Chapter 2

The Chemistry of Life

KEY CONCEPTS

1. Living organisms are made from chemical compounds, and everything they do must obey all the laws of chemistry and physics. To understand organisms, one must have a basic appreciation of the principles of chemistry.

2. Most of the substances in organisms are based on carbon-containing compounds. Carbon atoms can form complex chains held together by stable covalent bonds. The large number of possible structures provides a basis for the complex activity of organisms.

3. The chemical properties of water make it uniquely suited as a milieu for living beings.

4. The functional chemical units of living organisms--carbohydrates, lipids, proteins, and nucleic acids--are large polymeric molecules formed from simpler monomers--amino acids, sugars, fatty acids, and nucleotides. The information that directs the assembly of the polymers is encoded in the structure of the nucleic acid polymers.

2.1 CHEMISTRY AND PLANTS

There are many ways to study plants. Poets, painters, anthropologists, and agriculturalists all have their own ideas about the importance and usefulness of the earth's flora (see endnote "*PLANTS, PEOPLE, AND THE ENVIRONMENT: Plants as Pharmacists*"). In recent years, biologists have made notable strides in understanding how plants function. Much of this understanding has come from deducing the chemical basis of life, particularly plant life. To fathom the most important discoveries about plant life, one must grasp the basic concept of chemistry. What are plants made of? Why are the stems of some plants (such as grasses) soft, whereas those of others (such as trees) are hard? What substances do plants need to grow? How is it possible to manipulate the characteristics of plants through biotechnology? The answers to all these questions are based on chemistry. This chapter provides an overview of the concepts needed to understand plant cell structure and function.

2.2 THE UNITS OF MATTER

Every type of matter--including all the components of living cells and organisms and all the nonliving materials on which living things depend--is built from very small units. **Atoms** and **molecules** (Fig. 2.1) are the smallest particles that retain the chemical characteristics of their type of matter.

Matter made from only one type of atom is called an **element**. There are 92 elements found in nature. Although physicists have produced several more elements, they are unstable and short-lived. Some of the most prominent elements in living organisms are listed in Table 2.1, together with the letter symbols that chemists use to identify them.

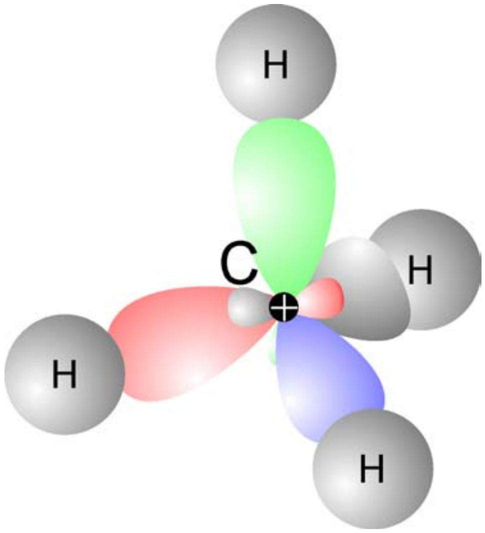


Figure 2.1. The structure of the methane molecule. Methane is formed from one carbon (C) and four hydrogen (H) atoms. The C nucleus is at the center of the structure. Two non-binding electrons (not shown) are in a spherical shell around the C. Four binding electrons in four orbitals (colored) extend tetrahedrally from the C. Each overlaps a single spherical orbital (gray) around an H nucleus. Each C orbital and H orbital actually form a "hybrid" orbital populated by the C and H electrons. The sharing of the orbital by the electrons is stable and represents a bond between the atoms.

Table 2.1 The Twelve Most Common Elements in Living Organisms

Element	Symbol	Number of Protons
Hydrogen	H	1
Carbon	C	6
Nitrogen	N	7
Oxygen	O	8
Sodium	Na	11
Magnesium	Mg	12
Phosphorus	P	15
Sulfur	S	16
Chlorine	Cl	17
Potassium	K	19
Calcium	Ca	20
Iron	Fe	26

The elements are listed in order of size (number of protons).

Matter made from molecules is called a **compound**. Molecules are made from two or more atoms. There are many thousands of kinds of molecules, which differ in size, shape, and behavior. The largest molecules in a plant cell carry hereditary information; they are slender threads greater than 1 mm in length when extended. Molecules of table sugar (sucrose) are closer to the average size; about 300,000 molecules of sucrose placed end to end would span a millimeter. A plant builds all of its own molecules by rearranging the parts of simpler molecules taken from the environment.

Chemists indicate the composition of a molecule by using the elemental symbols and subscripts to show the kind and number of atoms present. Thus, the symbol CH_4 represents a molecule that has one carbon atom (the subscript 1 is assumed if no number is supplied) and four hydrogen atoms. The five atoms in this molecule are held together by interactions among their component parts.

Molecules Are Made of Atoms

A single molecule is formed from atoms arranged in specific positions relative to one another. The atoms in turn are formed from three types of particles: **protons**, each of which has 1 unit of mass and 1 unit of positive electrical charge; **neutrons**, which have 1 unit of mass but no electrical charge; and **electrons**, which have 0.0005 units of mass and 1 unit of negative electrical charge. The protons and neutrons form the atomic **nucleus**, a small kernel at the center of an atom. If an atom were magnified to the size of a house, the nucleus would be about as large as a pinhead. Electrons move around the nucleus in **orbitals**, ill-defined regions in the space outside the nucleus. The size of the atom, as measured by how many can be packed into a given volume, is determined by the distance of the outer electrons from the nucleus. The weight of the atom is determined mainly by the number of protons and neutrons, because each is about 1,840 times heavier than an electron.

The number of protons in the nucleus, known as the atomic number, determines the chemical characteristics of an atom and its identity. Although neutrons affect the weight of an atom, they influence its chemical characteristics only slightly. It is not uncommon in nature for an element to consist of atoms that differ in their number of neutrons. Such atoms are called isotopes of the element. For instance, the atoms of the element carbon may have six, seven, or eight neutrons. Because every atom of carbon has six protons--and because neutrons weigh as much as protons--the relative weights of these three isotopes are 12, 13, and 14; therefore, these isotopes are identified as ^{12}C, ^{13}C, and ^{14}C. The balance in the number of neutrons and protons seems to be a factor in holding the nucleus together. Nuclei with about the same number of neutrons and protons, such as ^{12}C and ^{13}C, tend to be stable. Nuclei with the number of neutrons much different from the number of protons may be unstable. Regardless of differences in stability, atoms with the same atomic number represent the same element and can take the same places within molecules.

Unstable atoms spontaneously decompose, a process known as radioactive decay. Atoms of ^{14}C are radioactive, giving off energetic electrons called beta (ß) particles as they decay into a more stable state. Radioactive atoms tend to be rare, especially among the elements that make up living organisms; therefore, radioactivity is seldom a factor in the chemistry of life. However, high concentrations of radioactive material can damage cells because the high-energy particles of radioactive decay can destroy the complex molecules they hit. On the other hand, low concentrations of radioactive atoms are useful in biological studies because their decay products are like spotlights, enabling researchers to track the fate of these atoms in chemical reactions and to trace their movement through cells and tissues.

Electrical Forces Attach Electrons to Nuclei

Electrical forces attach the electrons to the nuclei to form atoms and molecules. Each electron carries a unit of negative electrical charge, and each proton carries the same amount of positive electrical charge. Two particles attract one another if they carry opposite charges, which is why electrons are attracted to the nuclei. Particles repel one another if they carry charges of the same sign, so two or more electrons avoid one another as they move around the atom. An atom or molecules that has equal numbers of electrons and protons is said to be electrically neutral because any force that its electrons exert on a distant object is countered by an opposing force exerted by the protons.

Although nuclei take up fairly definite positions in a molecule, electrons are more difficult to locate. The orbitals that they occupy are not fixed lines, like the orbits of planets around the sun. Rather, they are fuzzy areas around the nuclei where a probability exists that an electron might be found at any particular time. In some parts of the orbital, the probability is greater (which means the electron spends more time there); in other parts, the probability is smaller (the electron spends less time). There is a general rule that applies to all orbitals. An orbital may have zero, one, or two electrons--no more. Once two electrons have occupied the orbital closest to the nucleus (where the attractive forces are greatest), no other electrons can join them. Other electrons must move to orbitals farther away. An atom or molecule is most stable when it has exactly two electrons in each orbital.

The potential energy of an electron depends on the position of the orbital it occupies. We can think of energy as the capacity to do work, which means to exert a force over a distance. It takes work, and thus energy, to move an electron away from the nucleus against the attractive electrical force. That energy is stored in the electron's position (thus, *potential* energy) and given up if the electron falls back toward the nucleus. Thus an electron in an orbital close to the nucleus has less potential energy than one in an orbital farther from the nucleus. Orbitals in which electrons have the same potential energy are said to be in the same shell. Electrons can change shells by losing or gaining energy. As an electron drops into an orbital of a shell closer to the nucleus, it gives up energy in the form of a photon (a unit of light or heat radiation), which leaves the atom and can sometimes be detected as a flash. Conversely, for an electron to move into an orbital of a shell farther from the nucleus, it must absorb a photon from the environment. Such changes in electron energy are at the heart of photosynthesis. An electron can also leave its home orbital and take up residence in the orbital of another atom, or it can move to an orbital shared by its atom and another atom, These movements lead to the formation of ionic and covalent bonds, respectively, and they result in the formation of new molecules.

