2.1 The Nature of Matter

Key Questions

What three subatomic particles make up atoms?

How are all of the isotopes of an element similar?

In what ways do compounds differ from their component elements?

What are the main types of chemical bonds?

Vocabulary

atom • nucleus • electron • element • isotope • compound • ionic bond • ion • covalent bond • molecule • van der Waals forces

Taking Notes

Outline Before you read, make an outline of the major headings in the lesson. As you read, fill in main ideas and supporting details under each head.

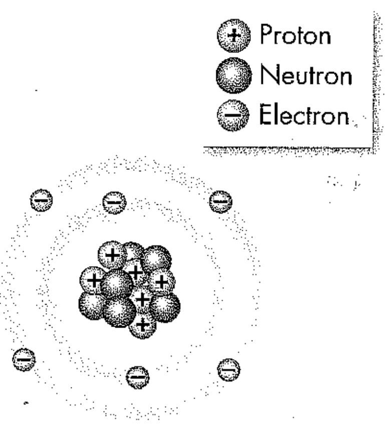


FIGURE 2–1 A Carbon Atom

THINK ABOUT IT What are you made of? Just as buildings are made from bricks, steel, glass, and wood, living things are made from chemical compounds. But it doesn't stop there. When you breathe, eat, or drink, your body uses the substances in air, food, and water to carry out chemical reactions that keep you alive. If the first task of an architect is to understand building materials, then what would be the first job of a biologist? Clearly, it is to understand the chemistry of life.

Atoms

What three subatomic particles make up atoms?

The study of chemistry begins with the basic unit of matter, the **atom.** The concept of the atom came first from the Greek philosopher Democritus, nearly 2500 years ago. Democritus asked a simple question: If you take an object like a stick of chalk and break it in half, are both halves still chalk? The answer, of course, is yes. But what happens if you break it in half again and again and again? Can you continue to divide without limit, or does there come a point at which you cannot divide the fragment of chalk without changing it into something else? Democritus thought that there had to be a limit. He called the smallest fragment the atom, from the Greek word *atomos,* which means "unable to be cut."

Atoms are incredibly small. Placed side by side, 100 million atoms would make a row only about 1 centimeter long—about the width of your little finger! Despite its extremely small size, an atom contains subatomic particles that are even smaller. **Figure 2–1** shows the subatomic particles in a carbon atom. **The subatomic particles that make up atoms are protons, neutrons, and electrons.**

Protons and Neutrons Protons and neutrons have about the same mass. However, protons are positively charged particles (+) and neutrons carry no charge at all. Strong forces bind protons and neutrons together to form the **nucleus,** at the center of the atom.

Electrons The **electron** is a negatively charged particle (–) with only 1/1840 the mass of a proton. Electrons are in constant motion in the space surrounding the nucleus. They are attracted to the positively charged nucleus but remain outside the nucleus because of the energy of their motion. Because atoms have equal numbers of electrons and protons, their positive and negative charges balance out, and atoms themselves are electrically neutral.

Elements and Isotopes

How are all of the isotopes of an element similar?

A chemical **element** is a pure substance that consists entirely of one type of atom. More than 100 elements are known, but only about two dozen are commonly found in living organisms. Elements are represented by one- or two-letter symbols. C, for example, stands for carbon, H for hydrogen, Na for sodium, and Hg for mercury. The number of protons in the nucleus of an element is called its atomic number. Carbon's atomic number is 6, meaning that each atom of carbon has six protons and, consequently, six electrons. See Appendix E, The Periodic Table, which shows the elements.

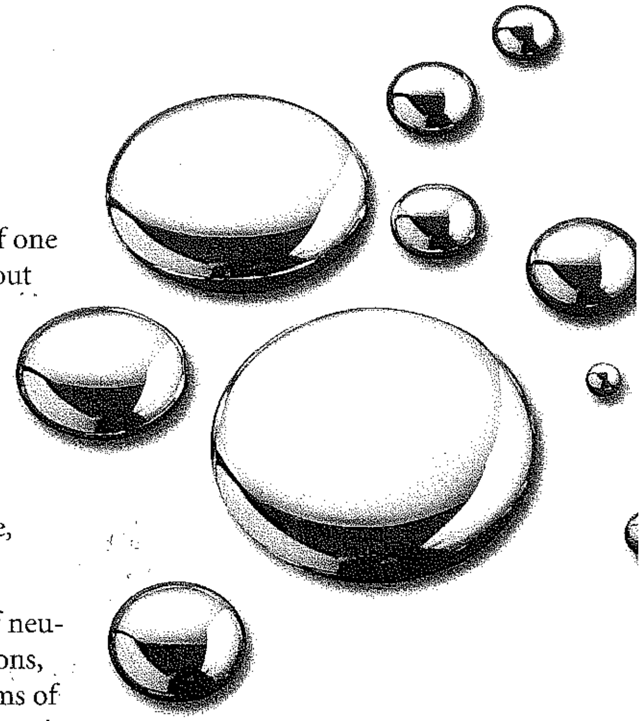


FIGURE 2–2 Droplets of Mercury Mercury, a silvery-white metallic element, is liquid at room temperature and forms droplets. It is extremely poisonous.

Isotopes Atoms of an element may have different numbers of neutrons. For example, although all atoms of carbon have six protons, some have six neutrons, some seven, and a few have eight. Atoms of the same element that differ in the number of neutrons they contain are known as **isotopes.** The total number of protons and neutrons in the nucleus of an atom is called its mass number. Isotopes are identified by their mass numbers. **Figure 2–3** shows the subatomic composition of carbon-12, carbon-13, and carbon-14 atoms. The weighted average of the masses of an element's isotopes is called its atomic mass. "Weighted" means that the abundance of each isotope in nature is considered when the average is calculated. **Because they have the same number of electrons, all isotopes of an element have the same chemical properties.**

Isotopes of Carbon

Isotope	Number of Protons	Number of Electrons	Number of Neutrons
Carbon–12 (nonradioactive)	6	6	6
Carbon–13 (nonradioactive)	6	6	7
Carbon–14 (radioactive)	6	6	8

FIGURE 2–3 Carbon Isotopes Isotopes of carbon all have 6 protons but different numbers of neutrons—6, 7, or 8. They are identified by the total number of protons and neutrons in the nucleus: carbon–12, carbon–13, and carbon–14. **Classify** ***Which isotope of carbon is radioactive?***

Radioactive Isotopes Some isotopes are radioactive, meaning that their nuclei are unstable and break down at a constant rate over time. The radiation these isotopes give off can be dangerous, but radioactive isotopes have a number of important scientific and practical uses.

Geologists can determine the ages of rocks and fossils by analyzing the isotopes found in them. Radiation from certain isotopes can be used to detect and treat cancer and to kill bacteria that cause food to spoil. Radioactive isotopes can also be used as labels or "tracers" to follow the movements of substances within organisms.

In Your Notebook *Draw a diagram of a helium atom, which has an atomic number of 2.*

Chemical Compounds

In what ways do compounds differ from their component elements?

In nature, most elements are found combined with other elements in compounds. A chemical **compound** is a substance formed by the chemical combination of two or more elements in definite proportions. Scientists show the composition of compounds by a kind of shorthand known as a chemical formula. Water, which contains two atoms of hydrogen for each atom of oxygen, has the chemical formula H_2O. The formula for table salt, NaCl, indicates that the elements that make up table salt—sodium and chlorine—combine in a 1 : 1 ratio.

The physical and chemical properties of a compound are usually very different from those of the elements from which it is formed. For example, hydrogen and oxygen, which are gases at room temperature, can combine explosively and form liquid water. Sodium is a silver-colored metal that is soft enough to cut with a knife. It reacts explosively with water. Chlorine is very reactive, too. It is a poisonous, yellow-greenish gas that was used in battles during World War I. Sodium chloride, table salt, is a white solid that dissolves easily in water. As you know, sodium chloride is not poisonous. In fact, it is essential for the survival of most living things.

BUILD Vocabulary

RELATED WORD FORMS The verb *react* means to act in response to something. The adjective *reactive* describes the tendency to respond or react.

Chemical Bonds

What are the main types of chemical bonds?

The atoms in compounds are held together by various types of chemical bonds. Much of chemistry is devoted to understanding how and when chemical bonds form. Bond formation involves the electrons that surround each atomic nucleus. The electrons that are available to form bonds are called valence electrons. **The main types of chemical bonds are ionic bonds and covalent bonds.**

Quick Lab
GUIDED INQUIRY

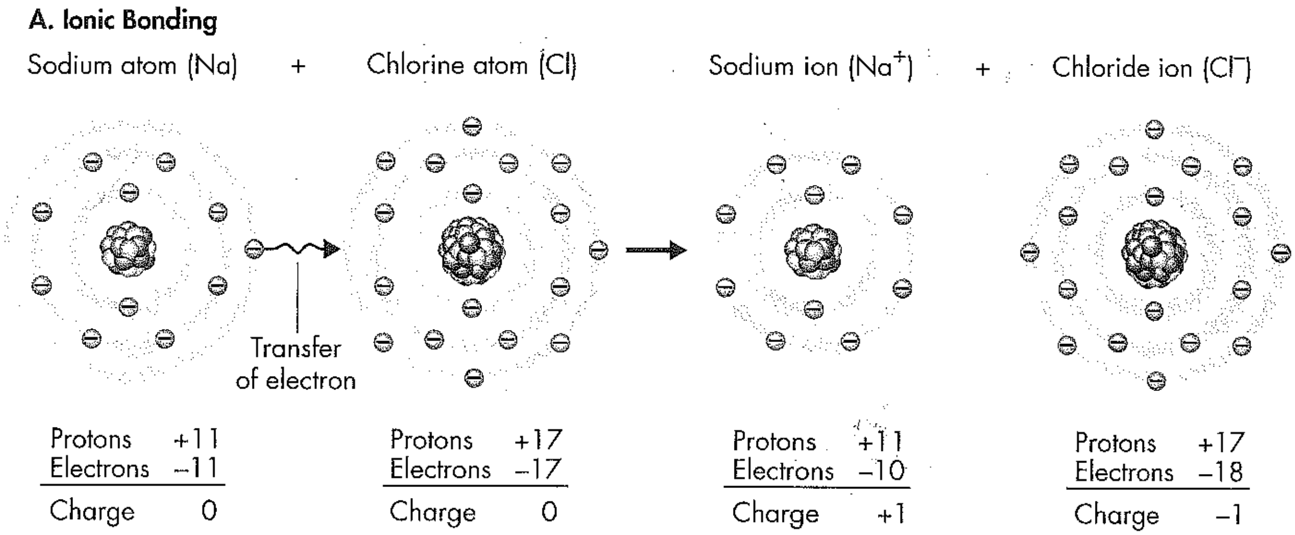
Model an Ionic Compound

1. You will be assigned to represent either a sodium atom or a chlorine atom.
2. Obtain the appropriate number of popcorn kernels to represent your electrons.
3. Find a partner with whom you can form the ionic compound sodium chloride—table salt.
4. In table salt, the closely packed sodium and chloride ions form an orderly structure called a crystal. With all your classmates, work as a class to model a sodium chloride crystal.

