chapter 30

THE CHEMICAL BASIS OF ANIMAL LIFE

Outline

- Atoms and Elements: Building Blocks of All Matter
  - Structure of Atoms
  - Energy-Level Shells
- Compounds and Molecules: Aggregates of Atoms
  - Covalent Bonds: Sharing Electron Pairs
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  - Ionic Bonds: Opposites Attract
- Acids, Bases, and Buffers
  - pH: Measuring Acidity and Alkalinity
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- The Molecules of Animals
  - Carbohydrates: Stored Energy and Structural Support
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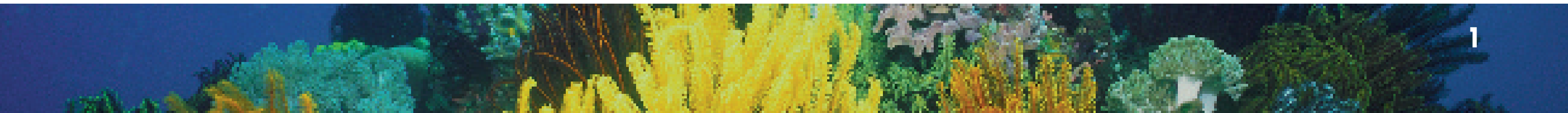
  - Nucleotides and Nucleic Acids: Information Storage, Chemical Messengers, and Energy Transfer

Concepts

1. Animals are made up of molecules, which are collections of atoms bound to one another. The life processes within an animal are based, to a large degree, on the chemical properties of atoms, ions, and molecules.
2. Carbon is the key element of organic molecules because it has unique physical and chemical characteristics.
3. Carbohydrates and lipids are principal sources of energy for most animals.
4. Proteins, nucleotides, and nucleic acids are large molecules that provide the basis for structure, function, information storage, energy transfer, and genetic regulation in animals.



Chemical processes are essential to everything that goes on within the body of an animal. Without these chemical processes, life as we know it could not exist. This chapter presents the chemistry you need to understand the basic chemical processes that enable animals to function in the environment as living entities.

Chemistry is the branch of science dealing with the composition of substances and reactions among these substances. In chemical reactions, bonds between atoms break or join to form different combinations of atoms or molecules. A knowledge of chemistry is essential for understanding the structure (**anatomy** [Gr. *ana,* again + *temnein,* to cut]) and function (**physiology** [Gr. *physis,* nature]) of animals because body functions involve chemical changes in structural units, such as cells. As interest in the chemistry of animals grew, and knowledge in this area expanded, a new subdivision of science called **biochemistry** ("the chemistry of life") emerged. Biochemistry is the study of the molecular basis of life.

ATOMS AND ELEMENTS: BUILDING BLOCKS OF ALL MATTER

Matter is anything that occupies space and has mass. It includes all of the solids, liquids, and gases in our environment, as well as those in bodies of all forms of life. **Mass** refers to the amount of matter in an object. Matter is composed of **elements,** chemical substances that ordinary chemical reactions cannot break down into simpler units. An element is designated by either a one- or two-letter abbreviation of its Arabic, English, German, or Latin name. For example, O is the symbol for the element oxygen, H stands for hydrogen, and Na is the symbol for sodium (from the Latin, *natrium*). Currently, scientists recognize 92 elements occurring in nature. Fifteen elements are found in large quantities in most animals, and four of these (carbon, hydrogen, oxygen, and nitrogen) account for the majority (97%) of an animal's body weight (table 30.1). The remaining 3% of an animal's weight consists primarily of calcium, phosphorus, and potassium. Elements present in trace amounts include sodium, sulfur, manganese, magnesium, copper, iodine, iron, and chlorine.

Elements are composed of units of matter called atoms. An **atom** (Gr. *atomos,* indivisible) is the smallest part of an element that can enter into a chemical reaction. Atoms vary in size, weight, and the diverse ways they interact with each other. For example, some atoms can combine with atoms like themselves or with dissimilar atoms; others lack this ability.

TABLE 30.1 NATURALLY OCCURRING ELEMENTS IN ANIMALS

ELEMENT	SYMBOL	ATOMIC NUMBER	ATOMIC MASS	PERCENT WET WEIGHT OF BODY*	
Oxygen	O	8	16	65	97%
Carbon	C	6	12	19	
Hydrogen	H	1	1	10	
Nitrogen	N	7	14	3	
Calcium	Ca	20	40	1	approximately 3%
Phosphorus	P	15	31	1	
Potassium	K	19	39	0.2	
Sulfur	S	16	32	0.1	
Sodium	Na	11	23	0.1	
Chlorine	Cl	17	35	0.1	
Magnesium	Mg	12	24	0.1	
Manganese	Mn	25	55	0.1	
Iron	Fe	26	56	0.1	
Copper	Cu	29	64	0.1	
Iodine	I	53	127	0.1	

*Includes water.

STRUCTURE OF ATOMS

Atoms have two main parts: a central core called a nucleus and the surrounding electron cloud (figure 30.1). The nucleus contains two major particles: the positively charged **protons (p^+)** and the uncharged **neutrons (n^0).** Surrounding the nucleus are negatively charged particles called **electrons (e^-).** Any one electron moves so rapidly around the nucleus that it cannot be found at any given point at any particular moment in time; therefore, its location is given as an electron cloud. Because the number of negatively charged electrons outside the nucleus is equal to the number of positively charged protons, the atom is electrically uncharged or neutral.

The number of protons and neutrons in a nucleus and the number and arrangement of electrons in the electron cloud determine an atom's chemical and physical properties. The **atomic number** of an element is the number of protons in the nucleus of one of its atoms. Elements are identified by their atomic number. For example, if an atom has one proton, it is hydrogen; if it has six, it is carbon; and if an atom has eight protons, it is oxygen.

Another measure of an atom is its atomic mass. The **atomic mass** is equal to the number of neutrons and protons in the atom's nucleus. Because carbon contains six protons and six neutrons, its atomic mass is 12 and is symbolized with a superscript preceding the element's symbol: ^{12}C (read "carbon-12"). Table 30.1 shows the atomic numbers and atomic masses of the more important elements in a typical animal.

Most naturally occurring elements are actually a mixture of slightly varying forms of that element. All atoms of a given element have the same number of protons in the nucleus, but some have different numbers of neutrons, and thus, different