Ionic Bonds Consist of Electrical Forces

It is possible for atoms and molecules to have more electrons than protons or vice versa. When they do, the atoms or molecules are called ions. The excess charge of an ion is denoted with a superscript. For example, K^+ indicates the potassium ion, with one more proton than electrons; SO_4^{2-} indicates the sulfate ion, with two more electrons than protons. Ions with a net positive charge are called **cations**; those with a net negative charge are called **anions**. Ions are formed when an electron moves from one originally neutral atom to another. For instance, the transfer of an electron from a sodium atom to a chlorine atom (Fig. 2.2) results in the formation of a sodium cation (Na^+) and chlorine anion (called chloride [Cl^-]). The loss of an electron is called **oxidation**; the gain of an electron is called **reduction**. In this transfer, the sodium is oxidized and chlorine is reduced (that is, the chlorine atom's charge is reduced from 0 to -1). Because the oxidation and reduction occur together, they often are referred to as an **oxidation-reduction (redox)** reaction.

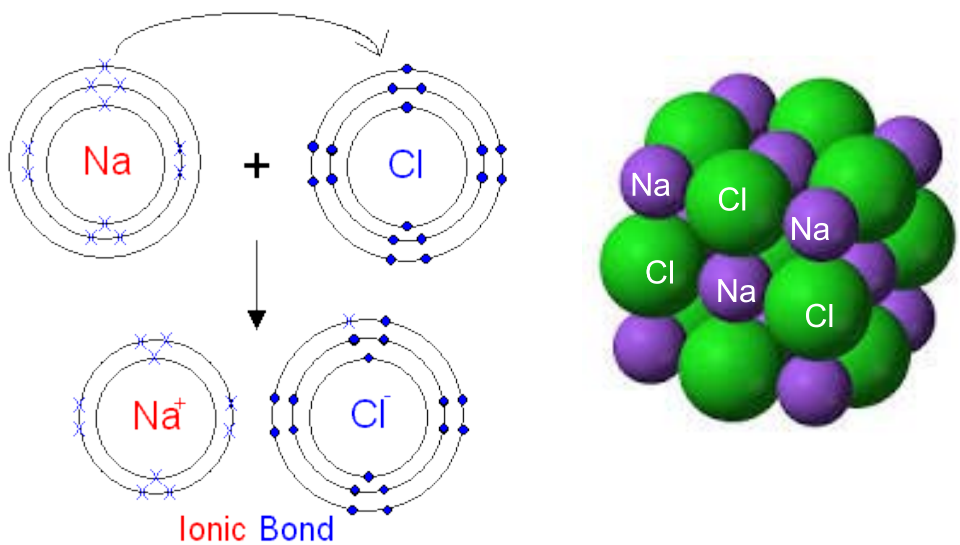


Figure 2.2. The oxidation of sodium and reduction of chlorine to form ions. In crystals, ions are held together by the mutual attraction of opposite electrical charges.

Ions with the same sign (both positive or both negative) repel each other, whereas ions with opposite signs attract each other. When two ions of opposite charge are held close together by electrical forces, chemists often say they are joined by an **ionic bond**. A compound containing anions and cations held together by ionic bonds is called a **salt**. As one example, sodium and chloride ions, connected by ionic bonds, form sodium chloride crystals, also known as table salt. The inorganic nutrients in fertilizer--for instance, calcium phosphate or potassium nitrate--are also salts.

Covalent Bonds Consist of Shared Electrons

The strongest type of chemical bond is a covalent bond. Most types of molecules are formed from covalently bonded atoms. Although some of the orbitals in such a molecule surround a single nucleus and are said to be nonbonding orbitals, other orbitals are distributed between two or more nuclei. These are said to be bonding orbitals, and the electrons occupying them are bonding electrons, shared by the nuclei. The nuclei that share the bonding electrons are said to be joined by a covalent bond. The covalent bond is strong because the electrons in the bonding orbital are in relative stable positions--that is, their attraction to the nuclei is strong and their mutual repulsion is minimized. It would take a lot of energy to separate the nuclei and move the electrons into different orbitals. Covalent bonds within a molecule can be shown in different ways (Fig. 2.3).

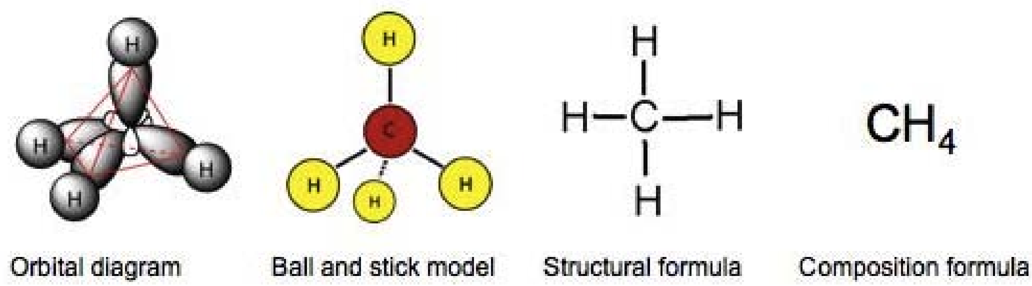


Figure 2.3. Several ways to symbolize a molecule of methane, which is held together by covalent bonds. Methane, a major component of natural gas, is produced when certain bacteria decompose organic matter in the absence of oxygen.

It is important to know how orbitals form around the nuclei of hydrogen (H), carbon (C), nitrogen (N), and oxygen (O), because these make up the bulk of the molecules of the cell. H is the simplest nucleus, consisting of just one proton. The charge on the proton is so weak that only one orbital forms around the nucleus. C, N, and O nuclei have six, seven, or eight protons, respectively, and they exert a much stronger attraction for electrons. Each of these nuclei is the center for five orbitals. The first orbital is in a spherical region very close to the nucleus. The two electrons in this orbital do not participate in covalent bonds. The four remaining orbitals are oblong and tend to orient themselves so that they are as far apart as possible, because the negative charges of the electrons repel one another. They are said to point to the vertices of a tetrahedron (Fig. 2.4).

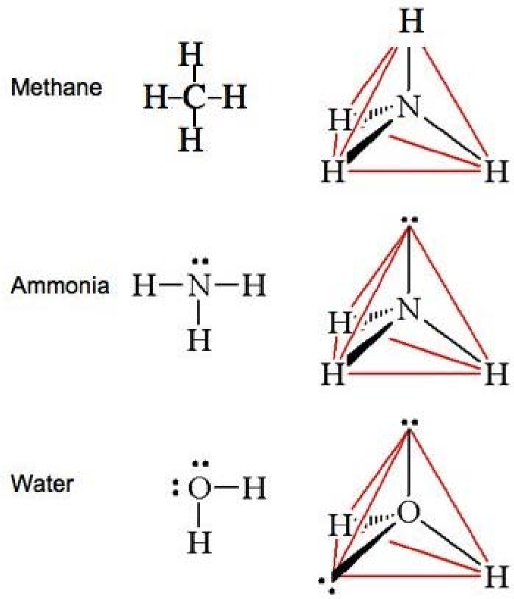


Figure 2.4. The three-dimensional structures of methane, ammonia, and water and their relationship to a tetrahedron.

When atoms come together to make molecules, bonding orbitals are formed. You can think of them as representing an overlap, or hybrid, of two orbitals from adjacent atoms (although they have a shape of their own). If possible, these orbitals form in such a way that each contains exactly two electrons.

Carbon has six electrons. Two of the electrons are in the inner, nonbonding orbital; four are available for sharing in the outer, bonding orbitals. Thus all four of the outer orbitals can participate in the formation of bonding orbitals. This is seen most simply with methane, CH_4. The C nucleus with its inner electron forms the center of the molecule. Each of the outer, oblong orbitals forms a bonding orbital with an H nucleus embedded in one end and the C nucleus in the other (Fig. 2.4). Each of these orbitals contains two electrons. If we think of an H nucleus as getting a half-share in the electrons of a bonding orbital, then one unit of negative charge is available to balance its unit of positive charge. Similarly, there are six units of negative charge available to balance the six protons in the C nucleus: two in the inner orbital and one each from the four bonding orbitals (again, a half-share of the two electrons in each orbital). Overall, the molecule is neutral. This illustrates the general rule that each C nucleus forms four covalent bonds. Of course, C can form bonds with other nuclei besides H, such as N and O. Most important, it can form bonds with other C nuclei to produce chains of carbon atoms. In a **hydrocarbon compound**, each C nucleus is bound to one or more other C nuclei and to hydrogen nuclei (Fig. 2.5).

