Chapter 2

Chemical Basis of Life

2.1 Lesson 2.1: Matter

Lesson Objectives

- Describe elements and compounds, and explain how mixtures differ from compounds.
- Define energy, and describe how energy can be changed from one form to another.
- Identify three states of matter, and explain how they differ.

Introduction

Living things are made of **matter.** In fact, matter is the "stuff" of which all things are made. Anything that occupies space and has mass is known as matter. Matter, in turn, consists of chemical substances.

Chemical Substances

A chemical substance is a material that has a definite chemical composition. It is also homogeneous, so the same chemical composition is found uniformly throughout the substance. A chemical substance may be an element or a chemical compound.

Elements

An **element** is a pure substance that cannot be broken down into different types of substances. Examples of elements include carbon, oxygen, hydrogen, and iron. Each element is made up of just one type of atom. An atom is the smallest particle of an element that still characterizes the element. As shown in **Figure** 2.1, at the center of an atom is a nucleus. The nucleus contains positively charged particles called protons and electrically neutral particles called neutrons. Surrounding the nucleus is a much larger electron cloud consisting of negatively charged electrons. An atom is electrically neutral if it has the same number of protons as electrons. Each element has atoms with a characteristic number of protons. For example, all carbon atoms have six protons, and all oxygen atoms have eight protons.

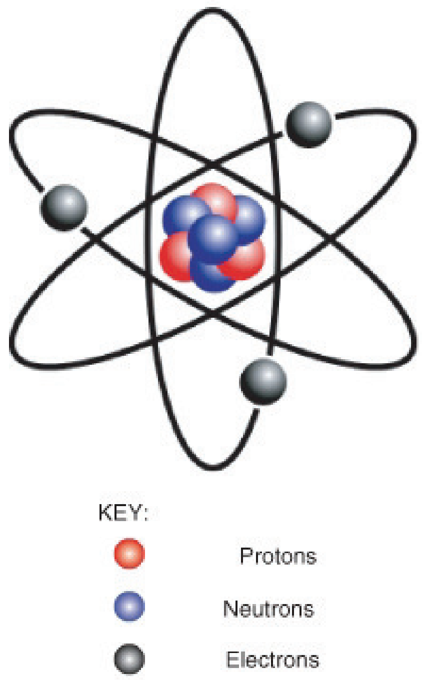

Figure 2.1: Model of an Atom. The protons and neutrons of this atom make up its nucleus. Electrons surround the nucleus. KEY: Red = protons, Blue = neutrons, Black = electrons. (16)

There are almost 120 known elements (**Figure** 2.2). The majority of known elements are classified as metals. Metals are elements that are lustrous, or shiny. They are also good conductors of electricity and heat. Examples of metals include iron, gold, and copper. Fewer than 20 elements are classified as nonmetals. Nonmetals lack the properties of metals. Examples of nonmetals include oxygen, hydrogen, and sulfur. Certain other elements have properties of both metals and nonmetals. They are known as metalloids. Examples of metalloids include silicon and boron.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1A	2A	3B	4B	5B	6B	7B		8B		1B	2B	3A	4A	5A	6A	7A	8A
1 **H** 1.01																	2 **He** 4.00
3 **Li** 6.94	4 **Be** 9.01											5 **B** 10.8	6 **C** 12.0	7 **N** 14.0	8 **O** 16.0	9 **F** 19.0	10 **Ne** 20.2
11 **Na** 23.0	12 **Mg** 24.3											13 **Al** 27.0	14 **Si** 28.1	15 **P** 30.1	16 **S** 32.1	17 **Cl** 35.5	18 **Ar** 39.9
19 **K** 39.1	20 **Ca** 40.1	21 **Sc** 45.0	22 **Ti** 47.9	23 **V** 50.9	24 **Cr** 52.0	25 **Mn** 54.9	26 **Fe** 55.9	27 **Co** 58.9	28 **Ni** 58.7	29 **Cu** 63.6	30 **Zn** 65.4	31 **Ga** 69.7	32 **Ge** 72.6	33 **As** 74.9	34 **Se** 79.0	35 **Br** 79.9	36 **Kr** 83.8
37 **Rb** 85.5	38 **Sr** 87.6	39 **Y** 88.9	40 **Zr** 91.2	41 **Nb** 92.9	42 **Mo** 95.9	43 **Tc** [98]	44 **Ru** 101	45 **Rh** 103	46 **Pd** 106	47 **Ag** 108	48 **Cd** 112	49 **In** 115	50 **Sn** 119	51 **Sb** 122	52 **Te** 128	53 **I** 127	54 **Xe** 133
55 **Cs** 133	56 **Ba** 137	57 **La** 139	72 **Hf** 178	73 **Ta** 181	74 **W** 184	75 **Re** 186	76 **Os** 190	77 **Ir** 192	78 **Pt** 195	79 **Au** 197	80 **Hg** 201	81 **Ti** 204	82 **Pb** 207	83 **Bi** 209	84 **Po** [209]	85 **At** [210]	86 **Rn** [222]
87 **Fr** [223]	88 **Ra** 226	89 **Ac** 227	104 **Rf** [261]	105 **Db** [262]													
			58 **Ce** 140	59 **Pr** 141	60 **Nd** 144	61 **Pm** [145]	62 **Sm** 150	63 **Eu** 152	64 **Gd** 157	65 **Tb** 159	66 **Dy** 163	67 **Ho** 165	68 **Er** 167	69 **Tm** 169	70 **Yb** 173	71 **Lu** 175	
			90 **Th** 232	91 **Pa** 231	92 **U** 238	93 **Np** 237	94 **Pu** [244]	95 **Am** [243]	96 **Cm** [247]	97 **Bk** [247]	98 **Cf** [251]	99 **Ex** [252]	100 **Fm** [257]	101 **Md** [258]	102 **No** [259]	103 **Lr** [260]	

Figure 2.2: The Periodic Table. (3)

Chemical Compounds

A **chemical compound** is a new substance that forms when atoms of two or more elements react with one another. A chemical reaction is a process that changes some chemical substances into other chemical substances. A compound that results from a chemical reaction always has a unique and fixed chemical composition. The substances in the compound can be separated from one another only by another chemical reaction. This is covered further in the *Chemical Reactions* lesson.

The atoms of a compound are held together by chemical bonds. Chemical bonds form when atoms share electrons. There are different types of chemical bonds, and they vary in how strongly they hold together the atoms of a compound. Two of the strongest types of bonds are covalent and ionic bonds. Covalent bonds form between atoms that have little if any difference in electronegativity. Electronegativity is the power of an atom to attract electrons toward itself. Ionic bonds, in contrast, form between atoms that are significantly different in electronegativity.