Analyze and Conclude

1. Relate Cause and Effect Describe the exchange of popcorn kernels (electrons) that took place as you formed the ionic bond. What electrical charges resulted from the exchange?

2. Use Models How were the "ions" arranged in the model of the crystal? Why did you and your classmates choose this arrangement?



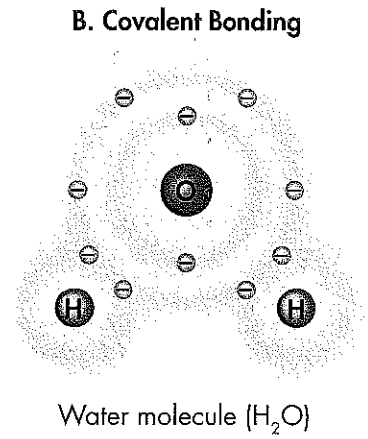


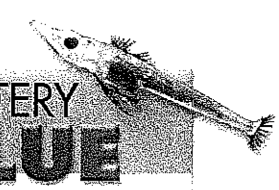
FIGURE 2–4 Ionic Bonding and Covalent Bonding A. The compound sodium chloride forms when sodium loses its valence electron to chlorine. **B.** In a water molecule, each hydrogen atom shares two electrons with the oxygen atom.

Ionic Bonds An **ionic bond** is formed when one or more electrons are transferred from one atom to another. Recall that atoms are electrically neutral because they have equal numbers of protons and electrons. An atom that loses electrons becomes positively charged. An atom that gains electrons has a negative charge. These positively and negatively charged atoms are known as **ions.**

Figure 2–4A shows how ionic bonds form between sodium and chlorine in table salt. A sodium atom easily loses its one valence electron and becomes a sodium ion (Na^+). A chlorine atom easily gains an electron and becomes a chloride ion (Cl^-). In a salt crystal, there are trillions of sodium and chloride ions. These oppositely charged ions have a strong attraction, forming an ionic bond.

Covalent Bonds Sometimes electrons are shared by atoms instead of being transferred. What does it mean to share electrons? It means that the moving electrons actually travel about the nuclei of both atoms, forming a **covalent bond.** When the atoms share two electrons, the bond is called a single covalent bond. Sometimes the atoms share four electrons and form a double bond. In a few cases, atoms can share six electrons, forming a triple bond. The structure that results when atoms are joined together by covalent bonds is called a molecule. The **molecule** is the smallest unit of most compounds. The diagram of a water molecule in **Figure 2–4B** shows that each hydrogen atom is joined to water's lone oxygen atom by a single covalent bond. When atoms of the same element join together, they also form a molecule. Oxygen molecules in the air you breathe consist of two oxygen atoms joined by covalent bonds.

In Your Notebook *In your own words, describe the differences between ionic and covalent bonds.*

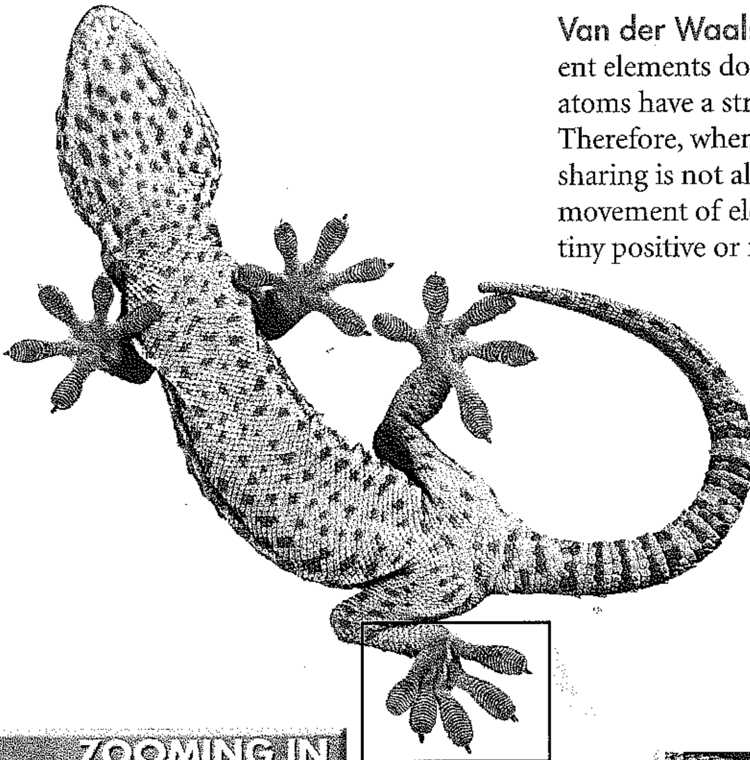


MYSTERY CLUE

Fish do not break water molecules into their component atoms to obtain oxygen. Rather, they use oxygen gas dissolved in the water. How are the atoms in an oxygen molecule (O_2) joined together?

Van der Waals Forces Because of their structures, atoms of different elements do not all have the same ability to attract electrons. Some atoms have a stronger attraction for electrons than do other atoms. Therefore, when the atoms in a covalent bond share electrons, the sharing is not always equal. Even when the sharing is equal, the rapid movement of electrons can create regions on a molecule that have a tiny positive or negative charge.

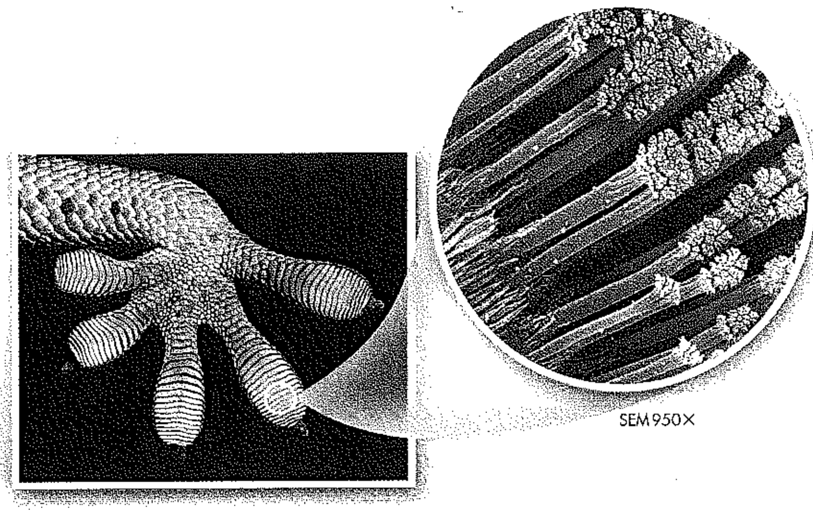
When molecules are close together, a slight attraction can develop between the oppositely charged regions of nearby molecules. Chemists call such intermolecular forces of attraction **van der Waals forces,** after the scientist who discovered them. Although van der Waals forces are not as strong as ionic bonds or covalent bonds, they can hold molecules together, especially when the molecules are large.



ZOOMING IN

VAN DER WAALS FORCES AT WORK

FIGURE 2–5 The underside of each foot on this Tokay gecko is covered by millions of tiny hairlike projections. The projections themselves are made of even finer fibers, creating more surface area for "sticking" to surfaces at the molecular level. This allows geckos to scurry up walls and across ceilings.



2.1 Assessment

Review Key Concepts

1. a. Review Describe the structure of an atom.

b. Infer An atom of calcium contains 20 protons. How many electrons does it have?

2. a. Review Why do all isotopes of an element have the same chemical properties?

b. Compare and Contrast Compare the structure of carbon–12 and carbon–14.

3. a. Review What is a compound?

b. Apply Concepts Water (H_2O) and hydrogen peroxide (H_2O_2) both consists of hydrogen and oxygen atoms. Explain why they have different chemical and physical properties.

4. a. Review What are two types of bonds that hold the atoms within a compound together?

b. Classify A potassium atom easily loses its one valence electron. What type of bond will it form with a chlorine atom?