Nitrogen has one more proton than carbon and thus has one more electron than carbon. The extra electron fills up one of the outer orbitals, so that each N nucleus can participate in only three bonds. A good example is NH_3 (ammonia, Fig. 2.4). Similar considerations apply to the behavior of oxygen, as illustrated by H_2O (water). Oxygen has two more protons than carbon, and it thus attract two more

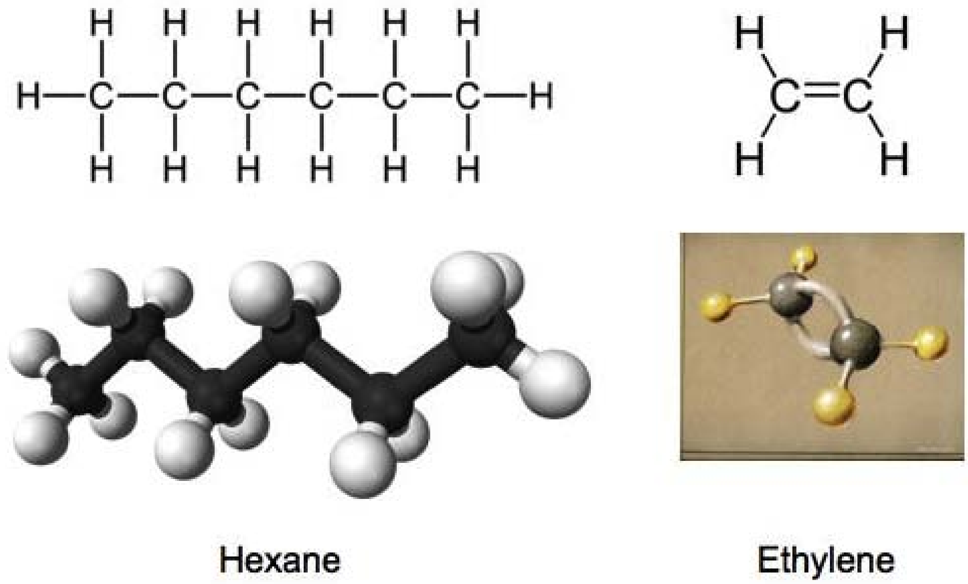


Figure 2.5. Two hydrocarbon compounds: hexane, with single bonds between the carbon atoms, and ethylene, which contains a double bond. Because atoms on either end of a single bond can rotate relative to each other, a molecule such as hexane is very flexible. In contrast, all six atoms of ethylene are confined to a single plane.

electrons. These fill up two of the outer orbitals, so that an O nucleus can form only two covalent bonds with hydrogen atoms.

It is possible for two nuclei to form two or three bonding orbitals and thus to share four or six electrons. The sharing of four electrons forms a double bond; sharing six electrons forms a triple bond. Chemists represent double bonds by two lines--for example, C=C. Ethylene, a very short hydrocarbon chain with two carbon and four hydrogen atoms, contains a double bond (Fig. 2.5). The two C nuclei are connected by two bonding orbitals: one occupying an oval region in the center, and the other consisting of two sausage-shaped regions on either side. The double bond resists being twisted, so that the six nuclei of this molecule sit rigidly in a single plane. In longer hydrocarbon chains, occasional double bonds produce kinks in otherwise flexible molecules. Although triple bonds are rare in the molecules found in cells, double bonds such as C=C, C=O, and C=N are common.

2.3 THE MILIEU OF LIFE

Water is the environment of life--even for terrestrial organisms--at the cellular and molecular levels. The physical and chemical properties of water are essential to cellular reactions and processes. Perhaps the three most important characteristics of water are its ability to dissolve a great many compounds, to remain a liquid over a wide range of temperatures, and to form weak hydrogen bonds with itself and with other molecules. These characteristics derive from the arrangement of its atoms.

Water Owes Its Unique Properties to Its Polarity

The amount and distribution of electrical charge in a molecule are important in predicting its behavior. Some molecules have their electrons spaced evenly throughout the orbitals; these molecules are called **nonpolar**. Other molecules have local regions of positive, negative, or both charges; these are said to be **polar**.

Polarity is established within a molecule because electrons that are shared between two unlike nuclei may spend more of their time closer to one nucleus than the other. A measure called **electronegativity** expresses the tendency of a nucleus to attract electrons. Nuclei of oxygen and nitrogen are more electronegative than those of carbon, sulfur (S), hydrogen, and phosphorus (P). Because of these differences, a molecule tends to be more negative near N and O nuclei and more positive near C, H, P, and S nuclei. Water is the quintessential example of a polar molecule (Fig. 2.6). The high electronegativity of the O nucleus attracts electrons--not only the electrons in the nonbonding orbitals, but also the electrons in the bonding orbitals. As a result, there is a deficiency of electrons near the H nuclei. This means that there is a slight negative charge at the O nucleus and slight positive charges at the two H nuclei. This property of water is extremely important in determining the structures of the molecules that make up a living organism. These molecules--proteins, carbohydrates, lipids, and nucleic acids (introduced later in this chapter)--assume three-dimensional shapes, determined in part by their interaction with water. Their three-dimensional shapes are critical for their functions. This is why all life exists in a watery environment. Although some organisms can survive being dried and rehydrated, as far as we know no life can function without water.

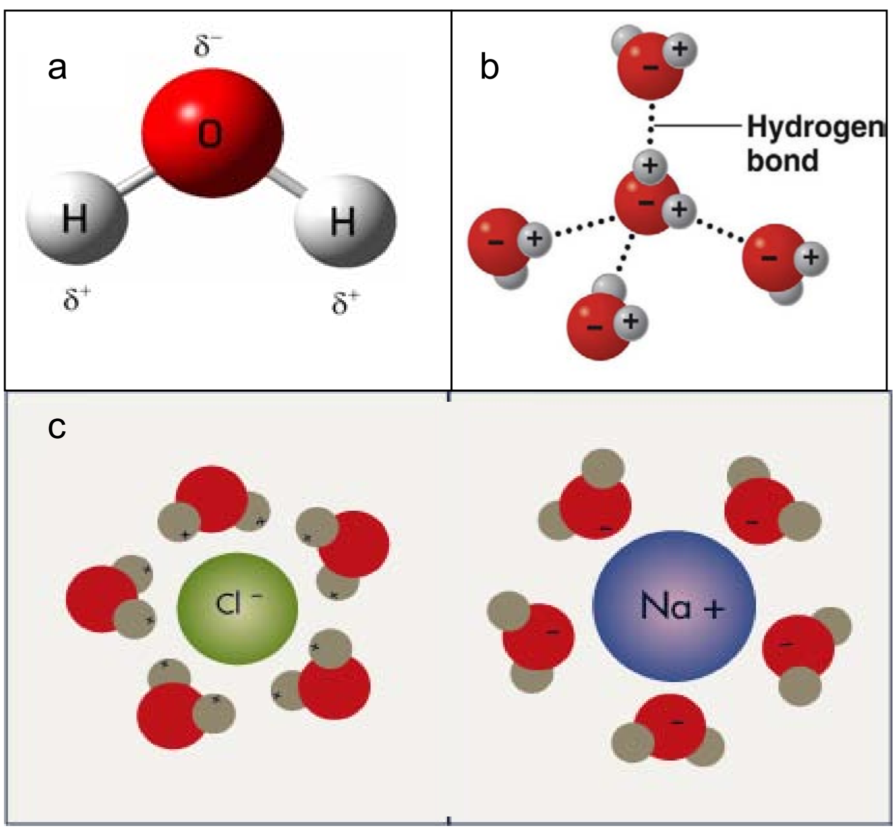


Figure 2.6. Properties of water. The polarity of water (shown in (**a**) is the reason water can (**b**) form hydrogen bonds and (**c**) dissolve substances, such as the salt ions shown here.

Hydrogen Bonds Form between Polar Molecules

A strong polarity in an orbital involving H leads to a new type of bond. Again, water provides the best example. The H of one water molecule can be attracted to the electrons around the O of a neighboring water molecule because of their opposite charges. In fact, the H can bounce between the electronegative Os of the two water molecules. This is a stable situation; therefore, it is said that a hydrogen bond has formed between the molecules. A hydrogen bond is represented by a dotted line: for example, O···H. Each of the two Hs in a water molecule can participate in a hydrogen bond. Even though this bond is only about 1/16 as strong as a covalent bond, the large number of hydrogen bonds among water molecules makes water more stable (less volatile) than we might otherwise expect. This means that a water molecule can evaporate (leave the liquid state and move into the gaseous state) only by simultaneously breaking all the hydrogen bonds that connect it to other molecules in the liquid. Consequently, water can absorb a large amount of heat as it evaporates, and it releases the same amount of heat as it condenses. The absorption of heat removes heat that otherwise would increase the water's temperature; the condensation provides heat to keep the water warm. Thus evaporation and condensation tend to stabilize the temperature of liquid water. This fact is important to living systems, which are damaged by large swings in temperature.

Other molecules besides water can form hydrogen bonds. This happens when an H nucleus that is sharing electrons with O or N comes close to another O or N, with the three nuclei approximately in a straight line, such as: O-H···N. Many biological molecules that contain O-H or N-H groups participate by attracting an H from a water molecule. Biological molecules may also form hydrogen bonds with each other. Examples can be found later in this chapter when carbohydrates (Fig. 2.10) and nucleic acids (Fig. 2.16) are introduced.

Water Dissolves Polar and Ionic Substances

The polarity of water and its ability to form hydrogen bonds make it an excellent solvent for many other substances. A pure substance in the sold form consists of many molecules of the same kind packed regularly (a crystal) or irregularly (an amorphous solid such as glass) and held together with chemical (but not covalent) bonds. On contact with water, the molecules at the surface of the solid can leave to become surrounded by and bound to water molecules. The mass is said to *dissolve*; the molecules that become intermixed in the water (the **solvent**) are the **solute** molecules. This homogenous mixture is called a **solution**. The more hydrogen bonds that can form between the solute and the water, the more easily soluble is the solute. Polar, nonionic molecules, such as ammonia (NH_3, Fig. 2.4), are very soluble for that reason. Ions also are soluble, but for a different reason. Water molecules surround each ion with their oppositely charge poles pointing at the ion (Fig. 2.6c). Most biological molecules either form hydrogen bonds with water or are ionic, and thus they dissolve in water. This allows the molecules to move, mix, and react chemically with one another; it is one of the principle reasons all life exists in a water solution.

