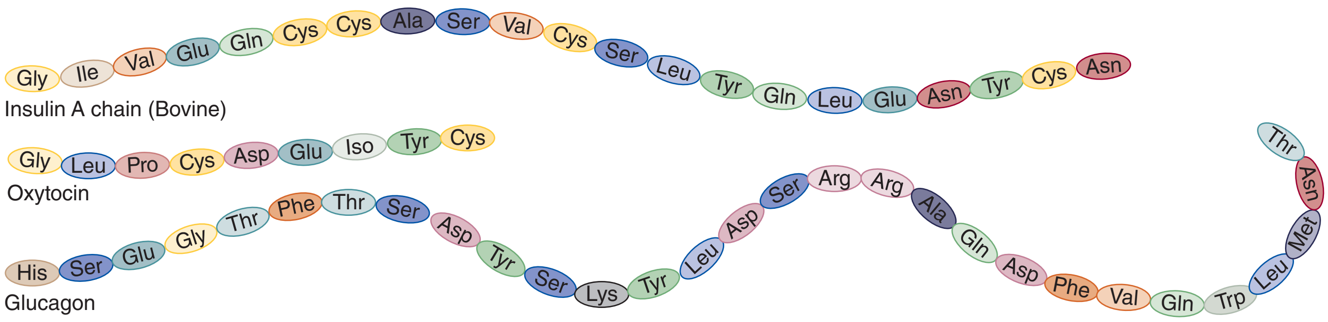

FIGURE 2-13 Examples of proteins.

whereas protein-based hormones control growth and development. Enzymes are catalysts for nearly every chemical reaction taking place in the body.

TEST YOUR UNDERSTANDING

1. List some of the functions of proteins in the human body.
2. Explain how a peptide bond forms.
3. Differentiate between fibrous and globular proteins.

FOCUS ON PATHOLOGY

Protein–energy undernutrition (PEU) is an energy deficit caused by chronic deficiency of all macronutrients, and usually includes many micronutrient deficiencies as well. It can be sudden and total (starvation) or gradual. Severity ranges from subclinical deficiencies to obvious wasting (edema, hair loss, skin atrophy) to starvation. Multiple organ systems are often impaired. Diagnosis usually involves laboratory testing, including serum albumin.

Nucleic Acids

Nucleic acids are large organic molecules (macromolecules) that carry genetic information or form structures within cells. They are composed of carbon, hydrogen, oxygen, nitrogen, and phosphorus. Nucleic acids are actually the largest molecules in the body. Nucleic acids store and process information at the molecular level inside the cells. The two classes of nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. Nucleic acids are found in all living things, cells, and viruses. Individual strands of DNA and RNA have a similar structure (**FIGURE 2-14**).

Nucleotides are the structural units of nucleic acids. These complex units consist of a nitrogen-containing base, a pentose sugar, and a phosphate group. The nucleotide structure is based on five major types of nitrogen-containing bases:

- *Adenine (A)*: A large, two-ring base (purine)
- *Guanine (G)*: Also a purine
- *Cytosine (C)*: A smaller, single-ring base (pyrimidine)
- *Thymine (T)*: Also a pyrimidine
- *Uracil (U)*: Also a pyrimidine

The DNA in our cells determines our inherited characteristics, including hair color, eye color, and blood type. DNA affects all aspects of body structure and function. DNA molecules encode the information needed to build proteins. By directing structural protein synthesis, DNA controls the shape and physical characteristics of the human body.

Several forms of RNA cooperate to manufacture specific proteins by using the information provided by DNA. Important structural differences distinguish RNA from DNA. An RNA molecule consists of