Apply the Big idea

Matter and Energy

5. Why do you think it is important that biologists have a good understanding of chemistry?

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Technology & BIOLOGY

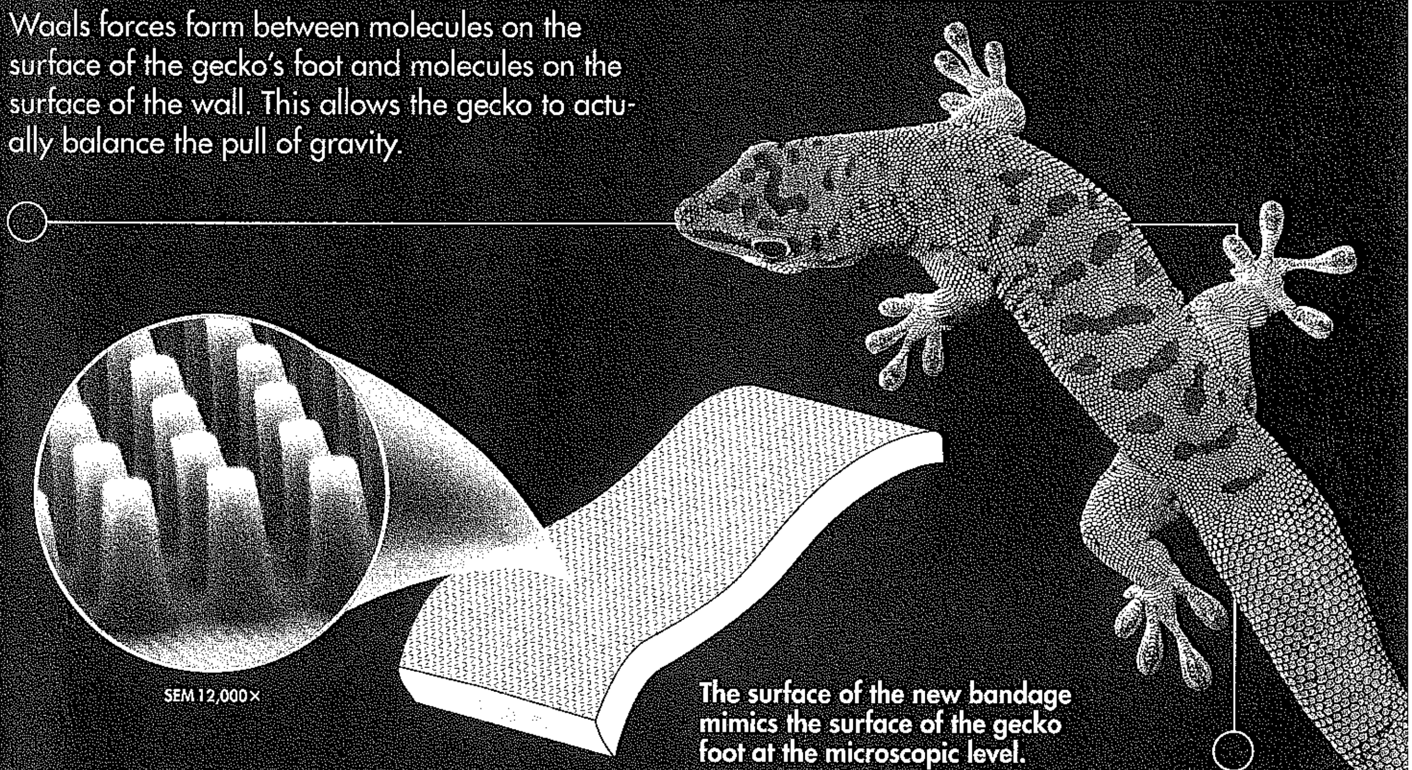
A Nature-Inspired Adhesive

People who keep geckos as pets have always marveled at the way these little lizards can climb up vertical surfaces, even smooth glass walls, and then hang on by a single toe despite the pull of gravity. How do they do it? No, they do not have some sort of glue on their feet and they don't have suction cups. Incredibly, they use van der Waals forces.

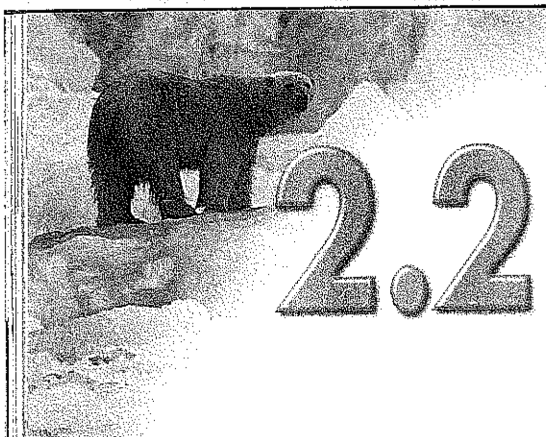
A gecko foot is covered by as many as half a million tiny hairlike projections. Each projection is further divided into hundreds of tiny, flat-surfaced fibers. This design allows the gecko's foot to come in contact with an extremely large area of the wall at the molecular level. Van der Waals forces form between molecules on the surface of the gecko's foot and molecules on the surface of the wall. This allows the gecko to actually balance the pull of gravity.

If it works for the gecko, why not for us? That's the thinking of researchers at the Massachusetts Institute of Technology, who have now used the same principle to produce a bandage. This new bandage is held to tissue by van der Waals forces alone. Special materials make it possible for the new bandage to work even on moist surfaces, which means that it may be used to reseal internal tissues after surgery. By learning a trick or two from the gecko, scientists may have found a way to help heal wounds, and even save lives in the process.

WRITING **Suppose you are a doctor reviewing this new bandage for its potential applications. In what ways might you use such a bandage? Present your ideas as a list.**



The surface of the new bandage mimics the surface of the gecko foot at the microscopic level.



2.2 Properties of Water

Key Questions

How does the structure of water contribute to its unique properties?

How does water's polarity influence its properties as a solvent?

Why is it important for cells to buffer solutions against rapid changes in pH?

Vocabulary

hydrogen bond • cohesion • adhesion • mixture • solution • solute • solvent • suspension • pH scale • acid • base • buffer

Taking Notes

Venn Diagram As you read, draw a Venn diagram showing the differences between solutions and suspensions and the properties that they share.

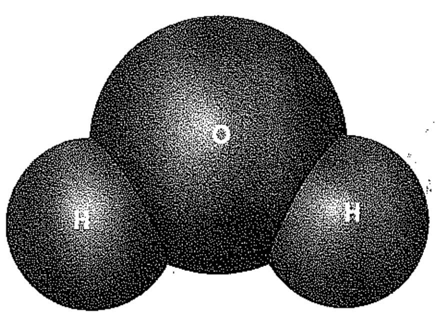


FIGURE 2–6 A Water Molecule A water molecule is polar because there is an uneven distribution of electrons between the oxygen and hydrogen atoms. The negative pole is near the oxygen atom and the positive pole is between the hydrogen atoms.

THINK ABOUT IT Looking back at our beautiful planet, an astronaut in space said that if other beings have seen the Earth, they must surely call it "the blue planet." He referred, of course, to the oceans of water that cover nearly three fourths of Earth's surface. The very presence of liquid water tells a scientist that life may also be present on such a planet. Why should this be so? Why should life itself be connected so strongly to something so ordinary that we often take it for granted? The answers to those questions suggest that there is something very special about water and the role it plays in living things.

The Water Molecule

How does the structure of water contribute to its unique properties?

Water is one of the few compounds found in a liquid state over most of the Earth's surface. Like other molecules, water (H_2O) is neutral. The positive charges on its 10 protons balance out the negative charges on its 10 electrons. However, there is more to the story.

Polarity With 8 protons, water's oxygen nucleus attracts electrons more strongly than the single protons of water's two hydrogen nuclei. As a result, water's shared electrons are more likely to be found near the oxygen nucleus. Because the oxygen nucleus is at one end of the molecule, as shown in **Figure 2–6**, water has a partial negative charge on one end, and a partial positive charge on the other.

A molecule in which the charges are unevenly distributed is said to be "polar," because the molecule is a bit like a magnet with two poles. The partial charges on a polar molecule are written in parentheses, (–) or (+), to show that they are weaker than the charges on ions such as Na^+ and Cl^-.

Hydrogen Bonding Because of their partial positive and negative charges, polar molecules such as water can attract each other. The attraction between a hydrogen atom with a partial positive charge and another atom with a partial negative charge is known as a **hydrogen bond.** The most common partially negative atoms involved in hydrogen bonding are oxygen, nitrogen, and fluorine.

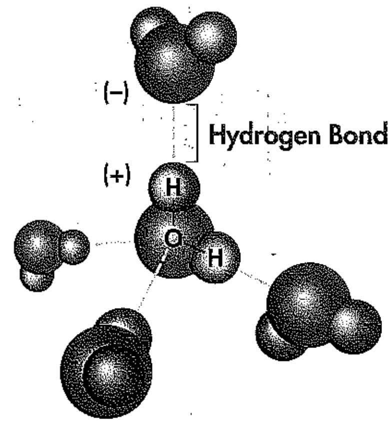
Hydrogen bonds are not as strong as covalent or ionic bonds, but they give one of life's most important molecules many of its unique characteristics. **Because water is a polar molecule, it is able to form multiple hydrogen bonds, which account for many of water's special properties.** These include the fact that water expands slightly upon freezing, making ice less dense than liquid water. Hydrogen bonding also explains water's ability to dissolve so many other substances, a property essential in living cells.

▶***Cohesion*** **Cohesion** is an attraction between molecules of the same substance. Because a single water molecule may be involved in as many as four hydrogen bonds at the same time, water is extremely cohesive. Cohesion causes water molecules to be drawn together, which is why drops of water form beads on a smooth surface. Cohesion also produces surface tension, explaining why some insects and spiders can walk on a pond's surface, as shown in **Figure 2–7.**

▶***Adhesion*** On the other hand, **adhesion** is an attraction between molecules of different substances. Have you ever been told to read the volume in a graduated cylinder at eye level? As shown in **Figure 2–8,** the surface of the water in the graduated cylinder dips slightly in the center because the adhesion between water molecules and glass molecules is stronger than the cohesion between water molecules. Adhesion between water and glass also causes water to rise in a narrow tube against the force of gravity. This effect is called capillary action. Capillary action is one of the forces that draws water out of the roots of a plant and up into its stems and leaves. Cohesion holds the column of water together as it rises.

▶***Heat Capacity*** Another result of the multiple hydrogen bonds between water molecules is that it takes a large amount of heat energy to cause those molecules to move faster, which raises the temperature of the water. Therefore, water's heat capacity, the amount of heat energy required to increase its temperature, is relatively high. This allows large bodies of water, such as oceans and lakes, to absorb large amounts of heat with only small changes in temperature. The organisms living within are thus protected from drastic changes in temperature. At the cellular level, water absorbs the heat produced by cell processes, regulating the temperature of the cell.