Nonpolar molecules such as hydrocarbons (in which the C and H nuclei have similar electronegativities and the electrons are evenly distributed) cannot form hydrogen bonds with water or anything else. If tossed into water, these molecules force the water to form a sort of cage around them--an energetically unfavorable (unstable) situation. Over time, the nonpolar molecules will tend to move together and stick together to minimize the amount of water that is used to form cages: this tendency is called a **hydrophobic bond** (because in sticking together the nonpolar molecules act as though they had a fear of or an adversity to water). In contrast, nonpolar solutes will dissolve in nonpolar solvents (such as oil or kerosene), but polar solutes will not. In general, we can predict that polar or **hydrophilic** molecules will dissolve in polar solvents (water), and nonpolar or **hydrophobic** molecules will dissolve in nonpolar solvents (oil).

Acids Donate--and Bases Accept--Hydrogen Nuclei

In water solutions, both within and outside living cells, there is a rapid exchange of H nuclei among solutes and the water solvent. Molecules that contain an H nucleus bonded to a strongly electronegative atom (the same molecules that might donate an H to a hydrogen bond) can lose the H nucleus entirely. The H is not really lost, of course; in general, it is transferred to a molecule of the surrounding solvent (water) forming a hydronium ion. The original molecule retains the two electrons in the bonding orbital and thus acquires an extra unit of negative charge. Molecules that donate an H nucleus are called **acids**. Molecules that accept an H nucleus are called **bases**. For example:

H-Cl (hydrochloric acid) + H-O-H ⇔ H-O-H (hydronium) + Cl$^-$ (chloride)
/
H
(acid) (base) (acid) (base)

Water can be both an acid and a base, as follows:

H-O-H + H-O-H ⇔ H-O-H (hydronium) + OH$^-$ (hydroxyl)
/
H
(acid) (base) (acid) (base)

These are reversible reactions: The hydronium and chloride can react together to form hydrochloric acid and water, and the hydronium and hydroxyl can react to form two molecules of water. In these examples (considering the reactions in both directions, hydrochloric acid, water, and hydronium are the acids, and chloride, hydroxyl, and water are the bases.

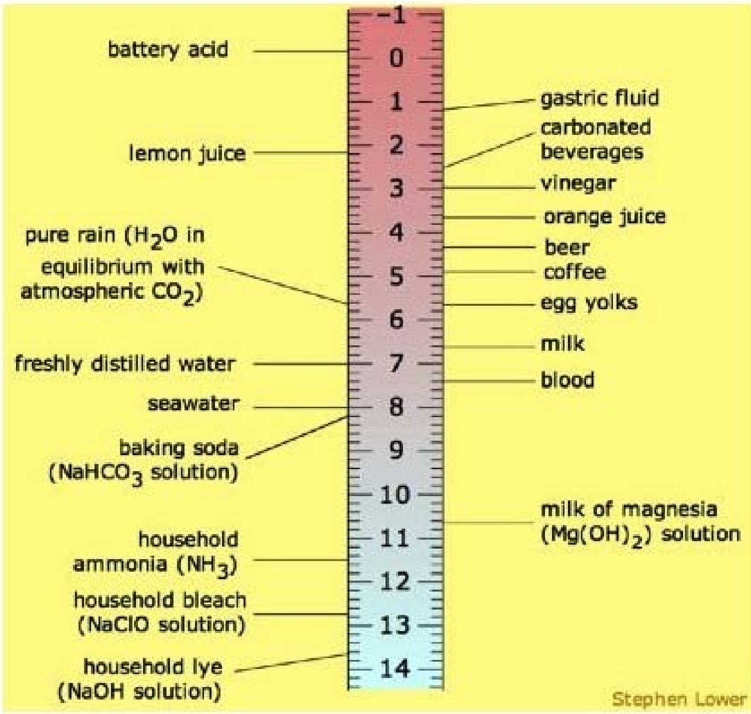


Figure 2.7. The pH scale. Acidic solutions (pH<7) are associated with a sour taste. Basic solutions (pH>7) often are bitter and have a slippery feel, rather like soap.

The concentration of hydronium ions determines the acidity of the solution. More hydronium means a more acidic solution. Chemists express the hydronium concentration by a measure known as pH (Fig. 2.7). A change of 1 unit on the pH scale is a 10-fold change in hydronium concentration. The lower the pH, the greater the hydronium concentration. Therefore, a solution with pH of 4 has 10 times the concentration of hydronium as a solution with a pH of 5. Acids and bases can be defined as substances that decrease and increase, respectively, the pH of a solution, and solutions can be classified as acidic or basic according to their pH. The acidic juice squeezed from a lemon has a pH of about 2 to 3. Pure water, which is neither acidic nor basic, has a pH of 7. Household bleach, a basic solution, has a pH of about 12.

Instead of talking about hydronium, chemists often abbreviate the concept by referring to the H^+ ion itself. From this viewpoint, pH refers to the H^+ concentration, although free H^+ never occurs in water solution. Most of the figures in this book will indicate hydronium by the symbol H^+.

2.4 THE SUBSTANCE OF LIFE

Living Organisms Are Made of Chemicals

All plants (and other organisms) are made of chemical compounds. These compounds influence the shapes that plant cells and their subunits take and determine their functions. Compounds that contain primarily carbon are called organic compounds, because they were first associated with living organisms. As the techniques of laboratory carbon chemistry have advanced, it has become useful to distinguish the molecules that actually occur in cells--they often are referred to as **bio-organic**. Bio-organic molecules are based on a carbon skeleton and generally include oxygen and hydrogen. They may often contain nitrogen, phosphorus, and/or sulfur in their structures. Other elements that may be associated with bio-organic molecules (generally attached with ionic bonds) include iron, calcium, potassium, and magnesium, and less frequently, sodium, boron, zinc, manganese, molybdenum, chlorine, and copper.

Biological molecules are often large and complex, but they are easier to understand when we use the concept of **functional groups**. A functional group is a small part of a larger molecule, but one that can participate in chemical reactions. Some functional groups are acids and bases (Fig. 2.8). For instance, the functional groups carboxyl (R-COOH) and phosphoryl ($R\text{-}OPO_3H_2$) are acids and can donate H^+ nuclei to water (R stands for the remainder of the molecule and is not part of the functional group). The amino group ($R\text{-}NH_2$) acts as a base and accepts H^+ nuclei from hydronium. Other functional groups may participate in hydrogen bonds, hydrophobic bonds, or oxidation-reduction reactions.

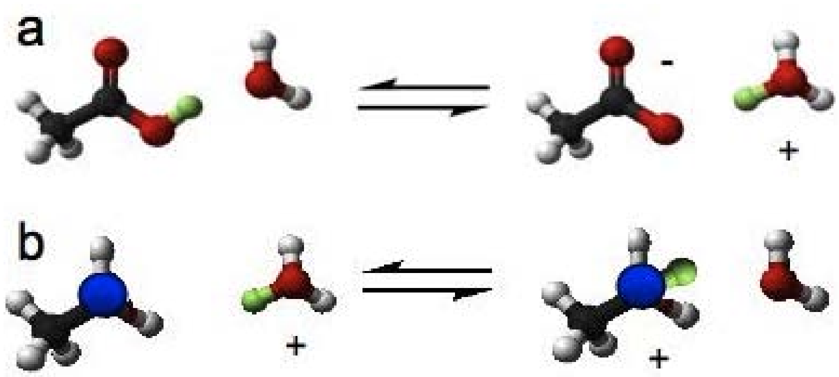


Figure 2.8. Acid-base reactions in functional groups. (**a**) The release of an H^+ nucleus by acetic acid. Note that the functional group ends up with a negative charge. (**b**) In accepting an H^+, the basic amino group acquires a positive charge.

Most of the organic compounds found in living systems can be classified into four families: carbohydrates, lipids, proteins, and nucleic acids (Table 2.2). Together these molecules act as structural and fuel molecules, speed up chemical reactions, and serve as libraries of genetic information. The following sections discuss these compounds.

Table 2.2 The Most Important Types of Biomolecules

Class	Components	Polymer	Role
Carbohydrate	Simple sugars	Starch, glycogen, cellulose	Energy, storage, structure (for example, cell wall)
Protein	Amino acids	Polypeptide chain	Catalysis, structure, movement
Lipid	Fatty acids, glycerol, phosphate, or sugar	Phospholipid, glycolipid, triglyceride	Membrane structure, energy storage
Nucleic acid	Base (adenine [A], guanine [G], cytosine [C], thymine [T], or uracil [U]), sugar, phosphate	DNA, RNA	Information storage, protein synthesis

Carbohydrates Include Sugars and Polysaccharides

Carbohydrates include simple sugars, oligosaccharides, and polysaccharides. Simple sugars are formed from carbon atoms with associated oxygen and hydrogen atoms in the proportions $C_nH_{2n}O_n$ (n=3-7). The carbon atoms in a simple sugar often are arranged in a ring, with each carbon covalently bonded to one or two other carbon atoms, H and O (Fig 2.9). **Oligosaccharides** are small chains of two or more simple sugars. **Polysaccharides** are long chains of simple sugars (Fig. 2.10). Some polysaccharides--for instance, **cellulose** and **pectin**--contribute to structure, especially in the cell wall. Cellulose forms cables that are very strong and can keep a cell from bursting under pressure; pectin acts as a glue to hold cells together in tissues.