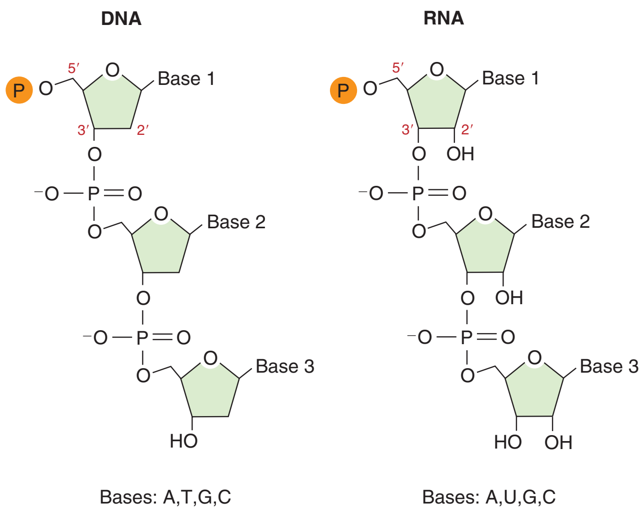

FIGURE 2-14 Strand structures of DNA and RNA.

a single chain of nucleotides. Human cells have three types of RNA:

1. Messenger RNA (mRNA)
2. Transfer RNA (tRNA)
3. Ribosomal RNA (rRNA)

A DNA molecule consists of a pair of nucleotide chains (**FIGURE 2-15A**). The two DNA strands twist around each other in a **double helix** that resembles a spiral staircase. **TABLE 2-3** compares the characteristics of DNA and RNA.