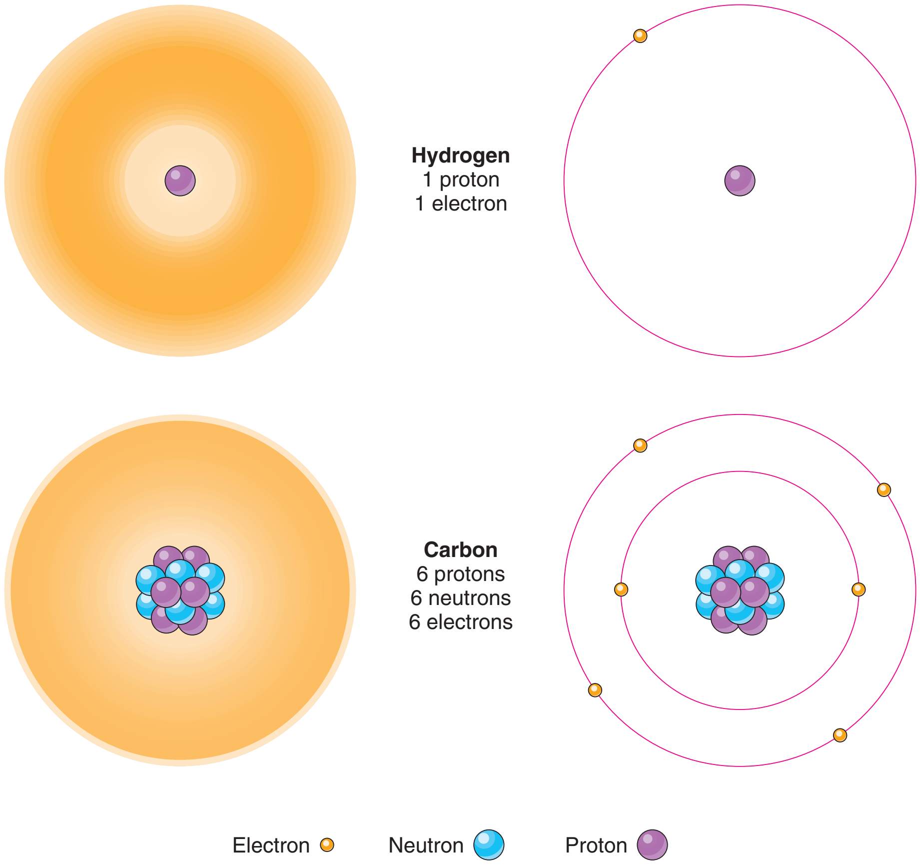


FIGURE 30.1

Structure of Hydrogen and Carbon Atoms. Both the shaded orange spheres on the left and the concentric circles on the right represent the electron orbitals and indicate probable electron positions. Both of these diagrams are extremely simplified. At this scale, the nucleus of these two representative atoms would only be an invisible dot, and the electrons would be too close to the nucleus.

atomic masses. These different forms with the same atomic number but different atomic masses are **isotopes.** For example, the most common form of carbon atom has six protons and six neutrons in the nucleus and an atomic mass of 12 (^{12}C). A carbon isotope with six protons and seven neutrons has an atomic mass of 13 (^{13}C), and a carbon isotope with six protons and eight neutrons has an atomic mass of 14 (^{14}C) (figure 30.2).

Some isotopes (e.g., ^{12}C and ^{13}C) are stable and do not break down. Other isotopes (e.g., ^{14}C) are unstable and tend to break down (decay or decompose) by periodically emitting small particles and energy. These unstable isotopes are **radioisotopes** (radioactive isotopes). Oxygen, iron, cobalt, iodine, and phosphorus are examples of elements that have radioactive isotopes.

ENERGY-LEVEL SHELLS

The electrons of an atom are distributed around its nucleus in orbitals called **energy-level shells** or **clouds of electrons** (figure 30.3). The location of these electrons in relation to the nucleus greatly influences the way atoms react with each other. Seven energy-level shells are possible. Each shell can hold only a certain number of electrons. The shell nearest the nucleus never has more than two electrons. The second and third shells can each have as many as eight electrons. Larger numbers fill the more distant shells. When the shell of an atom holds the maximum number of electrons possible, the shell is complete and stable. An atom with an incomplete, or unstable, outer shell tends to gain, lose, or share electrons with another atom. For example, an atom of sodium has eleven electrons arranged as illustrated in figure 30.3: two in the first shell, eight in the second shell, and one in the third shell. As a result of this arrangement, this atom tends to form chemical bonds with other atoms in which it loses the single electron from its outer shell. This leaves the second shell filled and the atom stable.

COMPOUNDS AND MOLECULES: AGGREGATES OF ATOMS

In addition to being an element, a substance can also be a compound. A **compound** is composed of atoms of two or more elements chemically united in fixed proportions. For example, water has two H atoms and one O atom. This composition does not change (i.e., a compound cannot be separated into its pure

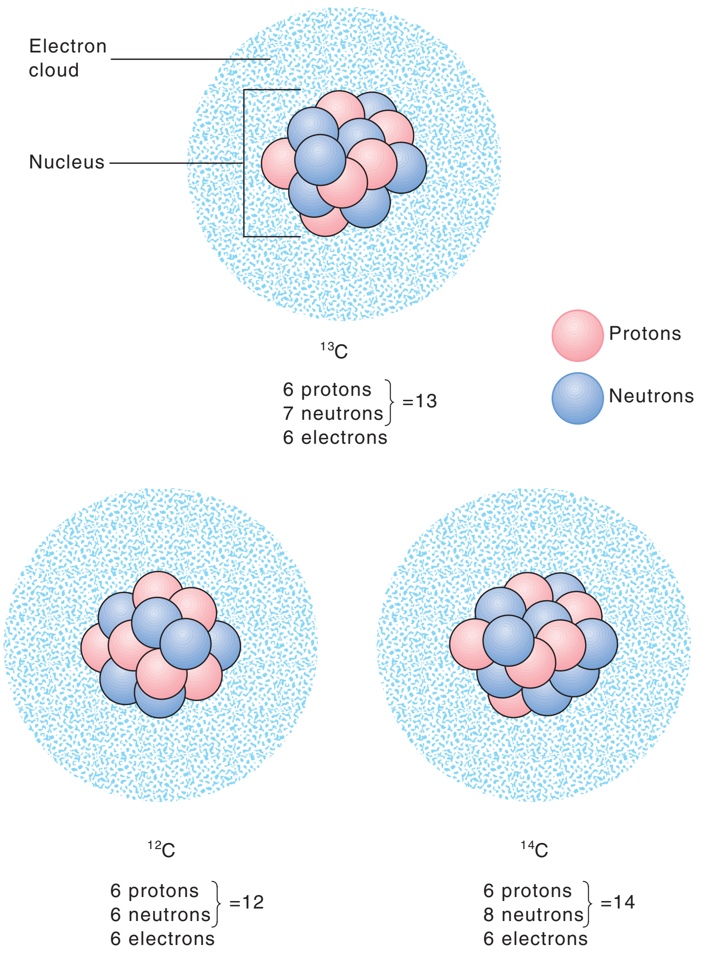


FIGURE 30.2

Isotopes—Variations on Normal Atomic Structure. The nuclei of these carbon isotopes differ in their number of neutrons, although each has six protons. ^{12}C has six neutrons, ^{13}C has seven neutrons, and ^{14}C has eight neutrons.

components—the atoms of the elements present—except by chemical methods).

When atoms interact chemically to form **molecules,** electrical forces called chemical bonds hold the atoms together. Three types of chemical bonds are covalent, hydrogen, and ionic.

COVALENT BONDS: SHARING ELECTRON PAIRS

When atoms share outer-shell electrons with other atoms, the chemical bond that forms is a **covalent bond** (the prefix *co-* indicates a shared condition) (figure 30.4). In covalent bonding, electrons are always shared in pairs. When a pair of electrons is shared (one from each molecule), a single bond forms (e.g., the hydrogen [H—H] molecule); when two pairs are shared, a double bond forms (e.g., the oxygen [O═O] molecule); and when three are shared, a triple bond forms (e.g., the nitrogen [N≡N] molecule).