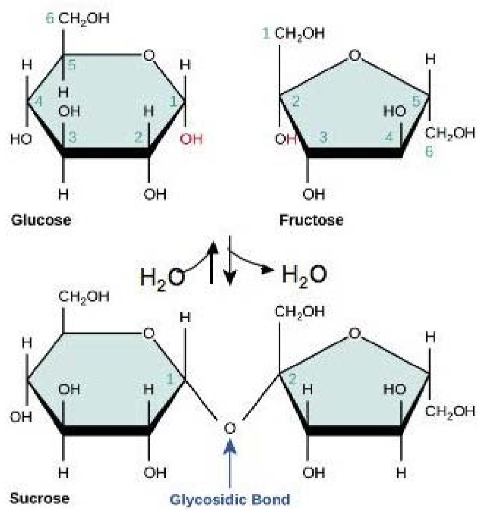


Figure 2.9. Structural formulas of two simple sugars, glucose and fructose, the most common sugars in plants, and sucrose, also known as common table sugar. The formation of the bond between glucose and fructose is formally a dehydration reaction (releases H_2O). The bond can be broken by hydrolysis (adding H_2O).

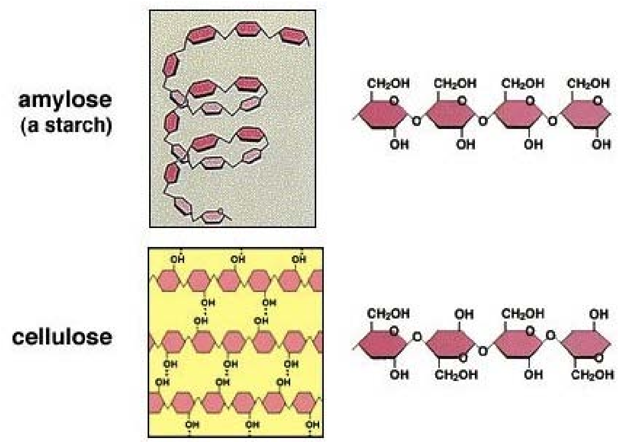


Figure 2.10. Models of the polysaccarides amyose and cellulose. In both molecules, the monomer is the sugar glucose. The two molecules differ in the ways the glucose monomers are connected. This allows the cellulose to form a straight chain, whereas the amylose forms helices in solution.

Other polysaccharides are used for storage of energy. **Starch**, for instance, a polymer of the simple sugar glucose, is made and stored in green plants. Glycogen, another polymer of glucose that is generally larger than starch and more highly branched, is made and stored in some algae and in animals. These compounds, when broken down, provide energy to run chemical reactions and other activities of an organism

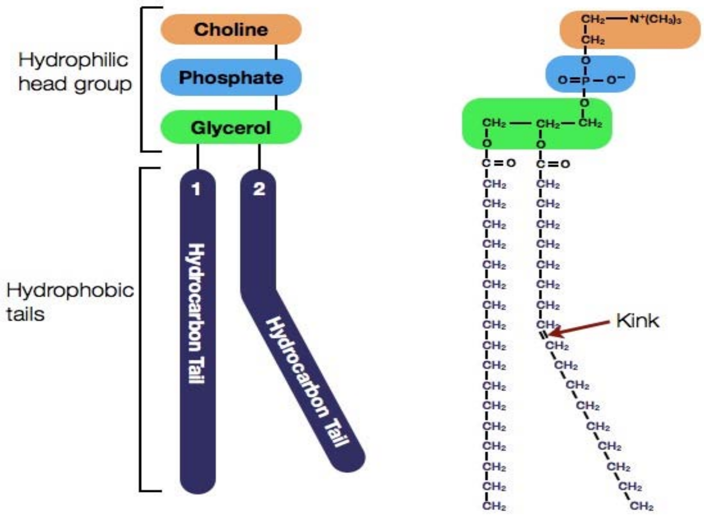
Energy in this context has different constraints than it did when energy levels of electrons were discussed in section 2.2. When a molecule absorbs a photon and an electron gains potential energy, or it emits a photon and an electron loses potential energy, total energy is conserved. In an organism, when molecules participate in a chemical reaction and their potential energy is converted to other forms, such as the potential energy of new molecules or kinetic energy (energy of motion) or heat, the total amount of energy is conserved--it is the same before and after the reaction. But useful energy, known as **free energy**, is not conserved. A portion is lost during every reaction. This is because a portion is converted to heat and other forms that are disordered and lost to the environment. (Chemists say that entropy has increased.) To say that polysaccharides store energy means that these compounds are rich in free energy. But the free energy is dissipated as these compound are used. This is one reason organisms need a continual supply of energy.

Lipids Are Insoluble in Water

The name **lipid** applies to any oil-soluble (nonpolar) substance in the cell; however, two classes of lipids--the **phospholipids** and **glycolipids**, which associate to form thin sheets (Fig. 2.11)--play special roles in plant cells. These lipids do have water-soluble (polar, hydrophilic) functional groups, which may be phosphate groups (in phospholipids) or sugars (in glycolipids). They also have water-insoluble (nonpolar, hydrophobic) components, which are the hydrocarbon ends of fatty acids. A fatty acid is a molecule with a hydrocarbon chain attached to a carboxylic acid. The carbon atoms of the hydrocarbon chain may all be connected by single covalent bonds, in which case the chain is flexible but generally straight, or they may have one or more double bonds, which insert a bend in the chain. A hydrocarbon chain with all single bonds is said to be **saturated** (with H atoms); a hydrocarbon chain with one or more double bonds is **unsaturated**. The phosphate or sugars and the fatty acids are connected by a three-carbon molecule called glycerol (Fig. 2.11 left). By forming sheets two molecules in thickness, phospholipids and glycolipids are able to bury their hydrophobic hydrocarbons in the middle, away from the solvent water, and expose their hydrophilic components to the water. These sheets provide the structural basis for the **membranes** that are found throughout cells (Fig. 2.11 right).

Sterols are another type of lipid that contributes to membrane structure. Sterols are large, multiringed hydrocarbons that dissolve in the hydrophobic part of a membrane and keep it flexible, preventing it from developing cracks. In animals, the primary sterol is cholesterol; in plants (including the vegetables and fruits that you eat), there is no cholesterol; a related molecule, ergosterol, has the same function.

Other lipids, the **triglycerides**, are used as energy storage compounds because the oxidation of their components releases a great deal of useful free energy. Triglycerides have three fatty acid molecules attached to a glycerol connector. They are insoluble in water and form discrete lipid bodies inside plant cells. Extracted from plant organs, they form oils (liquid at room temperature) or fats (solid at room temperature), depending on the lengths of the fatty acid hydrocarbons and whether they have double bonds. Fatty acids in oils are shorter, have more double bonds, or both. Most salad oils are triglycerides extracted from seeds of maize, soybean,



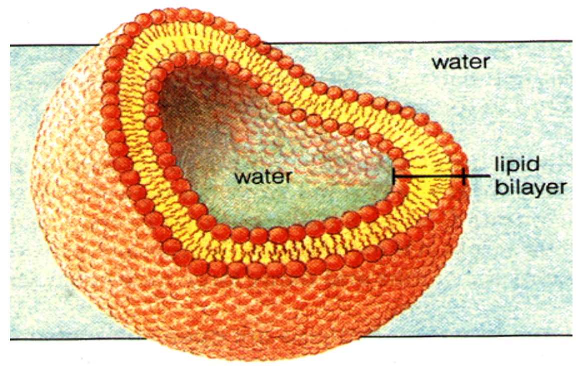


Figure 2.11. Phospholipids and membranes. Left: model of a phospholipid--note the hydrophilic head group and the hydrocarbon tails. Right: phospholipids in solution form a bilayer that keeps water away from the tails and in contact with the heads. The bilayer is flexible, and the individual molecules can move relative to one another as long as they stay in the plane of the bilayer.

sunflower, sesame, cotton, peanut, or other plants. Three commercially important fats from plants are palm "oil", coconut "oil", and cocoa butter.

Proteins have Diverse Shapes and Functions

Proteins are large molecules formed by stringing together many **amino acids**--one hundred to several hundred--into a long, unbranched chain. The amino acids are the **monomers** (individual units) that form the protein **polymer** (multiunit molecule). Each amino acid has a **backbone** containing an amino group, a central carbon, and a carboxyl group (Fig. 2.12). The amino and carboxylic acid groups are responsible for the name "amino acid." Twenty different types of amino acids are found in proteins. They all have the same backbone, but each has a different **side chain** attached to the central carbon.

The amino acids can be linked together at their backbones: an amino group of one amino acid attached to the carboxyl group of a second amino acid; the amino group of the second amino acid attached to the carboxyl group of a third amino acid, and so on (Fig. 2.13). The bonds linking the amino acids are called **peptide** bonds; therefore the chain is called a **polypeptide chain**. Any one of the 20 different types of amino acids may be placed in any of the positions on the chain. Thus there are 20^{100} different possible arrangements of chains that are 100 amino acids in length, and even more possibilities exist with longer chains. Every particular type of protein has its own specific arrangement of amino acids, sometimes called its **primary structure**. This arrangement promotes the folding of the protein into a very specific three-dimensional shape, with different parts of the protein held together by hydrogen bonds between parts of the backbone (**secondary structure**) and by ionic, hydrogen, and hydrophobic bonds between the side chains of the different amino acids (**tertiary structure**); Fig. 2.14). Individual protein molecules may associate with each other or with other types of proteins to form larger structures (**quaternary structures**).