An example of a chemical compound is water. A water molecule forms when oxygen (O) and hydrogen (H) atoms react and are held together by covalent bonds. Like other compounds, water always has the same chemical composition: a 2:1 ratio of hydrogen atoms to oxygen atoms. This is expressed in the chemical formula H_2O. A model of a water molecule is shown in **Figure** 2.3.

Figure 2.3: Model of a water molecule, showing the arrangement of hydrogen and oxygen atoms (17)

Compounds that contain mainly the elements carbon and hydrogen are called **organic compounds**. This is because they are found mainly in living organisms. Most organic compounds are held together by covalent bonds. An example of an organic compound is glucose ($C_6H_{12}O_6$), which is shown in **Figure** 2.4. Glucose is a simple sugar that living cells use for energy. All other compounds are called inorganic compounds. Water is an example of an inorganic compound. You will read more about organic compounds in Lesson 2.2.

Mixtures vs. Compounds

Like a chemical compound, a **mixture** consists of more than one chemical substance. Unlike a compound, a mixture does not have a fixed chemical composition. The substances in a mixture can be combined in any proportions. A mixture also does not involve a chemical reaction. Therefore, the substances in a mixture are not changed into unique new substances, and they can be separated from each other without a chemical reaction.

The following examples illustrate these differences between mixtures and compounds. Both examples involve the same two elements: the metal iron (Fe) and the nonmetal sulfur (S).

- When iron filings and sulfur powder are mixed together in any ratio, they form a mixture. No chemical reaction occurs, and both elements retain their individual properties. A magnet can be used to mechanically separate the two elements by attracting the iron filings out of the mixture and leaving the sulfur behind.
- When iron and sulfur are mixed together in a certain ratio and heated, a chemical reaction occurs. This results in the formation of a unique new compound, called iron

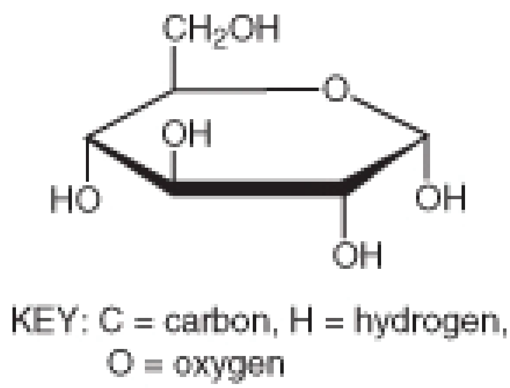

Figure 2.4: Glucose Molecule. This model represents a molecule of glucose, an organic compound composed of carbon, hydrogen, and oxygen. The chemical formula for glucose is $C_6H_{12}O_6$. This means that each molecule of glucose contains six carbon atoms, twelve hydrogen atoms, and six oxygen atoms. NOTE: Each unlabeled point where lines intersect represents another carbon atom. Some of these carbons and the oxygen atom are bonded to another hydrogen atom, not shown here. (6)

sulfide (FeS). A magnet cannot be used to mechanically separate the iron from the iron sulfide because metallic iron does not exist in the compound. Instead, another chemical reaction is required to separate the iron and sulfur.

Matter and Energy

Energy is a property of matter that is defined as the ability to do work. The concept of energy is useful for explaining and predicting most natural phenomena, and it is foundational for an understanding of biology. All living organisms need energy to grow and reproduce. However, energy can never be created or destroyed. It is always conserved. This is called the law of conservation of energy. Therefore, organisms cannot create the energy they need. Instead, they must obtain energy from the environment. Organisms also cannot destroy or use up the energy they obtain. They can only change it from one form to another.

Forms of Energy

Energy can take several different forms. Common forms of energy include light, chemical, and heat energy. Other common forms are kinetic and potential energy.

How Organisms Change Energy

In organisms, energy is always changing from one form to another. For example, plants obtain light energy from sunlight and change it to chemical energy in food molecules. Chemical energy is energy stored in bonds between atoms within food molecules. When other organisms eat and digest the food, they break the chemical bonds and release the chemical energy. Organisms do not use energy very efficiently. About 90 percent of the energy they obtain from food is converted to heat energy that is given off to the environment.

Kinetic and Potential Energy

Energy also constantly changes back and forth between kinetic and potential energy. **Kinetic energy** is the energy of movement. For example, a ball falling through the air has kinetic energy because it is moving (**Figure** 2.5). **Potential energy** is the energy stored in an object due to its position. A bouncing ball at the top of a bounce, just before it starts to fall, has potential energy. For that instant, the ball is not moving, but it has the potential to move because gravity is pulling on it. Once the ball starts to fall, the potential energy changes to kinetic energy. When the ball hits the ground, it gains potential energy from the impact. The potential energy changes to kinetic energy when the ball bounces back up into the air. As the ball gains height, it regains potential energy because of gravity.

Figure 2.5: Energy in a bouncing ball is transformed from potential energy to kinetic energy and then back to potential energy. This cycle of energy changes keeps repeating as long as the ball continues to bounce. The ball rises less on each successive bounce because some energy is used to resist air molecules. (7)

Like the ball, every time you move you have kinetic energy — whether you jump or run or just blink your eyes. Can you think of situations in which you have potential energy? Obvious examples might include when you are standing on a diving board or at the top of a ski slope or bungee jump. What gives you potential energy in all of these situations? The answer is gravity.

States of Matter

The amount of energy in molecules of matter determines the **state of matter**. Matter can exist in one of several different states, including a gas, liquid, or solid state. These different states of matter have different properties, which are illustrated in **Figure** 2.6.

- A **gas** is a state of matter in which atoms or molecules have enough energy to move freely. The molecules come into contact with one another only when they randomly collide. Forces between atoms or molecules are not strong enough to hold them together.
- A **liquid** is a state of matter in which atoms or molecules are constantly in contact but have enough energy to keep changing positions relative to one another. Forces between atoms or molecules are strong enough to keep the molecules together but not strong enough to prevent them from moving.
- A **solid** is a state of matter in which atoms or molecules do not have enough energy to move. They are constantly in contact and in fixed positions relative to one another.

Forces between atoms or molecules are strong enough to keep the molecules together and to prevent them from moving.

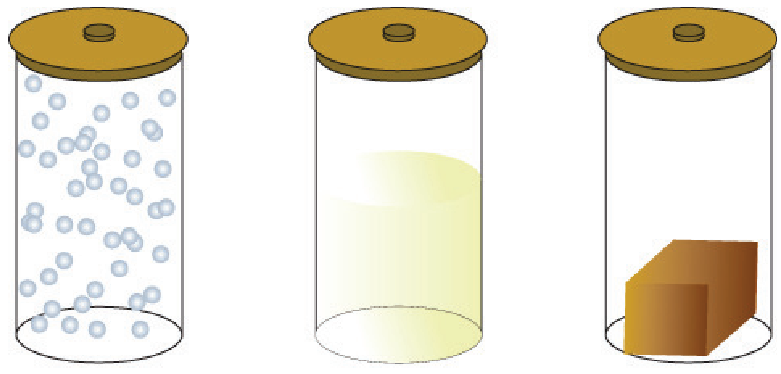

Figure 2.6: States of Matter. (4)

All three containers contain a substance with the same mass, but the substances are in different states. In the left-hand container, the substance is a gas, which has spread to fill its container. It takes both the shape and volume of the container. In the middle container, the substance is a liquid, which has spread to take the shape of its container but not the volume. In the right-hand container, the substance is a solid, which takes neither the shape nor the volume of its container.