In Your Notebook *Draw a diagram of a meniscus. Label where cohesion and adhesion occur.*



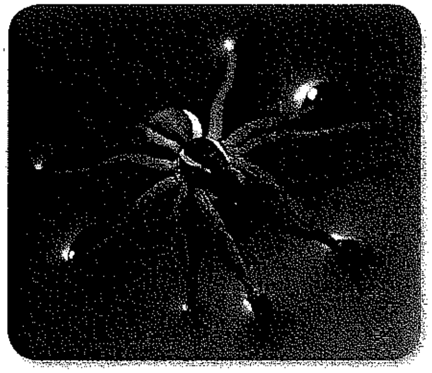


FIGURE 2–7 Hydrogen Bonding and Cohesion Each molecule of water can form multiple hydrogen bonds with other water molecules. The strong attraction between water molecules produces a force sometimes called "surface tension," which can support very lightweight objects, such as this raft spider. **Apply Concepts** ***Why are water molecules attracted to one another?***

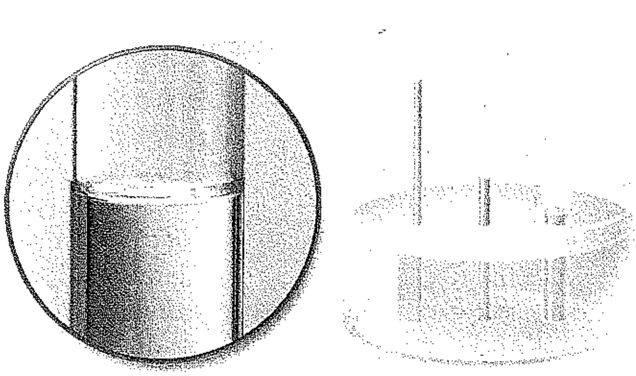


FIGURE 2–8 Adhesion Adhesion between water and glass molecules is responsible for causing the water in these columns to rise. The surface of the water in the glass column dips slightly in the center, forming a curve called a meniscus.

MYSTERY CLUE

The solubility of gases increases as temperatures decrease. Think about when a can of warm soda is opened—the carbon dioxide dissolved in it fizzes out more rapidly because the gas is less soluble at warm temperatures. How might the temperature of antarctic waters affect the amount of dissolved oxygen available for ice fish?

Solutions and Suspensions

How does water's polarity influence its properties as a solvent?

Water is not always pure; it is often found as part of a mixture. A **mixture** is a material composed of two or more elements or compounds that are physically mixed together but not chemically combined. Salt and pepper stirred together constitute a mixture. So do sugar and sand. Earth's atmosphere is a mixture of nitrogen, oxygen, carbon dioxide, and other gases. Living things are in part composed of mixtures involving water. Two types of mixtures that can be made with water are solutions and suspensions.

Solutions If a crystal of table salt is placed in a glass of warm water, sodium and chloride ions on the surface of the crystal are attracted to the polar water molecules. Ions break away from the crystal and are surrounded by water molecules, as illustrated in **Figure 2–9.** The ions gradually become dispersed in the water, forming a type of mixture called a solution. All the components of a **solution** are evenly distributed throughout the solution. In a saltwater solution, table salt is the **solute**—the substance that is dissolved. Water is the **solvent**—the substance in which the solute dissolves. **Water's polarity gives it the ability to dissolve both ionic compounds and other polar molecules.**

Water easily dissolves salts, sugars, minerals, gases, and even other solvents such as alcohol. Without exaggeration, water is the greatest solvent on Earth. But even water has limits. When a given amount of water has dissolved all of the solute it can, the solution is said to be saturated.

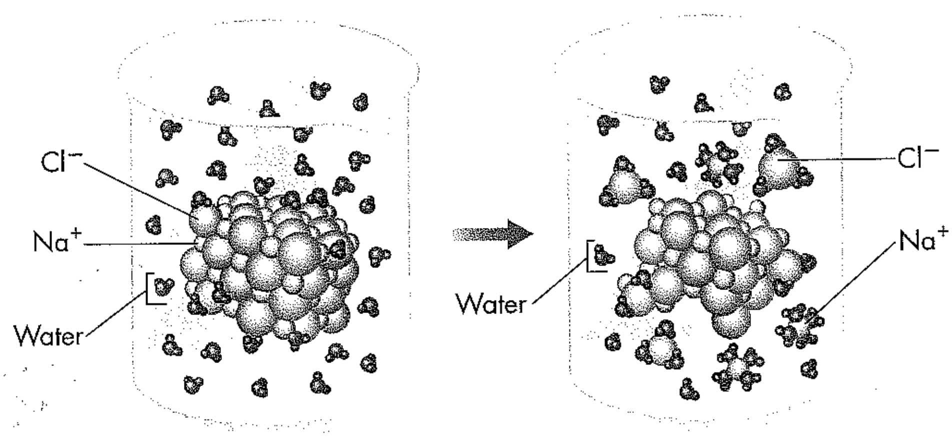


FIGURE 2–9 A Salt Solution When an ionic compound such as sodium chloride is placed in water, water molecules surround and separate the positive and negative ions.
Interpret Visuals ***What happens to the sodium ions and chloride ions in the solution?***

Suspensions Some materials do not dissolve when placed in water, but separate into pieces so small that they do not settle out. The movement of water molecules keeps the small particles suspended. Such mixtures of water and nondissolved material are known as **suspensions.** Some of the most important biological fluids are both solutions and suspensions. The blood that circulates through your body is mostly water. The water in the blood contains many dissolved compounds. However, blood also contains cells and other undissolved particles that remain in suspension as the blood moves through the body.

Acids, Bases, and pH

Why is it important for cells to buffer solutions against rapid changes in pH?

Water molecules sometimes split apart to form ions. This reaction can be summarized by a chemical equation in which double arrows are used to show that the reaction can occur in either direction.

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

$$\text{water} \rightleftharpoons \text{hydrogen ion} + \text{hydroxide ion}$$

How often does this happen? In pure water, about 1 water molecule in 550 million splits to form ions in this way. Because the number of positive hydrogen ions produced is equal to the number of negative hydroxide ions produced, pure water is neutral.

The pH Scale Chemists devised a measurement system called the **pH scale** to indicate the concentration of H^+ ions in solution. As **Figure 2–10** shows, the pH scale ranges from 0 to 14. At a pH of 7, the concentration of H^+ ions and OH^- ions is equal. Pure water has a pH of 7. Solutions with a pH below 7 are called acidic because they have more H^+ ions than OH^- ions. The lower the pH, the greater the acidity. Solutions with a pH above 7 are called basic because they have more OH^- ions than H^+ ions. The higher the pH, the more basic the solution. Each step on the pH scale represents a factor of 10. For example, a liter of a solution with a pH of 4 has 10 times as many H^+ ions as a liter of a solution with a pH of 5.

In Your Notebook *Order these items in order of increasing acidity: soap, lemon juice, milk, acid rain.*

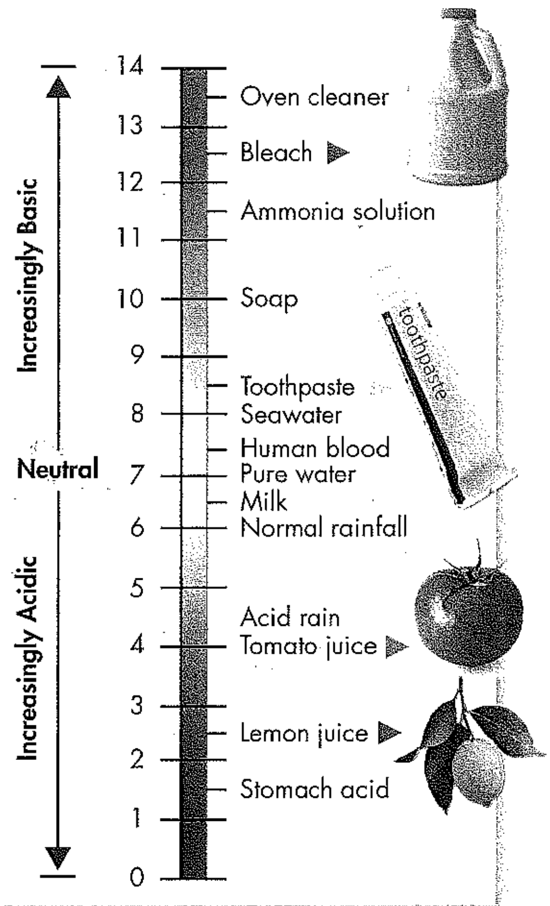


FIGURE 2–10 The pH Scale The concentration of H^+ ions determines whether solutions are acidic or basic. The most acidic material on this pH scale is stomach acid. The most basic material on this scale is oven cleaner.

Quick Lab
GUIDED INQUIRY

Acidic and Basic Foods

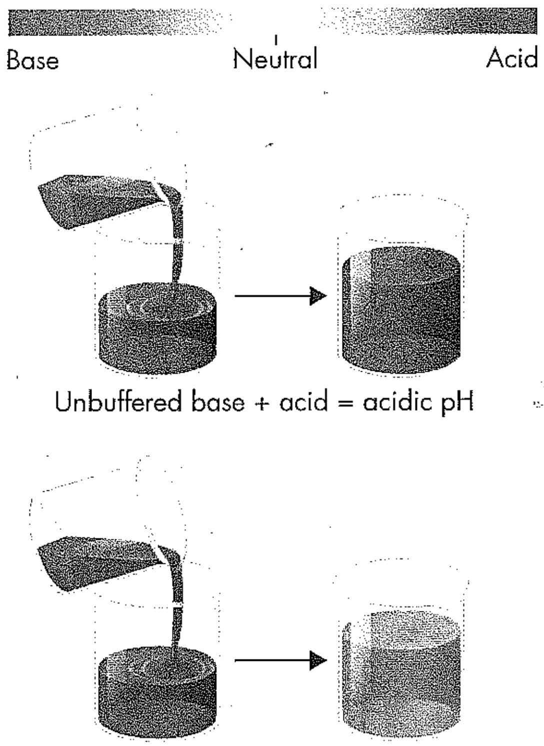
1. Predict whether the food samples provided are acidic or basic.
2. Tear off a 2-inch piece of pH paper for each sample you will test. Place these pieces on a paper towel.
3. Construct a data table in which you will record the name and pH of each food sample.
4. Use a scalpel to cut a piece off each solid. **CAUTION:** *Be careful not to cut yourself. Do not eat the food.* Touch the cut surface of each sample to a square of pH paper. Use a dropper pipette to place a drop of any liquid sample on a square of pH paper. Record the pH of each sample in your data table.