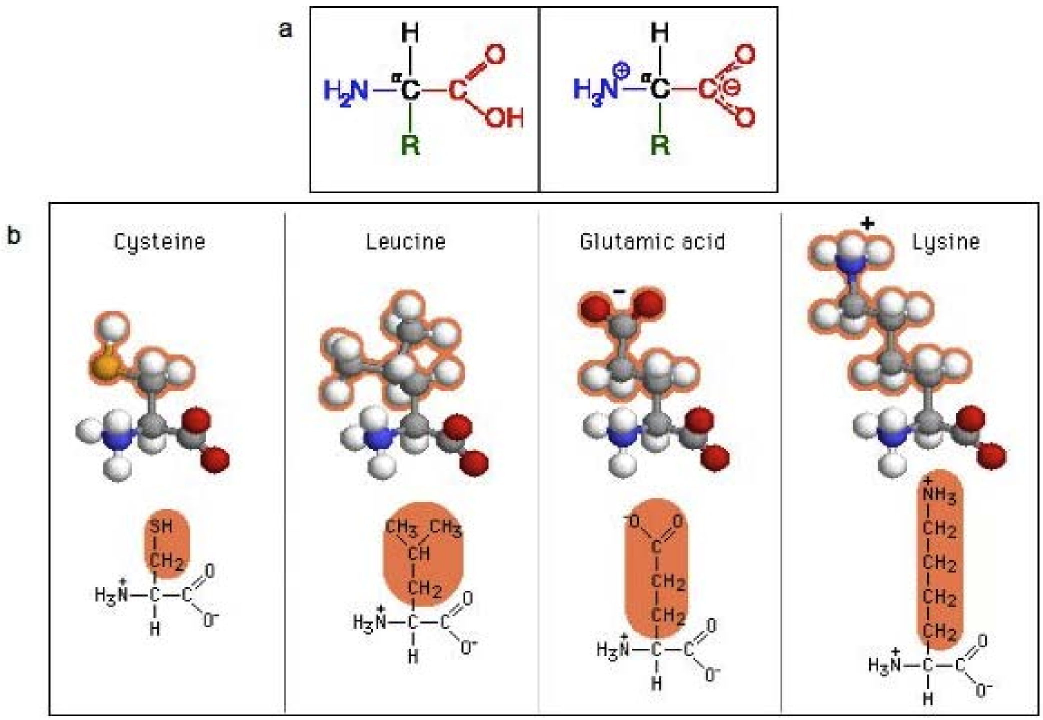


Figure 2.12. Amino acid structures. (a) The general formula for an amino acid. R represents the side chain. The zwitterionic (+,-) form at the right is the form found in solution. (b) Four of the 20 possible amino acids found in proteins. Notice that these molecules differ only in their side chains.

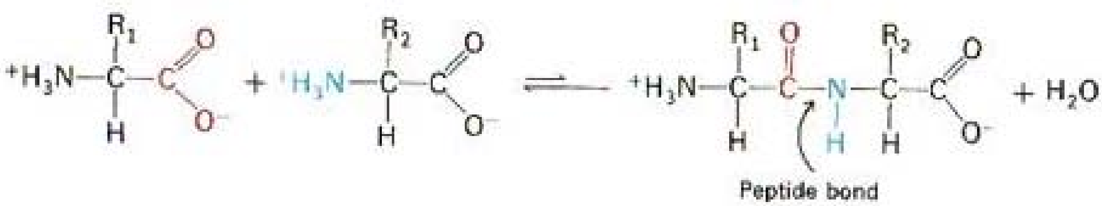


Figure 2.13. Peptide bond formation. Different amino acids can polymerize through peptide bonds to form a polypeptide chain. The length of the chain and the order of the amino acids vary according to the type of protein. The formation of a peptide bond is formally a dehydration reaction (releases H_2O). A peptide bond can be broken by hydrolysis (adding H_2O).

The functional properties of a protein depend on its three-dimensional shape. Large protein complexes give form to the cell, direct movement within the cell, or provide a scaffold for chemical reactions. Most **enzymes**, which catalyze the chemical reactions of the cell, are proteins. Like starch and triglycerides, some proteins may be used for storage of energy (for example, in seeds).

Heating a solution of a protein to a temperature of 50ºC or more breaks the relatively weak ionic, hydrogen, and hydrophobic bonds between the side chains and unwraps the protein; this changes its three-dimensional shape, even though it does not alter the order of the amino acids in the polypeptide chain. Protein molecules that have been heated or otherwise treated to change their three-dimensional shape lose their function. These protein molecules are said to be **denatured**. Denatured proteins will often form large masses and become insoluble. The proteins in a cooked egg white are a good example.

Cells depend on functioning proteins to live. The function of a protein depends on its three-dimensional shape. And a protein's shape depends on the arrangement of amino acids in its polypeptide chain. Thus, the information that guides the arrangement of amino acids into a polypeptide chain is a key element of life. This information is carried by other biological molecules, as explained in the following section.

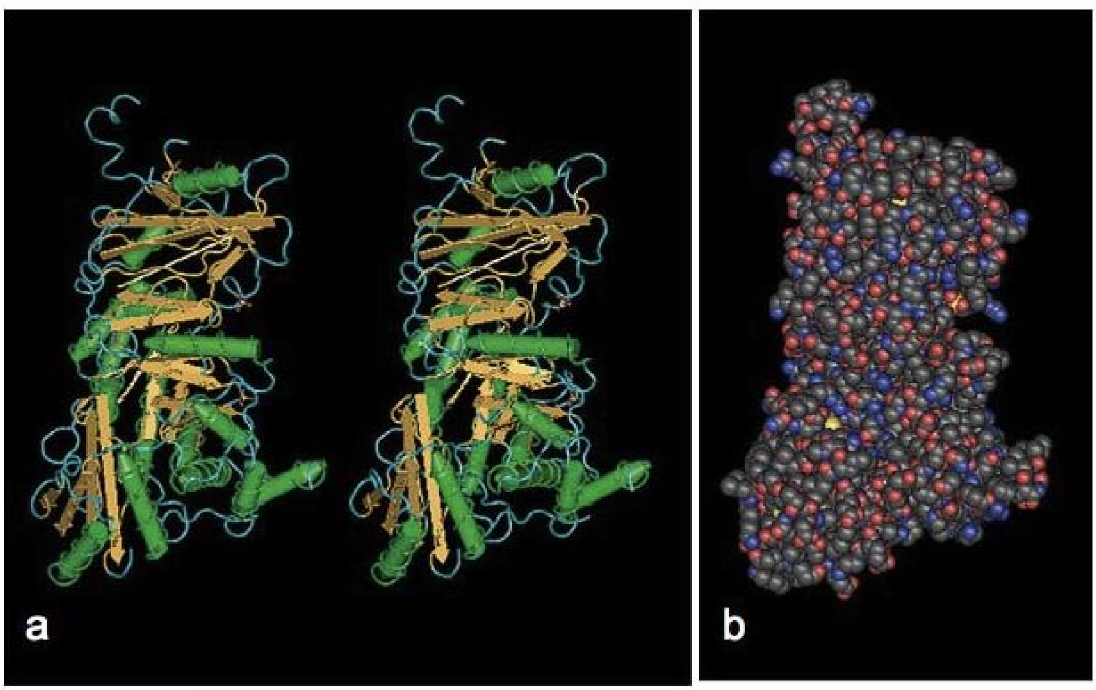


Figure 2.14. Models of protein structure. This protein is a subunit of Rubisco, a key enzyme in photosynthesis. (a) A stereo diagram showing the twists of the protein backbone. The green cylinders indicate regions where the backbone forms a helix (called an a-helix). The orange ribbons show regions where several quasi-parallel stretches of backbone are connected (called a ß-pleated sheet). Stare at the drawing while focusing at an imaginary point in the distance. The images should seem to converge to form a three-dimensional image in the middle. (b) The same protein in a "space-filling" model, which shows individual atoms.

Nucleic Acids Store and Transmit Information

There are two types of **nucleic acids**: **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. Both DNA and RNA are polymers--that is, long unbranched chains of nucleotide monomers. Each nucleotide is formed from a simple five-carbon sugar attached to a phosphate group and to a one- or two-ringed molecule called a base. (The word *base* in this context has a different meaning from that used earlier in this chapter. There, base referred to any compound that accepted H^+. Here, it refers to a few specific molecules.) The sugars give the nucleic acids their names: the sugar of DNA nucleotides in deoxyribose; the sugar of RNA is ribose. Chains of nucleotides are formed by attaching the phosphate group of one nucleotide to the sugar of another (Fig. 2.15).

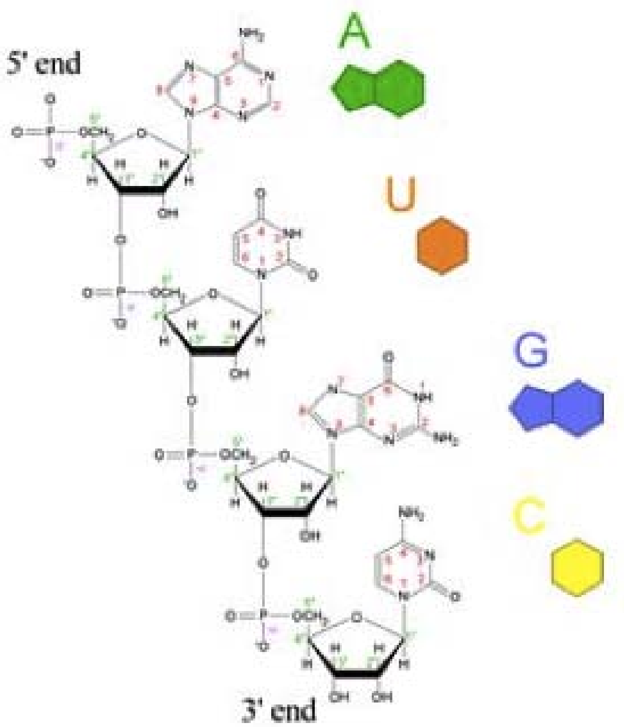


Figure 2.15. Structure of a nucleic acid polymer. The basic nucleotide subunit has a base (A, U or T, G, C), sugar, and a phosphate. DNA and RNA nucleotides are distinguished by their sugars (the one shown here has ribose and is RNA). The form the polynucleotide chain, the nucleotides are connected through the sugars and phosphates.

