CHAPTER 2

The Nature of Life

OVERVIEW

This chapter begins with a discussion of the attributes of living organisms. These include growth, reproduction, response to stimuli, metabolism, movement, complexity of organization, and adaptation to the environment. Then it examines the chemical and physical bases of life. A brief look at the elements and their atoms is followed by a discussion of compounds, molecules, valence, bonds, ions, acids, bases, and salts. Forms of energy and the chemical components of cells are examined next. The chapter concludes with an introduction to macromolecules: carbohydrates, lipids, proteins, and nucleic acids.

Some Learning Goals

1. Learn the attributes of living organisms.
2. Define matter; describe its basic state.
3. Understand the nature of compounds and describe acids, bases, and salts.
4. Know the various forms of energy.
5. Learn the elements found in cells.
6. Understand the nature of carbohydrates, lipids, and proteins.

ave you ever dropped a pellet of dry ice (frozen carbon dioxide) into a pan of water and watched what happens? The solid pellet darts randomly about the surface, looking like a highly energetic bug waterskiing, as the warmer water rapidly converts it to a gas. Does all that motion make the dry ice alive? Hardly; yet one of the attributes of living things is the capacity to move. But if living things move, what about plants? If a tree remains fixed in one place and doesn't crawl down the sidewalk, does that mean it isn't alive? Again the answer is no, but these questions do serve to point out some of the difficulties encountered in defining *life*. In fact, some argue that there is no such thing as life—only living organisms—and that life is a concept based on the collective attributes of living -organisms.

ATTRIBUTES OF LIVING ORGANISMS

Composition and Structure

The activities of living organisms originate in tiny structural units called *cells*, which consist of *cytoplasm* (a souplike fluid) bounded by a very thin membrane. All living cells contain genetic material that controls their development and activities. In the cells of many organisms, this genetic material, known as *DNA* (an abbreviation for deoxyribonucleic acid), is housed in a somewhat spherical structure called the *nucleus*, which is suspended in the cytoplasm. In bacteria and other simple cells, however, the DNA is distributed directly in the cytoplasm. The cells of plants, algae, fungi, and many simpler organisms have a *cell wall* outside of the membrane that bounds the cytoplasm. The cell wall provides support and rigidity. Cells are discussed in more detail in Chapter 3.

Growth

Some have described **growth** as simply an increase in *mass* (a body of *matter*—the basic "stuff" of the universe), usually accompanied by an increase in *volume.* Most growth results from the production of new cells and includes variations in *form*—some the result of inheritance, some the result of response to the environment. What happens, for example, if you plant two tulip bulbs of the same variety in poor soil but don't give them the same care? If you water one just enough to allow it to grow, while you water the other one freely and work fertilizers and conditioners into the soil around it, you might expect the second one to grow larger and produce more flowers than the first. In other words, although the two plants grew from the same variety of tulip, they differ in form, following patterns of growth dictated by the DNA and the environment. Various aspects of growth are discussed in Chapter 11.

Reproduction

Dinosaurs were abundant 160 million years ago, but none exist today. Hundreds of mammals, birds, reptiles, plants, and other organisms are now listed as endangered or threatened species, and many of them will become extinct within the next decade or two. All of these once-living or threatened organisms have one feature in common: it became impossible or it has become difficult for them to reproduce. **Reproduction** is such an obvious feature of living organisms that we take it for granted—until it no longer takes place.

When organisms reproduce, the offspring always resemble the parents: guppies never have puppies—just more guppies—and a petunia seed, when planted, will not develop into a pineapple plant. Also, offspring of one kind tend to resemble their parents more than they do other individuals of the same kind. The laws governing these aspects of inheritance are discussed in Chapter 13.

Response to Stimuli

If you stick a pin into a pillow, you certainly don't expect any reaction from the pillow, but if you stick the same pin into a friend, you know your friend will react immediately (assuming he or she is conscious) because responding to stimuli is a major characteristic of all living things. You might argue, however, that when you stuck a pin into your house plant, nothing happened, even though you were fairly certain the plant was alive. You might not have been aware that the house plant did indeed respond, but in a manner very different from that of a human. Plant responses to stimuli are generally of a different nature than those of animals. If the house plant's food-conducting tissue was pierced, it probably responded by producing a plugging substance called **callose** in the affected cells. Some studies have shown that callose may form within as little as 5 seconds after wounding. Also, an unorganized tissue called **callus,** which forms much more slowly, may be produced at the site of the wound. Responses of plants to injury and to other stimuli, such as light, temperature, and gravity, are discussed in Chapters 9 through 11.

Metabolism

Definitions of metabolism vary somewhat but are mostly based on the observation that metabolism is *the collective product of all the biochemical reactions taking place within an organism*. All living organisms undergo various metabolic activities, which include the production of new cytoplasm, the repair of damage, and normal cell maintenance. The most important activities include **respiration,** an energy-releasing process that takes place in all living things; **photosynthesis,** an energy--harnessing process in green cells that is, in turn, associated with energy storage; **digestion,** the conversion of large or insoluble food molecules to smaller soluble ones; and **assimilation,** the conversion of raw materials into cytoplasm and other cell substances. These topics are discussed in Chapters 9 through 11.

Movement

At the beginning of this chapter, we mentioned that plants generally don't move from one place to another (although their reproductive cells may do so). This does not mean, however, that plants do not exhibit movement, a universal characteristic of living things. The leaves of sensitive plants (*Mimosa pudica*) fold within a few seconds after being disturbed or subjected to sudden environmental changes, and the tiny underwater traps of bladderworts (*Utricularia*) snap shut in less than one-hundredth of a second. But most plant movements, when compared with those of animals, are slow and imperceptible and are mostly related to growth phenomena. They become obvious only when demonstrated experimentally or when shown by time-lapse photography. Time-lapse photo-graphy often reveals many types and directions of motion, particularly in young organs. Movement is not confined to the organism as a whole but occurs down to the cellular level. For example, the cytoplasm of living cells constantly flows like a river within cells; this streaming motion is called *cyclosis*, or *cytoplasmic streaming.* Cyclosis usually appears to run clockwise or counterclockwise within the boundaries of each cell, but movement may actually be in various directions.