Analyze and Conclude

1. Analyze Data Were most of the samples acidic or basic?

2. Evaluate Was your prediction correct?

FIGURE 2–11 Buffers Buffers help prevent drastic changes in pH. Adding acid to an unbuffered solution causes the pH of the unbuffered solution to drop. If the solution contains a buffer, however, adding the acid will cause only a slight change in pH.



Unbuffered base + acid = acidic pH

Buffered base + acid = basic pH

Acids Where do all those extra H^+ ions in a low-pH solution come from? They come from acids. An **acid** is any compound that forms H^+ ions in solution. Acidic solutions contain higher concentrations of H^+ ions than pure water and have pH values below 7. Strong acids tend to have pH values that range from 1 to 3. The hydrochloric acid (HCl) produced by the stomach to help digest food is a strong acid.

Bases A **base** is a compound that produces hydroxide (OH^-) ions in solution. Basic, or alkaline, solutions contain lower concentrations of H^+ ions than pure water and have pH values above 7. Strong bases, such as the lye (commonly NaOH) used in soapmaking, tend to have pH values ranging from 11 to 14.

Buffers The pH of the fluids within most cells in the human body must generally be kept between 6.5 and 7.5. If the pH is lower or higher, it will affect the chemical reactions that take place within the cells. Thus, controlling pH is important for maintaining homeostasis. One of the ways that organisms control pH is through dissolved compounds called buffers. **Buffers** are weak acids or bases that can react with strong acids or bases to prevent sharp, sudden changes in pH. Blood, for example, has a normal pH of 7.4. Sudden changes in blood pH are usually prevented by a number of chemical buffers, such as bicarbonate and phosphate ions. **Buffers dissolved in life's fluids play an important role in maintaining homeostasis in organisms.**

2.2 Assessment

Review Key Concepts

1. **a. Review** What does it mean when a molecule is said to be "polar"?
   b. Explain How do hydrogen bonds between water molecules occur?
   c. Use Models Use the structure of a water molecule to explain why it is polar.
2. **a. Review** Why is water such a good solvent?
   b. Compare and Contrast What is the difference between a solution and a suspension?
3. **a. Review** What is an acid? What is a base?
   b. Explain The acid hydrogen fluoride (HF) can be dissolved in pure water. Will the pH of the solution be greater or less than 7?
   c. Infer During exercise, many chemical changes occur in the body, including a drop in blood pH, which can be very serious. How is the body able to cope with such changes?

WRITE ABOUT SCIENCE

Creative Writing

4. Suppose you are a writer for a natural history magazine for children. This month's issue will feature insects. Write a paragraph explaining why some bugs, such as the water strider, can walk on water.

2.3 Carbon Compounds

THINK ABOUT IT In the early 1800s, many chemists called the compounds created by organisms "organic," believing they were fundamentally different from compounds in nonliving things. Today we understand that the principles governing the chemistry of living and nonliving things are the same, but the term "organic chemistry" is still around. Today, organic chemistry means the study of compounds that contain bonds between carbon atoms, while inorganic chemistry is the study of all other compounds.

Key Questions

What elements does carbon bond with to make up life's molecules?

What are the functions of each of the four groups of macromolecules?

Vocabulary

monomer • polymer • carbohydrate • monosaccharide • lipid • nucleic acid • nucleotide • protein • amino acid

Taking Notes

Compare/Contrast Table As you read, make a table that compares and contrasts the four groups of organic compounds.

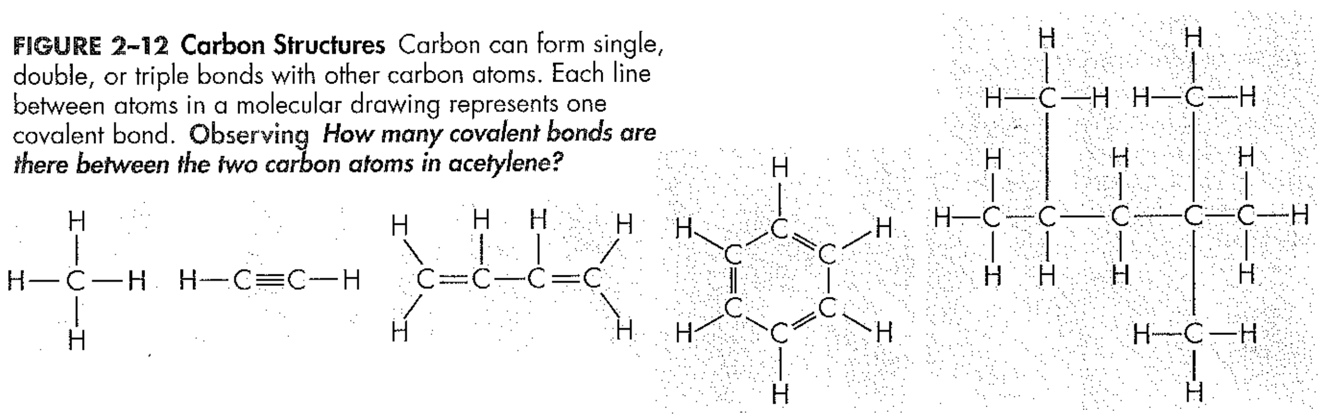
The Chemistry of Carbon

What elements does carbon bond with to make up life's molecules?

Why is carbon so interesting that a whole branch of chemistry should be set aside just to study carbon compounds? There are two reasons for this. First, carbon atoms have four valence electrons, allowing them to form strong covalent bonds with many other elements. **Carbon can bond with many elements, including hydrogen, oxygen, phosphorus, sulfur, and nitrogen to form the molecules of life.** Living organisms are made up of molecules that consist of carbon and these other elements.

Even more important, one carbon atom can bond to another, which gives carbon the ability to form chains that are almost unlimited in length. These carbon-carbon bonds can be single, double, or triple covalent bonds. Chains of carbon atoms can even close up on themselves to form rings, as shown in **Figure 2–12.** Carbon has the ability to form millions of different large and complex structures. No other element even comes close to matching carbon's versatility.

FIGURE 2–12 Carbon Structures Carbon can form single, double, or triple bonds with other carbon atoms. Each line between atoms in a molecular drawing represents one covalent bond. **Observing** ***How many covalent bonds are there between the two carbon atoms in acetylene?***



Methane **Acetylene** **Butadiene** **Benzene** **Isooctane**

Macromolecules

What are the functions of each of the four groups of macromolecules?

Many of the organic compounds in living cells are so large that they are known as macromolecules, which means "giant molecules." Macromolecules are made from thousands or even hundreds of thousands of smaller molecules.

Most macromolecules are formed by a process known as polymerization (pah lih mur ih ZAY shun), in which large compounds are built by joining smaller ones together. The smaller units, or **monomers,** join together to form **polymers.** The monomers in a polymer may be identical, like the links on a metal watch band; or the monomers may be different, like the beads in a multicolored necklace. **Figure 2–13** illustrates the process of polymerization.

Biochemists sort the macromolecules found in living things into groups based on their chemical composition. The four major groups of macromolecules found in living things are carbohydrates, lipids, nucleic acids, and proteins. As you read about these molecules, compare their structures and functions.

BUILD Vocabulary

WORD ORIGINS Monomer comes from the Greek words *monos,* meaning "single," and *meros,* meaning "part." *Monomer* means "single part." The prefix *poly-* comes from the Greek word *polus,* meaning "many," so **polymer** means "many parts."

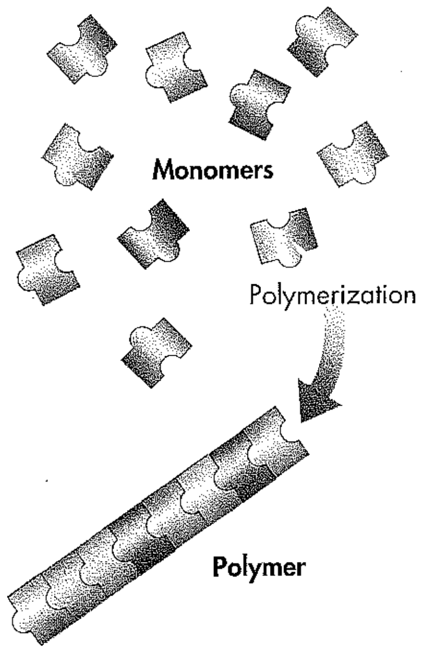
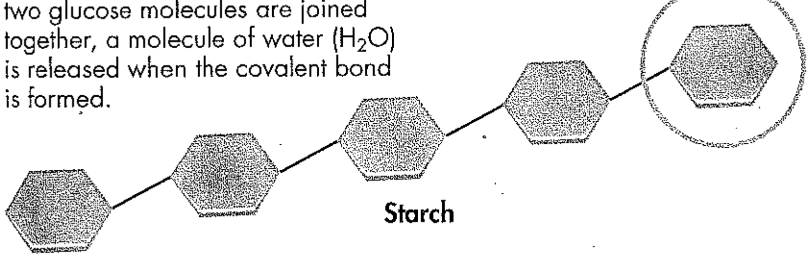


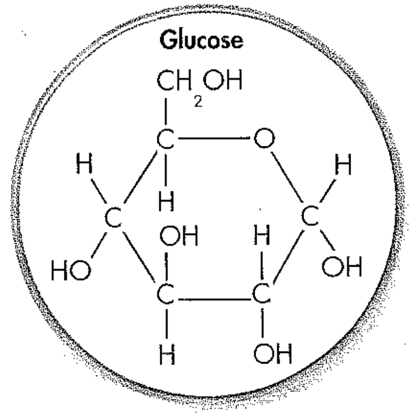
FIGURE 2–13 Polymerization When monomers join together, they form polymers. **Using Analogies** ***How are monomers similar to links in a chain?***

Carbohydrates **Carbohydrates** are compounds made up of carbon, hydrogen, and oxygen atoms, usually in a ratio of 1 : 2 : 1. **Living things use carbohydrates as their main source of energy. Plants, some animals, and other organisms also use carbohydrates for structural purposes.** The breakdown of sugars, such as glucose, supplies immediate energy for cell activities. Many organisms store extra sugar as complex carbohydrates known as starches. As shown in **Figure 2–14,** the monomers in starch polymers are sugar molecules.

