2.1 Basic Chemistry

Learning Outcomes

Upon completion of this section, you should be able to

1. Describe how protons, neutrons, and electrons relate to atomic structure.
2. Identify the beneficial and harmful uses of radiation.

Everything—including the book you're holding, the chair you're sitting on, the water you drink, and the air you breathe—is composed of matter. **Matter** refers to anything that takes up space and has mass. Matter has many diverse forms, but it can exist only in three distinct states: solid, liquid, and gas.

All matter, both nonliving and living, is composed of certain basic substances called **elements.** An element is a substance that cannot be broken down to simpler substances with different properties by ordinary chemical means. (A property is a physical or chemical characteristic, such as density, solubility, melting point, and reactivity.) Only 92 naturally occurring elements serve as the building blocks of all matter. Other elements have been "human-made" and are not biologically important.

Earth's crust and its organisms are composed of elements, but they differ as to which elements are predominant (Figure 2.1). Only six elements—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur—are basic to life, and they make up about 95% of the body weight of organisms. The acronym CHNOPS helps us remember these six elements. The properties of these elements are essential to the uni ness of cells and organisms. Other elements, inclu sodium, potassium, calcium, iron, and magnesium, are important to all organisms.

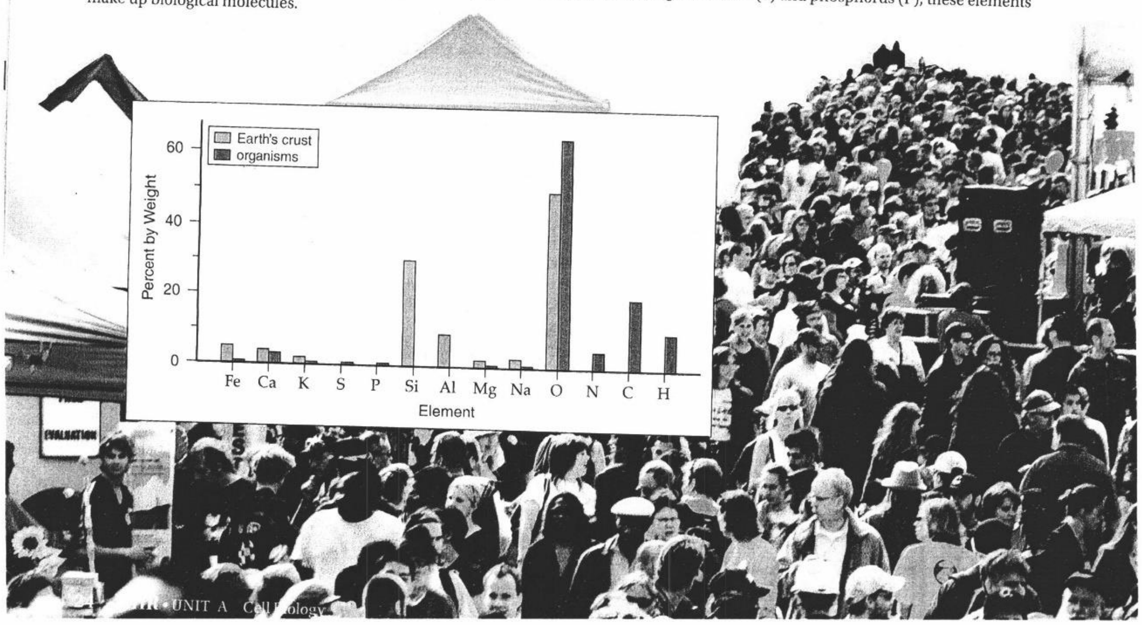
Atomic Structure

In the early 1800s, the English scientist John Dalton champi the atomic theory, which says that elements consist of tiny ticles called **atoms.** An atom is the smallest part of an element displays the properties of the element. An element and its a share the same name. The atomic symbol is composed of or two letters, which stands for this name. For example, the syn H means a hydrogen atom, the symbol Cl stands for chlorine, the symbol Na (for *natrium* in Latin) is used for a sodium ato

Physicists have identified a number of subatomic parti that make up atoms. The three best-known subatomic ticles are positively charged **protons,** uncharged **neutr** and negatively charged **electrons.** Protons and neutrons located within the nucleus of an atom, and electrons m around the nucleus. Figure 2.2 shows the arrangement of subatomic particles in a helium atom, which has only two el trons. In Figure 2.2*a*, the stippling shows the probable locat of electrons, and in Figure 2.2*b*, the circle represents an el tron orbital, the location of electrons.

The concept of an atom has changed greatly since Dalto day. If an atom could be drawn the size of a football stadiu the nucleus would be like a gumball in the centre of the fie

Figure 2.1 Elements that make up Earth's crust and its organisms. Humans are just one of the many organisms that exist on Earth. The graph inset shows that Earth's crust primarily contains the elements silicon (Si), aluminum (Al), and oxygen (O). Organisms primarily contain the elements oxygen (O), nitrogen (N), carbon (C), and hydrogen (H). Along with sulfur (S) and phosphorus (P), these elements make up biological molecules.



: electrons would be tiny specks whirling about in the upper ıds. Most of an atom is empty space. We can only indicate orbital where the electrons are expected to be most of the e. In our analogy, the electrons might very well stray outside stadium at times.

All atoms of an element have the same number of protons. s is called the **atomic number.** The number of protons in the :leus makes each atom unique. The atomic number is often tten as a subscript to the lower left of the atomic symbol.

Each atom also has its own **mass number,** which is depen- ıt on the number of subatomic particles in that atom. Pro- s and neutrons are assigned one atomic mass unit (AMU) h. Electrons are so small that their AMU is considered zero nost calculations (Figure 2.2*c*). Therefore, the mass number ın atom is the sum of protons and neutrons in the nucleus. : term *atomic mass* is used, rather than *atomic weight,* :ause mass is constant while weight changes according to gravitational force of a body. The gravitational force of Earth reater than that of the Moon. Therefore, substances weigh ; on the Moon even though their mass has not changed. The mic mass is often written as a superscript to the upper left he atomic symbol. For example, the carbon atom can be ed in this way:

mass number ——— 12 C ——— atomic symbol
tomic number ——— 6

$$^{12}_{6}\mathrm{C}$$

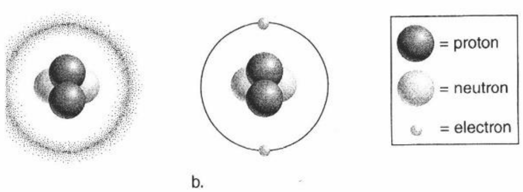
ıtopes

topes are atoms of the same element that differ in the num- · of neutrons. Isotopes have the same number of protons, : they have different atomic masses. Because the number of protons gives an atom its identity, changing the number of neutrons affects the atomic mass but not the name of the atom. For example, the element carbon has three common isotopes:

$$^{12}_{6}\mathrm{C} \qquad ^{13}_{6}\mathrm{C} \qquad ^{14}_{6}\mathrm{C}$$

radioactive

Carbon-12 has six neutrons, carbon-13 has seven neutrons, and carbon-14 has eight neutrons. Unlike the other two isotopes of carbon, carbon-14 is unstable. It changes over time into nitrogen-14, which is a stable isotope of the element nitrogen. As carbon-14 decays, it releases various types of energy in the form of rays and subatomic particles, and therefore it is a **radioactive isotope.** Today, biologists use radiation to date objects, create images, and trace the movement of substances through the human body.



Subatomic Particles			
›article	Electric Charge	Atomic Mass Unit (AMU)	Location
›roton	+1	1	Nucleus
ɿeutron	0	1	Nucleus
:lectron	−1	0	Electron shell

ıure 2.2 Model of helium (He). Atoms contain subatomic ticles called protons, neutrons, and electrons. Protons and neutrons within the nucleus, and electrons are outside the nucleus. **a.** The ıpling shows the probable location of the electrons in the helium m. **b.** A circle termed an *electron orbital* represents the average ıtion of an electron. **c.** The electric charge and the atomic mass units he subatomic particles vary as shown.

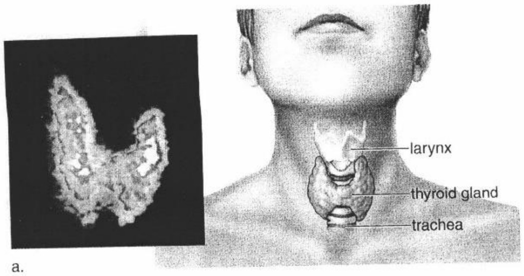
Low Levels of Radiation

The chemical behaviour of a radioactive isotope is essentially the same as that of the stable isotopes of an element. This means that you can put a small amount of radioactive isotope in a sample and it becomes a tracer or tag by which to detect molecular changes.

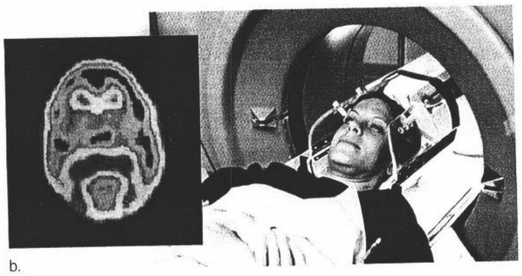
The importance of chemistry to medicine is nowhere more evident than in the many medical uses of radioactive isotopes. Specific tracers are used in imaging the body's organs and tissues. For example, after a patient drinks a solution containing a minute amount of radioactive ^{131}I, it becomes concentrated in the thyroid—the only organ to take up iodine. A subsequent image of the thyroid indicates whether it is healthy in structure and function (Figure 2.3*a*). Positron emission tomography (PET) is a way to determine the comparative activity of tissues. Radioactively labelled glucose, which emits a subatomic particle known as a positron, is injected into the body. The radiation given off is detected by sensors and analyzed by a computer. The result is a colour image that shows which tissues took up glucose and are metabolically active (Figure 2.3*b*). A PET scan of the brain can help diagnose a brain tumour, Alzheimer's disease, epilepsy, or whether a stroke has occurred.

High Levels of Radiation

Radioactive substances in the environment can harm cells, damage DNA, and cause cancer. When researchers such as Marie Curie began studying radiation in the 19th century its harmful effects were not known, and many developed cancer. The release of radioactive particles following a nuclear power plant accident, such as occurred in Japan in 2011 following the tsunamis, can have far-reaching and long-lasting effects on human health. However, the effects of radiation can also be put to good use (Figure 2.4). Radiation from radioactive isotopes has been used for many years to sterilize medical and dental products. Radiation is now used to sterilize some mail in the United States to free it of possible pathogens, such as anthrax spores. The ability of radiation to kill cells is often applied to cancer cells. Targeted radioisotopes can be introduced into the body



a.



b.