Complexity of Organization

The cells of living organisms are composed of large numbers of **molecules** (the smallest unit of an element or compound retaining its own identity). Typically there are more than 1 trillion molecules in a single cell. The molecules are not simply mixed, like the ingredients of a cake or the concrete in a sidewalk, but are organized into compartments, membranes, and other structures within cells and tissues. Even the most complex nonliving object has only a tiny fraction of the types of molecules of the simplest living organism. Furthermore, the arrangements of these molecules in living organisms are highly structured and complex. Bacteria, for example, are considered to have the simplest cells known, yet each cell contains a minimum of 600 different kinds of protein as well as hundreds of other substances, with each component having a specific place or being a part of a specific structure within the cell. When flowering plants and other larger living objects are examined, the complexity of organization is overwhelming, and the number of molecule types can run into the millions.

Adaptation to the Environment

If you skip a flat stone across a body of water and it lands on the opposite shore, the stone is not affected by the change from air to water to land during its brief journey; it does not respond to its environment. Living organisms, however, do respond to the air, light, water, and soil of their environment, as will be explained in later chapters. They are also, after countless generations of natural selection (as discussed in Chapter 15), genetically adapted to their environment in many subtle ways. Some weeds (e.g., dandelions) can thrive in a wide variety of soils and climates, whereas many species now threatened with extinction have adaptations to their environment that are so specific they cannot tolerate even relatively minor changes.

CHEMICAL AND PHYSICAL BASES OF LIFE

The Elements: Units of Matter

The basic “stuff of the universe,” called matter, occurs in three states—*solid, liquid,* and *gas.* In simple terms, matter’s characteristics are as follows:

1. It occupies space.
2. It has *mass,* which we commonly associate with weight.
3. It is composed of **elements.** There are 93 elements that occur naturally on our planet. At least 19 more elements have been produced artificially. Only a few of the -nat-ural elements (e.g., nitrogen, oxygen, gold, silver, copper) occur in pure form; the others are found combined together chemically in various ways. Each element has a designated symbol, often derived from its Latin name. The symbol for copper, for example, is **Cu** (from the Latin *cuprum*); and for sodium, **Na** (from the Latin *natrium*). The symbols for carbon, hydrogen, and oxygen are **C, H,** and **O,** respectively.

The smallest stable subdivision of an element that can exist is called an **atom.** Atoms are so minute that until the mid-l980s, individual atoms were not directly visible to us with even the most powerful electron microscopes. We have known for over 100 years, however, that atoms consist of several kinds of subatomic particles. Each atom has a tiny **nucleus** consisting of **protons,** which are particles with positive electrical charges, and other particles called **neutrons,** which have no electrical charges. Both protons and neutrons have a small amount of mass. If the nucleus, which contains nearly all of the atom’s mass, were enlarged so that it was as big as a beach ball, the atom, which is mostly space, would be larger than a professional football stadium (Fig. 2.1). Because each atom is mostly space, solid objects are not as "solid" as they appear. Objects that hit each other are not actually contacting solid surfaces. Instead, negative charges on the objects repel each other. Without these charges, the objects would pass through each other.

Atoms are extremely long-lived. It is estimated that they survive for about 10^{35} years. Accordingly, the atoms in every living thing were once found in stars. Each tree you see outside your window probably contains a billion atoms, many of which may well have been in the bodies of your ancestors.

Each atom of an element has a specific number of protons in its nucleus, ranging from one in hydrogen, the lightest element, to 92 in uranium, the heaviest natural element. This number is referred to as the *atomic number.* The atomic number is often shown as a subscript to the left of the chemical symbol. For example, nitrogen, which has seven protons in its nucleus, has its atomic number of seven shown as $_7N$. The combined number of protons and neutrons in a single atom is referred to as its *atomic mass* (Table 2.1). The atomic mass number is commonly shown as a superscript to the left of the chemical symbol. For example, the atomic mass of nitrogen, which has seven protons and seven neutrons in its nucleus, is shown as ^{14}N, and when both the atomic number and the atomic mass are shown, the chemical symbol appears as $^{14}_7N$.

Electrons, which are little more than negative electric charges, whirl around an atom’s nucleus. Electron masses are about 1,840 times lighter than those of both protons and neutrons and are so minute that they are generally disregarded. Since opposite electric charges attract each other, the positive electric charges of protons attract the negative electric charges of electrons and determine the paths of the electrons whirling around the nucleus.

The region occupied by electrons around the nucleus is called an **orbital.** Each orbital has an imaginary axis and is somewhat cloudlike, but it doesn't have a precise boundary, and so we can't be certain of an electron's position within an orbital at any time. This has led to an orbital being defined as *a volume of space in which a given electron occurs 90% of the time.* Electrons actually occupy all space in an orbital simultaneously, so they do not circle around the nucleus like planets. In addition, according to the quantum leap theory of physics, an electron can move instantaneously from one orbital to another without visiting the space between them!

Electrons may be located in one or more energy levels of an atom, and their distance from the nucleus depends on their energy level. Each energy level is usually referred to as an *electron shell.* The outermost electron shell determines how or if an atom reacts with another atom. Only two electrons can occupy the first and lowest energy level associated with the innermost orbital; this orbital is more or less spherical and is so close to the nucleus that it is often not shown on diagrams of atoms. One to several additional orbitals, which are mostly spindle shaped (like the tips of cotton swabs), generally occupy much more space. Up to eight electrons can be held by the second energy level, and although the third and fourth energy levels can hold more than eight electrons each, they can become unstable if more than eight electrons are present. If an electron in one orbital is provided with more energy, it can jump to an orbital farther away from the nucleus. Conversely, if an electron releases energy, it drops to an energy level closer to the nucleus. The electrons of each orbital tend to repel those of other orbitals, so that the axes of all the orbitals of an atom are oriented as far apart from each other as possible; the outer parts of the orbitals, however, actually overlap more than shown in diagrams of them. Orbitals usually have diameters thousands of times more extensive than that of an atomic nucleus (Fig. 2.2).