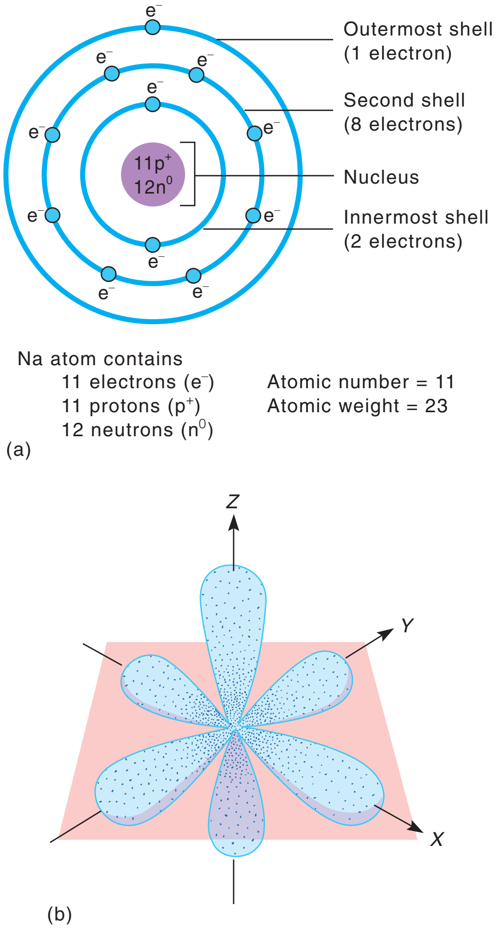


FIGURE 30.3

How Electrons Are Arranged in Atoms. *(a)* Sodium (Na) atom, showing its three energy-level shells. *(b)* In reality, electrons are not found in a definite location but travel rapidly in a three-dimensional space (X, Y, and Z planes) around the nucleus.

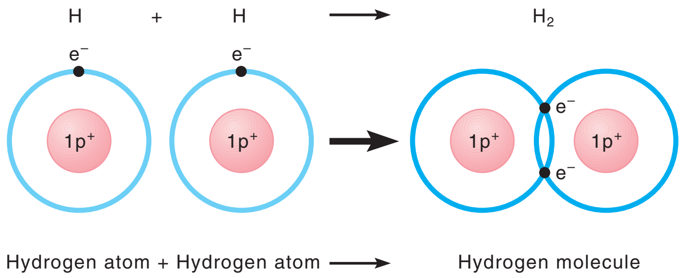


FIGURE 30.4

A Covalently Bonded Molecule—Hydrogen (H_2). A single covalent bond forms when two hydrogen atoms share a pair of electrons.

In a molecule like H_2, the electrons spend as much time orbiting one nucleus as the other. Therefore, the distribution of charges is symmetrical, and the bond is called a **nonpolar covalent bond.** Because of this equal sharing, the molecule is electrically balanced, and the molecule as a whole is neutral.

In other molecules, such as H_2O, where two hydrogen atoms combine with one oxygen atom, the electrons spend more time orbiting the oxygen nucleus than the hydrogen nuclei. Because the electrical charge from the cloud of moving electrons is asymmetrical, the bond is called a **polar covalent bond.** Such a bond leaves the oxygen atom with a slightly negative charge and the hydrogens with a slightly positive charge, even though the entire molecule is electrically neutral. The shape of the H_2O molecule reflects this polarity; rather than the linear arrangement H—O—H, the two hydrogens are at one end, a bit like the corners of a triangle. This shape and polarity can lead to the formation of another kind of chemical bond—the hydrogen bond.

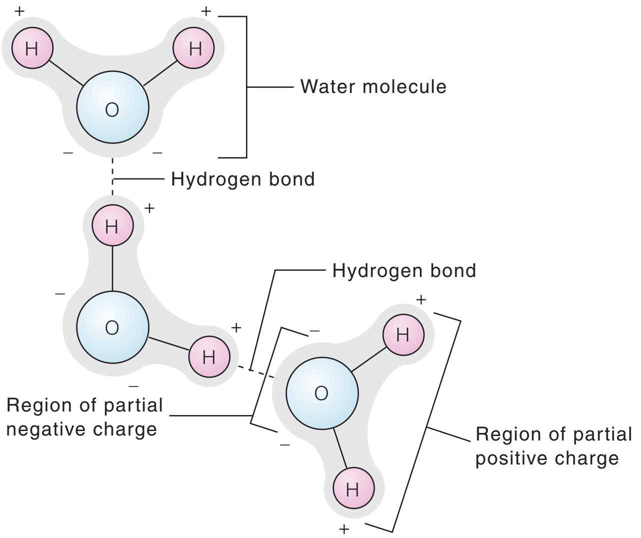


FIGURE 30.5

Hydrogen Bonds and Water Droplets. Hydrogen bonds form when oxygen atoms of different water molecules weakly join by the attraction of the electronegative oxygen for the positively charged hydrogen. Because of the arrangement of electron orbitals and the bonding angles between oxygen and hydrogen, the molecule as a whole is polar (it carries a slight negative charge at one end and a slight positive charge at the other end). This polarity is responsible for many important properties of water.

HYDROGEN BONDS

In molecules in which hydrogen bonds to certain other atoms (e.g., O, N, or Fe), the hydrogen electron is drawn toward another atom, leaving a proton behind. As a result, the hydrogen atom gains a slight positive charge. The remaining proton is attracted to negatively charged atoms of, for example, oxygen in nearby molecules. When this happens, a weak attraction, called a **hydrogen bond,** forms. The hydrogen atom in one water molecule forms a hydrogen bond with the oxygen atom in another water molecule, and so forth, until many molecules bond (figure 30.5).

IONIC BONDS: OPPOSITES ATTRACT

When an atom either gains or loses electrons, it acquires an electrical charge and is called an **ion** (Gr. *ion,* going). If an atom loses one or more electrons, it becomes positively charged because more positively charged protons are now in the nucleus than negatively charged electrons surrounding the nucleus. This positive charge is shown as one or more "plus" signs. Conversely, if an atom gains one or more electrons, it becomes negatively charged, and this negative charge is shown as one or more "minus" signs. A positive ion is known as a cation, and a negative ion is an anion. Examples of cations are sodium (Na^+), potassium (K^+), hydrogen (H^+), calcium (Ca^{2+}), and iron (Fe^{3+}). Some anions are chloride (Cl^-), hydroxyl (OH^-), bicarbonate ($HCO_3{}^-$), sulfate ($SO_4{}^{2-}$), phosphate ($PO_4{}^{3-}$), and carboxyl (COO^-).

Ionic bonds form when an atom or group of atoms develops an electrical charge (because of an electron loss or gain) and attracts an atom or group of atoms with an opposite charge. Figure 30.6 shows how an ionic bond forms between sodium and chlorine to produce sodium chloride. When a sodium atom and chlorine atom come together, the sodium atom donates an electron to the chlorine atom. This electron transfer changes the balance between the protons and electrons in each of the two atoms. The sodium atom ends up with one more proton than it has electrons, and the chlorine atom with one more electron than it has protons. The sodium atom is left with a net charge of +1 (Na^+), and the