Figure 2.3 Low levels of radiation. **a.** The missing area in this thyroid scan (*upper left*) indicates the presence of a tumour that does not take up the radioactive iodine. **b.** A PET (positron emission tomography) scan reveals which portions of the brain are most active (yellow and red colours).

so that the subatomic particles emitted destroy only cancer cells, with little risk to the rest of the body. X rays, another form of high-energy radiation, can be used for medical diagnosis.

Check Your Progress 2.1

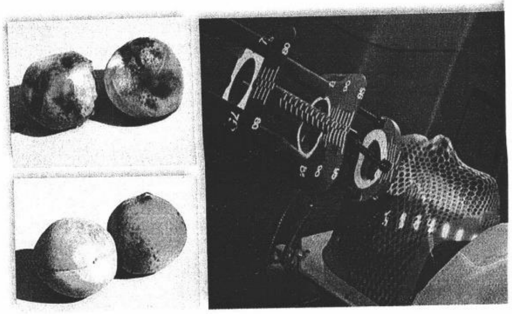
1. Explain why the key elements in Earth's crust would differ from those present in living organisms.
2. Explain how radiation can be both beneficial and harmful to humans.
3. Explain the differences between oxygen 16 and oxygen 18.

2.2 Molecules and Compounds

Learning Outcomes

Upon completion of this section, you should be able to

1. Describe how elements are combined into molecules and compounds.
2. List the different types of bonds that occur between elements.
3. Compare the relative strengths of ionic, covalent, and hydrogen bonds.



a. b.

Figure 2.4 High levels of radiation. **a.** Radiation kills bacteri and fungi. Irradiated peaches (*bottom*) spoil less quickly and can be ke for a longer length of time. **b.** Physicians use radiation therapy to kill cancer cells.

Atoms, except for noble gases, routinely bond with one anoth A **molecule** is formed when two or more atoms covalently bo together. For example, oxygen does not exist in nature a single atom, O. Instead, two oxygen atoms are joined to forr molecule of oxygen, O_2. When atoms of two or more differ elements bond together, the product is called a **compou** Water (H_2O) is a compound that contains atoms of hydrog and oxygen. We can also speak of molecules of water beca a molecule is the smallest part of a compound that still has properties of that compound.

Electrons possess energy, and the bonds that e between atoms also contain energy. Organisms are dire dependent on chemical-bond energy to maintain their or nization. When a chemical reaction occurs, electrons shi their relationship to one another, and energy may be giver or absorbed. This same energy is used to carry on our d lives.

Ionic Bonding

In an electrically neutral atom, the positive charges of the tons in the nucleus are balanced by the negative charge electrons moving about the nucleus. Ions form when elect are transferred from one atom to another. For example, sod (Na) tends to be an electron donor (Figure 2.5*a*). Chlorine on the other hand, tends to be an electron acceptor. Wh sodium atom and a chlorine atom come together, an electr transferred from the sodium atom to the chlorine atom.

This electron transfer causes a charge imbalance in atom. The sodium atom has one more proton than it has trons. Therefore, it has a net charge of +1 (symbolize Na^+). The chlorine atom has one more electron than it protons. Therefore, it has a net charge of −1 (symbolize Cl^-). Such charged particles are called **ions.** Sodium (and chloride (Cl^-) are not the only biologically important Some, such as potassium (K^+), are formed by the transf a single electron to another atom. Others, such as cal electrons.

onic compounds are held together by an attraction between ively and positively charged ions called an **ionic bond.** ı sodium reacts with chlorine, an ionic compound called m chloride (NaCl) results. Sodium chloride is a salt, com- y known as table salt because it is used to season our Figure 2.5*b*). Salts can exist as a dry solid, but when salts aced in water they release ions as they dissolve. NaCl sepa- nto Na^+ and Cl^-. In biological systems, because they are 90 percent water, ionic compounds exist primarily in a iated state (they are dissolved).

ılent Bonding

alent bond results when two atoms share electrons. If gen is in the presence of a strong electron acceptor, it gives electron to become a hydrogen ion (H^+). But if this is not le, hydrogen can share an electron with another atom. For le, one hydrogen atom will share with another hydrogen Their two orbitals overlap, and the electrons are shared n them (Figure 2.6*a*).

nore common way to symbolize that atoms are shar- ctrons is to draw a line between the two atoms, as in uctural formula H—H. In a molecular formula, the omitted and the molecule is simply written as H_2.

netimes, atoms share more than one pair of electrons. e covalent bond occurs when two atoms share two pairs rons (Figure 2.6*b*). To show that oxygen gas (O_2) con- louble bond, the molecule can be written as O═O.

It is also possible for atoms to form triple covalent bonds, as in nitrogen gas (N_2), which can be written as N≡N. Single covalent bonds between atoms are quite strong, but double and triple bonds are even stronger.

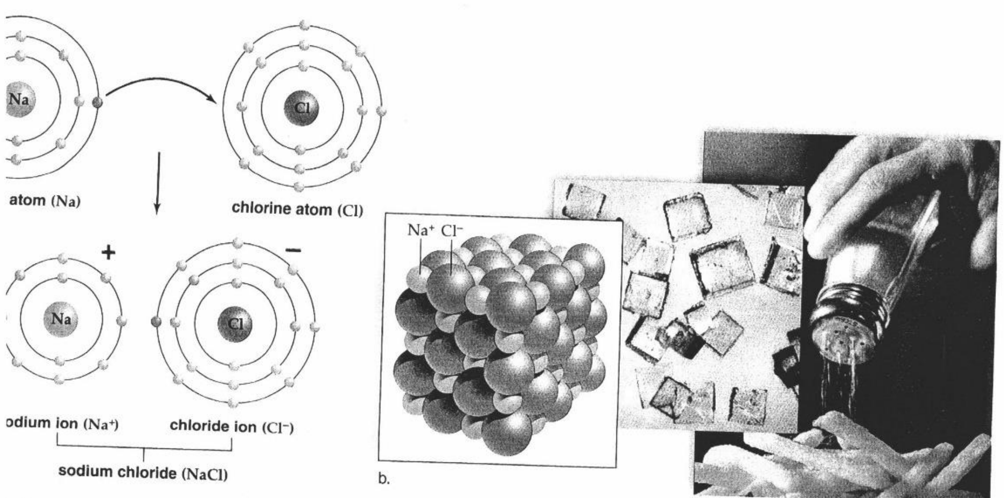
Shapes of Molecules

Structural formulas make it seem as if molecules are one-dimensional, but actually molecules have a three-dimensional shape that often determines their biological function. Molecules consisting of only two atoms are always linear, but a molecule such as methane with five atoms (Figure 2.6*c*) has a tetrahedral shape. Why? Because, as shown in the ball-and-stick model, each bond is pointing to the corners of a tetrahedron (Figure 2.6*d, left*). The space-filling model comes closest to the actual shape of the molecule. In space-filling models, each type of atom is given a particular colour—carbon is always black and hydrogen is always off-white (Figure 2.6*d, right*).

The shapes of molecules are related to the structural and functional roles they play in organisms. For example, hormones have specific shapes that allow them to be recognized by the cells in the body. Antibodies combine with disease-causing agents, like a key fits a lock, to protect us. Similarly, homeostasis is maintained only when enzymes have the proper shape to carry out their particular reactions in cells.

Nonpolar and Polar Covalent Bonds

When the sharing of electrons between two atoms is fairly equal, the covalent bond is said to be a nonpolar covalent bond. All the



Formation of sodium chloride (table salt). **a.** To form sodium chloride, an electron is transferred from the sodium atom to the n. **b.** In a sodium chloride crystal, ionic bonding between Na^+ and Cl^- causes the atoms to assume a three-dimensional lattice in which each s surrounded by six chloride ions, and each chloride ion is surrounded by six sodium ions. This forms crystals, such as in table salt.

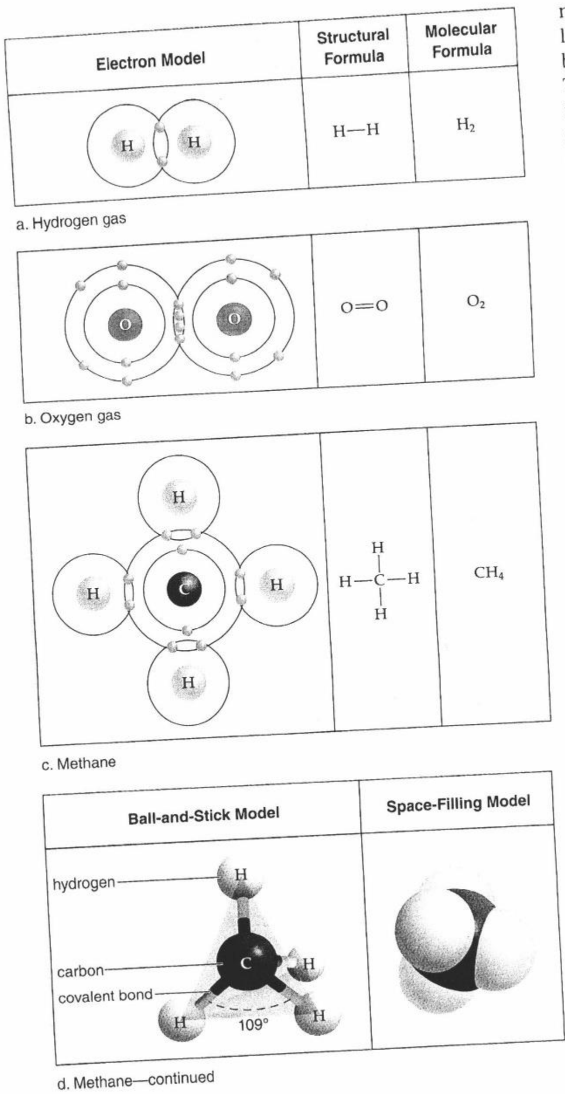


Figure 2.6 Covalently bonded molecules. In a covalent bond, atoms share electrons. **a.** A molecule of hydrogen (H_2) contains two hydrogen atoms sharing a pair of electrons. This single covalent bond can be represented in any of these three ways. **b.** A molecule of oxygen (O_2) contains two oxygen atoms sharing two pairs of electrons. This results in a double covalent bond. **c.** A molecule of methane (CH_4) contains one carbon atom bonded to four hydrogen atoms. **d.** When carbon binds to four other atoms, as in methane, each bond actually points to one corner of a tetrahedron. Ball-and-stick models and space-filling models are three-dimensional representations of a molecule.

molecules in Figure 2.6, including methane (CH_4), are nonpolar. In the case of water (H_2O), however, the sharing of electrons between oxygen and each hydrogen is not completely equal. The attraction of an atom for the electrons in a covalent bond is called its **electronegativity.** The larger oxygen atom, with the greater number of protons, is more electronegative than the hydrogen atom. The oxygen atom can attract the electron pair to a greater extent than each hydrogen atom can. It may help tc think of electronegativity as where the electron pair chooses tc "spend its time." In a water molecule, the shared electron pai spends more time around the nucleus of the oxygen atom thar around the nucleus of the hydrogen atom. This causes the oxy gen atom to assume a slightly negative charge (δ^-), and it cause the hydrogen atoms to assume slightly positive charges (δ^+ The unequal sharing of electrons in a covalent bond creates polar covalent bond.In the case of water, the molecule itself is polar molecule (Figure 2.7*a*).