Because each atom usually has as many electrons as it does protons, the negative electric charges of the electrons balance the positive charges of the protons, making the atom electrically neutral. The number of neutrons in the atoms of an element can vary slightly, so the element may occur in forms having different weights but with all forms behaving alike chemically. Such variations of an element are called **isotopes.** The element oxygen (Fig. 2.3), for example, has seven known isotopes. The nucleus of one of these isotopes contains eight protons and eight neutrons; the nucleus of another isotope holds eight protons and ten neutrons, and the nucleus of a third isotope consists of eight protons and nine neutrons. If the number of neutrons in an isotope of a particular element varies too greatly from the average number of neutrons for its atoms, the isotope may be unstable and split into smaller parts, with the release of a great deal of energy. Such an isotope is said to be *radioactive.*

Molecules: Combinations of Elements

The atoms of most elements can combine with other atoms of the same or different elements; in fact, most elements do not exist independently as single atoms. When two or more elements are united in a definite ratio by chemical bonds, the substance is called a **compound.** Table salt (sodium chloride, NaCl), for example, is a compound consisting of sodium and chlorine atoms combined in a 1:1 ratio.

A **molecule** consists of two or more atoms bound together and is the smallest independently existing particle of a compound or element. The molecules of the gases oxygen and hydrogen, for example, exist in nature as combin-ations of two atoms of oxygen (O_2) or two atoms of hydrogen (H_2), respectively. Water molecules (H_2O) consist of two atoms of hydrogen and one atom of oxygen (Fig. 2.4). Molecules are in constant motion, with an increase or decrease in temperature speeding up or slowing down the motion. The more molecular movement there is, the greater the chances are that some molecules will collide with each other. Also, the chances of random collisions increase in proportion to the density of the molecules (i.e., the number of molecules present in a given space).

Random collisions between molecules capable of sharing electrons are the basis for all chemical reactions. The reactions often result in new molecules being formed. Each chemical reaction in a cell usually takes place in a watery fluid and is controlled by a specific *enzyme.* Enzymes are organic *catalysts* (a catalyst speeds up a chemical reaction without being used up in the reaction; enzymes are discussed on page 26).

When a water molecule is formed, two hydrogen atoms become attached to an oxygen atom at an angle averaging 105° in liquid water (for ice, the angle is precisely 105°). The electrons of the three atoms are shared and form an electron cloud around the core, giving the molecule an asymmetrical shape. Although the electron and proton charges balance each other, the asymmetrical shape and unequal sharing of the electrons in the bond between oxygen and hydrogen cause one side of the water molecule to have a slight positive charge and the other a slight negative charge. Such molecules are said to be *polar.* Since negative charges attract positive charges, polarity affects the way in which molecules become aligned toward each other; polarity also causes molecules other than water to be water soluble.

Water molecules form a cohesive network as their slightly positive hydrogen atoms are attracted to the slightly negative oxygen atoms of other water molecules (Fig. 2.5). The cohesion between water molecules is partly responsible for their movement through fine (capillary) tubes, such as those present in the wood and other parts of plants. The attraction between the hydrogen atoms of water and other negatively charged molecules, such as those of fibers, also causes *adhesion* (attraction of charged molecules to each other) and is the basis for water wetting substances. When there is no attraction between water and other substances (e.g., between water and the waxy surface of a cabbage leaf), the cohesion between the water molecules results in droplets beading in the same way that raindrops bead on a freshly waxed automobile.

Valence

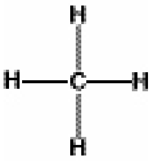
The combining capacity of an atom or ion based on electron number is called **valence.** For example, atoms of the element calcium, an important element in cell walls and in transmitting chem-ical "messages" in plant cells, have a valence of two, while those of the element chlorine have a valence of one. In order for the atoms of these two elements to combine, there must be a balance between electrons lost or gained (i.e., the valences must balance); it takes *two* chlorine atoms, for example, to combine with *one* calcium atom. The compound formed by the union of calcium and chlorine is called *calcium chloride*. It is customary to use standard abbreviations taken from the Latin names of the elements when giving chemical formulas or equations. Calcium -chloride is shown as $CaCl_2$, indicating that one atom of calcium (Ca^{++}) required two atoms of chlorine (Cl^-) to form a calcium chloride molecule.

Bonds and Ions

Bonds are forces that form molecules by attracting and holding atoms together. Bonds can form in several different ways. The number of electrons in an atom's outermost energy level determines how many chemical bonds can be formed by that particular atom. If the number of electrons in the outermost energy level is less than eight, the atom may lose, gain, or share electrons, resulting in an outermost energy level that contains the maximum number of electrons. Three types of chemical bonds are of particular significance for living organisms:

1. **Covalent bonds** form when two atoms complete their outermost energy level by sharing a pair of electrons in the outermost orbital; they hold two or more atomic nuclei together and travel between them, keeping them at a stable distance from each other. For example, the single orbital of a hydrogen atom, which has just one electron, is usually filled by attracting an electron from another hydrogen atom. As a result, two hydrogen atoms share their single electrons, making a combined orbital with two electrons. The combined orbital, with its two hydrogen atoms, forms a molecule of hydrogen gas. The covalent bond is shown as a single line, so that hydrogen gas (H_2) is depicted as H—H.

   Except for hydrogen and helium, which have only one orbital, elements can have up to four more orbitals in each energy level. Carbon atoms, for example, have six electrons—two in the innermost orbital and one in each of the four outer orbitals of the second shell; by covalent bonding, carbon can share four electrons. When four hydrogen atoms bond to one carbon atom, a molecule of methane gas (CH_4) is formed. To illustrate the bonds, the structural formula for CH_4 is shown as follows:

   When one pair of electrons is shared, the bond is said to be *single*. When two pairs of electrons are shared, the bond is referred to as *double*, and *triple* bonds are formed when three pairs of electrons are shared. Double bonds are shown in structural formulas with double lines (e.g., C=C), and triple bonds are shown with three lines (e.g., C≡N). In covalent bonds involving molecules such as those of hydrogen (H_2), where electrons are shared equally, the bonds are said to be *nonpolar*. However, *polar covalent bonds* (e.g., those of a water molecule) are formed when electrons are closer to one atom than to another and therefore are shared unequally. Because the electrons are shared unequally, parts of the molecule are not electrically neutral and are slightly charged. Covalent bonds are the strongest of the three types of bonds discussed here and are the principal force binding together atoms that make up some important biological molecules discussed later in this chapter (Fig. 2.6).