▶ *Simple Sugars* Single sugar molecules are also known as **monosaccharides** (mahn oh SAK uh rydz). Besides glucose, monosaccharides include galactose, which is a component of milk, and fructose, which is found in many fruits. Ordinary table sugar, sucrose, consists of glucose and fructose. Sucrose is a disaccharide, a compound made by joining two simple sugars together.

FIGURE 2–14 Carbohydrates Starches form when sugars join together in a long chain. Each time two glucose molecules are joined together, a molecule of water (H_2O) is released when the covalent bond is formed.





▶ *Complex Carbohydrates* The large macromolecules formed from monosaccharides are known as polysaccharides. Many animals store excess sugar in a polysaccharide called glycogen, which is sometimes called "animal starch." When the level of glucose in your blood runs low, glycogen is broken down into glucose, which is then released into the blood. The glycogen stored in your muscles supplies the energy for muscle contraction and, thus, for movement.

Plants use a slightly different polysaccharide, called starch, to store excess sugar. Plants also make another important polysaccharide called cellulose. Tough, flexible cellulose fibers give plants much of their strength and rigidity. Cellulose is the major component of both wood and paper, so you are actually looking at cellulose as you read these words!

Lipids

Lipids are a large and varied group of biological molecules that are generally not soluble in water. **Lipids** are made mostly from carbon and hydrogen atoms. The common categories of lipids are fats, oils, and waxes. **Lipids can be used to store energy. Some lipids are important parts of biological membranes and waterproof coverings.** Steroids synthesized by the body are lipids as well. Many steroids, such as hormones, serve as chemical messengers.

Many lipids are formed when a glycerol molecule combines with compounds called fatty acids, as shown in **Figure 2–15.** If each carbon atom in a lipid's fatty acid chains is joined to another carbon atom by a single bond, the lipid is said to be saturated. The term *saturated* is used because the fatty acids contain the maximum possible number of hydrogen atoms.

If there is at least one carbon-carbon double bond in a fatty acid, the fatty acid is said to be unsaturated. Lipids whose fatty acids contain more than one double bond are said to be polyunsaturated. If the terms *saturated* and *polyunsaturated* seem familiar, you have probably seen them on food package labels. Lipids that contain unsaturated fatty acids, such as olive oil, tend to be liquid at room temperature. Other cooking oils, such as corn oil, sesame oil, canola oil, and peanut oil, contain polyunsaturated lipids.

In Your Notebook *Compare and contrast saturated and unsaturated fats.*

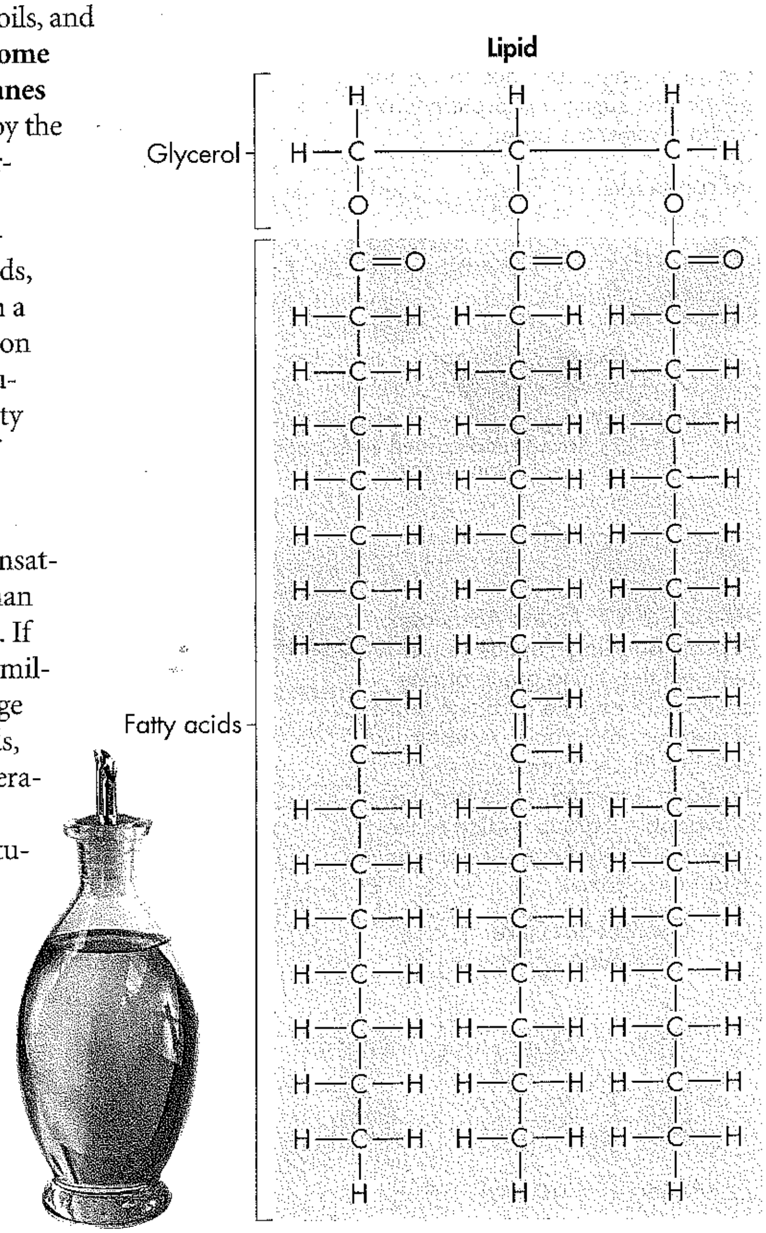


FIGURE 2–15 Lipids Lipid molecules are made up of glycerol and fatty acids. Liquid lipids, such as olive oil, contain mainly unsaturated fatty acids.

Analyzing Data

Comparing Fatty Acids

The table compares four different fatty acids. Although they all have the same number of carbon atoms, their properties vary.

1. Interpret Data Which of the four fatty acids is saturated? Which are unsaturated?

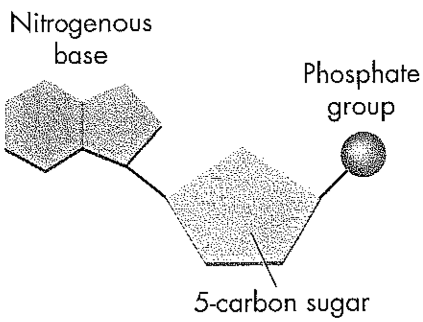
2. Observe How does melting point change as the number of carbon-carbon double bonds increases?

Effect of Carbon Bonds on Melting Point

Fatty Acid	Number of Carbons	Number of Double Bonds	Melting Point (°C)
Stearic acid	18	0	69.6
Oleic acid	18	1	14
Linoleic acid	18	2	−5
Linolenic acid	18	3	−11

3. Infer If room temperature is 25°C, which fatty acid is a solid at room temperature? Which is liquid at room temperature?

FIGURE 2–16 Nucleic Acids The monomers that make up a nucleic acid are nucleotides. Each nucleotide has a 5-carbon sugar, a phosphate group, and a nitrogenous base.

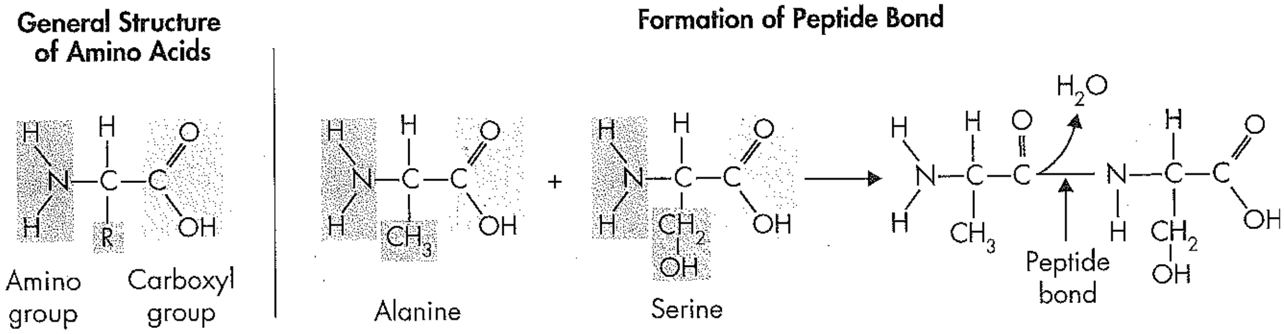


Nucleic Acids **Nucleic acids** are macromolecules containing hydrogen, oxygen, nitrogen, carbon, and phosphorus. Nucleic acids are polymers assembled from individual monomers known as nucleotides. **Nucleotides** consist of three parts: a 5-carbon sugar, a phosphate group ($-PO_4$), and a nitrogenous base, as shown in **Figure 2–16.** Some nucleotides, including the compound known as adenosine triphosphate (ATP), play important roles in capturing and transferring chemical energy. Individual nucleotides can be joined by covalent bonds to form a polynucleotide, or nucleic acid.

Nucleic acids store and transmit hereditary, or genetic, information. There are two kinds of nucleic acids: ribonucleic acid (RNA) and deoxyribonucleic acid (DNA). As their names indicate, RNA contains the sugar ribose and DNA contains the sugar deoxyribose.