Different nucleotides are distinguished by their different bases. There are four types of nucleotides in DNA, which have bases called A (adenine), T (thymine), G (guanine), or C (cytosine). There are four corresponding types of nucleotides in RNA, with A, U (uracil), G, or C bases. The nucleotide bases can bind together with hydrogen bonds to form complementary pairs. A binds only to T (or U); G binds only to C (Fig 2.16).

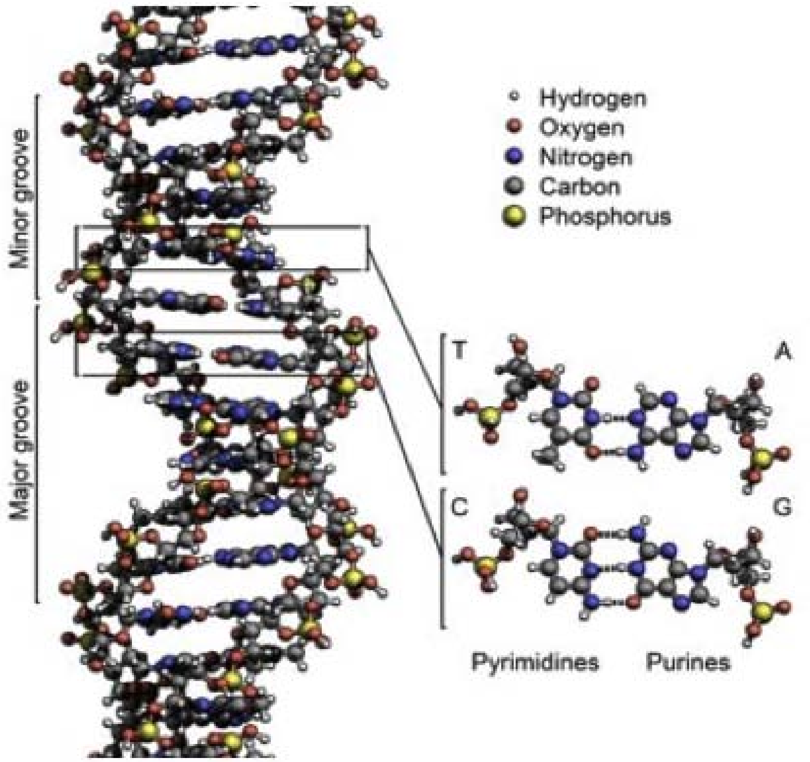


Figure 2.16. The DNA double helix. The complementary bases A and T and also G and C can form base pair complexes, connected by two and three hydrogen bonds, respectively.

DNA is formed from two chains of nucleotides wound around each other in a formation called a **double helix** (Fig. 2.16). At each position, the base of one chain is hydrogen-bonded to the corresponding base of the other chain. The two chains are called complementary, just as the individual bases are complementary. DNA stores **genetic information** in its sequence of nucleotide bases. Thus, a sequence of bases such as ATGCCC has a different meaning from another sequence, such as AAGTTA. Consequently, the order of the bases in DNA is critical to its function, as the order of amino acids is critical to the function of proteins. Although there are not as many types of bases as amino acids, the potential variation for DNA is much great than for proteins because DNA molecules are so much longer. A single DNA molecule generally has several million nucleotides.

Genetic information is used to specify the order of amino acids in proteins. A set of three bases on a DNA molecule specifies one amino acid according to a **genetic code**. A section of DNA containing 100 sets of three bases, all in order, can specify the amino acid sequence of a protein of 100 amino acids. Such a section of DNA (together with extra bases controlling when the genetic information is expressed to form proteins) is a **gene**.

RNA is made from a single strand of nucleotides. There are various types of RNA. Some are extended, whereas others may loop back on themselves and be wound into different shapes. The different types of RNA molecules have different functions, but almost all are involved in some way in the control and use of genetic information to synthesize proteins. How DNA and RNA contribute to the process of synthesizing proteins is described in a later chapter.

DNA REPLICATION. Reproduction is one of the most important and complex characteristics of living organisms. It is axiomatic that when a cell or organism reproduces, it must pass its genetic information to its progeny. This means that new copies of the information, and thus new copies of DNA base sequences, must be synthesized. The original DNA chains serve as templates to guide the formation of the new DNA. When a cell produces a copy of DNA identical to an original DNA double helix, we say that the original has been *replicated*.

The basic process of DNA replication involves the separation of the two original complementary strands of DNA. Each strand can serve as a template for the assembly of a new complementary strand (Fig. 2.17). An enzyme attaches the nucleotides together one by one, choosing at each step a nucleotide with a base that is complementary to the opposite base on the template. The result is two identical double helical molecules of DNA, each with one original and one new strand.

The actual synthesis of a new DNA molecule is more complicated, with synthesis starting in the middle of the molecule and working outward in both directions. Additional enzymes are needed to separate the strands and to promote unwinding and rewinding of the double helices, as well as to weld together separate, adjacent segments of newly synthesized strands. It is amazing that the process works at all, given the millions of nucleotides that must be joined in proper sequences to produce one new full copy of genetic information. It is essential that it does work, however, because DNA forms the molecular foundation for all organisms.

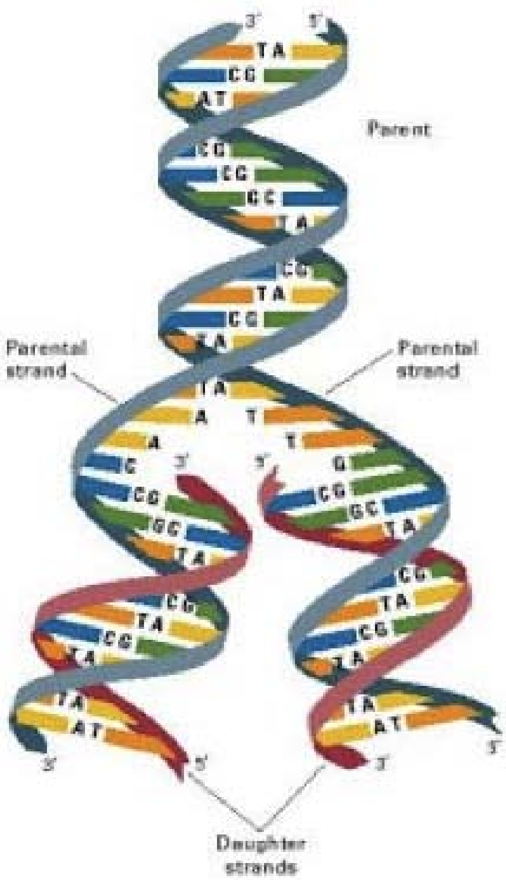


Figure 2.17. The replication of a DNA molecule. Shown is a DNA molecule that has been partially unzipped by the breaking of the hydrogen bonds between the bases. Each strand serves as a template for creating a new, complementary DNA strand. The template strand and the new strand stay together after replication is complete.

KEY TERMS

acids
amino acids
anions
atoms
bases
carbohydrates
cations
cellulose
compound
covalent bond
deoxyribonucleic acid (DNA)
DNA replication
double helix
electronegativity
electrons
elements
enzymes
free energy
functional groups
gene
genetic code
glycolipids
hydrocarbon compound
hydrogen bond
hydrophilic
hydrophobic
hydrophobic bond
ionic bond
lipid
membranes
molecules
monomers
neutrons
nonpolar
nucleic acid
nucleus
oligosaccharides
orbitals
oxidation-reduction (redox)
pectin
peptide bond
phospholipids
polar
polymer
polypeptide chain
polysaccharides
primary structure
proteins
protons
quaternary structures
ribonucleic acid (RNA)
salt
secondary structure
sidechain
starch
sterols
tertiary structure
triglycerides

SUMMARY

1. All matter is made up of simple units called molecules. Molecules are made of atoms. An atom contains a nucleus (with protons and neutrons) and electrons, which move around the nucleus in orbitals.

2. Matter made from one type of atom is an element; matter made of more than one type of atom is a compound. The number of protons in the nucleus defines the type of atom; the number of neutrons contributes to the weight of the atom and the stability of the nucleus. Unstable nuclei are radioactive.

3. Protons have a positive charge. Electrons have a negative charge. An atom or molecule with the same number of protons and electrons is electrically neutral.

4. An atom or molecule with more protons than electrons has a net positive charge and is called a cation. An atom or molecule with fewer protons than electrons has a net negative charge and is called an anion.

5. The transfer of an electron from one atom or molecule to another oxidizes the first and reduces the second.

6. The attractive force that holds together a positive ion and a negative ion is called an ionic bond.

7. Electrons that are shared between two atoms in a bonding orbital form a covalent bond between the two atoms and hold them together. Hydrogen atoms participate in one covalent bond, oxygen atoms in two, nitrogen atoms in three, and carbon atoms in four.