2. **Ionic bonds.** In nature, some electrons in the outermost orbital are not really shared but instead are completely removed from one atom and transferred to another, particularly between elements that can strongly attract or easily give up an electron. Molecules that lose or gain electrons become positively or negatively charged particles called *ions*. Ionic bonds form whenever one or more electrons are donated to another atom and result whenever two oppositely charged ions come in contact. Ions are shown with their charges as superscripts. For example, table salt (sodium chloride) is formed by ionic bonding between an ion of sodium (Na^+) and an ion of chlorine (Cl^-). The sodium becomes a positively charged ion when it loses one of its electrons, which is gained by an atom of chlorine. This extra electron makes the chlorine ion negatively charged, and the sodium ion and chlorine ion become bonded together by the force of the opposite charge (Fig. 2.7).

   Some ions, such as those of magnesium (Mg^{++}), give up two electrons and therefore have two positive charges. Such ions can form ionic bonds with two single negatively charged ions such as those of chlorine (Cl^-), forming magnesium chloride ($MgCl_2$). Many biologically important molecules exist as ions in living matter.

3. **Hydrogen bonds** form as a result of attraction between positively charged hydrogen atoms in polar molecules and negatively charged atoms in other polar molecules. Negatively charged oxygen and/or nitrogen atoms of one molecule may at-

tract positively but weakly charged hydrogen atoms of other molecules, forming a weak bond. Hydrogen bonds are very important in nature because of their abundance in many biologically significant molecules. They have, however, only about 7% to 10% of the strength of covalent bonds. Hydrogen bonds help cellular processes by maintaining the shapes of proteins such as enzymes, which make different compounds fit together precisely to complete a chemical reaction.

Acids, Bases, and Salts

Water molecules are held together by weak hydrogen bonds. In pure water, however, a few molecules sometimes dissociate into hydrogen (H^+) and hydroxyl (OH^-) ions, with the number of H^+ ions precisely equaling the number of OH^- ions.

Acids, which include things that taste sour like cranberry or lemon juice, are chemicals that release hydrogen ions (H^+) when dissolved in water, resulting in proportionately more hydrogen than hydroxyl ions being present. Some acids, such as the acetic acid of vinegar, release relatively few hydrogen ions and are said to be weak. Strong acids such as sulfuric acid dissociate almost completely into hydrogen and sulfate ions.

Bases (also referred to as *alkaline compounds*) usually feel slippery or soapy. They are defined as *compounds that release negatively charged hydroxyl ions (OH^-) when dissolved in water.* Caustic soda, which is sodium hydroxide (NaOH), is a base that dissociates in water to positively charged sodium ions (Na^+) and negatively charged hydroxyl ions (OH^-). Bases can also be defined as *compounds that accept H^+ ions.*

The acidity or alkalinity of the soil or water in which a plant occurs affects how it lives and grows or even if it can exist in a particular environment. Similarly, the acidity or alkalinity of the fluids inside cells has to be stable or various chemical reactions vital to life itself can’t take place.

The pH Scale

The concentration of H^+ ions present is used to define degrees of acidity or alkalinity on a specific scale, called the **pH scale.** The scale ranges from 0 to 14, with each unit representing a tenfold change in H^+ concentration. Pure water has a pH of 7—the point on the scale where the number of H^+ and OH^- ions is exactly the same, or the neutral point.[1] The lower a number is below 7, the higher the degree of acidity; conversely, the higher a number is above 7, the higher the degree of alkalinity. Vinegar, for example, has a pH of 3, tomato juice has a pH of 4.3, and egg white has a pH of 8. Precipitation with a pH of less than 4.5 is now commonly referred to as *acid rain* (acid deposition). Acid rain (discussed in Chapter 25) is associated with industrial emissions, and appears to be causing damage to vegetation, soil organisms, and buildings in some parts of the world, including North America.

When an acid and a base are mixed, the H^+ ions of the acid bond with the OH^- ions of the base, forming water (H_2O). The remaining ions bond together, forming a salt. If hydrochloric acid (HCl) is mixed with a base—for example, sodium hydroxide (NaOH)—water (H_2O) and sodium chloride (NaCl), a salt, are formed. The reaction is represented by symbols in an equation that shows what occurs:

$$\mathbf{HCl + NaOH \rightarrow H_2O + NaCl}$$

Energy

Energy is the ability or capacity to do work or to produce a change in motion or matter. Energy exists in several forms and is required for growth, reproduction, movement, cell or tissue damage repair, and other activities of whole organisms, cells, or molecules. On earth, the sun is the ultimate source of life energy.

Thermodynamics is the study of energy and its conversions from one form to another. Scientists apply two laws of thermodynamics to energy. *The first law of thermodynamics* states that energy is constant—it cannot be increased or diminished—but it can be converted from one form to another. Among its forms are *chemical, electrical, heat,* and *light* energy.

The *second law of thermodynamics* states that when energy doesn’t enter or leave a given system and is converted from one form to another, it (energy) flows from a high to a low state. For example, heat will always flow from a hot iron to cold clothing but never from the cold clothing to the hot iron. Furthermore, energy will be released during the conversion. The total amount of energy in the universe, however, remains constant. Such energy-yielding reactions are vital to the normal functions of cells and provide the energy needed for other cell reactions that require energy. Both types of reactions are discussed in Chapter 10.

Forms of energy include *kinetic* (motion) and *potential* energy. Potential energy is defined as the “capacity to do work owing to the position or state of a particle.” For example, when an individual with a snowboard on the top of a hill rides down the hill, the potential energy is converted to kinetic energy. Some chemical reactions release energy, and others require an input of energy (Fig. 2.8).

Although all electrons have the same weight and electrical charge, their amount of potential energy varies. Electrons with the least potential energy are located within the single spherical orbital closest to the atom’s nucleus, and electrons with the most potential energy are in the outermost orbital (Fig. 2.9). Some of the numerous energy exchanges and carriers that occur in living cells are discussed in later chapters.

Chemical Components of Cells

The living substance of cells consists of cytoplasm and the structures within it. The numerous internal structures, which vary considerably in size, are discussed in Chapter 3. About 96% of cytoplasm and its included structures are composed of the elements carbon, hydrogen, oxygen, and nitrogen; 3% consists of phosphorus, potassium, and sulfur. The remaining 1% includes calcium, iron, magnesium, sodium, chlorine, copper, manganese, cobalt, zinc, and minute quantities of other elements. When a plant first absorbs these elements from the soil or atmosphere, or when it uses breakdown products within the cell, the elements are in the form of simple molecules or ions. These simple forms may be converted to very large, complex molecules through the metabolism of the cells.

