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.

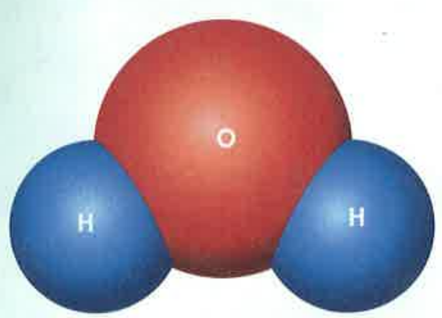


FIGURE 2–6 A Water Molecule A water molecule is polar because there is an uneven distribution of electrons between the oxygen and hydrogen atoms. The negative pole is near the oxygen atom and the positive pole is between the hydrogen atoms.

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.*

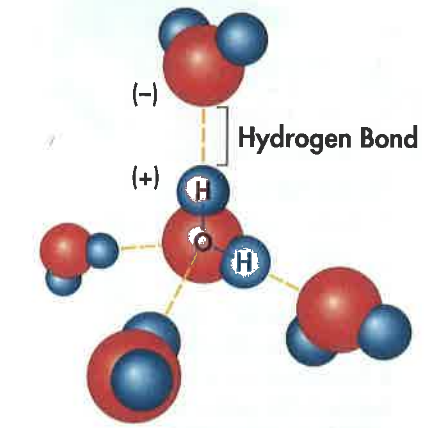


FIGURE 2–7 Hydrogen Bonding and Cohesion Each molecule of water can form multiple hydrogen bonds with other water molecules. The strong attraction between water molecules produces a force sometimes called "surface tension," which can support very lightweight objects, such as this raft spider. **Apply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

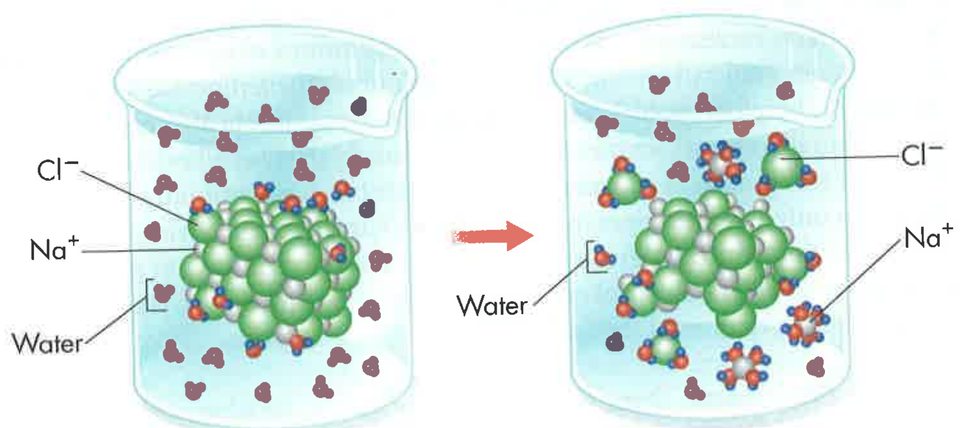


FIGURE 2–9 A Salt Solution When an ionic compound such as sodium chloride is placed in water, water molecules surround and separate the positive and negative ions. **Interpret Visuals** *What happens to the sodium ions and chloride ions in the solution?*

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.

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

water ⇌ hydrogen ion + 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.