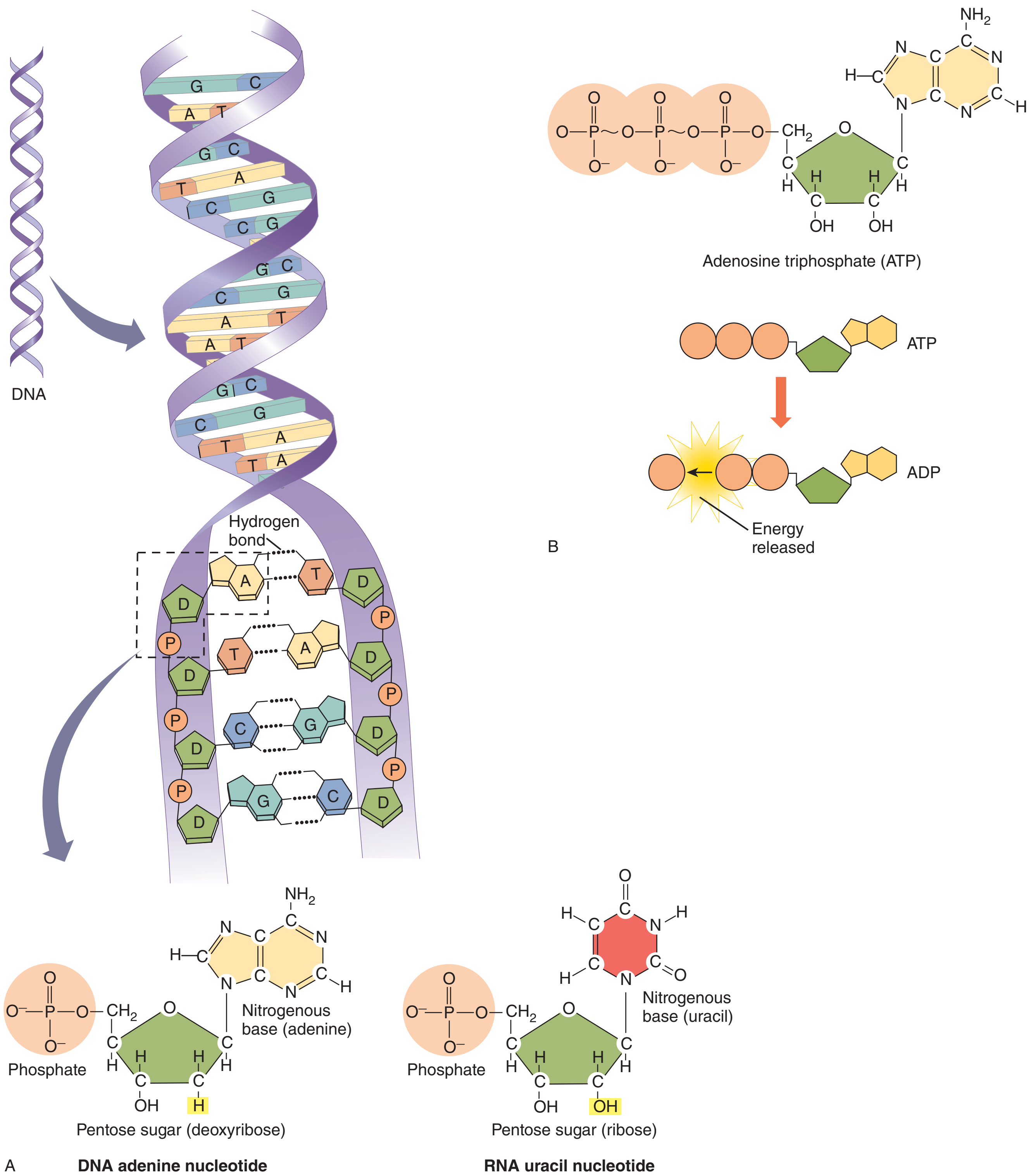

FIGURE 2-15 (**A**) Nucleic acids, DNA, a DNA nucleotide, and an RNA nucleotide. (**B**) ATP.

TABLE 2-3 Characteristics of DNA and RNA

Characteristic	DNA	RNA
Structure	Double stranded and coiled into a double helix	Single stranded, either straight or folded
Major functions	Genetic material, direction of protein synthesis; it self-replicates before cell division	Synthesizes proteins based on genetic instructions
Major site in the cells	Nucleus	Cytoplasm (the cell area outside the nucleus)
Sugar	Deoxyribose	Ribose
Bases	Adenosine, cytosine, guanine, thymine	Adenine, cytosine, guanine, uracil

TEST YOUR UNDERSTANDING

1. List three types of RNA.
2. Distinguish between DNA and RNA.
3. What is the structure of nucleotides?

Enzymes

Enzymes are globular proteins that promote chemical reactions by lowering the **activation energy** requirements. Activation energy is the energy that must be overcome for a chemical reaction to occur. Therefore, they make chemical reactions possible and catalyze the reactions that sustain life. This means that enzymes are catalysts. Enzyme molecules are manufactured by cells to promote specific reactions. Enzymes are among the most important of all the body's proteins. Nearly everything that occurs in the human body relies on a specific enzyme. In the body, enzymes assist in the digestion of food, drug metabolism, protein formation, and many other types of reactions. Enzymes make metabolic reactions possible inside cells by controlling temperature conditions that otherwise would be too mild for them to occur.

Enzymes are complex molecules. When they are not used in the reactions they catalyze, they are recycled. Enzymatic reactions, which are reversible, can be written as:

$$A + B \xrightleftharpoons{\text{enzyme}} AB$$

Enzymes cannot cause a chemical reaction between molecules that would not react without them. They increase the speed of enzymatic reactions greatly, between 100,000 to more than 1 billion times the rate of a reaction that is uncatalyzed. Otherwise, biochemical reactions would occur extremely slowly, almost to no effect. Enzymes are vital in making these reactions occur at an adequate pace.

Enzyme Characteristics

Enzymes differ in their makeup. Some are only made of proteins, whereas others have a two-part structure, consisting of a protein portion (the *apoenzyme*) and a **cofactor**. Collectively, these two parts are referred to as the **holoenzyme**. Enzyme cofactors may be either a metal element ion (such as iron or copper) or an organic molecule that assists the reaction. Most organic cofactors are derived from B (or other) vitamins, in which case they are referred to as **coenzymes**.

Enzymes have chemical-specific actions. Some control one chemical reaction, whereas others regulate a small group of similar reactions by binding to molecules that are only slightly different. Enzymes act on substances referred to as **substrates**. Certain enzymes, when present, determine which reactions are sped up and which reactions will occur. If there is no enzyme, there is no reaction. Enzymes are often named after their substrates, using the suffix *-ase*. For example, a lipid is catalyzed by an enzyme called a *lipase*. Another enzyme, called a *catalase*, breaks down hydrogen peroxide into water and oxygen. Hydrogen peroxide is a toxic substance that results from certain metabolic reactions.