The large molecules invariably have “backbones” of carbon atoms within them and are said to be *organic*. The myriad of chemical reactions of living organisms is based on organic compounds. Most other molecules that -contain no carbon atoms are called *inorganic*. Exceptions include carbon dioxide (CO_2) and sodium bicarbonate ($NaHCO_3$). The name “organic” was given to most of the chemicals of living things when it was believed that only living organisms could produce molecules containing carbon. Today, many organic compounds can be produced artificially in the laboratory, and scientists sometimes hesitate to classify as either organic or inorganic some of the 4 million carbon-containing compounds thus far identified. Most scientists, nevertheless, agree that inorganic compounds usually do not contain carbon.

Monomers and Polymers

The large molecules comprising the majority of cell components are called *macromolecules*, or **polymers.** Polymers are formed when two or more small units called **monomers** bond together. The bonding between monomers occurs when a hydrogen (H^+) is removed from one monomer and a hydroxyl (OH^-) is removed from another, creating an electrical attraction between them. Since the components of water (H^+ and OH^-) are removed (*dehydration*) in the formation (*synthesis*) of a bond, the process is referred to as *dehydration synthesis.* Dehydration synthesis is controlled by an enzyme (see page 26).

Hydrolysis, which is essentially the opposite of dehydration synthesis, occurs when a hydrogen from water becomes attached to one monomer and a hydroxyl group to the other. Energy is released when a bond is broken by hydrolysis. This energy may be stored temporarily or used in the manufacture or renewal of cell components.

Four of the most important classes of polymers found in cells are *carbohydrates, lipids, proteins,* and *nucleic acids.*

Carbohydrates

Carbohydrates are the most abundant organic compounds in nature. They include sugars and starches and contain C, H, and O in a ratio of, or close to a ratio of, 1C:2H:1O (CH_2O). The number of CH_2O units in a carbohydrate can vary from as few as three to as many as several thousand. There are three basic kinds of carbohydrates:

1. *Monosaccharides* are simple sugars with backbones consisting of three to seven carbon atoms. Among the most common monosaccharides are *glucose* ($C_6H_{12}O_6$) and *fructose*, which is an *isomer* of glucose. Isomers are molecules with identical numbers and kinds of atoms, but with different structures and shapes. Accordingly, fructose, which is found in fruits, has the same $C_6H_{12}O_6$ formula as glucose, but the different arrangement of its atoms gives it different properties, such as a slightly sweeter taste. Glucose, which is produced by photosynthesis in green plant cells, is a primary source of energy in the cells of all living organisms (Fig. 2.10).
2. *Disaccharides* are formed when two monosaccharides become bonded together by dehydration synthesis. The common table sugar **sucrose** ($C_{12}H_{22}O_{11}$) is a disaccharide formed from a molecule of glucose and a molecule of fructose; a molecule of water is removed during synthesis. The removal of a molecule of water during the formation of a larger molecule from smaller molecules is referred to as a *condensation reaction.* Sucrose is the form in which sugar is usually transported throughout plants and is also the form of sugar stored in the roots of sugar beets and the culms (stems) of sugar cane.
3. *Polysaccharides* are formed when several to many monosaccharides bond together. Polysaccharide polymers sometimes consist of thousands of simple sugars attached to one another in long, branched or unbranched chains or in coils. For example, *starches,* which are the main carbohydrate reserve of plants, are polysaccharides that usually consist of several hundred to several thousand coiled glucose units. When many glucose molecules become a starch molecule, each glucose gives up a molecule of water. The formula for starch is $(C_6H_{10}O_5)_n$, the n representing many units. In order for a starch molecule to become available as an energy source in cells, it has to be hydrolyzed; that is, it has to be broken up into individual glucose molecules through the restoration of a water molecule for each unit.

Throughout the world, starches are major sources of carbohydrates for human consumption—the principal starch crops being potatoes, wheat, rice, and corn in temperate areas, and cassava and taro in tropical areas.

Cellulose, the chief structural polymer in plant cell walls, is a polysaccharide consisting of 3,000 to 10,000 unbranched chains of glucose molecules. Although cellulose is very widespread in nature, its glucose units are bonded together differently from those of starch, and most animals digest it much less readily than they do starch. Organisms that do digest cellulose, such as the protozoans living in termite guts, caterpillars, and some fungi, produce special enzymes capable of facilitating the breakdown of bonds between the carbons and the glucose units of the cellulose; the organisms then can digest the released glucose.

Lipids

Lipids are fatty or oily substances that are mostly insoluble in water because they have no polarized components. They typically store about twice as much energy as similar amounts of carbohydrate and play an important role in the longer term energy reserves and structural components of cells. Like carbohydrates, lipid molecules contain carbon, hydrogen, and oxygen, but there is proportionately much less oxygen -present. Examples of lipids include **fats,** which are solid at room temperature (Fig. 2.11), and **oils,** which are liquid. An oil molecule is produced when a unit of *glycerol*—a three-carbon compound that has three hydroxyl (—OH) groups—combines with three *fatty acids.* A fatty acid has a carboxyl (—COOH) group at one end and typically has an even number of carbon atoms to which hydrogen atoms can become attached.

Most fatty acid molecules consist of a chain with 16 to 18 carbon atoms. If hydrogen atoms are attached to every available bonding site of these fatty acid carbon atoms, as in most animal fats such as butter and those found in meats, the fat is said to be *saturated.* If there is at least one double bond between two carbons and there are fewer hydrogen atoms attached, the fat is said to be *unsaturated.* If there are three or more double bonds between the carbons of a fatty acid, as in some vegetable oils such as those of canola, olive, or safflower, the fat is said to be *polyunsaturated.* Unsaturated vegetable oils can become saturated by bubbling hydrogen gas through them, as is done in the manufacture of margarine. Human diets high in saturated fats often ultimately lead to clogging of arteries and other heart diseases, while diets low in saturated fats promote better health. However, some fat in the diet appears to be essential to normal animal and human absorption of nutrients, and there is concern that consumption of “fake” fat introduced to the public in the late 1990s could lead to health problems. Like polysaccharides and proteins (discussed in the next section), lipids are broken down by hydrolysis.