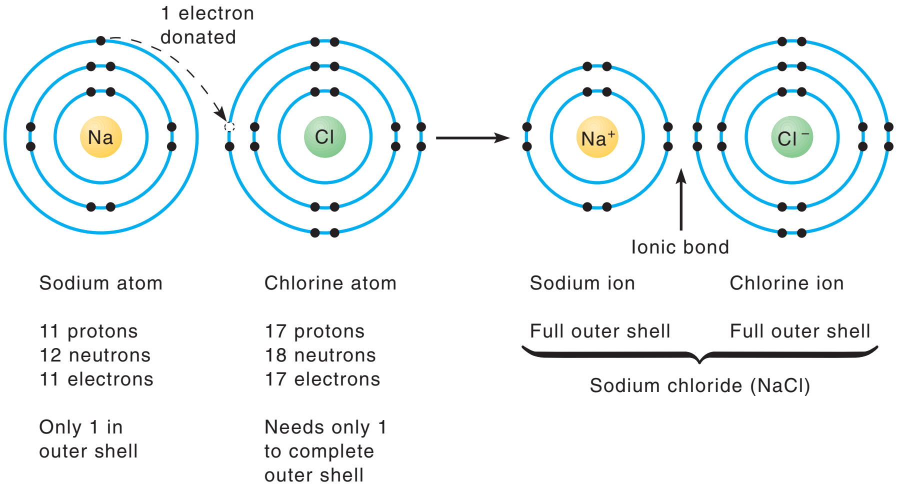


FIGURE 30.6

An Ionically Bonded Molecule—Table Salt (NaCl). In the formation of sodium chloride, an electron from the outermost shell transfers from the sodium atom to the chlorine atom, giving both atoms complete outermost shells. This transfer gives the sodium atom a net charge of +1 (sodium ion) and the chlorine atom a net charge of –1 (chloride ion). An ionic bond forms between the oppositely charged ions.

net charge of the chlorine atoms is −1 (Cl^-). These opposite charges attract each other and form the ionic bond.

Acids, Bases, and Buffers

An **electrolyte** is any substance, such as sodium chloride (NaCl), that conducts electricity when in solution. Many fluids contain strong electrolytes that break down (ionize) into ions. Most acids and bases are electrolytes.

An **acid** is a substance that releases hydrogen ions (H^+) when dissolved in water. Because a hydrogen atom without its electron is only a proton, an acid can be described as a proton donor:

$$HCl \rightarrow H^+ + Cl^-$$

One molecule of hydrogen chloride dissolves in water to produce hydrochloric acid, which dissociates into one hydrogen ion and one chloride ion.

In contrast, a **base** (or alkali) is a substance that releases hydroxyl ions (OH^-) when dissolved in water:

$$NaOH \rightarrow Na^+ + OH^-$$

One molecule of sodium hydroxide dissolves in water to produce one sodium ion and one hydroxyl ion.

When a base dissolves in water, it removes free protons (H^+) from the water; therefore, it is a proton acceptor:

$$OH^- + H^+ \rightarrow H_2O$$

pH: Measuring Acidity and Alkalinity

Hydrogen and hydroxyl ions often affect the chemical reactions involved with life processes. Therefore, the concentrations of these ions in body fluids are important. The higher the concentration of hydrogen ions (H^+), the more acidic the solution, and the higher the concentration of hydroxyl (OH^-) ions, the more basic (alkaline) the solution. A solution is neutral when the number of hydrogen ions equals the number of hydroxyl ions.

The **pH scale,** which runs from 0 to 14, measures acidity and alkalinity (table 30.2). Acidic solutions have a pH less than 7, and basic (alkaline) solutions have a pH above 7. A pH of 7 is neutral. Each whole number on the pH scale represents a tenfold change (logarithmic) in acidity; therefore, a solution with a pH of 3 is 10 times more acidic than a solution with a pH of 4, and a pH of 9 is 10 times more basic than a pH of 8. Actually, the pH value is equal to the negative logarithm of the hydrogen ion concentration:

$$\mathrm{pH} = -\log\,[H^+]$$

or

$$\mathrm{pH} = \log(1/[H^+])$$

pH: Control with Buffers

Maintenance of a stable internal environment in an animal requires a relatively constant pH of the body fluids. Too much of a strong acid or base can destroy cell stability. Also, too sudden a

TABLE 30.2 The Relationship between Hydrogen Ion (H^+) Concentration, Hydroxyl Ion (OH^-) Concentration, and pH

H^+ (Hydrogen Ion)	pH		Examples	OH^- (Hydroxyl Ion)
$10^{0} = 1$		0	Battery acid	$10^{-14} = 0.00000000000001$
$10^{-1} = 0.1$		1	Gastric (stomach) juice	$10^{-13} = 0.0000000000001$
$10^{-2} = 0.01$		2	Lemon juice	$10^{-12} = 0.000000000001$
$10^{-3} = 0.001$	Acidic	3	Grapefruit juice	$10^{-11} = 0.00000000001$
$10^{-4} = 0.0001$		4	Tomato juice	$10^{-10} = 0.0000000001$
$10^{-5} = 0.00001$		5	Coffee	$10^{-9} = 0.000000001$
$10^{-6} = 0.000001$		6	Urine, milk	$10^{-8} = 0.00000001$
$10^{-7} = 0.0000001$	Neutral	7	Distilled water	$10^{-7} = 0.0000001$
$10^{-8} = 0.00000001$		8	Seawater	$10^{-6} = 0.000001$
$10^{-9} = 0.000000001$		9	Baking soda	$10^{-5} = 0.00001$
$10^{-10} = 0.0000000001$		10	Milk of magnesia	$10^{-4} = 0.0001$
$10^{-11} = 0.00000000001$	Basic	11	Household ammonia	$10^{-3} = 0.001$
$10^{-12} = 0.000000000001$	(alkaline)	12	Household bleach	$10^{-2} = 0.01$
$10^{-13} = 0.0000000000001$		13	Oven cleaner	$10^{-1} = 0.1$
$10^{-14} = 0.00000000000001$		14	Lye	$10^{0} = 1$

change in pH may be destructive. The fluid systems of most animals contain chemical substances that help regulate the acid-base balance. These substances, called **buffers,** resist changes in pH by accepting H^+ ions when they are in excess and donating H^+ ions when they are depleted. The most important buffers are the bicarbonates, phosphates, and organic molecules, such as amino acids and proteins.

The carbonic acid–bicarbonate ion system is important in buffering the blood of many vertebrates:

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

Carbonic acid dissociates to form hydrogen ion and bicarbonate ion.

In this example, if H^+ ions are added to the system, they combine with HCO_3^- to form H_2CO_3 (the reaction goes to the left). This reaction removes H^+ ions and keeps the pH from changing. If excess OH^- ions are added, they react with the H^+ ions to form water, and more H_2CO_3 will ionize and replace the H^+ ions that were used (the reaction goes to the right). Again, pH stability is maintained.

THE MOLECULES OF ANIMALS

The chemicals that enter into, or are produced by, metabolic reactions can be divided into two large groups: (1) **organic molecules,** which contain carbon atoms, and (2) **inorganic molecules,** which lack carbon atoms. (A few simple molecules containing carbon, such as CO_2, are considered for convenience to be inorganic.)

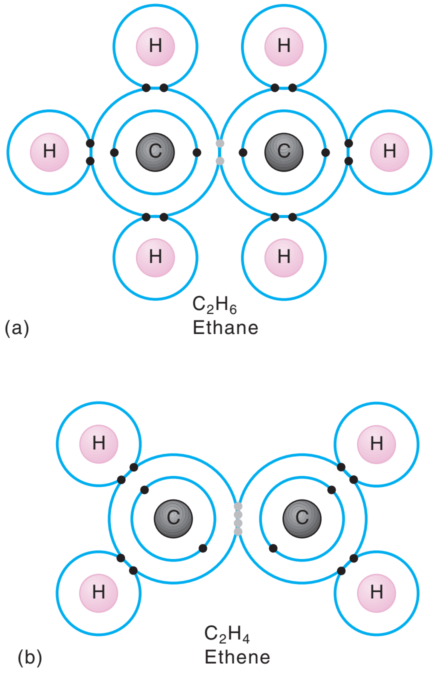


FIGURE 30.7

Carbon Bonding. *(a)* A single covalent bond joins two carbon atoms. The remaining three pairs of electrons are shared with hydrogen atoms in this molecule. *(b)* A double covalent bond joins two carbon atoms. In this case, only two pairs of electrons are shared with hydrogen atoms.