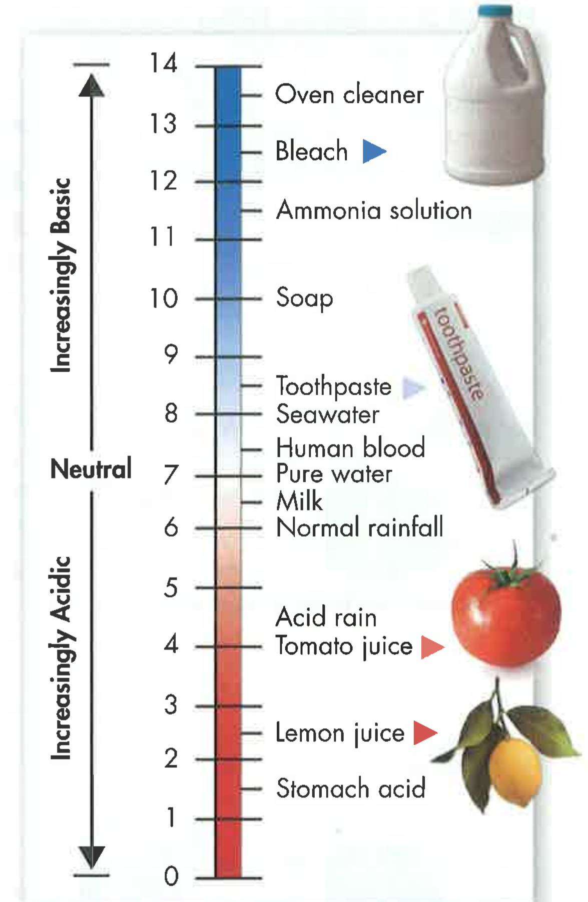


FIGURE 2–10 The pH Scale The concentration of H^+ ions determines whether solutions are acidic or basic. The most acidic material on this pH scale is stomach acid. The most basic material on this scale is oven cleaner.

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

Quick Lab
GUIDED INQUIRY

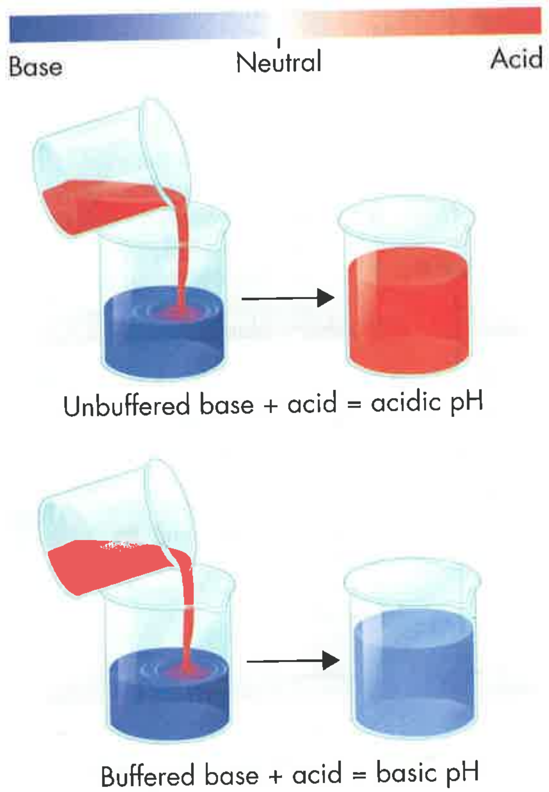
Acidic and Basic Foods

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.



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.

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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.