Every cell holds hundreds of various enzymes, each of which recognizes its specific substrates. Enzyme molecules have three-dimensional shapes (conformations) that allow them to identify their

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substrates. The coiled and twisted polypeptide chain of each enzyme fits the shape of its substrate. The **active site** of an enzyme molecule combines with portions of its substrate molecules temporarily. This forms an enzyme–substrate complex (**FIGURE 2-16**).

When enzyme–substrate complexes are formed, some chemical bonds within the substrates are distorted or strained. Requiring less energy as a result, the enzyme is released as it was originally configured. Enzyme-catalyzed reactions can be summarized as:

Substrate molecule + Enzyme molecule ⇒ Enzyme-substance complex ⇒ Product (changed substrates) + Enzyme molecule

These reactions are often reversible. Sometimes, the same enzyme catalyzes the reaction in both directions. The reactions occur at differing rates, based on the number of molecules of the enzyme and its substrate. Some enzymes process a few substrate molecules every second, whereas others can process thousands in the same length of time.

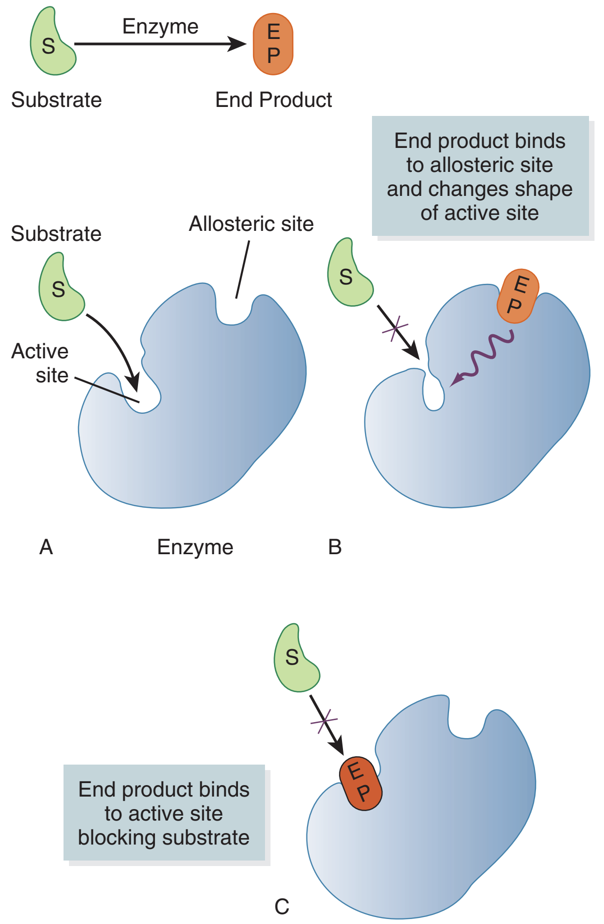

FIGURE 2-16 Enzyme-catalyzed reaction.

TEST YOUR UNDERSTANDING

1. Define enzymes and explain their functions.
2. Define the terms cofactor, holoenzyme, and coenzymes.
3. Define substrates.

FOCUS ON PATHOLOGY

Metabolic disorders are genetic disorders that result in biochemical defects such as enzyme deficiencies. They cause the body to be unable to catabolize or efficiently use the nutrients required for growth, repair, and energy. Newborns are routinely screened for metabolic disorders, because they can harm early physical and mental development. The most common metabolic disorders include **phenylketonuria**, **maple syrup urine disease**, **galactosemia**, and **homocystinuria**.

Adenosine Triphosphate

Although glucose is the primary cellular fuel, it does not directly power cellular work. When glucose is catabolized, the released energy is paired with the synthesis of **adenosine triphosphate (ATP)**. Some of the released energy is stored by ATP bonds in small "packets." Therefore, ATP is the main molecule in cells that transfers energy. It provides a type of energy that all body cells can use immediately.

The structure of ATP is an adenine-containing RNA nucleotide, with two additional phosphate groups added (**FIGURE 2-15B**). The triphosphate "tail" of ATP is ready to chemically release enormous amounts of energy. ATP is a highly unstable molecule that stores energy, because its three phosphate groups are negatively charged and closely packed. They repel each other, and when the terminal high-energy phosphate bonds are hydrolyzed, the molecule becomes more stable.