The most important characteristics of organic molecules depend on properties of the key element, carbon—the indispensable element for all life. The carbon atom has four electrons in its outer orbital; thus, it must share four additional electrons by covalent bonding with other atoms to fill its outer orbital with eight electrons. This unique bonding requirement enables carbon to bond with other carbon atoms to form chains and rings of varying lengths and configurations, as well as to bond with hydrogen and other atoms.

With only four electrons in the outer shell, carbon atoms can form covalent bonds to fill this shell. Adjacent carbon atoms may share one or two pairs of electrons. When they share one pair of electrons, a single covalent bond forms, leaving each carbon free to bond to as many as three other atoms (figure 30.7*a*). When adjacent carbon atoms share two pairs of electrons, a double covalent bond forms, leaving each carbon free to bond to only two additional atoms (figure 30.7*b*).

Hydrocarbons are organic molecules that contain only carbon and hydrogen, and most have their carbons bonded in a linear fashion. Hydrocarbons form the framework of all organic molecules.

The carbon chain or ring of many organic molecules provides a relatively inactive molecular "backbone," to which reactive groups or atoms attach. These functional groups of the molecule are responsible for the molecule's unique chemical properties and behavior. Figure 30.8 shows some of the more important functional groups.

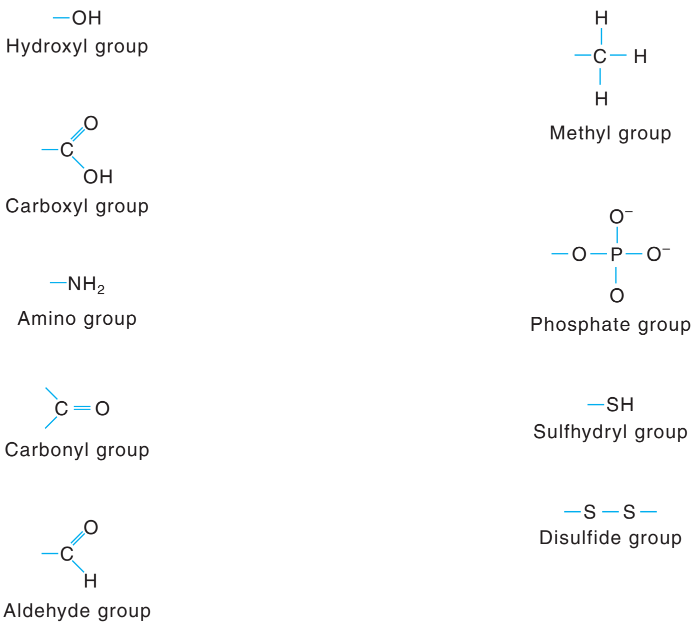


FIGURE 30.8

Some Functional Groups of Organic Molecules. Functional groups confer distinctive properties to carbon compounds. The "unfilled" bond attaches to a carbon or other atom in the rest of the molecule.

The important groups of organic molecules in animals include carbohydrates, lipids, proteins, nucleotides, and nucleic acids. Each of these groups is now briefly discussed.

CARBOHYDRATES: STORED ENERGY AND STRUCTURAL SUPPORT

Carbohydrates are animals' major source of energy. Most animal cells have the chemical machinery to break down the energy-rich carbon-hydrogen (C—H) bonds in sugars and starches. Simple carbohydrates (e.g., monosaccharides) are composed of atoms of carbon, hydrogen, and oxygen.

Carbohydrates are classified according to their molecular structure. The simplest types with short carbon chains are **monosaccharides** (Gr. *monos,* single + *sakharon,* sugar) or sugars. As their name implies, monosaccharides taste sweet. Monosaccharides are the building blocks of more complex carbohydrate molecules. Four common monosaccharides in animals are glucose, fructose, glyceraldehyde, and dihydroxyacetone (figure 30.9).

Two monosaccharides can combine to form a **disaccharide** (*di,* two) (figure 30.10) by removing a molecule of water (dehydration synthesis). Disaccharides all have the same molecular formula, $C_{12}H_{22}O_{11}$. Compounds with the same molecular formula but different structure are **isomers.** Each isomer has unique properties. Examples of disaccharide isomers are sucrose, lactose, and maltose. Sucrose (table sugar) is a disaccharide formed by linking a molecule of glucose to a molecule of fructose. If a glucose molecule bonds to another monosaccharide, galactose, the resulting disaccharide is lactose (commonly called milk sugar). Maltose, two joined glucose subunits, gives barley seeds a sweet taste. Beer brewers ferment barley into alcohol.

Other carbohydrates consist of many monosaccharides joined to form **polysaccharides** (*poly,* many) (figure 30.11). Glycogen, a major storage form for glucose in animals, is a polysaccharide. Because the number of glucose units within the glycogen molecule may vary, it is symbolized by the formula $(C_6H_{10}O_5)_n$, with *n* equal to the number of glucose units in the molecule. Other biologically important polysaccharides include chitin (a major component of the exoskeleton of insects and of crustaceans, such as lobsters and crabs), starch (a storage form of carbohydrate in plants), and cellulose (a woody structural component of the cell wall of plants).

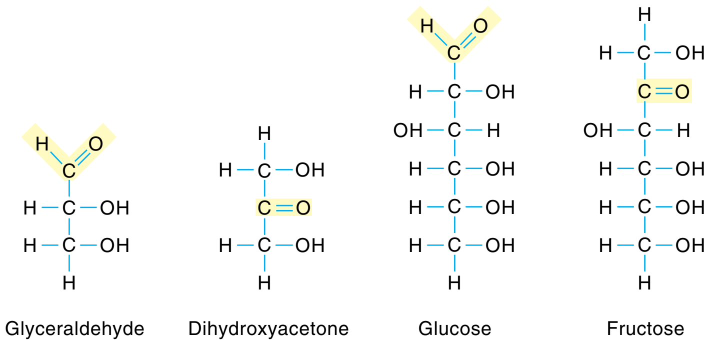


FIGURE 30.9

Monosaccharides. Structural formulas of four simple sugars: glyceraldehyde and dihydroxyacetone have three carbons (i.e., they are trioses), and glucose and fructose have six carbons (i.e., they are hexoses). The functional groups are shaded. Note that glyceraldehyde and dihydroxyacetone, and glucose and fructose have the same ratio and number of atoms; thus, they are structural isomers of each other.