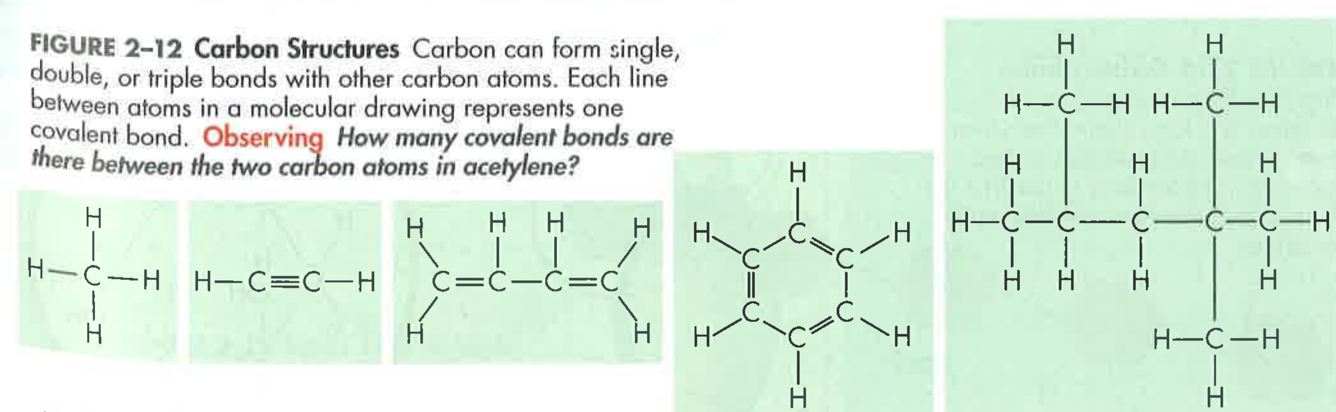
The Chemistry of Carbon

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

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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."

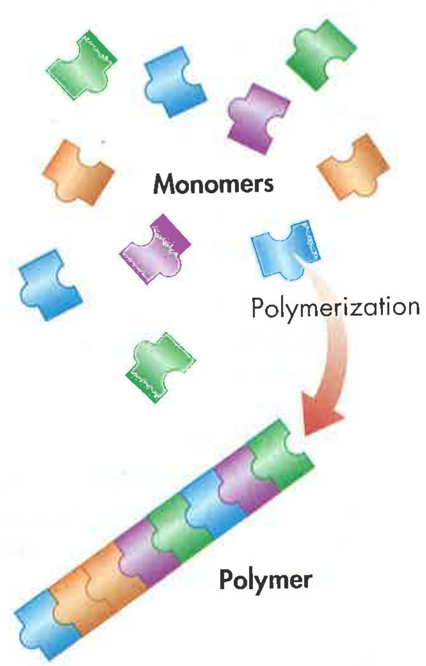


FIGURE 2–13 Polymerization When monomers join together, they form polymers. **Using Analogies** *How are monomers similar to links in a chain?*

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.

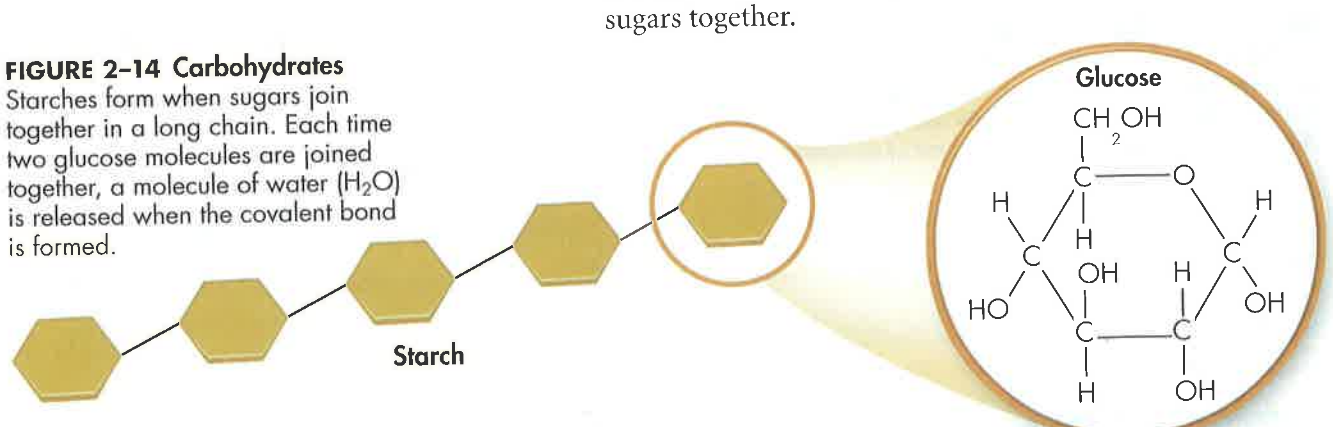
Most macromolecules are formed by a process known as polymerization (pah lih mur ih ZAY shun), in which large compounds are built by joining smaller ones together. The smaller units, or **monomers,** join together to form **polymers.** The monomers in a polymer may be identical, like the links on a metal 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.