What Determines a Substance's State?

Which state a substance is in depends partly on temperature and air pressure. For example, at the air pressure found at sea level, water exists as a liquid at temperatures between 0° C and 100° C. Above 100° C, water exists as a gas (water vapor). Below 0° C, water exists as a solid (ice). Different substances have a different range of temperatures at which they exist in each state. For example, oxygen is gas above -183° C, but iron is a gas only above 2861° C. These differences explain why some substances are always solids at normal Earth temperatures, whereas others are always gases or liquids.

Changing States

Matter constantly goes through cycles that involve changing states. Water and all the elements important to organisms, including carbon and nitrogen, are constantly recycled on Earth (see *Principles of Ecology*). As matter moves through its cycles, it changes state repeatedly. For example, in the water cycle, water repeatedly changes from a gas to a liquid or solid and back to a gas again. How does this happen?

Adding energy to matter gives its atoms or molecules the ability to resist some of the forces holding them together. For example, heating ice to its melting point (0°C) gives its molecules enough energy to move. The ice melts and becomes liquid water. Similarly, heating liquid water to its boiling point (100°C) gives its molecules enough energy to pull apart from one another so they no longer have contact. The liquid water vaporizes and becomes water vapor.

Lesson Summary

- Matter consists of elements and compounds. A compound forms when elements combine in fixed proportions and undergo a chemical reaction. A mixture forms when substances combine in any proportions without a chemical reaction.
- Energy is a property of matter. It cannot be created or destroyed. Organisms obtain light energy from sunlight or chemical energy from food and change the energy into different forms, including heat energy.
- Matter can exist in one of several different states, including a gas, liquid, or solid state. States of matter differ in the amount of energy their molecules have. When matter recycles, it changes state by gaining or losing energy.

Review Questions

1. Define element, and give an example of an element.
2. State how a compound differs from an element, and give an example of a compound.
3. What is energy?
4. What are three common states of matter?
5. Describe two ways that energy changes form in the following sequence of events.
   (a) A plant grows in the sun. → A rabbit eats the plant.
6. Describe a real-life situation in which the energy of an object or person changes back and forth between kinetic energy and potential energy. Identify each time energy changes form.
7. Compare and contrast mixtures and compounds.
8. Explain what happens to molecules of matter when matter changes state from a liquid to a gas.

Further Reading / Supplemental Links

- David Bodanis, *$E = mc^2$: A Biography of the World's Most Famous Question.* Walker and Co., 2005.
- John Emsley, *Nature's Building Blocks: An A-Z Guide to the Elements.* Oxford University Press, 2003.

- Nevin Katz, *Elements, Compounds, and Mixtures: Middle and High School (Mr. Birdley Teaches Science).* Incentive Publications, 2007.
- http://en.wikipedia.org

Vocabulary

chemical compound Unique substance with a fixed composition that forms when atoms of two or more elements react.

element Pure substance made up of just one type of atom.

energy Property of matter that is defined as the ability to do work.

gas State of matter in which atoms or molecules have enough energy to move freely.

kinetic energy Form of energy that an object has when it is moving.

liquid State of matter in which atoms or molecules are constantly in contact but have enough energy to keep changing positions relative to one another.

matter All the substances of which things are made.

mixture Combination of chemical substances that does not have a fixed composition and does not result from a chemical reaction.

organic compound Type of chemical compound that contains carbon and hydrogen and is found mainly in organisms.

potential energy Form of energy that is stored in an object due to its position.

solid State of matter in which atoms or molecules do not have enough energy to move.

state of matter Condition that matter is in, depending on how much energy its atoms or molecules have.

Points to Consider

Like all living things, you contain many organic compounds. For example, your brain is using the organic compound glucose as you read these words. Glucose provides brain cells with energy.

- What are some other organic compounds in your body?
- What roles do you think other organic compounds might play?
- Why are organic compounds able to carry out these roles?
- How do organic compounds differ from inorganic compounds?

2.2 Lesson 2.2: Organic Compounds

Lesson Objectives

- Explain why **carbon** is essential to life on Earth.
- Describe the structure and function of carbohydrates.
- Describe the structure and function of lipids.
- Describe the structure and function of proteins.
- Describe the structure and function of nucleic acids.

Introduction

Organic compounds are chemical substances that make up organisms and carry out life processes. All organic compounds contain the elements carbon and hydrogen. Because carbon is the major element in organic compounds, it is essential to all known life on Earth. Without carbon, life as we know it could not exist.

The Significance of Carbon

Why is carbon so important to organisms? The answer lies with carbon's unique properties. Carbon has an exceptional ability to bind with a wide variety of other elements. Carbon atoms can form multiple stable bonds with other small atoms, including hydrogen, oxygen, and nitrogen. Carbon atoms can also form stable bonds with other carbon atoms. In fact, a carbon atom may form single, double, or even triple bonds with other carbon atoms. This allows carbon atoms to form a tremendous variety of very large and complex molecules.

Nearly 10 million carbon-containing organic compounds are known. Types of carbon compounds in organisms include carbohydrates, lipids, proteins, and nucleic acids. The elements found in each type are listed in Table 1. Elements other than carbon and hydrogen usually occur within organic compounds in smaller groups of elements called **functional groups**. When organic compounds react with other compounds, generally just the functional groups are involved. Therefore, functional groups generally determine the nature and functions of organic compounds.

Table 2.1: **Organic Compounds**

Type of Compound	Elements It Contains	Examples
Carbohydrates	Carbon, hydrogen, oxygen	Glucose, Starch, Glycogen
Lipids	Carbon, hydrogen, oxygen	Cholesterol, Triglycerides (fats) Phospholipids
Proteins	Carbon, hydrogen, oxygen, nitrogen, sulfur	Enzymes, Antibodies
Nucleic Acids	Carbon, hydrogen, oxygen, nitrogen, phosphorus	Deoxyribonucleic acid (DNA) Ribonucleic acid (RNA)

This table lists the four types of organic compounds, the elements they contain, and examples of each type of compound.

Carbohydrates

Carbohydrates are organic compounds that contain only carbon, hydrogen, and oxygen. They are the most common of the four major types of organic compounds. There are thousands of different carbohydrates, but they all consist of one or more smaller units called monosaccharides.