LIPIDS: ENERGY, INTERFACES, AND SIGNALS

Unlike the other three groups of organic molecules, **lipids** are nonpolar organic molecules that are insoluble in polar water but

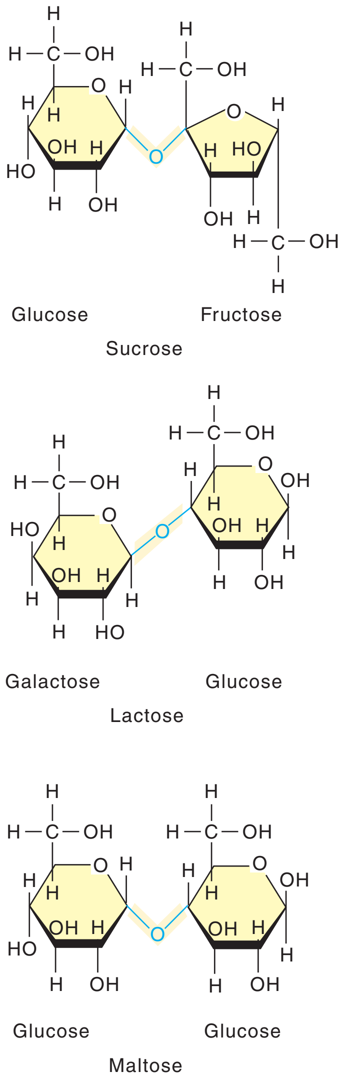


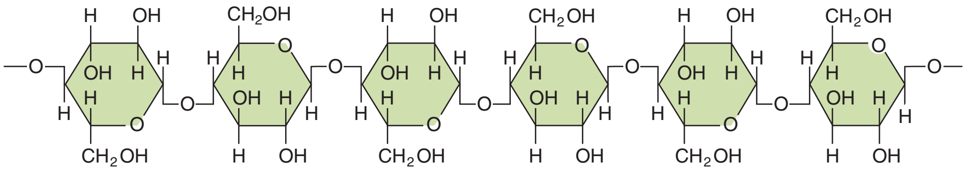
FIGURE 30.10

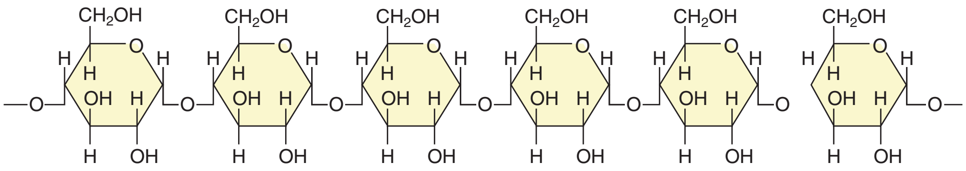
Disaccharides. Sucrose is ordinary table sugar, and lactose is the sugar in milk. Maltose is found in malt.

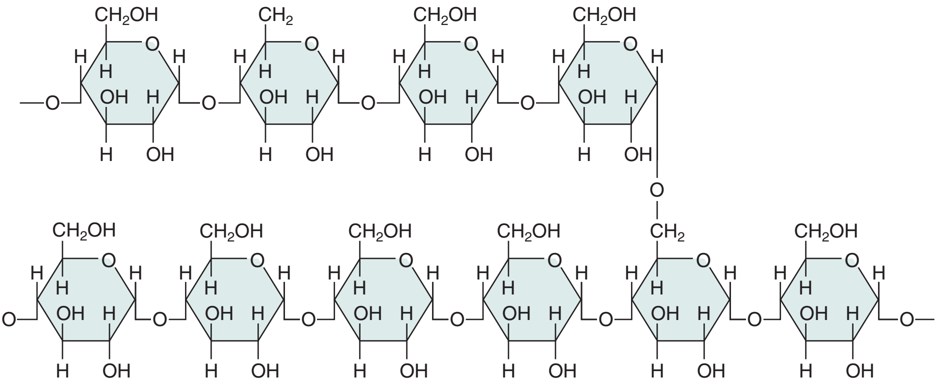
soluble in nonpolar organic solvents, such as ether, alcohol, and chloroform. Phospholipids and cholesterol are lipids that are important constituents of cell membranes. The most common lipids in animals, however, are fats. Fats build cell parts and supply energy for cellular activities.

Lipid molecules are composed primarily of carbon, hydrogen, and oxygen atoms, although some may contain small amounts of phosphorus and nitrogen. They contain a much smaller proportion of oxygen than do carbohydrates, as the formula for the fat, tristearin, $C_{57}H_{110}O_6$, illustrates.

The building blocks of fat molecules are fatty acids and glycerol. Fatty acids contain long hydrocarbon chains bonded to carboxyl (—COOH) groups. Glycerol is a three-carbon alcohol, with each carbon bearing a hydroxyl (—OH) group. Three fatty acid molecules combine with one glycerol molecule by joining to each of the three carbon atoms in the glycerol backbone (figure


Cellulose section


Starch section


Glycogen section

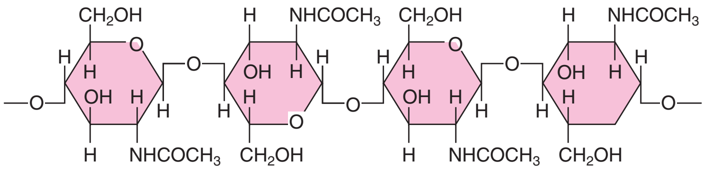

Chitin section

FIGURE 30.11

Polysaccharides. Cellulose, starch, and glycogen are all chains of glucose subunits, but they differ in structure. Notice that the glucose subunits of cellulose link differently than the glucose subunits of starch. Glycogen is also a glucose polymer, but is more highly branched than either cellulose or starch. Chitin is a polymer of acetylglucosamine units.

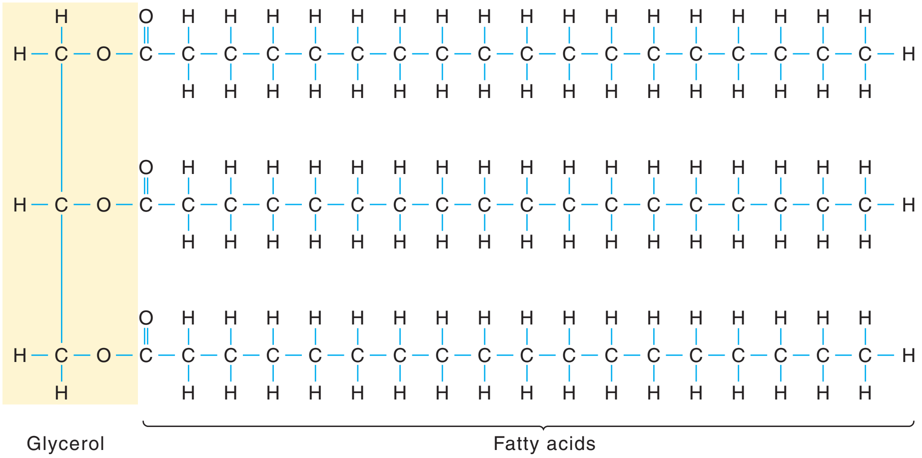


FIGURE 30.12

Triglycerides. A triglyceride is a fat molecule consisting of a glycerol molecule bonded to three fatty acid molecules. Beef fat, with three stearic acids, is shown.

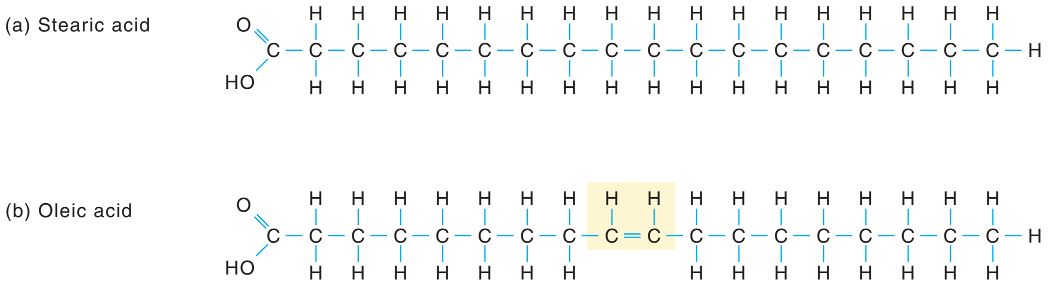


FIGURE 30.13

Fatty Acids. Structural formulas for *(a)* saturated (stearic) and *(b)* unsaturated (oleic) fatty acids. Note the double bond in the carbon backbone of oleic acid.