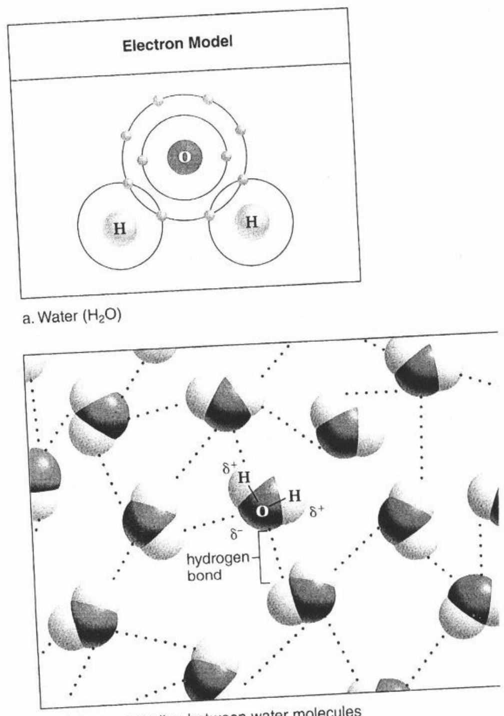


Figure 2.7 Water molecule. **a.** The electron model of wat **b.** Hydrogen bonding between water molecules. A hydrogen bonc is the attraction of a slightly positive hydrogen to a slightly negati atom in the vicinity. Each water molecule can hydrogen-bond to other molecules in this manner. When water is in its liquid state, hydrogen bonds are forming and others are breaking at all times.

Hydrogen Bonding

Polarity within a water molecule causes the hydrogen atoms in one molecule to be attracted to the oxygen atoms in other water molecules (Figure 2.7*b*). This attraction, although weaker than an ionic or covalent bond, is called a **hydrogen bond.** Because a hydrogen bond is easily broken, it is often represented by a dotted line. Hydrogen bonding is not unique to water. Many biological molecules have polar covalent bonds involving an electropositive hydrogen and usually an electronegative oxygen or nitrogen. In these instances, a hydrogen bond can occur within the same molecule or between different molecules.

Although a hydrogen bond is more easily broken than a covalent bond, many hydrogen bonds taken together are quite strong. Hydrogen bonds between cellular molecules help maintain their proper structure and function. For example, hydrogen bonds hold the two strands of DNA together. When DNA makes a copy of itself, each hydrogen bond easily breaks, allowing the DNA to unzip. On the other hand, the hydrogen bonds acting together add stability to the DNA molecule. As we shall see, many of the important properties of water are the result of hydrogen bonding.

Check Your Progress 2.2

1. Explain whether carbon dioxide (CO_2) and nitrogen gas (N_2) are considered to be molecules, compounds, or both.
2. Explain why hydrogen ions form polar bonds that have a partially positive charge.

.3 Chemistry of Water

Learning Outcomes

Upon completion of this section, you should be able to

1. Evaluate which properties of water are important for biological life.
2. Identify common acidic and basic substances.
3. Describe how buffers are important to living organisms.

ıe first cell(s) evolved in water, and organisms are composed of to 90% water. Water is a polar molecule, and water molecules e hydrogen-bonded to one another (refer to Figure 2.7*b*). Due hydrogen bonding, water molecules cling together. Without drogen bonding between molecules, water would change m a solid to liquid state at −100°C and from a liquid to gaseous te at −91°C. This would make most of the water on Earth am, and life unlikely. But because of hydrogen bonding, ter is a liquid at temperatures typically found on Earth's sure. It melts at 0°C and boils at 100°C. These and other unique perties of water make it essential to the existence of life.

Properties of Water

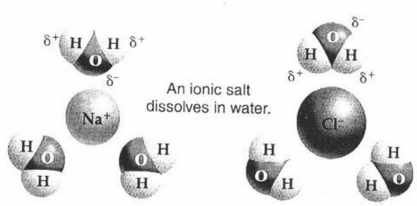
Water has a high heat capacity. A **calorie** is the amount of heat energy needed to raise the temperature of 1 g of water by 1°C. In comparison, other covalently bonded liquids require input of only about half this amount of energy to rise 1°C in temperature. The many hydrogen bonds that link water molecules help water absorb heat without a great change in temperature.

Converting 1 g of the coldest liquid water to ice requires the loss of 80 calories of heat energy. Water holds onto its heat, and its temperature falls more slowly than that of other liquids. This property of water is important not only for aquatic organisms but also for all organisms. Because the temperature of water rises and falls slowly, organisms are better able to maintain their normal internal temperatures and are protected from rapid temperature changes.

Water has a high heat of vaporization. Converting 1 g of the hottest water to a gas requires an input of 540 calories of heat energy. Water has a high heat of vaporization because hydrogen bonds must be broken before water boils and changes to a vaporized state. Water's high heat of vaporization gives animals in a hot environment an efficient way to release excess body heat (Figure 2.8). When an animal sweats, or gets splashed, body heat is used to vaporize the water, thus cooling the animal.

Temperatures along coasts are moderate due to water's high heat capacity and high heat of vaporization. During the summer, the ocean absorbs and stores solar heat, and during the winter, the ocean slowly releases it. In contrast, the interior regions of continents can experience severe changes in temperature.

Water is a solvent. Due to its polarity, water facilitates chemical reactions, inside and outside living organisms. It dissolves a great number of substances. A solution contains dissolved substances called **solutes.** When ionic salts—for example, sodium chloride (NaCl)—are put into water, the negative ends of the water molecules are attracted to the sodium ions, and the positive ends of the water molecules are attracted to the chloride ions. This causes the sodium ions and the chloride ions to separate, or dissociate, in water:



Water is also a solvent for larger molecules that contain ionized atoms or are polar molecules.

Molecules that can attract water are said to be **hydrophilic.** When ions and molecules disperse in water, they move about and collide, allowing reactions to occur. Nonionized and nonpolar molecules, such as oil, that cannot attract water are said to be **hydrophobic.**

Water molecules are cohesive and adhesive. Cohesion is apparent because water flows freely, and yet water molecules do not separate from each other. They cling together because of hydrogen bonding. Water exhibits adhesion because its positive and negative poles allow it to adhere to polar surfaces. Cohesion and adhesion allow water to fill a tubular vessel. Therefore, water is an excellent transport system, both inside and outside of living organisms. Unicellular organisms rely on external water to transport nutrient and waste molecules, but multicellular organisms often contain internal vessels through which water transports nutrients and wastes. For example, the liquid portion of our blood, which transports dissolved and suspended substances throughout the body, is 90% water. Cohesion and adhesion contribute to water's role as a lubricant. For example, water reduces wear on joints and helps them move more smoothly.

Cohesion and adhesion also contribute to the transport of water in plants. The roots of plants absorb water while the leaves lose water through evaporation. A plant contains a system of vessels that reaches from the roots to the leaves. Water evaporating from the leaves is immediately replaced with water molecules from the vessels. Because water molecules are cohesive, a tension is created that pulls a water column up from the roots. Adhesion of water to the walls of the vessels also helps prevent the water column from breaking apart.

Water has a high surface tension. The stronger the force between molecules in a liquid, the greater the surface tension. As with cohesion, hydrogen bonding causes water to have a high surface tension. This property makes it possible for humans to skip rocks on water. The water strider, a common insect, can even walk on top of a pond without breaking the surface.

Frozen water (ice) is less dense than liquid water. As liquid water cools, the molecules come closer together. They are densest at 4°C, but they are still moving about, bumping into each other (Figure 2.9). At temperatures below 4°C, including at 0°C when water is frozen, the water forms a regular crystal lattice that is rigid and has more open space between the water molecules. For this reason water expands as it freezes, which is why cans of soda burst when placed in a freezer or why frost heaves make northern roads bumpy in the winter. It also means that ice is less dense than liquid water, and floats on liquid water.

If ice did not float on water it would sink, and ponds, lakes, and perhaps even regions of the ocean would freeze solid. This would make life impossible in the water and also on land.

Figure 2.8 The advantage of water's high heat of vaporization. When body temperature increases, sweat is produced by glands in the dermal layer of the skin. The evaporation of the water off your skin aids in cooling your body.

When a body of water freezes on the surface, the ice acts as an insulator to prevent the water below it from freezing. This protects aquatic organisms so that they can survive the winter. As ice melts in the spring, it draws heat from the environment, helping to prevent a sudden change in temperature that might be harmful to life.

Acids and Bases

When water ionizes, it releases an equal number of hydrogen ions (H^+; also called protons[1]) and hydroxide ions (OH^-) into the solution:

$$\underset{\text{water}}{H{-}O{-}H} \rightleftharpoons \underset{\text{hydrogen ion}}{H^+} + \underset{\text{hydroxide ion}}{OH^-}$$

Only a few water molecules at a time dissociate, and the actual number of H^+ and OH^- is very small (1×10^{-7} moles/litre).[2]

Acidic Solutions (High H^+ Concentrations)

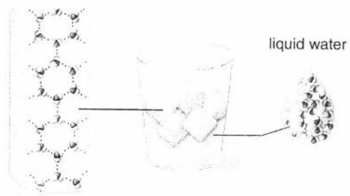
Lemon juice, vinegar, tomatoes, and coffee are all acidic solutions. **Acids** are substances that release hydrogen ions (H^+) when they dissociate in water. Therefore, they contain a higher concentration of H^+ than OH^-. For example, hydrochloric acid (HCl) is an important acid that dissociates in this manner:

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

Because dissociation is almost complete, HCl is called a strong acid. If hydrochloric acid is added to a beaker of water, the number of hydrogen ions (H^+) increases greatly.