Monosaccharides and Disaccharides

The general formula for a **monosaccharide** is:

$(CH_2O)_n$,

where n can be any number greater than two. For example, if n is 6, then the formula can be written:

$C_6H_{12}O_6$.

This is the formula for the monosaccharide glucose. Another monosaccharide, fructose, has the same chemical formula as glucose, but the atoms are arranged differently. Molecules with the same chemical formula but with atoms in a different arrangement are called isomers. Compare the glucose and fructose molecules in **Figure** 2.7. Can you identify their differences? The only differences are the positions of some of the atoms. These differences affect the properties of the two monosaccharides.

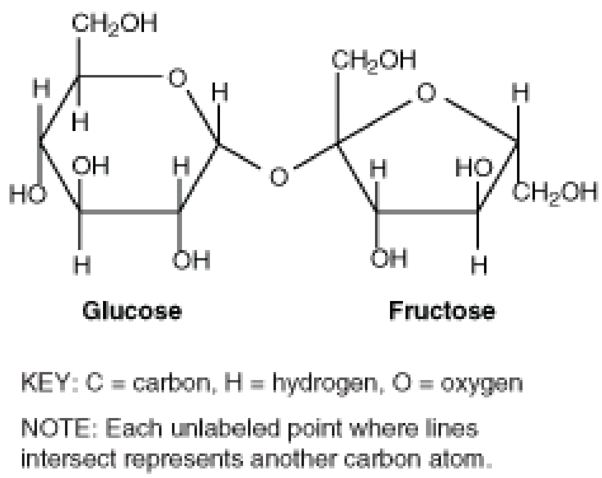

Figure 2.7: Sucrose Molecule. This sucrose molecule is a disaccharide. It is made up of two monosaccharides: glucose on the left and fructose on the right. (15)

If two monosaccharides bond together, they form a carbohydrate called a **disaccharide**. An example of a disaccharide is sucrose (table sugar), which consists of the monosaccharides glucose and fructose (**Figure** 2.7). Monosaccharides and disaccharides are also called **simple sugars**. They provide the major source of energy to living cells.

Polysaccharides

If more than two monosaccharides bond together, they form a carbohydrate called a **polysaccharide**. A polysaccharide may contain anywhere from a few monosaccharides to several thousand monosaccharides. Polysaccharides are also called **complex carbohydrates**. Their main functions are to store energy and form structural tissues. Examples of several polysaccharides and their roles are listed in Table 2.

Table 2.2: **Complex Carbohydrates**

Complex Carbohydrate	Function	Organism
Amylose	Stores energy	Plants
Glycogen	Stores energy	Animals
Cellulose	Forms cell walls	Plants
Chitin	Forms external skeleton	Some animals

These complex carbohydrates play important roles in living organisms.

Lipids

Lipids are organic compounds that contain mainly carbon, hydrogen, and oxygen. They include substances such as fats and oils. Lipid molecules consist of fatty acids, with or without additional molecules. **Fatty acids** are organic compounds that have the general formula $CH_3(CH_2)_nCOOH$, where n usually ranges from 2 to 28 and is always an even number.

Saturated and Unsaturated Fatty Acids

Fatty acids can be saturated or unsaturated. The term saturated refers to the placement of hydrogen atoms around the carbon atoms. In a **saturated fatty acid**, all the carbon atoms (other than the carbon in the -COOH group) are bonded to as many hydrogen atoms as possible (usually two hydrogens). Saturated fatty acids do not contain any other groups except -COOH. This is why they form straight chains, as shown in **Figure** 2.8. Because of this structure, saturated fatty acids can be packed together very tightly. This allows organisms to store chemical energy very densely. The fatty tissues of animals contain mainly saturated fatty acids.

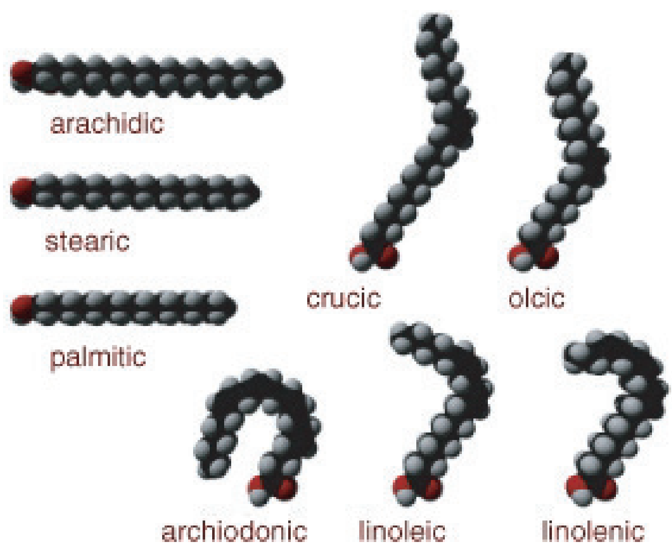

Figure 2.8: Saturated and Unsaturated Fatty Acids. Saturated fatty acids include arachidic, stearic, and palmitic fatty acids, shown on the left in this figure. Unsaturated fatty acids include all the other fatty acids in the figure. Notice how all the unsaturated fatty acids have bent chains, whereas the saturated fatty acids have straight chains. (24)

In an **unsaturated fatty acid**, some carbon atoms are not bonded to as many hydrogen atoms as possible. This is because they are bonded to one or more additional groups, including double and triple bonds between carbons. Wherever these other groups bind with carbon, they cause the chain to bend - they do not form straight chains (**Figure** 2.8). This gives unsaturated fatty acids different properties than saturated fatty acids. For example, unsaturated fatty acids are liquids at room temperature whereas saturated fatty acids are solids. Unsaturated fatty acids are found mainly in plants, especially in fatty tissues such as nuts and seeds.

Unsaturated fatty acids occur naturally in the bent shapes shown in **Figure** 2.8. However, unsaturated fatty acids can be artificially manufactured to have straight chains like saturated fatty acids. Called **trans fatty acids**, these synthetic lipids were commonly added to foods, until it was found that they increased the risk for certain health problems. Many food manufacturers no longer use trans fatty acids for this reason.

Types of Lipids

Lipids may consist of fatty acids alone or in combination with other compounds. Several types of lipids consist of fatty acids combined with a molecule of alcohol:

- **Triglycerides** are the main form of stored energy in animals. This type of lipid is commonly called fat. A triglyceride is shown in **Figure** 2.9.
- **Phospholipids** are a major component of the membranes surrounding the cells of all organisms.
- **Steroids** (or sterols) have several functions. The sterol **cholesterol** is an important part of cell membranes and plays other vital roles in the body. Other steroids are male and female sex hormones (see *Reproductive System and Human Development*).