30.12). Because there are three fatty acids, the resulting fat molecule is called a triglyceride neutral fat, or triacylglycerol.

Although the glycerol portion of every fat molecule is the same, there are many kinds of fatty acids and, therefore, many kinds of fats. Fatty acid molecules differ in the length of their carbon chains and in the ways the carbon atoms combine. The most common are even-numbered chains of 14 to 20 carbons. In some cases, the carbon atoms join by single carbon-carbon bonds, and each carbon atom binds to as many hydrogen atoms as possible. This type of fatty acid is saturated (figure 30.13*a*). Other fatty acids have one or more double bonds between carbon atoms and are unsaturated because the double bonds replace some of the hydrogen atoms, and therefore, the fatty acids contain fewer than the maximum number of hydrogen atoms (figure 30.13*b*). Fatty acids with one double bond are monounsaturated, and those with numerous double bonds are polyunsaturated.

Unsaturated fats have low melting points because their chains bend at the double bonds and the fat molecules cannot align closely with one another, which would lead to solidification. Consequently, the fat may be fluid at room temperature. A liquid fat is called an oil. Most plant fats are unsaturated. Animal fats, in contrast, are often saturated and occur as hard or solid fats.

A phospholipid molecule is similar to a fat molecule in that it contains a glycerol portion and fatty acid chains. However, the phospholipid has only two fatty acid chains. Phosphate (PO_4^{3-}) and nitrogen-containing groups replace the third chain. The polar phosphate and nitrogen groups are soluble in water (hydrophilic) and form the "head" of the molecule; the insoluble (nonpolar, hydrophobic) fatty acid portion forms the "tail." Phospholipids are the major structural components of cell membranes because of this tendency to be soluble at one end and insoluble at the other.

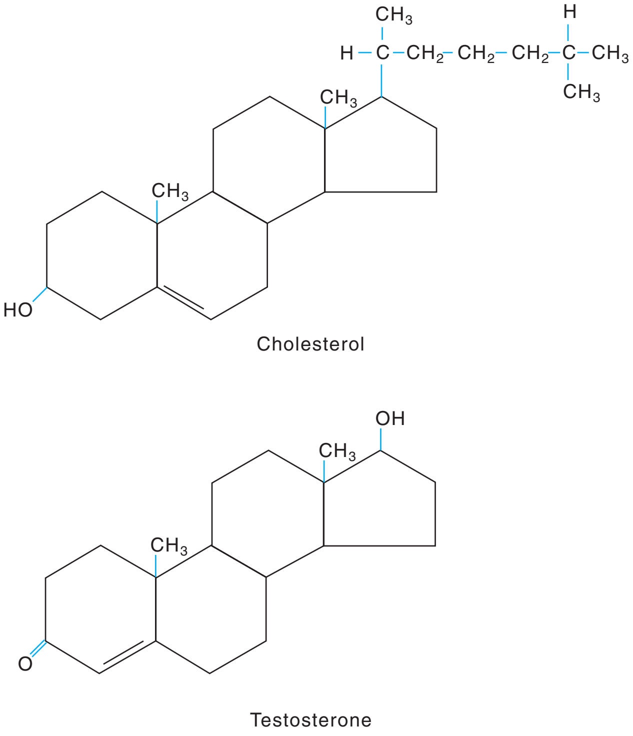


FIGURE 30.14

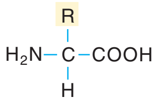
Steroids. Structures of two common steroids, showing the backbone of one five-carbon ring and three six-carbon rings. Cholesterol affects the fluidity of membranes. Testosterone is a male hormone in mammals that is responsible for the development and maintenance of secondary sexual characteristics, and for the maturation and functioning of sex organs.

Steroids are naturally occurring, lipid-soluble molecules composed of four fused carbon rings that provide a somewhat rigid structure (figure 30.14). Three of the rings are six-sided, and the fourth is five-sided. The four rings contain a total of 17 carbons. Cholesterol is an important biologically active steroid, as are vitamin D and hormones of the adrenal gland (e.g., aldosterone), the ovaries (e.g., estrogen), and the testes (e.g., testosterone).

PROTEINS: THE BASIS OF LIFE'S DIVERSITY

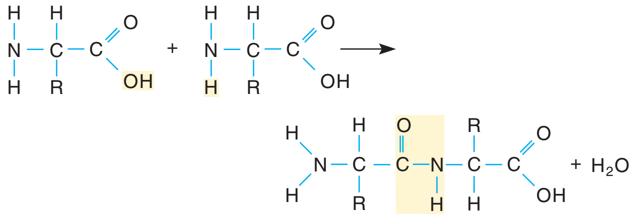
In animals, **proteins** are structural material, energy sources, protection against disease in higher animals, chemical messengers (hormones), and receptors on cell membranes. Some proteins play important roles in metabolic reactions by acting as biological catalysts called enzymes. They enter and speed up specific chemical reactions without being used up themselves. (Chapter 4 discusses enzymes in more detail.)

Proteins always contain atoms of carbon, hydrogen, nitrogen, oxygen, and sometimes, sulfur. The individual building blocks of proteins are **amino acids.** Amino acids always contain an amino group (—NH_2), a carboxyl group (—COOH), a hydrogen atom, and a functional group, designated R, all bonded to a central carbon atom:



$$H_2N-\overset{R}{\underset{H}{C}}-COOH$$

The nature of the R group linked to the central carbon atom determines the identity and unique chemical properties of each amino acid. Twenty different amino acids commonly occur in animals. Covalent bonds called **peptide bonds** link individual amino acids in chains. In the formation of a peptide bond, the carboxyl group of one amino acid bonds to the amino group of another amino acid, with the elimination of water (a dehydration synthesis reaction), as follows:



When two amino acids bond, they form a unit called a dipeptide; three bonded amino acids form a tripeptide. When many amino acids bond, they form a chain called a polypeptide.

In different proteins, the chain of amino acids can vary from fewer than 50 to more than 2,000 amino acids. Each type of protein contains a specific number and kind of amino acids arranged in a particular sequence. The protein molecule may be coiled and folded, or it may interact with other protein molecules to form a unique three-dimensional structure. Different kinds of protein molecules have different shapes related to their particular functions in life processes.

A protein molecule has several different levels of structure. The primary structure is the linear sequence of amino acids in the polypeptide chains comprising the molecule (figure 30.15*a*). The secondary structure of a protein is a repeating pattern of bonds (often hydrogen bonds) between amino acids, and it commonly takes the shape of an alpha helix or pleated sheet (figure 30.15*b*). The tertiary structure results from the helix folding into a three-dimensional shape (figure 30.15*c*). In some instances, two protein chains join to form a larger protein, the shape of which is called the quaternary structure (figure 30.15*d*).

NUCLEOTIDES AND NUCLEIC ACIDS: INFORMATION STORAGE, CHEMICAL MESSENGERS, AND ENERGY TRANSFER

Small organic compounds called nucleotides are essential to life. Each **nucleotide** is composed of three substances: (1) a nitrogen-containing organic base, (2) a five-carbon sugar (ribose or deoxyribose), and (3) phosphate (figure 30.16).