[1] A hydrogen atom contains one electron and one proton. A hydrogen ion has only one proton, so it is often simply called a proton.

[2] In chemistry, a mole is defined as the amount of matter that contains as many objects



'igure 2.9 **Ice floats on water.** Remarkably, water is more dense t 4°C than at 0°C. While most substances contract when they solidify, 'ater expands when it freezes because the water molecules in ice form a ıttice in which the hydrogen bonds are farther apart than in liquid water.

ʾasic Solutions (Low H^+ Concentrations)

aking soda and antacids are common basic solutions familiar to ıost people. **Bases** are substances that either take up hydrogen ›ns (H^+) or release hydroxide ions (OH^-). They contain a higher ›ncentration of OH^- than H^+. For example, sodium hydroxide ʼaOH) is an important base that dissociates in this manner:

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

ecause dissociation is almost complete, sodium hydroxide is ılled a strong base. If sodium hydroxide is added to a beaker ʼwater, the number of hydroxide ions increases.

H Scale

ıe **pH scale** is used to indicate the acidity or basicity (alkalinity) solutions.[3] The pH scale (Figure 2.10) ranges from 0 to 14. pH of 7 represents a neutral state in which the hydrogen ion and droxide ion concentrations are equal. A pH below 7 is an acidic lution because the hydrogen ion concentration [H^+] is greater ın the hydroxide concentration [OH^-]. A pH above 7 is basic cause [OH^-] is greater than [H^+]. As we move down the pH scale ›m pH 14 to pH 0, each unit has ten times the H^+ concentration the previous unit. As we move up the scale from 0 to 14, each it has ten times the OH^- concentration of the previous unit.

is defined as the negative log of the hydrogen ion concentration [H^+]. A log is the power to ch ten must be raised to produce a given number.

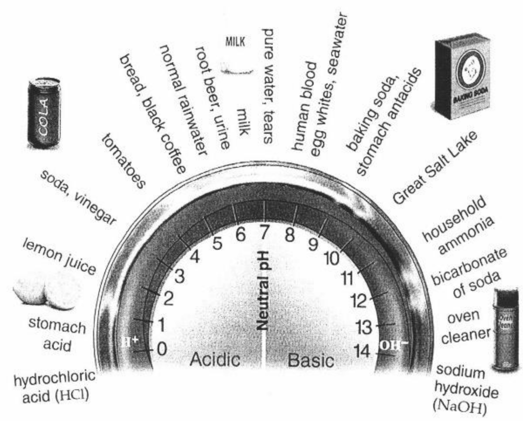


Figure 2.10 The pH scale. The dial of this pH meter indicates that pH ranges from 0 to 14, with 0 the most acidic and 14 the most basic. pH 7 (neutral pH) has equal amounts of hydrogen ions (H^+) and hydroxide ions (OH^-). An acidic pH has more H^+ than OH^-, and a basic pH has more OH^- than H^+.

The pH scale was devised to eliminate the use of cumbersome numbers. For example, the possible hydrogen ion concentrations of a solution are on the left in the following listing, and the pH is on the right:

[H^+] (moles per litre)	pH
0.000001 = 1×10^{-6}	6
0.0000001 = 1×10^{-7}	7
0.00000001 = 1×10^{-8}	8

To further illustrate the relationship between hydrogen ion concentration and pH, consider the following question: Which of the pH values listed indicates a higher hydrogen ion concentration [H^+] than pH 7, and therefore would be an acidic solution? A number with a smaller negative exponent indicates a greater quantity of hydrogen ions than one with a larger negative exponent. Therefore, pH 6 is an acidic solution.

Buffers and pH

A **buffer** is a substance that keeps pH within normal limits. Many commercial products, such as shampoos and deodorants, are buffered as an added incentive for us to buy them. Buffers resist pH changes because they can take up excess hydrogen ions (H^+) or hydroxide ions (OH^-).

In animals, the pH of body fluids is maintained within a narrow range. The pH of our blood when we are healthy is always about 7.4—that is, just slightly basic (alkaline). If the blood pH drops to about 7, acidosis results. If the blood pH rises to about 7.8, alkalosis results. Both conditions can be life threatening. Normally, pH stability is possible because the body has built-in mechanisms to prevent pH changes. Buffers are the most important of these mechanisms. For example, carbonic acid (H_2CO_3) is a weak acid that minimally dissociates and then re-forms in the following manner:

$$\underset{\text{carbonic acid}}{H_2CO_3} \underset{\text{re-forms}}{\overset{\text{dissociates}}{\rightleftarrows}} H^+ + \underset{\text{bicarbonate ion}}{HCO_3^-}$$

Blood always contains a combination of carbonic acid and bicarbonate ions. When hydrogen ions (H^+) are added to blood, the following reaction occurs:

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

When hydroxide ions (OH^-) are added to blood, this reaction occurs:

$$OH^- + H_2CO_3 \longrightarrow HCO_3^- + H_2O$$

These reactions prevent any significant change in blood pH.

Check Your Progress 2.3

1. Compare the difference between water's high heat capacity and high heat of vaporization.
2. Explain why a solution with a pH of 6 contains more H^+ than a solution with a pH of 8.
3. Explain why a weakly dissociating acid/base is a better buffer than a strongly dissociating one.

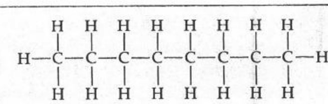
2.4 Organic Molecules

Learning Outcomes

Upon completion of this section, you should be able to

1. Compare inorganic molecules to organic molecules.
2. Identify the role of a functional group.
3. Recognize how monomers are joined to form polymers.

Inorganic molecules constitute nonliving matter, but even sc inorganic molecules such as salts (e.g., NaCl) and water pla important roles in living organisms. The molecules of life, how ever, are organic molecules. **Organic molecules** always contai carbon (C) and hydrogen (H). The chemistry of carbon account for the formation of the very large variety of organic molecule found in living organisms. Carbon atoms can share electrons cova lently with as many as four other atoms, as in methane (CH_4 Carbon atoms often share electrons with other carbon atom forming long hydrocarbon chains.



Under certain conditions, a hydrocarbon chain ca turn back on itself to form a ring compound. Attached to tl

SCIENCE IN YOUR LIFE ▶ BIOETHICS

Blue Gold

Environmentalists believe that the world is running out of clean drinking water. Over 97% of the world's water is salt water found in the oceans. Salt water is unsuitable for drinking without expensive desalination. Of the fresh water in the world, most is locked in frozen form in the polar ice caps and glaciers and therefore unavailable. This leaves only a small percentage in groundwater, lakes, and rivers that could be available for drinking, industry, and irrigation. However, some of that water is polluted and unsuitable.

Water has always been the most valuable commodity in the Middle East, even more valuable than oil. But as fresh water becomes limited and the world's population grows, the lack of sufficient clean water is becoming a worldwide problem.

The combination of increasing demand and dwindling supply has attracted global corporations that want to sell water. Water is being called the "blue gold" of the 21st century, and an issue has arisen regarding whether the water industry should be privatized. That is, could water rights be turned over to private companies to deliver clean water and treat wastewater at a profit, similar to the way oil and electricity are handled? Private companies have the resources to upgrade and modernize water delivery and treatment systems, thereby conserving more water. However, opponents of this plan claim that water is a basic human right required for life, not a need to be supplied by the private sector. In addition, a corporation might own the pipelines and treatment facilities, but who owns the rights to the water? For example, the Abbotsford-Sumas aquifer covers an area that includes British Columbia and Washington State. It is used for municipal drinking water, and by agriculture and industry, in both Canada and the United States. If water becomes a commodity, do we allow water to be taken away from people who cannot pay in order to give it to those who can?

Questions to Consider

1. Do you agree that the water industry should be privatized? Why or why not?
2. Is access to clean water a "need" or a "right"? If it is a right, who pays for that right?
3. Because water is a shared resource, everyone believes they can use water, but few people feel responsible for conserving it. What can you do to conserve water?

Functional Groups

	Structure	*Compound*	*Significance*
ɿl	R—OH	Alcohol as in ethanol	Polar, forms hydrogen bond Present in sugars, some amino acids
yl	R—C(=O)—H	Aldehyde as in formaldehyde	Polar Present in sugars
	R—C(=O)—R	Ketone as in acetone	Polar Present in sugars
yl)	R—C(=O)—OH	Carboxylic acid as in acetic acid	Polar, acidic Present in fatty acids, amino acids
	R—N(H)—H	Amine as in tryptophan	Polar, basic, forms hydrogen bonds Present in amino acids
dryl	R—SH	Thiol as in ethanethiol	Forms disulfide bonds Present in some amino acids
hate	R—O—P(=O)(OH)—OH	Organic phosphate as in phosphorylated molecules	Polar, acidic Present in nucleotides, phospholipids

ainder of molecule

n chains are **functional groups,** a specific combination ıded atoms that always react in the same way. Table 2.1 ɔme of the more common functional groups of biological :ules. Many molecules of life are macromolecules—that ːy contain many molecules joined together. A **monomer** *o,* one) is a simple organic molecule that exists individu- r can link with other monomers to form a **polymer** (*poly,* '). The polymers in cells form from monomers as follows:

Polymer	Monomer
carbohydrate (e.g., starch)	monosaccharide
lipid	fatty acids
protein	amino acid
nucleic acid	nucleotide

\side from carbohydrates, proteins, and nucleic acids, the r organic molecules in cells are lipids. You are very familiar carbohydrates, lipids, and proteins because certain foods ɲown to be rich in these molecules. The nucleic acid DNA es up our genes, which are hereditary units that control our and the structure of our bodies.