Waxes are lipids consisting of very long-chain fatty acids bonded to a very long-chain alcohol other than gly-cerol. Waxes, which are solid at room temperature, are found on the surfaces of plant leaves and stems. They are usually embedded in a matrix of *cutin* or *suberin,* which are also lipid polymers that are insoluble in water. The combinations of wax and cutin or wax and suberin function in waterproofing, reduction of water loss, and protection against microorganisms and small insects.

Phospholipids are constructed like fats, but one of the three fatty acids is usually replaced by a phosphate group; this can cause the molecule to become a polarized ion. When phospholipids are placed in water, they form a double-layered sheet resembling a membrane. Indeed, phospholipids are important components of all membranes found in living organisms.

Proteins, Polypeptides, and Amino Acids

The cells of living organisms contain from several hundred to many thousands of different kinds of **proteins,** which are second only to cellulose in making up the dry weight of plant cells. Each kind of organism has a unique combination of proteins that give it distinctive characteristics. There are, for example, hundreds of kinds of grasses, all of which have certain proteins in common and other proteins that make one grass different from another. The hundreds of kinds of daisies are distinguished from each other and from grasses by their particular combinations of proteins. Analysis of proteins helps evolutionary botanists sort out relationships and heredity among plants and is a popular, current area of research.

Proteins consist of carbon, hydrogen, oxygen, and nitrogen atoms, and sometimes also sulfur atoms. Proteins regulate chemical reactions in cells, and comprise the bulk of protoplasm apart from water. Protein molecules are usually very large and consist of one or more *polypeptide* chains with, in some instances, simple sugars or other smaller molecules attached.

Polypeptides are chains of amino acids. There are 20 different kinds of **amino acids,** and from 50 to 50,000 or more of them are present in various combinations in each protein molecule. Each amino acid has two special groups of atoms plus an *R group.* One functional amino acid group is called the *amino group* (—NH_2); the other, which is acidic, is called the *carboxyl group* (—COOH). The structure of an R group can vary from a single hydrogen atom to a complex ring. Some R groups are polar, while others are not, and each is distinctive for one of the 20 amino acids. Glycine (Fig. 2.12) is representative of general amino acid structure. Amino acids are linked together by **peptide bonds,** which are covalent bonds formed between the carboxyl carbon of one amino acid and the nitrogen of the amino group of another, a molecule of water being removed in the process.

Plants can synthesize amino acids they need from raw materials in their cells, but animals have to supplement from plant sources some amino acids they need, since they can manufacture only a few amino acids themselves.

Each polypeptide usually coils, bends, and folds in a specific fashion within a protein, which characteristically has three levels of structure and sometimes four:

1. A linear sequence of amino acids fastened together by peptide bonds forms the *primary structure* of a protein.
2. As hydrogen bonds form between oxygen atoms of carboxyl groups and hydrogen atoms of amino groups in different molecules, the polypeptide chain can coil to form a spiral-like staircase, called an *alpha helix.* The helix is one version of *secondary structures* that may form. Other -secondary structures include polypeptide chains that -double back and form hydrogen bonds between two lengths in what is referred to as a *beta sheet,* or *pleated sheet.*

3. *Tertiary structure* develops as the polypeptide further coils and folds. The tertiary structure is maintained by interactions and bonds among R groups.
4. If a protein is composed of more than one kind of polypeptide, a fourth, or *quaternary structure,* forms when the polypeptides associate (Fig. 2.13).

The three-dimensional structure of a protein may be somewhat flexible in solution, but chemicals or anything that disturbs the normal pattern of bonds between parts of the protein molecule can *denature* the protein. Denaturing alters the characteristic coiling and folding and adversely affects the protein's function and properties. Denaturing may be reversible, but if it is brought about by high temperatures or harsh chemicals, it may kill the cell of which the protein is a part. For example, boiling an egg, which is mostly protein, brings about an irreversible denaturing; the solid egg proteins simply can't be restored to their original semiliquid condition.

Storage Proteins

Some plant food-storage organs, such as potato tubers and onion bulbs, store small amounts of proteins in addition to large amounts of carbohydrates. Seeds, in particular, however, usually contain proportionately larger amounts of proteins in addition to their complement of carbohydrates and are very -important sources of nutrition for humans and animals. One example of an important protein source in human and animal diets is wheat gluten (to which, incidentally, some humans become allergic). The gluten consists of a complex of more than a dozen different proteins.

A seed's proteins get used during germination and its subsequent development into a seedling. Some legume seeds may contain more than 40% protein, but legumes are deficient in certain amino acids (e.g., methionine), and a human diet based on beans needs to be balanced with other storage proteins (e.g., those found in unpolished rice) to furnish a complete complement of essential amino acids. Some seed proteins, such as those of jequirity beans (*Abrus -precatorius*—used in India to induce abortions and as a contraceptive), are highly poisonous.

Enzymes

Enzymes are mostly large, complex proteins that function as organic catalysts under specific conditions of pH and temperature. By breaking down bonds and allowing new bonds to form, they facilitate cellular chemical reactions, even at very low concentrations, and are absolutely essential to life. None of the 2,000 or more chemical reactions in cells can take place unless the enzyme specific for each one is present and functional in the cell in which it is produced. Enzymes increase the reaction rate as much as a billion times, and without them, the chemical reactions in cells would take place much too slowly for living organisms to exist. Enzymes are often used repeatedly and usually do not break down during the reactions they accelerate.

Enzyme names normally end in *-ase* (e.g., maltase, sucrase, amylase). The material whose breakdown is catalyzed by an enzyme is known as the *substrate.* Maltose is a very common disaccharide composed of two glucose monomers. The enzyme maltase catalyzes the hydrolysis of maltose (its substrate) to glucose. Enzymes work by lowering the *energy of activation,* which is the minimal amount of energy needed to cause molecules to react with one another. An enzyme brings about its effect by temporarily bonding with potentially reactive molecules at a surface site. The reactive molecules temporarily fit into the active site, where a short-lived complex is formed. The reaction occurs rapidly, often at rates of more than 500,000 times per second. The complex then breaks down as the products of the reaction are released, with the enzyme remaining unchanged and capable of once more catalyzing the reaction (Fig. 2.14).