Lipids and Diet

Humans need lipids for many vital functions, such as storing energy and forming cell membranes. Lipids can also supply cells with energy. In fact, a gram of lipids supplies more than twice as much energy as a gram of carbohydrates or proteins. Lipids are necessary in the diet for most of these functions. Although the human body can manufacture most of the lipids it needs, there are others, called **essential fatty acids**, that must be consumed in food. Essential fatty acids include omega-3 and omega-6 fatty acids. Both of these fatty acids are needed for important biological processes, not just for energy.

Although some lipids in the diet are essential, excess dietary lipids can be harmful. Because lipids are very high in energy, eating too many may lead to unhealthy weight gain. A high-fat diet may also increase lipid levels in the blood. This, in turn, can increase the risk for

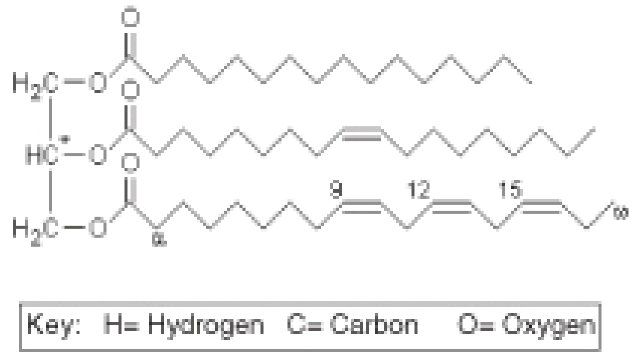

Figure 2.9: Triglyceride Molecule. The left part of this triglyceride molecule represents glycerol. Each of the three long chains on the right represents a different fatty acid. From top to bottom, the fatty acids are palmitic acid, oleic acid, and alpha-linolenic acid. The chemical formula for this triglyceride is $C_{55}H_{98}O_6$. KEY:H=hydrogen, C=carbon, O=oxygen (13)

health problems such as cardiovascular disease (see Circulatory and Respiratory Systems). The dietary lipids of most concern are saturated fatty acids, trans fats, and cholesterol. For example, cholesterol is the lipid mainly responsible for narrowing arteries and causing the disease atherosclerosis.

Proteins

Proteins are organic compounds that contain carbon, hydrogen, oxygen, nitrogen, and, in some cases, sulfur. Proteins are made of smaller units called **amino acids**. There are 20 different common amino acids needed to make proteins. All amino acids have the same basic structure, which is shown in **Figure** 2.10. Only the side chain (labeled R in the figure) differs from one amino acid to another. The variable side chain gives each amino acid unique properties. Proteins can differ from one another in the number and sequence (order) of amino acids. It is because of the side chains of the amino acids that proteins with different amino acid sequences have different shapes and different chemical properties.

Small proteins can contain just a few hundred amino acids. Yeast proteins average 466 amino acids. The largest known proteins are the titins, found in muscle, which are composed from almost 27,000 amino acids.

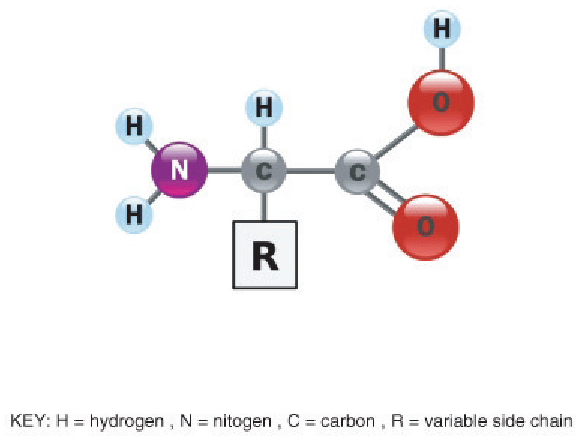

Figure 2.10: General Structure of Amino Acids. This model shows the general structure of all amino acids. Only the side chain, R, varies from one amino acid to another. For example, in the amino acid glycine, the side chain is simply hydrogen (H). In glutamic acid, in contrast, the side chain is CH_2CH_2COOH. Variable side chains give amino acids acids different chemical properties. The order of amino acids, together with the properties of the amino acids, determines the shape of the protein, and the shape of the protein determines the function of the protein. KEY: H = hydrogen, N = nitrogen, C = carbon, O = oxygen, R = variable side chain (18)

Protein Structure

Amino acids can bond together to form short chains called **peptides** or longer chains called **polypeptides** (**Figure** 2.11). Polypeptides may have as few as 40 amino acids or as many as several thousand. A protein consists of one or more polypeptide chains. The sequence of amino acids in a protein's polypeptide chain(s) determines the overall structure and chemical properties of the protein. Primary protein structure is sequence of a chain of amino acids.

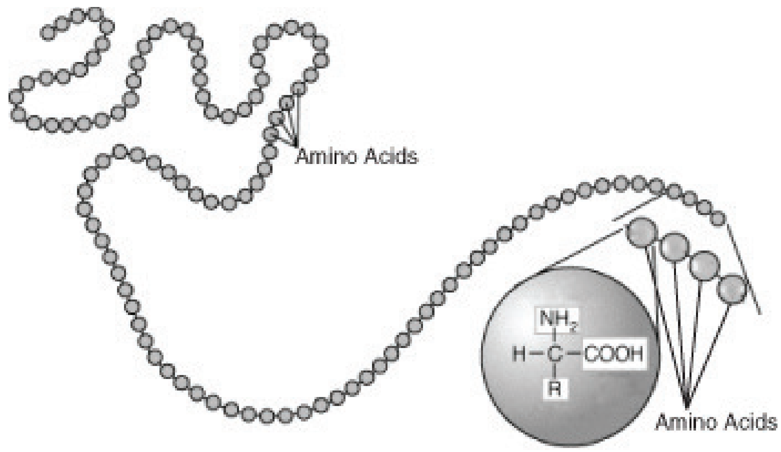

Figure 2.11: Polypeptide. This polypeptide is a chain made up of many linked amino acids. (22)

The amino acid sequence is the primary structure of a protein. As explained in **Figure** 2.12, a protein may have up to four levels of structure, from primary to quaternary. The complex structure of a protein allows it to carry out its biological functions.

Functions of Proteins

Proteins are an essential part of all organisms. They play many roles in living things. Certain proteins provide a scaffolding that maintains the shape of cells. Proteins also make up the majority of muscle tissues. Many proteins are enzymes that speed up chemical reactions in cells (see the *Chemical Reactions* lesson). Other proteins are antibodies. They bond to foreign substances in the body and target them for destruction (see the Immune System and Disease chapter). Still other proteins help carry messages or materials in and out of cells or around the body. For example, the blood protein hemoglobin bonds with oxygen and carries it from the lungs to cells throughout the body.

One of the most important traits of proteins, allowing them to carry out these functions, is their ability to bond with other molecules. They can bond with other molecules very specifically and tightly. This ability, in turn, is due to the complex and highly specific structure of protein molecules.