Adenosine phosphates and nucleotide coenzymes are nucleotides. Adenosine phosphates are small molecules that function as chemical messengers within and between cells, and as

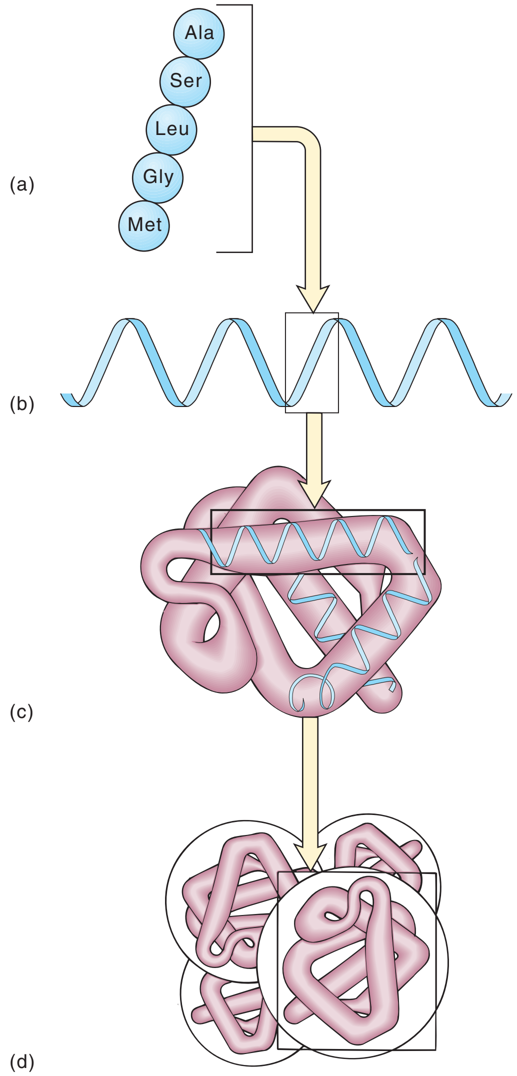


FIGURE 30.15

Levels of Protein Structure. *(a)* Primary structure is the protein's linear sequence of amino acids. *(b)* The repeating configurations in the structure of the amino acids determine secondary structure. *(c)* The three-dimensional folding of the secondary structure determines tertiary structure. *(d)* The three-dimensional arrangement of more than one polypeptide gives some proteins their quaternary structure.

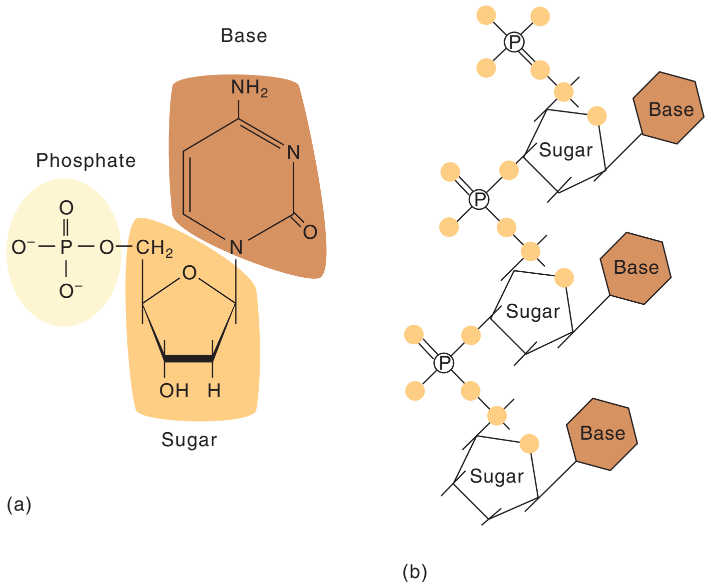


FIGURE 30.16

Nucleotides. *(a)* A nucleotide has a phosphate group, a ribose or deoxyribose sugar, and a nitrogen-containing base. Each of the five types of bases has a slightly different chemical composition. DNA uses four of the five, while RNA uses a different set of four. *(b)* A single-stranded DNA molecule consists of many nucleotide monomers joined to form a long chain.

energy transfer molecules. An example of a chemical messenger is cyclic adenosine monophosphate (cAMP). Adenosine triphosphate (ATP) is a nucleotide that functions as an energy carrier. Nucleotide coenzymes, such as NAD^+ and FAD, play an important role in energy transfer within the cell.

Nucleic acids are large single- or double-stranded chains of nucleotide subunits. The two nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA).** DNA makes up the chromosomes in the cell's nucleus, can replicate itself, and contains the genetic (hereditary) information of the cell. RNA may be present in either the nucleus or the cytoplasm (the part of the cell outside the nucleus) and carries information between the DNA and the cellular sites of protein synthesis.

SUMMARY

1. Matter is anything that has mass and occupies space. The most important particles of matter are protons, neutrons, and electrons, all of which associate to form atoms. The nucleus of an atom contains the protons and neutrons; electrons orbit around the nucleus.
2. The distribution of electrons in an atom's outermost shell largely determines the atom's chemical nature. Atoms tend to lose or gain electrons until the outer shell stabilizes.
3. Atoms react with other atoms to form molecules. Chemical bonds hold atoms together. A covalent bond results from the sharing of one or more pairs of electrons. A hydrogen bond forms from the attraction of the partial positive charge of a hydrogen atom of one water molecule to the partial negative charge of an oxygen atom of another water molecule. An ionic bond results from the attraction of opposite charges.
4. An acid releases hydrogen ions (protons) when dissolved in water. A base releases hydroxyl ions (accepts protons) when dissolved in water.
5. The pH scale measures a solution's alkalinity or acidity by indicating the concentration of free hydrogen ions in water. The fluid systems of most animals contain buffers that help regulate acid-base balance.
6. Simple carbohydrates are made of carbon, hydrogen, and oxygen, and are important energy sources for most animals. Carbohydrates are classified as monosaccharides, disaccharides, or polysaccharides, according to the number of sugars they contain.
7. Lipids are molecules containing many more C—H bonds than carbohydrates. Fats and oils are familiar lipids. Lipids can store large amounts of energy in an organism's body.
8. Proteins are large, complex molecules composed of smaller structural units called amino acids. Peptide bonds link amino acids in chains called polypeptides.
9. Nucleic acids are very large molecules composed of bonded units called nucleotides. The two nucleic acids are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Nucleic acids carry the hereditary messages and regulate protein synthesis. Two other nucleotides are the adenosine phosphates (cAMP and ATP) that function as energy transfer molecules within and between cells, and the nucleotide coenzymes (NAD^+ and FAD) that play a role in energy transfer within the cell.

SELECTED KEY TERMS

atom
atomic mass
atomic number
buffers
carbohydrates
disaccharide
electrons
elements
ion
isomer
mass
matter
neutrons
pH scale
proteins
protons
steroids

CRITICAL THINKING QUESTIONS

1. Given the major elements of which all living organisms are composed, is it likely that the earth's surface could have been the major chemical "breadbasket" for the origin of life? Explain.
2. What is meant by the statement, "Evolution resulted in carbon-based life"?
3. Why should a zoologist who studies animal life also be interested in the properties of chemical bonds?
4. The major biological molecules are polymers—long chains of subunits. Why are linear polymers so common in living animals?
5. Why are all forms of life composed of, and affected by, the same elements?