Many enzymes, derived mostly from bacteria and fungi, have very important industrial uses. For example, waste treatment plants, the dairy industry, and manufacturers of detergents all use enzymes that have been mass--produced by microorganisms in large vats. One such commercially marketed enzyme, known as *Beano*®™, is produced by the activities of *Aspergillis,* a mold. Beano breaks down complex sugars found in beans, broccoli, and many other vegetables consumed by humans. A few drops of the enzyme placed on these foods while they are being consumed effectively reduces the gas produced when enzymes in human digestive tracts are otherwise unable to accomplish the breakdown.

Nucleic Acids

Nucleic acids are exceptionally large, complex polymers originally thought to be confined to the nuclei of cells but now known also to be associated with other cell parts. They are vital to the normal internal communication and functioning of all living cells. The two types of nucleic acids—deoxyribonucleic acid (DNA) and ribonucleic acid (RNA)—are briefly introduced here and discussed in more detail in Chapter 13.

Deoxyribonucleic acid (DNA) molecules consist of double helical (spiral) coils of repeating subunits called **nucleotides.** Each nucleotide is composed of three parts: (1) a base containing nitrogen, (2) a five-carbon sugar, and (3) a phosphate (phosphoric acid) molecule. The phosphate of one nucleotide is attached to the sugar of the next nucleotide (Fig 2.15). Four kinds of nucleotides, each with a unique nitro-genous base, occur in DNA. DNA molecules contain, in units known as **genes,** the coded information that precisely determines the nature and proportions of the myriad substances found in cells and also the ultimate form and structure of the organism itself. If this coded information were written out, it would fill over 1,000 books of 300 pages each—at least for the more complex organisms. DNA molecules can replicate (duplicate themselves) in precise fashion. When a cell divides, the hereditary information contained in the DNA of the new cells is an exact copy of the original and can be passed on from generation to generation without change, except in the event of a *mutation* (discussed in Chapter 13).

Ribonucleic acid (RNA) is similar to DNA but differs in its sugar and one of its nucleotide components. It usually occurs as a single strand. Different forms of RNA are involved in protein synthesis. DNA and RNA are discussed in more detail in Chapter 13.

Summary

1. Activities of living organisms originate in cells. Structure and growth are among the attributes of living organisms. Growth has been described as an increase in volume; it results primarily from the production of new cells. Variations in form may be inherited or result from a response to the environment.
2. Reproduction involves offspring that are always similar in form to their parents; if reproduction ceases, the organism becomes extinct. Plants generally respond to stimuli more slowly and in a different fashion from -animals.
3. All living organisms exhibit metabolic activities, including respiration, digestion, assimilation, production of new cytoplasm, and in green organisms, photosynthesis; they also all exhibit movement. Cyclosis is the streaming motion of cytoplasm within living cells. Living organisms have a much more complex structure than nonliving objects and are adapted to their individual environments.
4. The basic "stuff of the universe" is called matter, which occurs in solid, liquid, or gaseous form. It is composed of elements, the smallest stable subdivision of which is an atom. Atomic nuclei contain positively charged protons and uncharged neutrons; the nuclei are surrounded by much larger orbitals of negatively charged electrons. Isotopes are forms of elements that have slight variations in the number of neutrons in their atoms.
5. The combining capacities of atoms or ions are called valence. Atoms can bond to other atoms, and those of most elements do not exist independently; compounds are substances composed of two or more elements combined in a definite ratio by chemical bonds; molecules are the smallest independently existing particles. In a covalent bond, pairs of electrons link two or more atomic nuclei; nitrogen and/or oxygen atoms of one molecule may form weak hydrogen bonds with hydrogen atoms of other molecules. If a molecule loses or gains electrons, it becomes an ion, which may form an ionic bond with another ion.
6. Water molecules are polar because they are asymmetrical in shape. Water molecules cohere to each other and adhere to other molecules.
7. Acids release positively charged hydrogen ions when dissolved in water. Bases release negatively charged hydroxyl ions when dissolved in water. The pH scale is used to measure degrees of acidity or alkalinity. Salts and water are formed when acids and bases are mixed.
8. Energy can be defined as "ability to produce a change in motion or matter" or as "ability to do work." Its forms include chemical, electrical, heat, light, kinetic, and poten-tial. The farther away from the nucleus an electron is, the greater the amount of energy required to keep it there.
9. Cells are composed of carbon, hydrogen, oxygen, and nitrogen, with a little phosphorus and potassium, plus small amounts of other elements. A plant may convert the simple molecules or ions it recycles or absorbs from the soil to very large, complex molecules. Organic mole-cules are usually large polymers that have a "backbone" of carbon atoms.
10. Carbohydrates contain carbon, hydrogen, and oxygen in a ratio of 1C:2H:1O. Carbohydrates occur as monosaccharides (simple sugars) and disaccharides (two simple sugars joined together). Polysaccharides may consist of many simple sugars condensed together; others are more complex. Simple sugars, when they are attached to one another, each give up a molecule of water, forming starch. Hydrolysis involves restoring a water molecule to each simple sugar when starch is broken down during digestion.
11. Lipids (e.g., fats, oils, and waxes), which are insoluble in water, consist of a unit of glycerol or other alcohol with three fatty acids attached. They contain carbon, hydrogen, and oxygen, with proportionately much less oxygen than is found in carbohydrates. Saturated fats have hydrogen atoms attached to every available bond of their carbon atoms; if there are very few places for hydrogen atoms to attach, the fat is said to be polyunsaturated. Phospholipids have a phosphate group replacing one fatty acid.
12. Proteins are usually large molecules composed of subunits called amino acids. Each amino acid has an amino group ($—NH_2$) and a carboxyl group (—COOH); these groups bond amino acids together, forming polypeptide chains; the bonds are called peptide bonds. Enzymes are large protein molecules that function as organic catalysts. Their names end in -ase. Some have important industrial uses.
13. There are two nucleic acids (DNA and RNA) associated primarily with cell nuclei. DNA and RNA molecules consist of chains of nucleotides. Four kinds of nucleotides, each with a unique nitrogenous base, occur in DNA. Helical coils of DNA contain coded information determining the nature and proportions of substances in cells and the ultimate form and structure of the organism. RNA has a different sugar and nucleotide.

Review Questions

1. What distinguishes a living organism from a nonliving object, such as a rock or a tin can?
2. What is meant by the term *organic*?
3. How are acids, bases, and salts distinguished from one another?
4. Distinguish among carbohydrates, lipids, and proteins.
5. What is energy, and what forms does it take?
6. How are polymers formed?
7. How is a protein molecule different from a nucleic acid molecule?