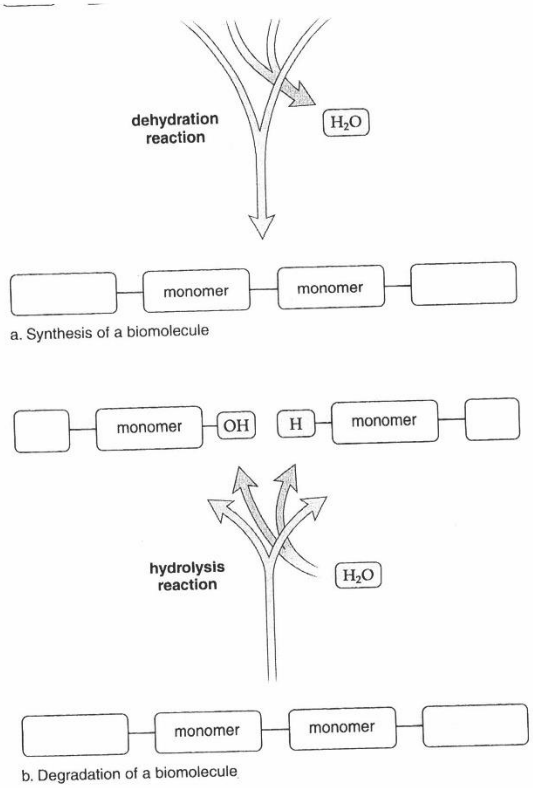


Figure 2.11 Synthesis and degradation of polymers. **a.** In cells, synthesis often occurs when monomers join (bond) during a dehydration reaction (removal of H_2O). **b.** Degradation occurs when the monomers in a polymer separate during a hydrolysis reaction (addition of H_2O).

Cells have a common way of joining monomers to build polymers. During a **dehydration reaction,** an —OH (hydroxyl group) and an —H (hydrogen atom), the equivalent of a water molecule, are removed as the reaction proceeds (Figure 2.11*a*). To degrade polymers, the cell uses a **hydrolysis reaction,** in which the components of water are added (Figure 2.11*b*).

Check Your Progress 2.4

1. Explain why organic molecules are considered the molecules of life.
2. Compare and contrast dehydration and hydrolysis reactions.

2.5 Carbohydrates

Learning Outcomes

Upon completion of this section, you should be able to

1. Identify the structural components of a carbohydrate.
2. List several examples of important monosaccharides and polysaccharides.

Carbohydrates first and foremost function for quick fuel and short-term energy storage in all organisms, including humans. Carbohydrates play a structural role in woody plants, bacteria, and animals such as insects. In addition, carbohydrates on cell surfaces are involved in cell-to-cell recognition.

Carbohydrate molecules are characterized by the presence of the atomic grouping H—C—OH, in which the ratio of hydrogen atoms (H) to oxygen atoms (O) is approximately 2:1. Because this ratio is the same as the ratio in water, the term "hydrates of carbon" is often used.

Simple Carbohydrates

If the number of carbon atoms in a molecule is low (from three to seven), then the carbohydrate is a simple sugar, or **monosaccharide.** The designation **pentose** means a 5-carbon sugar, and the designation **hexose** means a 6-carbon sugar. **Glucose** is a hexose sugar found in our blood (Figure 2.12). Our bodies use glucose as an immediate source of energy. Other common hexoses are fructose, found in fruits, and galactose, a constituent of milk. These three hexoses (glucose, fructose, and galactose) all occur as ring structures with the molecular formula $C_6H_{12}O_6$. The exact shape of the ring differs, as does the arrangement of the hydrogen (—H) and hydroxyl (—OH) groups attached to the ring.

A **disaccharide** (*di,* two; *saccharide,* sugar) contains two monosaccharides that have joined during a dehydration reaction. Figure 2.13 shows how the disaccharide maltose forms when two glucose molecules bond together. Note the position of this bond. Our hydrolytic digestive juices can break this bond, and the result is two glucose molecules. When glucose and fructose join, the disaccharide sucrose forms. Sucrose is another disaccharide of special interest because we use it to sweeten our food. We acquire sucrose from plants such as sugarcane and sugar beets. You may also have heard of lactose, a disaccharide found in milk. Lactose is glucose combined with galactose. Some people are lactose intolerant because they cannot break down lactose. This leads to unpleasant gastrointestinal symptoms when they consume dairy products.

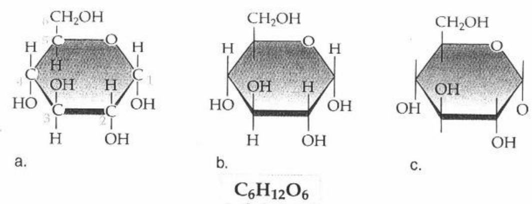


Figure 2.12 Three ways to represent the structure of glucose. $C_6H_{12}O_6$ is the molecular formula for glucose. The *far left* structure **(a)** shows the carbon atoms, but the *middle* structure **(b)** does not show the carbon atoms. The *far right* structure **(c)** is the simplest way to represent glucose. Note that in **a** and **b,** each carbon has an attached H and OH group. Those groups are assumed in **c.**

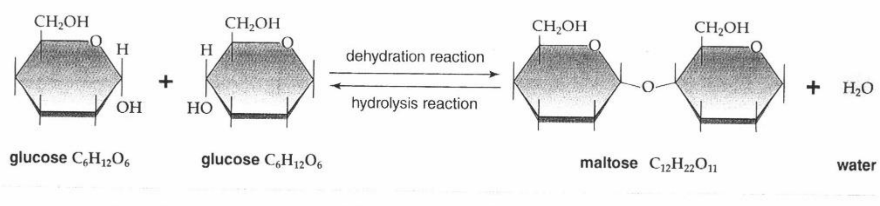
Complex Carbohydrates

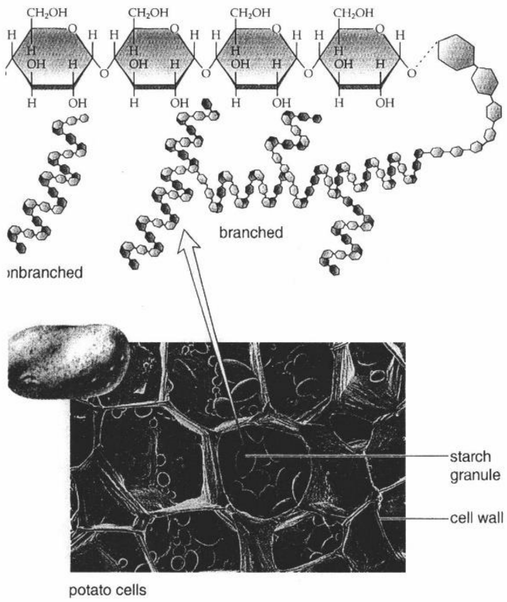
Long polymers such as starch, glycogen, and cellulose are **polysaccharides** that contain many glucose subunits.

Starch and Glycogen

Starch and **glycogen** are large storage forms of glucose found in plants and animals. Some of the polymers in starch are long chains of up to 4,000 glucose units. Starch has fewer side branches, or chains of glucose that branch off from the main chain, than does glycogen, as shown in Figures 2.14 and 2.15. Flour, which we use for baking and usually acquire by grinding wheat, is high in starch, and so are potatoes.

After we eat starchy foods such as potatoes and bread, starch is hydrolyzed into glucose, which will then enter the bloodstream. The liver stores glucose as glycogen. In between meals, the liver releases glucose so that the blood glucose concentration is always about 0.1%.





igure 2.14 Starch structure and function. Starch is ɔmposed of chains of glucose molecules. Some chains are branched, ; indicated. Starch is the storage form of glucose in plants. The electron ıicrograph shows starch granules in potato cells.

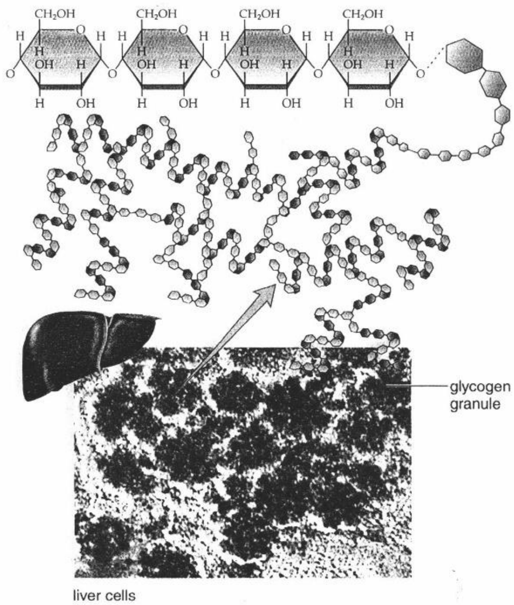


Figure 2.15 Glycogen structure and function. Glycogen is a highly branched polymer of glucose molecules that serves as the storage form of glucose in animals. The electron micrograph shows glycogen granules in liver cells.

:ellulose

ome types of polysaccharides function as structural components f cells. The polysaccharide **cellulose** is found in plant cell walls, 'hich helps account for the strong nature of these walls.

In cellulose (Figure 2.16), the glucose units are joined by slightly different type of linkage than that found in starch r glycogen. Notice the alternating up/down position of the xygen atoms in the linked glucose units in Figure 2.16. This nall difference is significant because it prevents us from igesting foods containing this type of linkage. Therefore, ellulose largely passes through our digestive tract as fibre, or ɔughage. Most doctors now recognize that fibre in the diet is ecessary to good health, and some studies have suggested it ıay even help prevent colon cancer.

Chitin, which is found in the exoskeleton (shell) of crabs and elated animals, is another structural polysaccharide. Scientists ave discovered that chitin can be made into a thread and used ; a suture material.

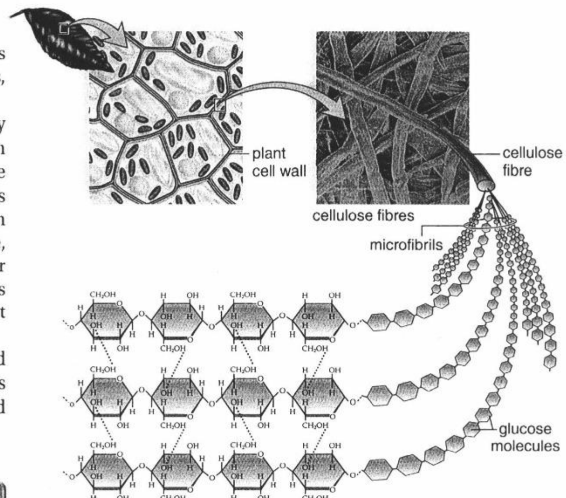


Figure 2.16 Cellulose structure and function. In cellulose, the linkage between glucose molecules is slightly different from that in starch or glycogen. Plant cell walls contain cellulose, and the rigidity of these cell walls permits non-woody plants to stand upright as long as they receive an adequate supply of water.

Check Your Progress 2.5

1. Identify the structural element that all carbohydrates have in common.
2. Explain why starch in plants is a source of glucose for our bodies but cellulose in plants is not.