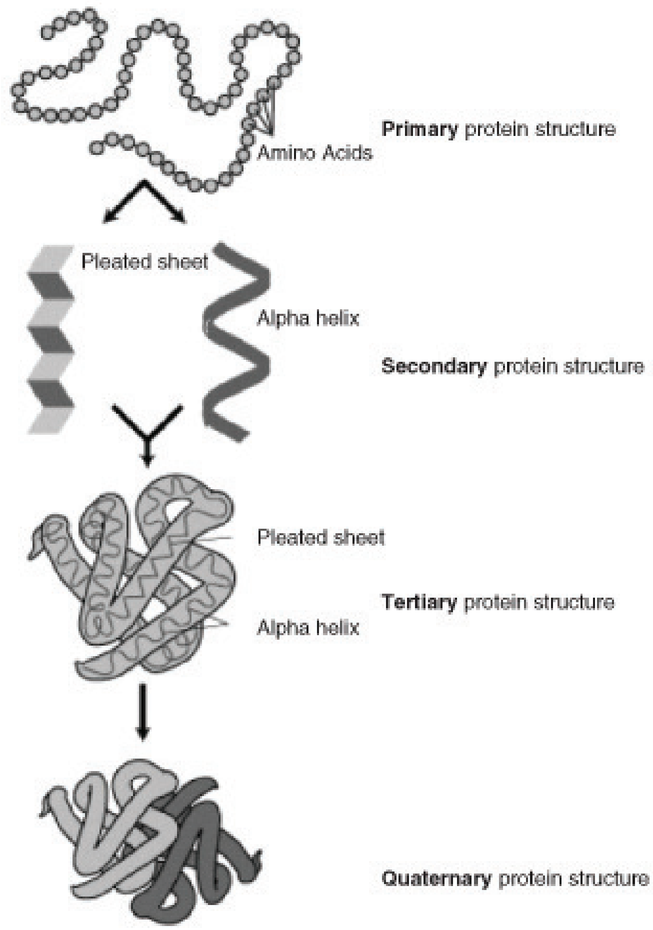

Figure 2.12: Protein Structure. Primary protein structure is the sequence of amino acids in a single polypeptide. Secondary protein structure refers to internal shapes, such as alpha helices and beta sheets, that a single polypeptide takes on due to bonds between atoms in different parts of the polypeptide. Tertiary protein structure is the overall three-dimensional shape of a protein consisting of one polypeptide. Quaternary protein structure is the shape of a protein consisting of two or more polypeptides. For a brief animation of protein structure, see www.stolaf.edu/people/giannini/flashanimat/proteins/protein%20structure.swf. (11)

Proteins and Diet

Proteins in the diet are necessary for life. Dietary proteins are broken down into their component amino acids when food is digested. Cells can then use the components to build new proteins. Humans are able to synthesize all but eight of the twenty common amino acids. These eight amino acids, called **essential amino acids**, must be consumed in foods. Like dietary carbohydrates and lipids, dietary proteins can also be broken down to provide cells with energy.

Nucleic Acids

Nucleic acids are organic compounds that contain carbon, hydrogen, oxygen, nitrogen, and phosphorus. They are made of smaller units called **nucleotides**. Nucleic acids are named for the nucleus of the cell, where some of them are found. Nucleic acids are found not only in all living cells but also in viruses. Types of nucleic acids include **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**.

Structure of Nucleic Acids

A nucleic acid consists of one or two chains of nucleotides held together by chemical bonds. Each individual nucleotide unit consists of three parts:

- a base (containing nitrogen)
- a sugar (ribose in RNA, deoxyribose in DNA)
- a phosphate group (containing phosphorus)

The sugar of one nucleotide binds to the phosphate group of the next nucleotide. Alternating sugars and phosphate groups form the backbone of a nucleotide chain, as shown in **Figure** 2.13. The bases, which are bound to the sugars, stick out at right angles from the backbone of the chain.

RNA consists of a single chain of nucleotides, and DNA consists of two chains of nucleotides. Bonds form between the bases on the two chains of DNA and hold the chains together (**Figure** 2.13). There are four different types of bases in a nucleic acid molecule: cytosine, adenine, guanine, and either thymine (in DNA) or uracil (in RNA). Each type of base bonds with just one other type of base. Cytosine and guanine always bond together, and adenine and thymine (or uracil) always bond with one another. The pairs of bases that bond together are called **complementary bases**.

The binding of complementary bases allows DNA molecules to take their well-known shape, called a **double helix**. **Figure** 2.14 shows how two chains of nucleotides form a DNA double helix. A simplified double helix is illustrated in **Figure** 2.15. It shows more clearly

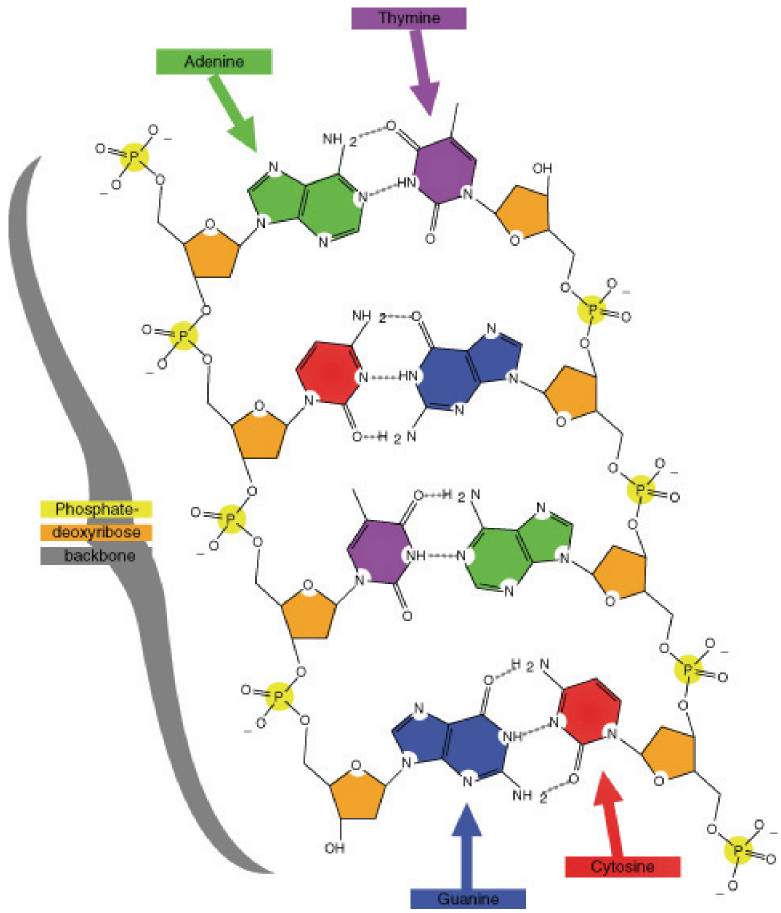

Figure 2.13: Part of a Nucleic Acid. This small section of a nucleic acid shows how phosphate groups (yellow) and sugars (orange) alternate to form the backbone of a nucleotide chain. The bases that jut out to the side from the backbone are adenine (green), thymine (purple), cytosine (pink), and guanine (blue). Bonds between complementary bases, such as between adenine and thymine, hold the two chains of nucleotides together. These bonds, called hydrogen bonds, are described in Lesson 2.4. (2)

how the two chains are intertwined. The double helix shape forms naturally and is very strong. Being intertwined, the two chains are difficult to break apart. This is important given the fundamental role of DNA in all living organisms.