The ATP bond energy is taken by the cells during coupled reactions. The cells use enzymes to transfer terminal phosphate groups from ATP to various compounds. The newly *phosphorylated* molecules temporarily have higher energy and can perform various types of cellular work. During this work, the molecules lose the phosphate group. The amount of energy needed for most biochemical reactions is closely related to the amount of energy released and transferred during the hydrolysis of ATP. Therefore, the cells are not damaged by an excessive energy release, and so very little energy is wasted.

When the terminal phosphate bond of ATP is cleaved, a molecule is given off that has two phosphate groups: *adenosine diphosphate (ADP)* and an inorganic phosphate group. There is a transfer of energy. ADP accumulates as ATP is hydrolyzed for cellular energy needs. When the terminal phosphate bond of ADP is cleaved, a similar amount of energy is liberated. This produces *adenosine monophosphate.*

As glucose and other fuel-providing molecules are oxidized, their bond energy is released and ATP supplies in the cells are replenished. The same amount of energy is needed to be acquired as is released when the terminal phosphates of ATP are cleaved. This energy must be used to reverse the reaction, reattaching phosphates and reforming energy-transferring phosphate bonds. Molecules cannot be made or degraded without ATP. Also, without ATP, cells cannot transport substances across boundaries, muscles cannot shorten to pull on other body structures, and the process of life will cease.

Certain compounds may be lethal because they interfere with the mitochondrial production of ATP. An example is cyanide, which when inhaled or absorbed has extreme effects on the brain and heart. When the cells do not have sufficient ATP, they die because they lack the energy needed for anabolic chemical reactions, active transport, and other cell processes.

Summary

Chemistry describes the composition of substances and how chemicals react with each other. The human body is made up of chemicals. Matter is composed of elements, some of which occur in a pure form. There are various states of matter, including gaseous, liquid, and solid states. Energy is different from matter, taking up space, having no mass, and only being measured by how it affects matter. Energy is the capacity to put matter into motion or to perform "work."

Many elements are combined with other elements. They are composed of atoms, which are the smallest complete units that still have the properties of the elements they form. Atoms of different elements have characteristic sizes, weights, and ways of interacting. An atom consists of one or more electrons surrounding a nucleus, which contains one or more protons and usually one or more neutrons. Electrons are negative, protons are positive, and neutrons are uncharged. When atoms combine, they gain, lose, or share electrons. Atoms of the same element may bond to form a molecule of that element. Compounds that release ions when they dissolve in water are known as electrolytes. A molecule is any chemical structure that consists of atoms held together by covalent bonds. Compounds are chemically pure, with identical molecules.

Mixtures are substances containing two or more components that are physically intermixed, and include colloids, solutions, and suspensions. Chemical bonds are energy exchanges between electrons of reacting atoms, and include ionic, covalent, and hydrogen bonds. Ionic bonds form between ions. Covalent bonds are formed when electrons are shared, producing molecules in which the shared electrons are located in a single orbital common to both atoms. When the positive hydrogen end of a polar molecule is attracted to the negative nitrogen or oxygen end of another polar molecule, the attraction is called a hydrogen bond. A chemical reaction occurs when a chemical bond is formed, broken, or rearranged. The four types of chemical reactions are synthesis, decomposition, exchange, and reversible reactions. Catalysts can increase the rate of chemical reactions without becoming chemically changed themselves or without becoming a part of the product.

Acids are electrolytes that release hydrogen ions in water. Bases are electrolytes that release ions that bond with hydrogen ions. Hydrogen ion concentrations can be measured by a value called pH. Biochemistry (biologic chemistry) is the study of chemical processes within and relating to living organisms. Organic chemicals are those that contain the elements carbon and hydrogen and generally oxygen as well. Inorganic chemicals do not contain these elements. Inorganic substances include water, oxygen, carbon dioxide, and salts. Organic substances include carbohydrates, lipids, and proteins. Carbohydrates provide much of the energy required by the body's cells and help to build cell structures. They contain various types of sugars, including monosaccharides, disaccharides, and polysaccharides. Lipids are insoluble in water, but may dissolve in other lipids, oils, ether, chloroform, or alcohol. Fats are the most common type of lipids. Unsaturated fats are safer than saturated or trans fats. Proteins are the most abundant organic components of the human body and are the basic structural materials of the body. Nucleic acids are large organic molecules that carry genetic information or form structures within cells. They include DNA and RNA.