Protein **Proteins** are macromolecules that contain nitrogen as well as carbon, hydrogen, and oxygen. Proteins are polymers of molecules called amino acids, shown in **Figure 2–17. Amino acids** are compounds with an amino group ($-NH_2$) on one end and a carboxyl group ($-COOH$) on the other end. Covalent bonds called peptide bonds link amino acids together to form a polypeptide. A protein is a functional molecule built from one or more polypeptides. **Some proteins control the rate of reactions and regulate cell processes. Others form important cellular structures, while still others transport substances into or out of cells or help to fight disease.**

FIGURE 2–17 Amino Acids and Peptide Bonding Peptide bonds form between the amino group of one amino acid and the carboxyl group of another amino acid. A molecule of water (H_2O) is released when the bond is formed. Note that it is the variable R-group section of the molecule that distinguishes one amino acid from another.



▶ ***Structure and Function*** More than 20 different amino acids are found in nature. All amino acids are identical in the regions where they may be joined together by covalent bonds. This uniformity allows any amino acid to be joined to any other amino acid—by bonding an amino group to a carboxyl group. Proteins are among the most diverse macromolecules. The reason is that amino acids differ from each other in a side chain called the R-group, which have a range of different properties. Some R-groups are acidic and some are basic. Some are polar, some are nonpolar, and some even contain large ring structures.

▶ ***Levels of Organization*** Amino acids are assembled into polypeptide chains according to instructions coded in DNA. To help understand these large molecules, scientists describe proteins as having four levels of structure. A protein's primary structure is the sequence of its amino acids. Secondary structure is the folding or coiling of the polypeptide chain. Tertiary structure is the complete, three-dimensional arrangement of a polypeptide chain. Proteins with more than one chain are said to have a fourth level of structure, describing the way in which the different polypeptides are arranged with respect to each other. **Figure 2–18** shows these four levels of structure in hemoglobin, a protein found in red blood cells that helps to transport oxygen in the bloodstream. The shape of a protein is maintained by a variety of forces, including ionic and covalent bonds, as well as van der Waals forces and hydrogen bonds. In the next lesson, you will learn why a protein's shape is so important.

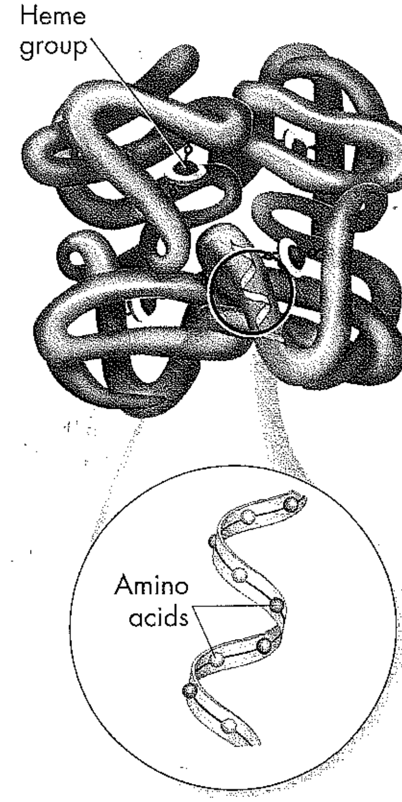


FIGURE 2–18 Protein Structure The protein hemoglobin consists of four subunits. The iron-containing heme group in the center of each subunit gives hemoglobin its red color. An oxygen molecule binds tightly to each heme molecule. **Interpret Visuals** ***How many levels of organization does hemoglobin have?***

2.3 Assessment

Review Key Concepts

1. a. Review What are the major elements of life?

b. Relate Cause and Effect What properties of carbon explain carbon's ability to form different large and complex structures?

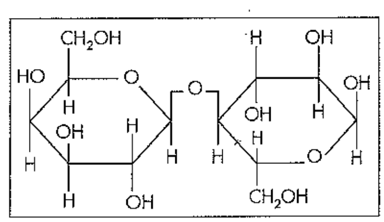
2. a. Review Name four groups of organic compounds found in living things.

b. Explain Describe at least one function of each group of organic compound.

c. Infer Why are proteins considered polymers but lipids not?

VISUAL THINKING

3. A structural formula shows how the atoms in a compound are arranged.



a. Observe What atoms constitute the compound above?

b. Classify What class of macromolecule does the compound belong to?

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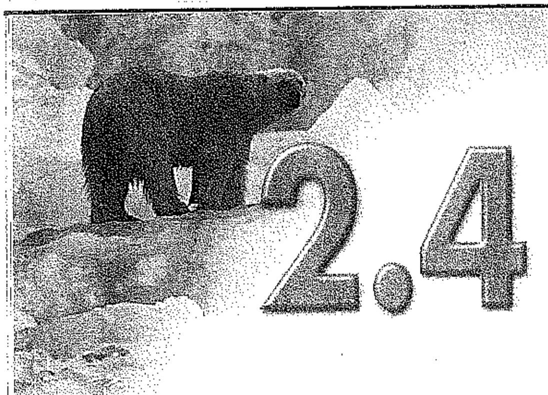


2.4 Chemical Reactions and Enzymes

Key Questions

What happens to chemical bonds during chemical reactions?

How do energy changes affect whether a chemical reaction will occur?

What role do enzymes play in living things and what affects their function?

Vocabulary

chemical reaction • reactant • product • activation energy • catalyst • enzyme • substrate

Taking Notes

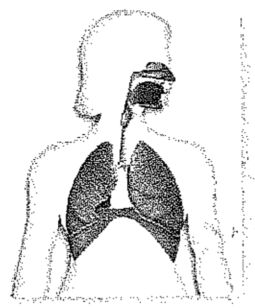
Concept Map As you read, make a concept map that shows the relationship among the vocabulary terms in this lesson.

THINK ABOUT IT Living things, as you have seen, are made up of chemical compounds—some simple and some complex. But chemistry isn't just what life is made of—chemistry is also what life does. Everything that happens in an organism—its growth, its interaction with the environment, its reproduction, and even its movement—is based on chemical reactions.

Chemical Reactions

What happens to chemical bonds during chemical reactions?

A **chemical reaction** is a process that changes, or transforms, one set of chemicals into another. An important scientific principle is that mass and energy are conserved during chemical transformations. This is also true for chemical reactions that occur in living organisms. Some chemical reactions occur slowly, such as the combination of iron and oxygen to form an iron oxide called rust. Other reactions occur quickly. The elements or compounds that enter into a chemical reaction are known as **reactants.** The elements or compounds produced by a chemical reaction are known as **products.** **Chemical reactions involve changes in the chemical bonds that join atoms in compounds.** An important chemical reaction in your bloodstream that enables carbon dioxide to be removed from the body is shown in **Figure 2–19.**



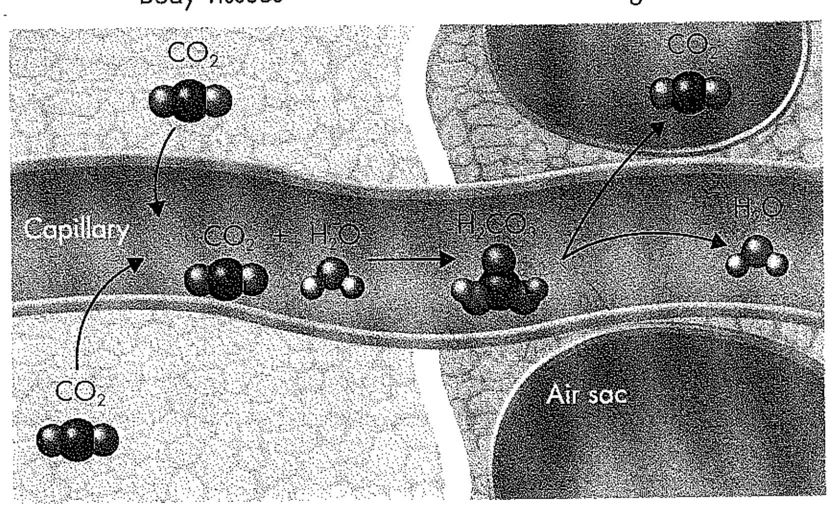


FIGURE 2–19 Carbon Dioxide in the Bloodstream As it enters the blood, carbon dioxide reacts with water to produce carbonic acid (H_2CO_3), which is highly soluble. This reaction enables the blood to carry carbon dioxide to the lungs. In the lungs, the reaction is reversed and produces carbon dioxide gas, which you exhale.

Energy in Reactions

How do energy changes affect whether a chemical reaction will occur?

Energy is released or absorbed whenever chemical bonds are formed or broken. This means that chemical reactions also involve changes in energy.

Energy Changes Some chemical reactions release energy, and other reactions absorb it. Energy changes are one of the most important factors in determining whether a chemical reaction will occur. **Chemical reactions that release energy often occur on their own, or spontaneously. Chemical reactions that absorb energy will not occur without a source of energy.** An example of an energy-releasing reaction is the burning of hydrogen gas, in which hydrogen reacts with oxygen to produce water vapor.

$$2H_2 + O_2 \longrightarrow 2H_2O$$

The energy is released in the form of heat, and sometimes—when hydrogen gas explodes—light and sound.

The reverse reaction, in which water is changed into hydrogen and oxygen gas, absorbs so much energy that it generally doesn't occur by itself. In fact, the only practical way to reverse the reaction is to pass an electrical current through water to decompose water into hydrogen gas and oxygen gas. Thus, in one direction the reaction produces energy, and in the other direction the reaction requires energy.

Energy Sources In order to stay alive, organisms need to carry out reactions that require energy. Because matter and energy are conserved in chemical reactions, every organism must have a source of energy to carry out chemical reactions. Plants get that energy by trapping and storing the energy from sunlight in energy-rich compounds. Animals get their energy when they consume plants or other animals. Humans release the energy needed to grow tall, to breathe, to think, and even to dream through the chemical reactions that occur when we metabolize, or break down, digested food.

Activation Energy Chemical reactions that release energy do not always occur spontaneously. That's a good thing because if they did, the pages of this book might burst into flames. The cellulose in paper burns in the presence of oxygen and releases heat and light. However, paper burns only if you light it with a match, which supplies enough energy to get the reaction started. Chemists call the energy that is needed to get a reaction started the **activation energy.** As **Figure 2–20** shows, activation energy is involved in chemical reactions regardless of whether the overall chemical reaction releases energy or absorbs energy.