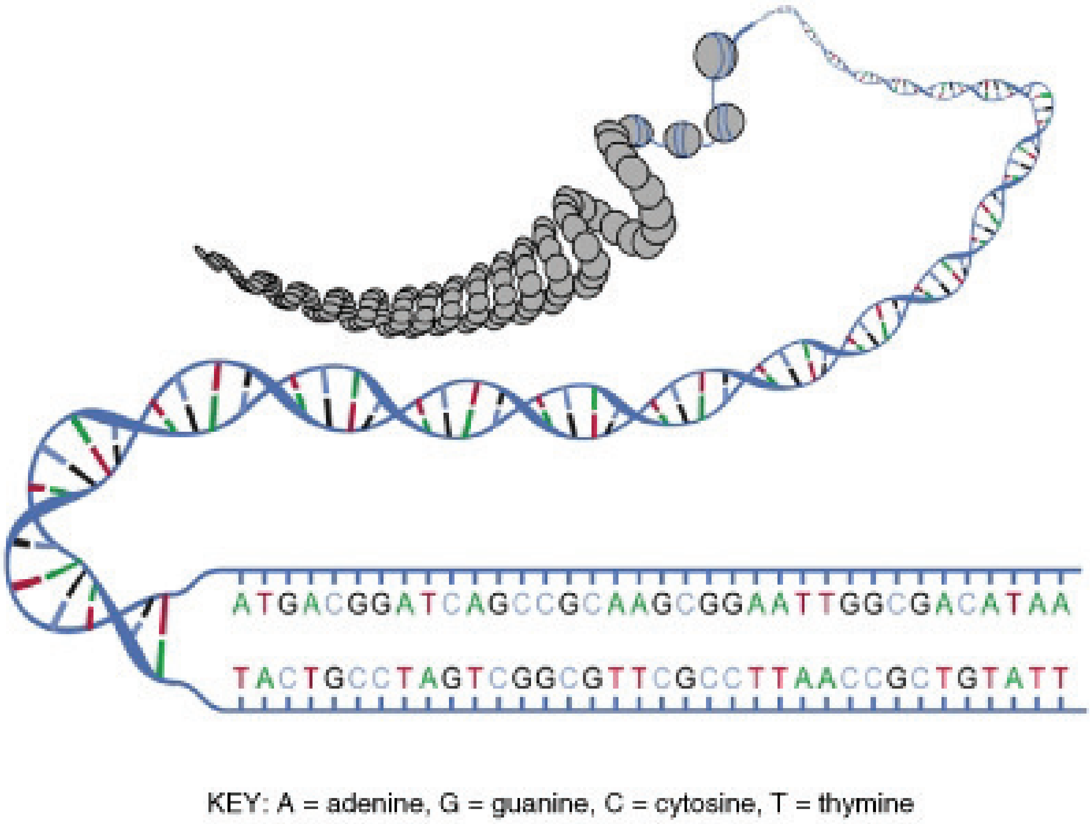

Figure 2.14: Double-Stranded Nucleic Acid. In this double-stranded nucleic acid, complementary bases (A and T, C and G) form bonds that hold the two nucleotide chains together in the shape of a double helix. Notice that A always bonds with T and C always bonds with G. These bonds help maintain the double helix shape of the molecule. (25)

Role of Nucleic Acids

The order of bases in nucleic acids is highly significant. The bases are like the letters of a four-letter alphabet. These "letters" can be combined to form "words." Groups of three bases form words of the genetic code. Each code word stands for a different amino acid. A series of many code words spells out the sequence of amino acids in a protein (**Figure** 2.16). In short, nucleic acids contain the information needed for cells to make proteins. This

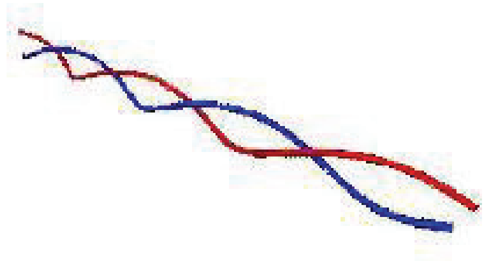

Figure 2.15: Simple Model of DNA. In this simple model of DNA, each line represents a nucleotide chain. The double helix shape forms when the two chains wrap around the same axis. (10)

information is passed from a body cell to its daughter cells when the cell divides. It is also passed from parents to their offspring when organisms reproduce.

How RNA codes for Proteins

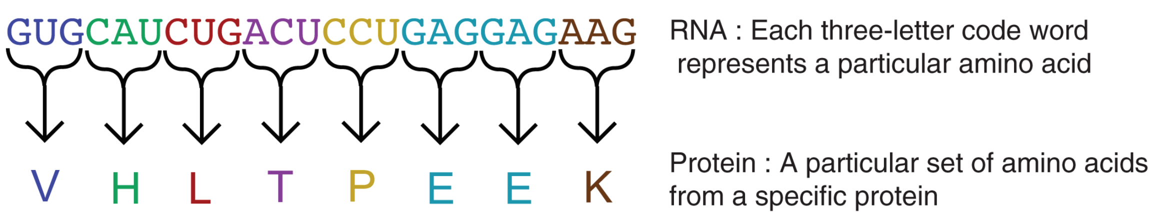

Figure 2.16: The letters G, U, C, and A stand for the bases in RNA. Each group of three bases makes up a code word, and each code word represents one amino acid (represented here by a single letter, such as V, H, or L). A string of code words specifies the sequence of amino acids in a protein. (26)

DNA and RNA have different functions relating to the genetic code and proteins. Like a set of blueprints, DNA contains the genetic instructions for the correct sequence of amino acids in proteins. RNA uses the information in DNA to assemble the amino acids and make the proteins. You will read more about the genetic code and the role of nucleic acids in protein synthesis in Chapter 8.