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.*

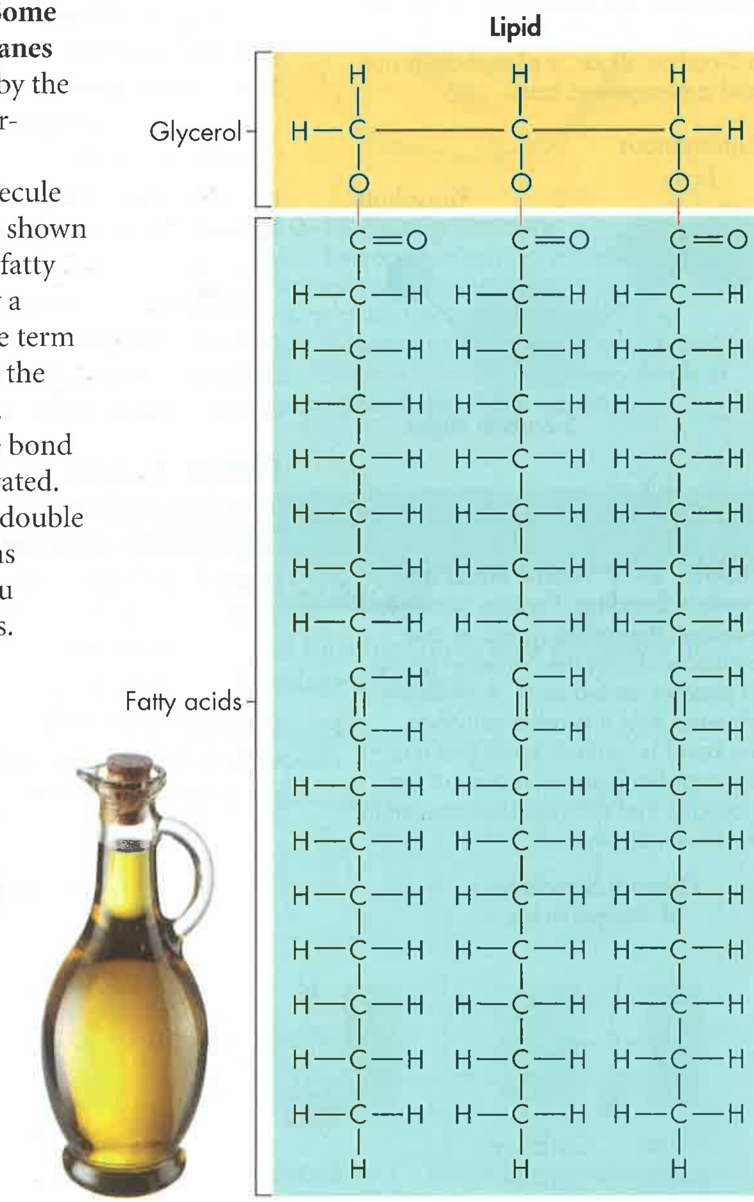


FIGURE 2–15 Lipids Lipid molecules are made up of glycerol and fatty acids. Liquid lipids, such as olive oil, contain mainly unsaturated fatty acids.

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?

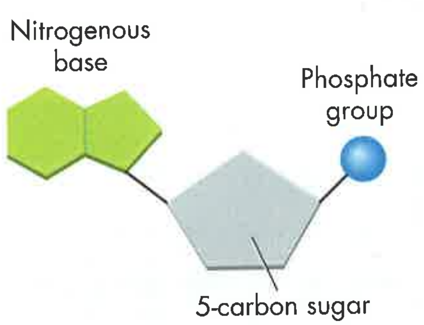
2. Observe How does melting point change as the number of carbon-carbon double bonds increases?