2.6 Lipids

Learning Outcomes

Upon completion of this section, you should be able to

1. Compare the structures of fats, phospholipids, and steroids.
2. Identify the functions lipids play in our bodies.

Lipids contain more energy per gram than other biological molecules. Fats and oils function as energy storage molecules in organisms. Phospholipids form a membrane that separates the cell from its environment, and form its inner compartments as well. The steroids are a large class of lipids that includes, among others, the sex hormones.

Lipids are diverse in structure and function, but they have a common characteristic: they do not dissolve in water. Lipids are hydrophobic.

Fats and Oils

The most familiar lipids are those found in fats and oils. **Fats** tend to be of animal origin (for example, lard and butter), and are solid at room temperature. **Oils,** which are usually of plant origin (for example, corn oil and soybean oil), are liquid at room temperature. Fat has several functions in the body: it is used for long-term energy storage, it insulates against heat loss, and it forms a protective cushion around major organs.

Fats and oils form when one glycerol molecule reacts with three fatty acid molecules (Figure 2.17). A fat molecule is sometimes called a **triglyceride** because of its three-part structure, and the term *neutral fat* is sometimes used because the molecule is nonpolar.

While fats and oils are hydrophobic molecules, the addition of emulsifiers can allow them to mix with water. Emulsifiers contain molecules with a nonpolar end and a polar end. The molecules position themselves about an oil droplet so that their nonpolar ends project inward and their polar ends proje outward. As a result, the fat or oil disperses in the water. Th process is called emulsification.

Emulsification takes place when dirty clothes are washe with soaps or detergents. It explains why some salad dressin are uniform in consistency (emulsified), while others separa into two layers. Also, fats are emulsified by bile in the inte tines before they are digested. The liver produces bile, which then stored in the gall bladder. Individuals who have had the gall bladder removed may have trouble digesting fatty foods

Saturated, Unsaturated, and Trans-Fatty Acids

A **fatty acid** is a hydrocarbon chain that ends with the acid group —COOH (Figure 2.17). Most of the fatty acids in ce contain 16 or 18 carbon atoms per molecule, although small ones with fewer carbons are also known.

Fatty acids are either saturated or unsaturated. **Saturat fatty acids** have no double covalent bonds between carb atoms. The carbon chain is saturated, so to speak, with the hydrogens it can hold. Saturated fatty acids account f the solid nature at room temperature of fats such as lard a butter. **Unsaturated fatty acids** have double bonds betwe carbon atoms wherever the number of hydrogens is less th two per carbon atom. Unsaturated fatty acids account for t liquid nature of vegetable oils at room temperature. Unsat rated fats are also often referred to as being "cis" or "trans." Th terminology refers to the configuration of the hydrogen ato in the double-bond of an unsaturated fat (Figure 2.18). **Tran fats** are often produced by hydrogenation, or the chemi addition of hydrogen to vegetable oils. This is done to conv the fat into a solid and is often found in processed foods.

Phospholipids

Phospholipids, as their name implies, contain a phosph group. Essentially they are constructed like fats except that place of the third fatty acid there is a polar phosphate group

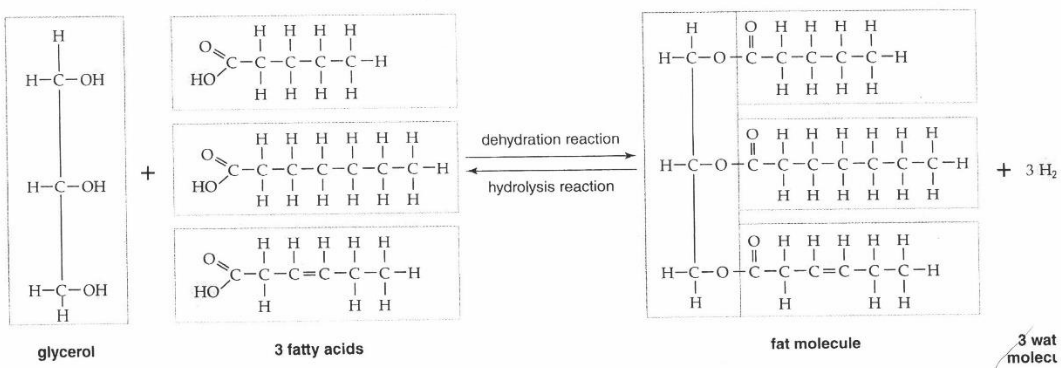
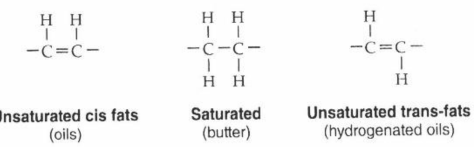
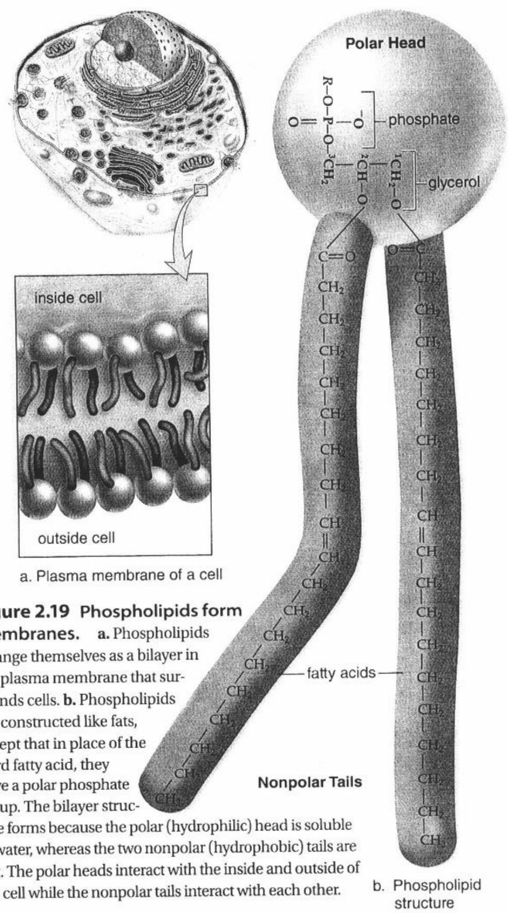


Figure 2.17 Synthesis and degradation of a triglyceride. Fatty acids can be saturated or unsaturated. Saturated fatty acids have no dou bonds between carbon atoms, whereas unsaturated fatty acids have one or more double bonds (coloured yellow) between carbon atoms. When a fat molecule (triglyceride) forms, three fatty acids combine with glycerol, and three water molecules are produced.



gure 2.18 Comparison of saturated fats, unsaturated ts, and trans-fats. Saturated fats have no double bonds between ꞉ carbon atoms, whereas unsaturated fats possess one or more double nds. In a trans-fat, the hydrogen atoms are on opposite sides of the uble bond.



a. Plasma membrane of a cell

b. Phospholipid structure

igure 2.19 Phospholipids form ıembranes. **a.** Phospholipids ·range themselves as a bilayer in ıe plasma membrane that surıunds cells. **b.** Phospholipids re constructed like fats, xcept that in place of the ıird fatty acid, they ave a polar phosphate roup. The bilayer strucıre forms because the polar (hydrophilic) head is soluble ı water, whereas the two nonpolar (hydrophobic) tails are ot. The polar heads interact with the inside and outside of ıe cell while the nonpolar tails interact with each other.

grouping that contains both phosphate and nitrogen. These ıolecules are not electrically neutral, as are fats, because the hosphate and nitrogen-containing groups are ionized. They ərm the polar (hydrophilic) head of the molecule, while the est of the molecule becomes the nonpolar (hydrophobic) tails Figure 2.19).

Phospholipids illustrate that the chemistry of a molecule helps determine its function. Phospholipids are the primary components of cellular membranes. In an aqueous environment, they spontaneously form a bilayer in which the hydrophilic heads face outward toward watery solutions and the tails form the hydrophobic interior. Plasma membranes separate extracellular from intracellular environments and are absolutely vital to the form and function of a cell.

Steroids

Steroids have a backbone of four fused carbon rings. Each one differs primarily by the arrangement of the atoms in the rings and the type of functional groups attached to them. Cholesterol is a steroid formed by the body that also enters the body as part of our diet. Cholesterol has several important functions. It is a component of an animal cell's plasma membrane and is the precursor of several other steroids, such as bile salts and the sex hormones testosterone and estrogen (Figure 2.20).

We now know that a diet high in saturated fats, trans-fats, and cholesterol can cause fatty material to accumulate inside the lining of blood vessels thereby reducing blood flow. The Health feature "A Balanced Diet" discusses which sources of carbohydrates, fats, and proteins are recommended for inclusion in the diet.

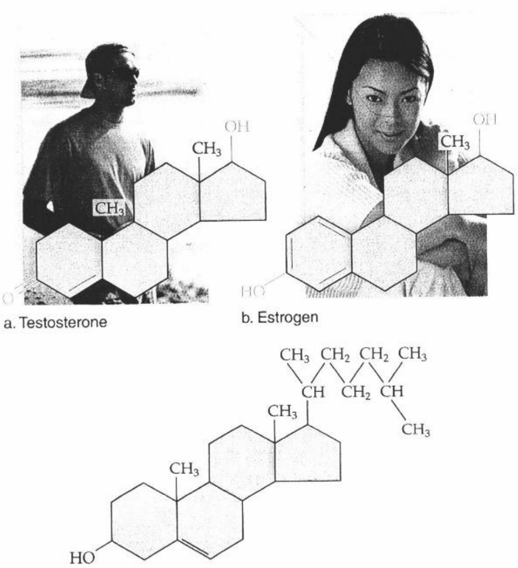


Figure 2.20 Steroids. All steroids have four adjacent rings, but their attached groups differ. The effects of **(a)** testosterone and **(b)** estrogen on the body largely depend on the difference in the attached groups (shown in blue). Cholesterol **(c)** is a precursor to testosterone, estrogen, and some other steroids.

Check Your Progress 2.6

1. List the two types of lipid molecules found in the plasma membranes of animal cells.
2. Explain how the presence of a double bond in an unsaturated fatty acid affects whether that substance is a solid or liquid.

2.7 Proteins

Learning Outcomes

Upon completion of this section, you should be able to

1. Describe the functions of proteins in cells.
2. Explain how a polypeptide is constructed from amino acids.
3. Compare the four levels of protein structure.