FIGURE 2–20 Activation Energy The peak of each graph represents the energy needed for the reaction to go forward. The difference between this required energy and the energy of the reactants is the activation energy. **Interpret Graphs** ***How do the energy of the reactants and products differ between an energy-absorbing reaction and an energy-releasing reaction?***

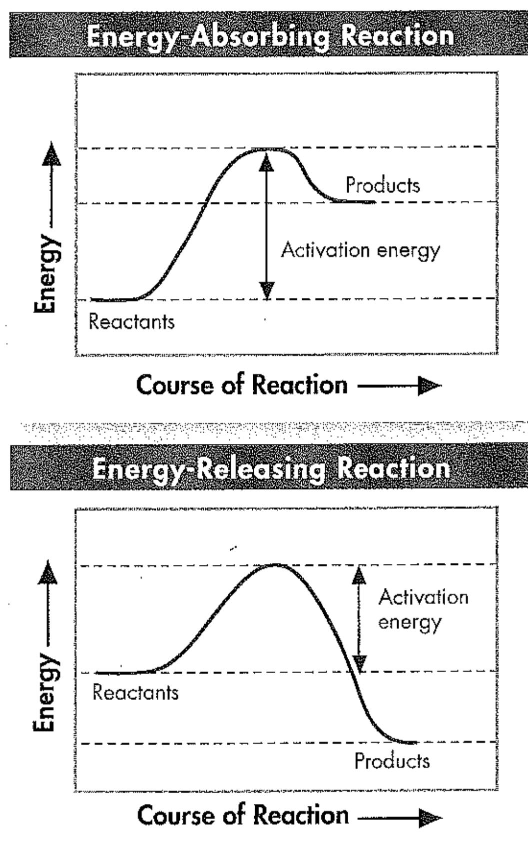


FIGURE 2–21 Effect of Enzymes Notice how the addition of an enzyme lowers the activation energy in this reaction. The enzyme speeds up the reaction.

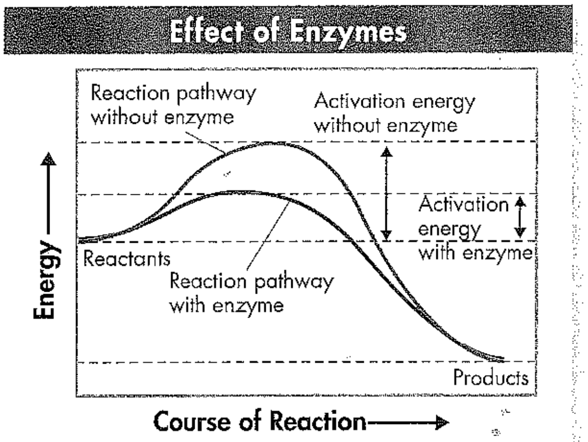
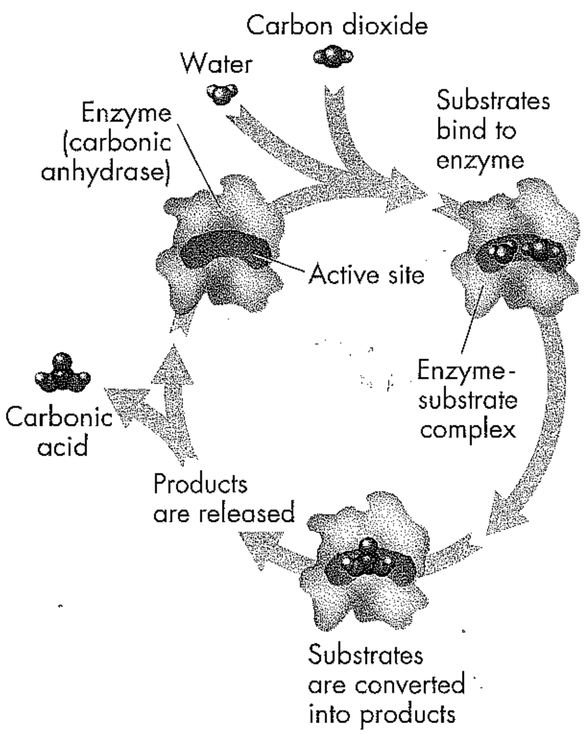


FIGURE 2–22 An Enzyme-Catalyzed Reaction The enzyme carbonic anhydrase converts the substrates carbon dioxide and water into carbonic acid (H_2CO_3). **Predicting** ***What happens to the carbonic anhydrase after the products are released?***



Enzymes

What role do enzymes play in living things and what affects their function?

Some chemical reactions that make life possible are too slow or have activation energies that are too high to make them practical for living tissue. These chemical reactions are made possible by a process that would make any chemist proud—cells make catalysts. A **catalyst** is a substance that speeds up the rate of a chemical reaction. Catalysts work by lowering a reaction's activation energy.

Nature's Catalysts **Enzymes** are proteins that act as biological catalysts. **Enzymes speed up chemical reactions that take place in cells.** Like other catalysts, enzymes act by lowering the activation energies, as illustrated by the graph in **Figure 2–21.** Lowering the activation energy has a dramatic effect on how quickly the reaction is completed. How big an effect does it have? Consider the reaction in which carbon dioxide combines with water to produce carbonic acid.

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

Left to itself, this reaction is so slow that carbon dioxide might build up in the body faster than the bloodstream could remove it. Your bloodstream contains an enzyme called carbonic anhydrase that speeds up the reaction by a factor of 10 million. With carbonic anhydrase on the job, the reaction takes place immediately and carbon dioxide is removed from the blood quickly.

Enzymes are very specific, generally catalyzing only one chemical reaction. For this reason, part of an enzyme's name is usually derived from the reaction it catalyzes. Carbonic anhydrase gets its name because it also catalyzes the reverse reaction that removes water from carbonic acid.

The Enzyme-Substrate Complex How do enzymes do their jobs? For a chemical reaction to take place, the reactants must collide with enough energy so that existing bonds will be broken and new bonds will be formed. If the reactants do not have enough energy, they will be unchanged after the collision.

Enzymes provide a site where reactants can be brought together to react. Such a site reduces the energy needed for reaction. The reactants of enzyme-catalyzed reactions are known as **substrates. Figure 2–22** provides an example of an enzyme-catalyzed reaction.

The substrates bind to a site on the enzyme called the active site. The active site and the substrates have complementary shapes. The fit is so precise that the active site and substrates are often compared to a lock and key, as shown in **Figure 2–23.**

Regulation of Enzyme Activity Enzymes play essential roles in controlling chemical pathways, making materials that cells need, releasing energy, and transferring information. Because they are catalysts for reactions, enzymes can be affected by any variable that influences a chemical reaction. **Temperature, pH, and regulatory molecules can affect the activity of enzymes.**

Many enzymes are affected by changes in temperature. Not surprisingly, those enzymes produced by human cells generally work best at temperatures close to 37°C, the normal temperature of the human body. Enzymes work best at certain ionic conditions and pH values. For example, the stomach enzyme pepsin, which begins protein digestion, works best under acidic conditions. In addition, the activities of most enzymes are regulated by molecules that carry chemical signals within cells, switching enzymes "on" or "off" as needed.

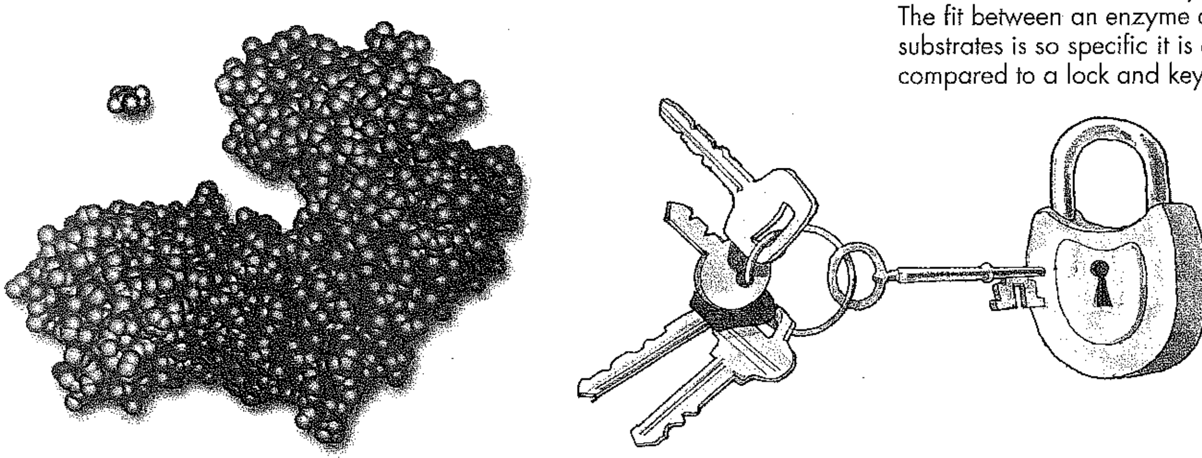
MYSTERY CLUE

The chemical reactions of living things, including those that require oxygen, occur more slowly at low temperatures. How would frigid antarctic waters affect the ice fish's need for oxygen?

VISUAL ANALOGY

UNLOCKING ENZYMES

FIGURE 2–23 This space-filling model shows how a substrate binds to an active site on an enzyme. The fit between an enzyme and its substrates is so specific it is often compared to a lock and key.



2.4 Assessment

Review Key Concepts

1. **a. Review** What happens to chemical bonds during chemical reactions?
   b. Apply Concepts Why is the melting of ice not a chemical reaction?
2. **a. Review** What is activation energy?
   b. Compare and Contrast Describe the difference between a reaction that occurs spontaneously and one that does not.
3. **a. Review** What are enzymes?
   b. Explain Explain how enzymes work, including the role of the enzyme-substrate complex.
   c. Use Analogies A change in pH can change the shape of a protein. How might a change in pH affect the function of an enzyme such as carbonic anhydrase? (*Hint:* Think about the analogy of the lock and key.)

VISUAL THINKING

4. Make a model that demonstrates the fit between an enzyme and its substrate. Show your model to a friend or family member and explain how enzymes work using your model.

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