In the body, enzymes promote chemical reactions by acting as catalysts to accelerate these reactions without themselves being permanently changed or consumed. Some enzymes are only made of protein, whereas others have a protein portion (apoenzyme) and a cofactor. Most organic cofactors are derived from B complex (or other) vitamins and are known as coenzymes. ATP pairs with catabolized glucose to power the body. ATP is the main molecule in cells that transfer energy and provides a type of energy that all body cells can use immediately.

KEY TERMS

Acids
Activation energy
Active site
Adenosine triphosphate (ATP)
Amino acids
Ammonia
Anions
Arachidonic acid
Atomic number
Atomic weight
Atoms
Bases
Bicarbonate ion
Biochemistry
Carbohydrates
Catalysts
Cations
Cellulose
Chemical reaction
Chemistry
Coenzymes
Cofactor
Collagen
Colloids
Compounds
Covalent bond
Crystals
Cytosol
Decomposition
Deoxyribonucleic acid (DNA)
Dipole
Disaccharides
Double helix
Eicosanoids
Electrolytes
Electronegativity
Electrons
Electropositive
Elements
Energy
Enzymes
Exchange reaction
Fatty acid
Fibrous proteins
Galactosemia
Globular proteins
Holoenzyme
Homocystinuria
Hydration layers
Hydrogen bond
Hydrogen ions
Inorganic
Ions
Isotope
Lipids
Lipoproteins
Macromolecules
Maple syrup urine disease
Matter
Mixtures
Molarity
Mole
Molecular weight
Molecule
Monosaccharides
Neutrons
Nonpolar covalent bond
Nonpolar molecule
Nucleic acids
Nucleus
Omega-3 fatty acids
Organic
Peptide bond
pH
Phenylketonuria
Phospholipid
Polar
Polysaccharides
Products
Proteins
Proteome
Protons
Radioisotopes
Reactants
Reversible reaction
Ribonucleic acid (RNA)
Salts
Saturated fats
Solutes
Solutions
Solvent
Steroid
Substrates
Surface tension
Suspensions
Synthesis
Trans fats
Triglycerides
Universal solvent
Unsaturated fats

LEARNING GOALS

The following learning goals correspond to the objectives at the beginning of this chapter:

1. Atoms are tiny particles that compose elements. A molecule is formed when two or more atoms bond. When two atoms of the same element bond, they produce molecules of that element such as hydrogen, oxygen, or nitrogen molecules.
2. Atoms can bond with other atoms by using chemical bonds that result from interactions between their electrons. The atoms may gain, lose, or share electrons. Atoms that either gain or lose electrons are called ions.
3. Each atom consists of a central nucleus and one or more electrons continually moving around it. Inside the nucleus are one or more protons and

neutrons. The number of protons in an atom is known as its atomic number.

4. The major groups of inorganic chemicals common in cells are oxygen, carbon dioxide, salts, and water. Other inorganic substances in cells include the ions of bicarbonate, calcium, carbonate, chloride, magnesium, phosphate, potassium, sodium, and sulfate.
5. Acids are electrolytes that release hydrogen ions in water such as hydrochloric acid. Bases are electrolytes that release ions that bond with hydrogen ions such as sodium hydroxide. Buffers are chemicals that resist pH changes. They combine with hydrogen ions when these ions are excessive and contribute hydrogen ions when these ions are reduced.
6. Lipids are not soluble in water, but may dissolve in other lipids, oils, ether, chloroform, or alcohol. Proteins are vital for many body functions. They can combine with carbohydrates or lipids, and always contain carbon, hydrogen, oxygen, and nitrogen atoms.
7. The term pH is defined as the measurement of hydrogen ion concentration. The pH scale ranges from 0 to 14, with 7 being the midpoint (an equal number of hydrogen and hydroxide ions) or "neutral"—neither acidic nor basic.
8. Organic substances in cells include carbohydrates, lipids, proteins, and nucleic acids. Carbohydrates provide much of the energy required by the body's cells and help to build cell structures. Lipids are vital for many cell functions such as the building of the cell membrane, and include fats, phospholipids, and steroids. Proteins are vital for body structures, functions, energy, enzymatic functions, defense (antibodies), and hormonal requirements. Nucleic acids carry genetic information or form structures within cells, and include DNA and RNA.
9. Steroid molecules include cholesterol, estrogen, progesterone, testosterone, cortisol, and estradiol.
10. Nucleic acids are macromolecules that carry genetic information or form structures within cells. They are composed of carbon, hydrogen, oxygen, nitrogen, and phosphorus. Nucleic acids are found in all living things, cells, and viruses.