Proteins are polymers composed of amino acid monomers. An amino acid has a central carbon atom bonded to a hydrogen atom and three functional groups. The name of the molecule is appropriate because one of these groups is an amino group (—NH_2) and another is an acidic group (—COOH). The third group is called an *R* group, which determines the uniqueness of each **amino acid.** The *R* group varies from having a single carbon to being a complicated ring structure (Figure 2.21).

Proteins perform many functions. Proteins such as keratin, which makes up hair and nails, and collagen, which lends support to ligaments, tendons, and skin, are structural proteins. Some proteins are enzymes. Enzymes are necessary contributors to the chemical workings of the cell, and the body. **Enzymes** speed chemical reactions. They work so quickly that a reaction that normally takes several hours or days without an enzyme takes only a fraction of a second with an enzyme. Many hormones, messengers that influence cellular metabolism, are also proteins. The proteins actin and myosin account for the movement of cells and the ability of our muscles to contract. Some proteins transport molecules in the blood. Hemoglobin is a complex protein in our blood that transports oxygen. Antibodies in blood and other body fluids are proteins that combine with foreign substances, preventing them from destroying cells and upsetting homeostasis.

Proteins in the plasma membrane of cells have various functions: some form channels that allow substances to enter and exit cells; some are carriers that transport molecules into and out of the cell; and some are enzymes.

Peptides

Figure 2.22 shows that a synthesis reaction between two amino acids results in a dipeptide and a molecule of water. A **polypeptide** is a chain of amino acids that are joined to one

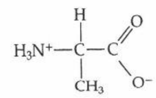
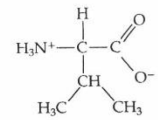
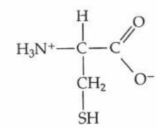
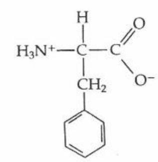
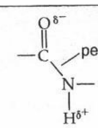
Name	Structural Formula	*R* Group
alanine (Ala)		*R* group has a single carbon atom
valine (Val)		*R* group has a branched carbon chain
cysteine (Cys)		*R* group contains sulfur
phenylalanine (Phe)		*R* group has a ring structure

Figure 2.21 Representative amino acids. Amino acids differ from one another by their *R* group. The simplest *R* group is a single hydrogen atom (H). *R* groups (blue) containing carbon vary as shown.

another by a **peptide bond.** The atoms associated with a peptide bond unevenly because oxygen is more electronegativ than nitrogen. Therefore, the hydrogen attached to the nitroge has a slightly positive charge, while the oxygen has a slightl negative charge:



The polarity of the peptide bond means that hydrogen bondin is possible between the C=O of one amino acid and the N— of another amino acid in a polypeptide. This hydrogen bondin influences the structure, or shape, of a protein.

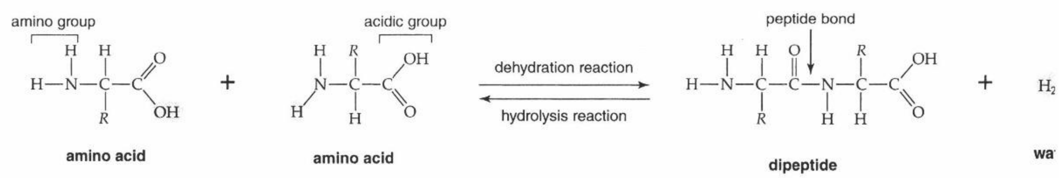


Figure 2.22 Synthesis and degradation of a dipeptide. A peptide bond is formed between the amino acid group of one amino acid and the carboxyl group of another amino acid. Following a dehydration reaction, a peptide bond joins two amino acids and a water molecule is released. Following a hydrolysis reaction, the bond is broken with the addition of water.

Levels of Protein Organization

Proteins can have up to four levels of structural organization (Figure 2.23). The first level, called the *primary structure,* is the linear sequence of the amino acids joined by peptide bonds. Polypeptides can be quite different from one another. A polypeptide chain is made from 20 different amino acids. Ea particular polypeptide has its own sequence of amino aci and its own sequence of *R* groups.

The *secondary structure* of a protein comes about wh the polypeptide takes on a certain orientation in space. A co ing of the chain results in an α (alpha) helix, or a right-hand

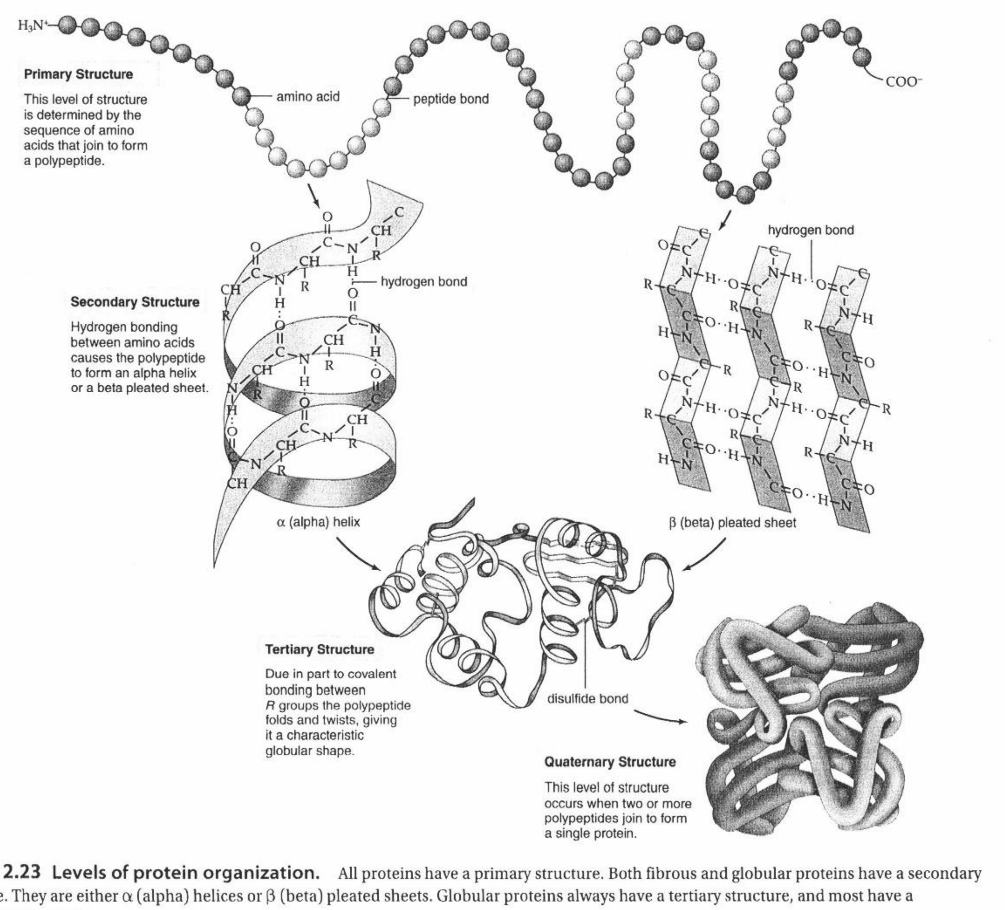


Figure 2.23 Levels of protein organization. All proteins have a primary structure. Both fibrous and globular proteins have a secondary structure. They are either α (alpha) helices or β (beta) pleated sheets. Globular proteins always have a tertiary structure, and most have a quaternary structure

spiral, similar to a spiral staircase. A folding of the chain esults in a β (beta) pleated sheet similar to a hand-held fan. Hydrogen bonding between peptide bonds holds the shape n place.

The *tertiary structure* of a protein is its final three-imensional shape. In muscles, myosin molecules have a rod hape ending in globular (globe-shaped) heads. In enzymes, ne polypeptide bends and twists in different ways. Invariably, ne hydrophobic portions are packed mostly on the inside, nd the hydrophilic portions are on the outside where they an make contact with water. The tertiary shape of a poly-eptide is maintained by various types of bonding among the groups; covalent, ionic, and hydrogen bonding all occur. ne common form of covalent bonding between *R* groups is disulfide (S—S) linkage between two cysteine amino acids.

Some proteins have only one polypeptide, and others ve more than one polypeptide, each with its own primary, condary, and tertiary structures. In proteins with multiple lypeptide chains, these separate polypeptides are arranged give such proteins a fourth level of structure, termed the *aternary structure.* Hemoglobin is a complex protein having uaternary structure. Most enzymes also have a quaternary ucture. Thus, proteins can differ in many ways, such as in gth, sequence, and structure. Each individual protein is emically unique as well.

The final shape of a protein is very important to its ction. As we will discuss in Chapter 5, enzymes cannot ction unless they have their normal shape. When proteins exposed to extremes in heat and pH, they undergo an versible change in shape. This is referred to as being **atured.** For example, we are all aware that adding acid to causes curdling and that heating causes egg white, which tains a protein called albumin, to coagulate. Denaturation rs because the normal bonding between the *R* groups has disturbed. Once a protein loses its normal shape, it is onger able to function normally. For example researchers othesize that an alteration in protein organization, form-structures called *prions*, is related to the development lzheimer's disease and Creutzfeldt-Jakob disease (the an form of "mad cow" disease).

eck Your Progress 2.7

List some of the functions of proteins.

Describe the structure of an amino acid.

Compare and contrast the four levels of protein structure.

2.8 Nucleic Acids

Learning Outcomes

Upon completion of this section, you should be able to

1. Compare the structure and function of DNA and RNA.
2. Explain the role of ATP in the cell.

The two types of nucleic acids are **DNA** (**deoxyribonucleic acid**) and **RNA** (**ribonucleic acid**). The discovery of the structure of DNA has had an enormous influence on biology and on society in general. DNA stores genetic information in the cell and in the organism. Further, the cell replicates and transmits this information when the cell copies itself as well as when the organism reproduces. The science of biotechnology is largely devoted to altering the genes in living organisms. We have discovered how many of our genes work and have learned how to manipulate them.

Structure of DNA and RNA

Both DNA and RNA are polymers of nucleotides. Every **nucleotide** is a molecular complex of three subunits (Figure 2.24)—phosphate (phosphoric acid), a pentose sugar, and a nitrogen-containing base. The nucleotides in DNA contain the sugar deoxyribose and the nucleotides in RNA contain the sugar ribose. This difference accounts for their respective names (Table 2.2). There are four different types of bases in DNA: **adenine** (**A**), **thymine** (**T**), **guanine** (**G**), and

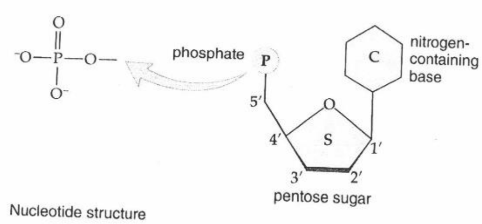


Figure 2.24 Structure of a nucleotide. Each nucleotide consists of a pentose sugar, a nitrogen-containing base, and a phosphate functional group.