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

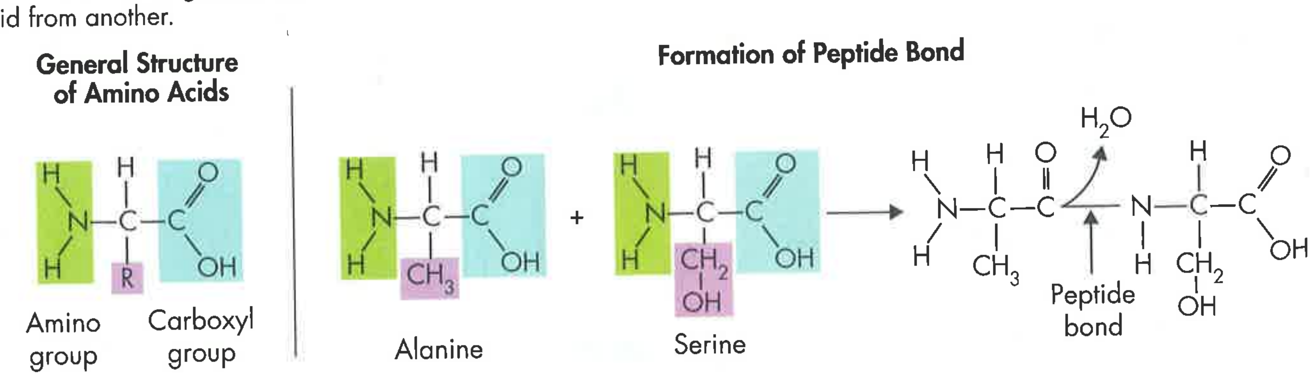
Nucleic acids are macromolecules containing hydrogen, oxygen, nitrogen, carbon, and phosphorus. Nucleic acids are polymers assembled from individual monomers known as nucleotides. **Nucleotides** consist of three parts: a 5-carbon sugar, a phosphate group ($–PO_4$), and a nitrogenous base, as shown in **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.

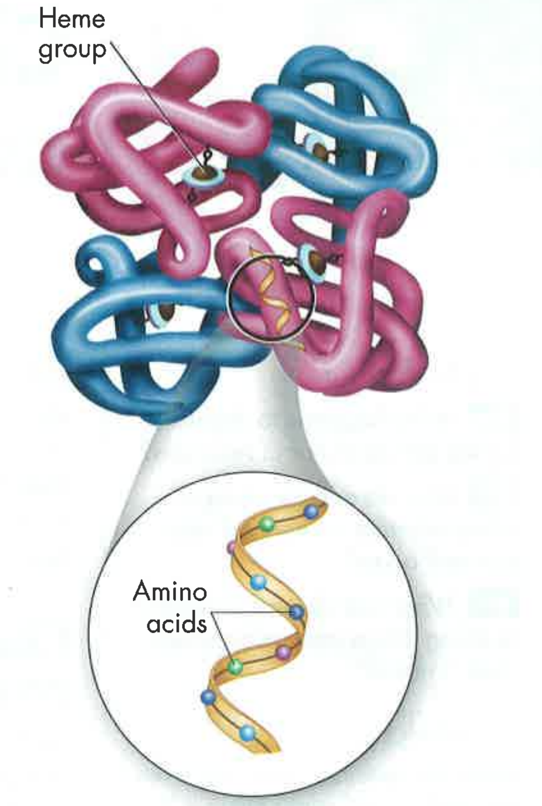


FIGURE 2–18 Protein Structure The protein hemoglobin consists of four subunits. The iron-containing heme group in the center of each subunit gives hemoglobin its red color. An oxygen molecule binds tightly to each heme molecule. **Interpret Visuals** ***How many levels of organization does hemoglobin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

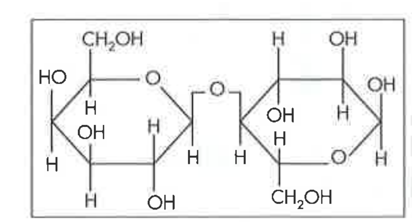
2. a. Review Name four groups of organic compounds found in living things.

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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