CRITICAL THINKING QUESTIONS

A 65-year-old man, who has had diabetes for two decades, was brought to the emergency department. He appeared confused and said he was feeling weak. His blood tests revealed elevation of ketone bodies.

1. Explain whether the physician should suspect alkalosis or acidosis, and why.
2. Explain the various types of alkalosis and acidosis.

REVIEW QUESTIONS

1. Which of the following represents an atomic number?
   A. Protons in an atom
   B. Protons and neutrons
   C. Electrons in an ion
   D. Neutrons in an atom
2. Which of the following elements is the most plentiful in the human body?
   A. Carbon
   B. Oxygen
   C. Sodium
   D. Potassium
3. Ions with a negative charge are known as which of the following?
   A. Cations
   B. Anions
   C. Polyatomic ions
   D. Radicals
4. The atomic weight of an element includes which of the following?
   A. Protons and neutrons in the nucleus
   B. Protons and electrons in the atom
   C. Electrons in the outer shells
   D. Neutrons in the nucleus.
5. An unstable isotope that emits subatomic particles spontaneously is referred to as
   A. a proton.
   B. an atom.
   C. a radioisotope.
   D. a neutron.
6. Which of the following is the smallest particle of an element that has the properties of that element?
   A. An electron
   B. An atom
   C. A neutron
   D. A proton

7. A solution containing an equal number of hydrogen ions and hydroxide ions is
   A. basic.
   B. alkaline.
   C. acidic.
   D. neutral.
8. Which of the following statements about water is false?
   A. It has a relatively low heat capacity.
   B. It contains hydrogen bonds.
   C. It dissolves many compounds.
   D. It is responsible for about two-thirds of the mass of the human body.
9. Which of the following is the most important high-energy compound in cells?
   A. Glucose
   B. Protein
   C. Fructose
   D. Adenosine triphosphate
10. The molecules that store and process genetic information at the molecular level are which of the following?
    A. Steroids. C. Nucleic acids.
    B. Carbohydrates. D. Lipids.
11. The building blocks of fat molecules are
    A. fatty acids.
    B. triglycerides.
    C. glycerols.
    D. fatty acids and glycerol.
12. Nucleic acids are composed of units called
    A. fatty acids. C. amino acids.
    B. nucleotides. D. adenosines.
13. Which of the following is an important buffer in body fluids?
    A. Hydrochloric acid
    B. Sodium bicarbonate
    C. Sodium chloride
    D. Water
14. A fatty acid that contains many double covalent bonds in its carbon chain is said to be
    A. polyunsaturated.
    B. monounsaturated.
    C. hydrogenated.
    D. saturated.
15. Which of the following is the most important metabolic fuel molecule in the body?
    A. Starch C. Glucose
    B. Protein D. Sucrose

ESSAY QUESTIONS

1. Provide the atomic symbols for sodium, potassium, hydrogen, oxygen, nitrogen, calcium, iron, and carbon.
2. Define radioisotopes.
3. Describe ionic and covalent bonds with two examples for each.
4. What are hydrogen bonds and how are they important in the body?
5. What are the four types of chemical reactions?
6. Define electrolytes, acids, and bases.
7. Define chemical equilibrium.
8. What is the mechanism of enzyme action?
9. List six examples of steroids.
10. Define the characteristics of nucleic acids.