TABLE 2.2 DNA Structure Compared with RNA Structure

	DNA	RNA
Sugar	Deoxyribose	Ribose
Bases	Adenine, guanine, thymine, cytosine	Adenine, guanine, uracil, cytosine
Strands	Double stranded with base pairing	Single stranded
Helix	Yes	No

cytosine (C). The base can have two rings (adenine or guanine) or one ring (thymine or cytosine). In RNA, the base **uracil (U)** replaces the base thymine. These structures are called bases because their presence raises the pH of a solution. The sequence of DNA is most often referred to in terms of the bases present.

The nucleotides form a linear molecule called a strand, which has a backbone made up of alternating phosphates and sugars with the bases projecting to one side of the backbone. The nucleotides and their bases occur in a specific order. After many years of work, researchers now know the sequence of the bases in human DNA—the human genome. This breakthrough is expected to lead to improved genetic counselling, gene therapy, and medicines to treat the causes of many human illnesses.

DNA is double stranded, with the two strands twisted about each other in the form of a **double helix** (Figure 2.25*a, b*). In DNA, the two strands are held together by hydrogen bonds between the bases. When unwound, DNA resembles a ladder. The uprights (sides) of the ladder are made entirely of the alternating phosphate and sugar molecules, and the rungs of the ladder are made only of complementary paired bases. Thymine (T) always pairs with adenine (A), and guanine (G) always pairs with cytosine (C). Complementary bases have shapes that fit together (Figure 2.25*c*).

Complementary base pairing allows DNA to replicate in a way that ensures the sequence of bases will remain the same. The base sequence of specific sections of DNA contain a code that specifies the sequence of amino acids in the proteins of the cell.

RNA is single stranded and is formed by complementary base pairing with one DNA strand. There are several types of RNA. One type of RNA, mRNA or messenger RNA, carries the information from the DNA strand to the ribosome where it is translated into the sequence of amino acids specified by the DNA.

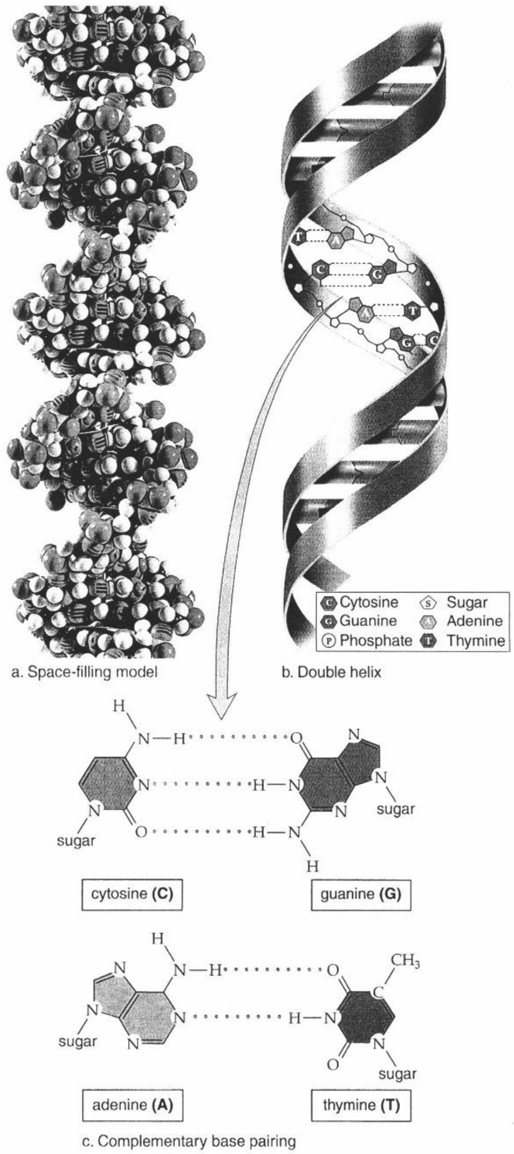


Figure 2.25 Overview of DNA structure. The structure of DNA is absolutely essential to its ability to replicate and to serve as the genetic material. **a.** Space-filling model of DNA's double helix. **b.** Complementary base pairing between strands. **c.** Ladder configuration. Notice that the uprights are composed of alternating phosphate and sugar molecules and that the rungs are complementary nitrogen-containing paired bases. The heredity information stored by DNA is the sequence of its bases, which determines the primary structure of the cell's proteins.

ATP (Adenosine Triphosphate)

In addition to being the monomers of nucleic acids, nucleotides have other metabolic functions in cells. Adenosine triphosphate (ATP) is a common and universal energy "currency" of the cells in living systems and it can be used for the following:

Chemical work. ATP supplies the energy needed to synthesize macromolecules (anabolism) that make up the cell, and therefore the organism.

Transport work. ATP supplies the energy needed to pump substances across the plasma membrane.

Mechanical work. ATP supplies the energy needed to permit muscles to contract, cilia and flagella to beat, chromosomes to move, and so forth. In most cases, ATP is the immediate source of energy for these processes.

ATP is a nucleotide composed of the nitrogen-containing base adenine and the 5-carbon sugar ribose (together called adenosine) and three phosphate groups (see Fig. 2.26). ATP is a "high-energy" molecule because of the energy stored in the chemical bonds of the phosphates. The last two ph
phate bonds are unstable and easily broken. In cells,
terminal phosphate bond usually is hydrolyzed, leaving
molecule ADP (adenosine diphosphate) and a molecul
inorganic phosphate P (Figure 2.26 and Figure 2.27). Wl
ATP is converted to ADP + P, the amount of energy relea
(about 7.3 kcal per mole) is sufficient for a particular b
logical function, and little energy is wasted. The cell uses
energy released by ATP breakdown to synthesize macrom
ecules such as carbohydrates and proteins. Muscle cells
the energy for muscle contraction, while nerve cells use it
the conduction of nerve impulses. After ATP breaks dowr
is rebuilt by the addition of P to ADP. Notice in Figure 2
that an input of energy is required to re-form ATP. Glucos
broken down in a step-wise fashion during cellular respi
tion so that the energy of glucose is converted to that of A
molecules in mitochondria. Only 39% of the free energy
glucose is transformed to ATP; the rest is lost as heat. ATP m
ecules serve as small "energy packets" suitable for supplyi
energy to a wide variety of a cell's chemical reactions. Wh
cells require energy, they "spend" ATP. Reactions in the c
that need energy require ATP. The more active the organis
the greater the demand for ATP.

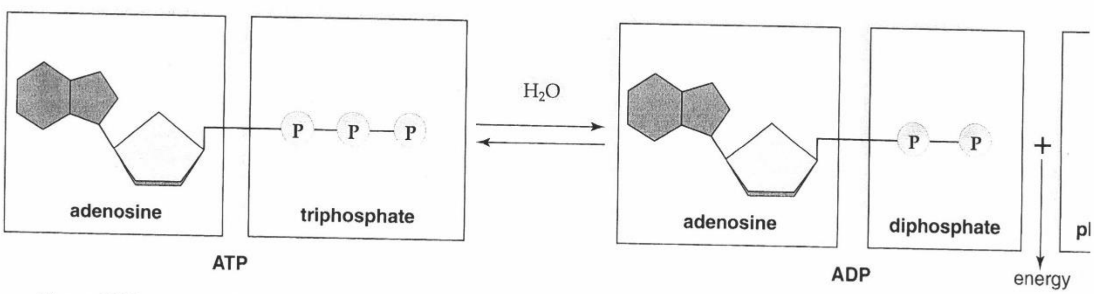


Figure 2.26 ATP reaction. ATP, the universal energy "currency" of cells, is composed of adenosine and three phosphate groups (called a triphosphate). When cells require energy, ATP undergoes hydrolysis, producing ADP + Ⓟ, with the release of energy.

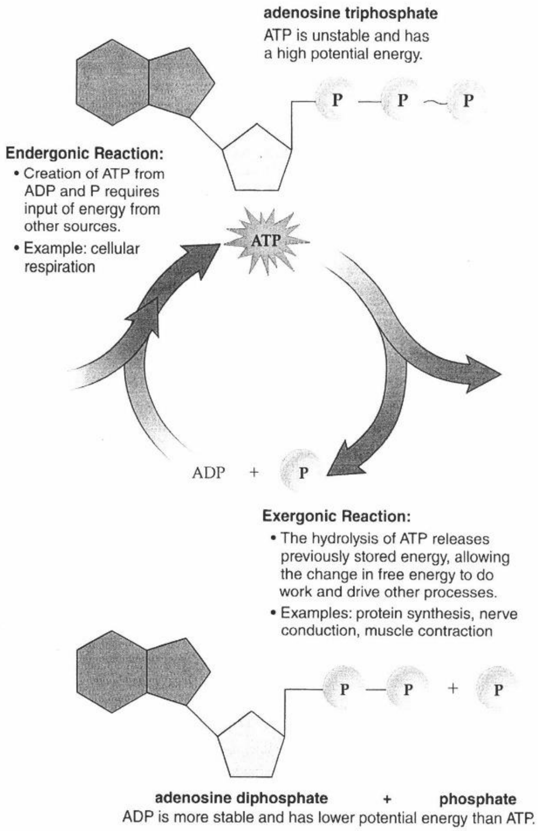


Figure 2.27 The ATP cycle. In cells, ATP carries energy between exergonic reactions and endergonic reactions. When a phosphate group is removed by hydrolysis, ATP releases the appropriate amount of energy for most metabolic reactions.

k Your Progress 2.8

ɪescribe the structure of nucleic acids.
ɪescribe how energy is stored in ATP.

king Connections Conclusion

e are thousands of proteins in the human body that ɔrm vital tasks. Small changes in the primary, second- :ertiary or quaternary structure of proteins can signifi- y alter their shape and lead to devastating results. The sorders that can be identified by the BC Newborn Screen- ɪrogram involve a change in the shape of a protein.

People with GAMT deficiency cannot synthesize creatine, a molecule that plays an important role in ATP synthesis. Only small quantities of ATP (adenosine triphosphate) are available to fuel most cellular reactions. If creatine is not available, very active cells that have high energy requirements exhaust their ATP supplies within seconds. Creatine replenishes ATP for a short time during intense activity by combining available phosphate. ts?