Discussion Questions

1. Can part of an organism be alive while another part is dead? Explain.
2. What is the difference between inherited form and form resulting from response to the environment?
3. What might happen if all enzymes were to work at half their usual speed?

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A flowering head of burdock (*Arctium lappa*), a weed whose burs catch in clothing and the fur and hide of animals. Burdock is cultivated in Japan for its edible roots.

Figure 2.1 Model of an oxygen atom. The nucleus in the center consists of eight electrically neutral neutrons and eight positively charged protons. Eight negatively charged electrons whirl around the nucleus. In a real atom the electrons would not be spaced or confined as shown in this simple diagram. The nucleus is one-millionth of one-billionth the diameter of the atom.

TABLE 2.1

Atomic Numbers, Masses, and Functions of Some Elements Found in Plants

ELEMENT	ATOMIC NUMBER	USUAL ATOMIC MASS	SOME FUNCTIONS
Hydrogen (H)	1	1	Part of nearly all organic molecules
Carbon (C)	6	12	Forms skeleton of organic molecules
Nitrogen (N)	7	14	Part of amino acids, nucleic acids, and chlorophyll
Oxygen (O)	8	16	Essential for most respiration; part of most organic molecules
Magnesium (Mg)	12	24	Basic element of chlorophyll
Phosphorus (P)	15	31	Part of ATP (a molecule involved in energy exchange); part of nucleic acid molecules
Sulfur (S)	16	32	Stabilizes a protein's three-dimensional structure
Potassium (K)	19	39	Helps stabilize balance between ions in cells
Calcium (Ca)	20	40	Important in the structure of cell walls
Iron (Fe)	26	56	Involved in electron transport during respiration

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Figure 2.2 Models of orbitals. *A.* The two electrons closest to the atom's nucleus occupy a single spherical orbit. *B.* Additional orbitals are dumbbell-shaped, with axes that are perpendicular to one another. The atom's nucleus is at the intersection of the axes.

Figure 2.3 Isotopes of oxygen portrayed two dimensionally. As mentioned in Figure 2.1, the nucleus is proportionally much smaller in an atom.

Figure 2.4 Models of oxygen, water, and hydrogen molecules. A water molecule is 0.6 nanometer in diameter. Each sphere represents the electron cloud of the outer orbital.

Figure 2.5 The asymmetrical shape of water molecules and the resulting unequal sharing of electrons in the bond between the oxygen and hydrogen atoms cause one side of a water molecule to have a slight positive charge and the other side a slight negative charge. Such molecules are said to be polar. The polarity of water molecules causes them to be attracted to one another in a cohesive network. The cohesion of water molecules is partly responsible for their capacity to be pulled in a continuous column through fine (capillary) tubes such as those of living wood.

Figure 2.6 A covalent bond between two oxygen atoms. In a covalent bond, electrons are shared as outer shells of atoms overlap. In this instance, two pairs of electrons are shared between the two atoms, and the shared electrons are counted as belonging to each atom.

Figure 2.7 Ionic bonding between a sodium atom and a chlorine atom. The sodium becomes positively charged when it loses one of its electrons, which is gained by an atom of chlorine. The gained electron makes the chlorine ion negatively charged, and the two ions become bonded together by the attraction of opposite charges.

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1. Note that although distilled water is theoretically "pure," its pH is always less than 7 because carbon dioxide from the air in which it is in contact dissolves in it, forming carbonic acid (H_2CO_3); the actual pH of distilled water is usually approximately 5.7.

Figure 2.8 *A.* An individual with a snowboard resting on top of the hill has potential energy (capacity to do work owing to its position). *B.* The potential energy is converted to kinetic energy when the snowboard goes down the hill.

Figure 2.9 Energy levels of electrons. The closer electrons are to the nucleus, the less energy they possess and vice versa. The energy levels are referred to as electron shells. *A.* An electron at a second energy level. *B.* An electron can absorb energy from sunlight or some other source and be boosted to a higher energy level. *C.* The absorbed energy can be released, with the electron dropping back to its original level (see Fig. 10.8).

Figure 2.10 Structures of glucose (left) and fructose (right) molecules. The numbers of atoms and locations of bonds are easy to see in the upper linear diagrams, but when these molecules are in solution, they are in the form of rings, as shown in the lower diagrams. Unless indicated otherwise, each junction in a ring contains a carbon atom.

Figure 2.11 Structural formula and model of the components of a fat molecule. H = hydrogen, C = carbon, O = oxygen. A typical fatty acid is 4 nanometers long.

Figure 2.12 Structural formula and model of the amino acid glycine.

Figure 2.13 The four levels of protein structure. The example shown is for an activated complex of the plant protein, ribulose bisphosphate carboxylase/oxygenase. *A.* The primary structure consists of a chain of amino acids bonded together. *B.* As the amino acid chain grows, rotation of the chain occurs to form an alpha helix, which is stabilized by hydrogen bonds. *C.* The coil or helix folds further and interacts with other amino acids in the chain to form a somewhat globular structure. *D.* Many chains combine into a single functional protein molecule. *(Parts C and D were derived from the protein database (PDB) ID 1AA1 as reported by T. C. Taylor, and I. Anderson, 1997. Structure of a product complex of spinach ribulose-1,5-bisphosphate carboxylase/oxygenase.* Biochemistry *26:4041–46. Molecular imaging was facilitated by J. L. Moreland, A. Gramada, O. Buzko, Q. Zhang, and P. E. Bourne. 2005. The molecular biology toolkit (mbt): A modular platform for developing molecular visualization applications.* BMC Bioinformatics *6:21–27.)*

Figure 2.14 How an enzyme facilitates a reaction. *A.* An enzyme and the raw material (substrate) for which it is specific. *B.* The substrate fits into the active site on the enzyme. *C.* The enzyme then changes shape, putting stress on the linkage between parts of the substrate. *D.* The bonds (linkage) are broken. *E.* The enzyme returns to its original shape, and the products are released. When an enzyme is combining substrates, the events shown proceed in reverse.

Figure 2.15 A nucleotide. DNA consists of double strands of subunits called *nucleotides,* which consist of a nitrogenous base, a five-carbon sugar, and a phosphate. This nucleotide contains cytosine as its nitrogenous base. The phosphate of one nucleotide is attached to the sugar of the next nucleotide.