8. Some atomic nuclei in a molecule pull electrons more strongly than others, creating a polarity of electric charge in the molecule. Water is an example of a polar compound, with a partial negative charge at the oxygen atoms and a partial positive charge near the hydrogen atoms. Electrical forces result in hydrogen bonds being formed between two water molecules or other molecules where a hydrogen nucleus can be positioned between two strong electronegative nuclei (O or N).

9. Polar molecules tend to dissolve in water and are called hydrophilic. Nonpolar molecules tend not to dissolve in water and are called hydrophobic.

10. Molecules that donate hydrogen nuclei are called acids; molecules that accept the hydrogen nuclei are called bases. Excess hydrogen nuclei in water are attached to the water molecules to form hydronium ions. The pH scale measures the concentration of hydronium ions in a solution.

11. A protein is a linear chain of amino acids connected by peptide bonds. Each type of protein has a specific order of amino acids and a specific three-dimensional structure. A protein that loses its three-dimensional structure is denatured.

12. Carbohydrates are simple sugars and polymers of sugars. Some contribute to structure, especially of the cell wall, and other are a form of energy storage.

13. Lipids are hydrophobic compounds made from hydrocarbons and other molecules. Phospholipids and glycolipids form sheets, called membranes, that separate compartments in a cell. Triglycerides serve as forms of energy storage.

14. Nucleic acids include DNA and RNA. Both are long, linear chains of nucleotides. DNA, a double-stranded molecule, stores genetic information in the sequence of its nucleotide bases. RNA, a single-stranded molecule, is an intermediate in the use of genetic information to make functional proteins.

15. The presence of two complementary chains in DNA and their use as templates form the chemical basis for the replication of genetic information.

Questions

1. How many protons and how many electrons are present in a molecule of (a) methane (CH_4); (b) ammonia (NH_3); and (c) water (H_2O)?

2. When an atom of ^{14}C undergoes radioactive decay, its nucleus emits an electron. Because the electron carries one negative charge, the nucleus has gained one positive charge. One of the neutrons in the nucleus has turned into a proton! Is the atom still an atom of carbon? Explain your answer.

3. Sketch a molecule of methane showing the positions of the nuclei of the five atoms and the general positions of the bonding and nonbonding electrons. Show that the total number of electrons in the molecule equals the total number of protons in the five nuclei.

4. Sketch a molecule of water showing the positions of the nuclei of the three atoms and the general positions of the bonding and nonbonding electrons. Show that the total number of electrons in the molecule equals the total number of protons in the three nuclei. Do all the outer orbitals of oxygen form chemical bonds? Show how the tendency of electrons to move to the large nucleus gives the molecule a polarity.

5. Sketch the following hydrocarbon molecules showing the positions of the C and H atoms (as well as you can on a flat piece of paper) and the number of covalent bonds between adjacent atoms. Remember that all carbon atoms should have four bonds and that some carbon atoms may have double bonds between them. Also, some carbon chains can form rings.

a. ethane (C_2H_6)
b. butane (C_4H_{10})
c. hexane (C_6H_{14})
d. cyclohexane (C_6H_{12})
e. ethylene (C_2H_4)
f. benzene (C_6H_6)

6. The pH of pure water is 7. What will the pH be if (a) you increase the hydrogen (hydronium) ion concentration 1000-fold; or (b) you add a compound that forms complexes with 99% of the hydrogen (hydronium) ions?

7. Explain why salad oil and vinegar separate after you shake them up together.

8. Rearrange the following list so that the large items are at the bottom and smallest at the top.

carbon atom
water
neutron

protein
proton
DNA
amino acid
electron
sugar
triglyceride

9. Match the monomers and polymers in the following lists:

amino acid	DNA
fatty acid	cellulose
nucleotide	enzyme
sugar	RNA
	phospholipids
	starch
	protein

PLANTS, PEOPLE, AND THE ENVIRONMENT*: Plants as Pharmacists*

Stems of a male *Ephedra* plant. *Ephedra equisetina* (common name Ma Huang) is the source of ephedrine, a stimulant, and pseudoephedrine, found in over-the-counter allergy medicines. Although the Food and Drug Administration does not regulate "dietary supplements," such as natural ephedra, a 2003 report indicated that the use of ephedra, particularly by athletes, may be associated with serious risks, including heart attacks, strokes, hypertension, respiratory depression, and psychiatric problems.

Plants are superb chemists. They synthesize a great variety of chemicals beyond those needed to perform the basic functions of cells. For many years these chemicals were known as secondary compounds because they were not needed for the functions of all cells. The term suggested that the compounds had no significance in the life of the plant. Now it is recognized that these compounds often play important roles, either as components of specialized cells or in the interactions between plants and other organisms with which they associate. For instance, some of the chemicals attract animals, promoting the transfer of pollen from one plant to another of the species or the dispersal of seed. Some of the chemicals are antibiotics or toxins, restricting the ability of pathogens and herbivores to feed off the plant.

The subject of ethnobotany, the use of plant extracts by people of many cultures, recently has become popular. An understanding of these uses may help us control disease bacteria that are becoming resistant to current antibiotics. They may also help cure conditions like AIDS and give us new ways of alleviating pain, anxiety, or neurologic disorders. The adjacent table lists several plants that produce compounds that affect the human nervous system. A few of these are in common and accepted use; a few are in common use but are legally discouraged; and some are only used medicinally.

Many of the chemicals in plants are used to prevent or to fight cancer. A large class of compounds, called antioxidants, prevents damage that seems to lead to cancer. These compounds include ascorbic (vitamin C), alpha-tocopherol (vitamin E), and beta-carotene (which is converted into vitamin A), all of which are accumulated in many fruits and vegetables. These work by reacting with (and thus taking out of circulation) chemicals with unpaired electrons (free radicals) that would otherwise combine with, oxidize, and inactivate DNA, RNA, proteins, or membrane lipids. They are accumulated in plants to protect the plants' own cells, but they probably do the same job in human bodies. Some plants have special compounds that may perform the same function. Broccoli contains sulforaphane, garlic and onions have allyl sulfides, and tea has catechins. Many of these chemicals have been found to prevent cancer in experimental animals. The evidence that they prevent human cancers is less well established and is a subject of current research.

Chemicals used to fight cancer are generally toxic to cancer cells. Because cancer cells reproduce rapidly, the most effective compounds are those that interfere with cell division. Such compounds include vincristine and vinblastine, which come from the periwinkle plant (*Vinca rosea*) and Taxol from yew trees (*Taxus brevifolia*). Psoralens from celery, parsley, and citrus leaves make cells sensitive to ultraviolet light; this treatment allows physicians to kill cells in localized regions by irradiating them with an ultraviolet laser. Gossypol (from cottonseed), which has been touted as a potential male contraceptive, also exhibits anticancer activity, possibly by stimulating the formation of free radicals that oxidize membrane lipids in cancer cells.

Even though chemists are becoming more proficient at designing and synthesizing complex molecules, the use of plant-derived chemicals will continue and expand. The specificity of biological catalysts (enzymes) in plant cells is the reason. There are many molecular structures, formed within plant cells, that are impossible for even the most skilled chemists to duplicate.

Plant Sources of Psychoactive and Neuroactive Agents

Source	Chemical	Effect, Use
Atropa belladonna (belladonna)	Atropine	Pupil dilation, heart rate acceleration
Cannabis sativum (hemp)	Tetrahydrocannabinol	Nausea reduction, appetite stimulation
Coffea arabica (coffee)	Caffeine	Stimulant, diuretic
Erythroxylon coca (coca)	Cocaine	Stimulant, anesthetic
Lophophora williamsii (peyote)	Mescaline	Hallucinogen
Nicotiana tabacum (tobacco)	Nicotine	Stimulant
Papaver somniferum (poppy)	Morphine, codeine	Anesthetic, narcotic
Thea sinensis (tea)	Theophylline	Stimulant, diuretic
Theobroma cacao (cocoa)	Theobromine	Stimulant, diuretic

Photos

CO T.M. Murphy

Fig. 2.2 http://www.gcsescience.com/a5-reaction-sodium-chlorine.htm;http://butane.chem.uiuc.edu/pshapley/GenChem1/L20/2.html

Fig. 2.3 http://chemwiki.ucdavis.edu/Wikitexts/Purdue/Purdue%3A_Chem_26505/Chapter_1._Electronic_Structure_and_Chemical_Bonding/1.07_Atomic_Orbitals_and_Covalent_Bonding

Fig. 2.5 http://commons.wikimedia.org/wiki/File:Hexane-3D-balls.png; http://scarc.library.oregonstate.edu/coll/pauling/bond/pictures/1964b4.1-ethylene.html

Fig. 2.7 http://chemwiki.ucdavis.edu/@api/deki/files/8232/639px-PH_scale.png

Fig. 2.8 http://upload.wikimedia.org/wikipedia/commons/9/96/Acetic-acid-dissociation-3D-balls.png

Fig. 2.9 https://www.boundless.com/physiology/textbooks/boundless-anatomy-and-physiology-textbook/general-chemistry-2/organic-compounds-39/the-carbohydrate-sugar-313-11429/

Fig. 2.11 http://ibbio.pbworks.com/w/page/59801063/Membranes

Fig. 2.16 http://en.wikipedia.org/wiki/DNA

Fig. 2.17 http://oakridgeapbio.pbworks.com/w/page/9716898/DNA%20Replication%20and%20Structure

Endnote Terence M. Murphy

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