Lesson Summary

- Carbon's exceptional ability to form bonds with other elements and with itself allows it to form a huge number of large, complex molecules called organic molecules. These molecules make up organisms and carry out life processes.
- Carbohydrates are organic molecules that consist of carbon, hydrogen, and oxygen. They are made up of repeating units called saccharides. They provide cells with energy, store energy, and form structural tissues.
- Lipids are organic compounds that consist of carbon, hydrogen, and oxygen. They are made up of fatty acids and other compounds. They provide cells with energy, store energy, and help form cell membranes.
- Proteins are organic compounds that consist of carbon, hydrogen, oxygen, nitrogen, and, in some cases, sulfur. They are made up of repeating units called amino acids. They provide cells with energy, form tissues, speed up chemical reactions throughout the body, and perform many other cellular functions.
- Nucleic acids are organic compounds that consist of carbon, hydrogen, oxygen, nitrogen, and phosphorus. They are made up of repeating units called nucleotides. They contain genetic instructions for proteins, help synthesize proteins, and pass genetic instructions on to daughter cells and offspring.

Review Questions

1. State the function of monosaccharides, such as glucose and fructose.
2. Why do molecules of saturated and unsaturated fatty acids have different shapes?
3. What determines the primary structure of a protein?
4. Identify the three parts of a nucleotide.
5. What type of organic compound is represented by the formula $CH_3(CH_2)_4COOH$? How do you know?
6. Bases in nucleic acids are represented by the letters A, G, C, and T (or U). How are the bases in nucleic acids like the letters of an alphabet.
7. Why is carbon essential to all known life on Earth?
8. Compare and contrast simple sugars and complex carbohydrates.
9. State two functions of proteins, and explain how the functions depend on the ability of proteins to bind other molecules to them.

Further Reading / Supplemental Links

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- Michael I. Gurr, John L. Harwood, and Keith N. Frayn, *Lipid Biochemistry: An Introduction*. Wiley, 2005.

- James D. Watson, *The Double Helix: A Personal Account of the Discovery of DNA*. Touchstone, 2001.
- David Whitford, *Proteins: Structure and Functions.* Wiley, 2005.
- http://en.wikipedia.org

Vocabulary

amino acid Small organic molecule that is a building block of proteins.

carbohydrate Type of organic compound that consists of one or more smaller units called monosaccharides.

cholesterol Type of steroid that is an important part of cell membranes and plays other vital roles.

complementary bases Nucleic acid bases that form bonds with each other and help hold together two nucleotide chains.

complex carbohydrate Another term for a polysaccharide.

deoxyribonucleic acid (DNA) Double-stranded nucleic acid that contains the genetic instructions for proteins.

disaccharide Small carbohydrate, such as sucrose, that consists of two monosaccharides.

double helix Normal shape of a DNA molecule in which two chains of nucleotides are intertwined.

essential amino acids Amino acids that the human body needs but cannot make and must consume in food.

essential fatty acids Fatty acids that the human body needs but cannot make and must consume in food.

fatty acid Organic compound found in lipids that has the general formula $CH_3(CH_2)_nCOOH$.

functional group Small group of elements within an organic compound that determines the nature and function of the organic compound.

lipid Type of organic compound that consists of one or more fatty acids with or without additional molecules.

monosaccharide Small carbohydrate, such as glucose, with the general formula $(CH_2O)_n$.

nucleic acid Type of organic compound that consists of smaller units called nucleotides.

nucleotide Small organic molecule that is a building block of nucleic acids.

peptide Short chain of amino acids.

phospholipid Type of lipid that is a major component of cell membranes.

polypeptide Long chain of amino acids.

polysaccharide Large carbohydrate that consists of more than two monosaccharides.

protein Type of organic compound that consists of smaller units called amino acids.

ribonucleic acid (RNA) Single-stranded nucleic acid that uses information contained in DNA to assemble amino acids and make proteins.

saturated fatty acid Type of fatty acid in which all the carbon atoms are bonded to as many hydrogen atoms as possible.

simple sugar Another term for a monosaccharide or disaccharide.

steroid Type of lipid that has several functions, such as forming cell membranes and acting as sex hormones.

trans fatty acid Artificial, unsaturated fatty acid that has properties similar to saturated fatty acids.

triglyceride Type of lipid that is the main form of stored energy in animals.

unsaturated fatty acid Type of fatty acid in which some carbon atoms are not bonded to as many hydrogen atoms as possible.

Points to Consider

Organisms are made up of thousands of very large, complex molecules called organic molecules. These molecules consist of repeating units of smaller molecules, such as amino acids or nucleotides.

- How do organic molecules form?
- How do smaller molecules join together to form larger molecules?
- What chemical processes are involved?

2.3 Lesson 2.3: Chemical Reactions

Lesson Objectives

- Describe what happens in a chemical reaction, and identify types of chemical reactions.
- Explain the role of energy in chemical reactions, and define activation energy.
- State factors that affect the rate of chemical reactions.
- Explain the importance of enzymes in organisms, and describe how enzymes work.

Introduction

A chemical compound may be very different from the substances that combine to form it. For example, the element chlorine (Cl) is a poisonous gas, but when it combines with sodium (Na) to form sodium chloride (NaCl), it is no longer toxic. You may even eat it on your food. Sodium chloride is just table salt. What process changes a toxic chemical like chlorine into a much different substance like table salt?

What are Chemical Reactions?

A **chemical reaction** is a process that changes some chemical substances into other chemical substances. The substances that start a chemical reaction are called **reactants**. The substances that form as a result of a chemical reaction are called **products**. During the reaction, the reactants are used up to create the products. For example, when methane burns in oxygen, it releases carbon dioxide and water. In this reaction, the reactants are methane (CH_4) and oxygen (O_2), and the products are carbon dioxide (CO_2) and water (H_2O).

Chemical Equations

A chemical reaction can be represented by a chemical equation. Using the same example, the burning of methane gas can be represented by the equation:

$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$.

The arrow in a chemical equation separates the reactants from the products and shows the direction in which the reaction occurs. If the reaction could also occur in the opposite direction, then two arrows, one pointing in each direction, would be used. On each side of the arrow, a mixture of chemicals is indicated by the chemical symbols joined by a plus sign (+). The numbers preceding some of the chemical symbols (such as 2 O_2) indicate how many molecules of the chemicals are involved in the reaction. (If there is no number in front of a chemical symbol, it means that just one molecule is involved.)

In a chemical reaction, the quantity of each element does not change. There is the same amount of each element at the end of the reaction as there was at the beginning. This is reflected in the chemical equation for the reaction. The equation should be balanced. In a balanced equation, the same number of atoms of a given element appear on each side of the arrow. For example, in the equation above, there are four hydrogen atoms on each side of the arrow.

Types of Chemical Reactions

In general, a chemical reaction involves the breaking and forming of chemical bonds. In the methane reaction above, bonds are broken in methane and oxygen, and bonds are formed in carbon dioxide and water. A reaction like this, in which a compound or element burns in oxygen, is called a **combustion reaction**. This is just one of many possible types of chemical reactions. Other types of chemical reactions include synthesis, decomposition, and substitution reactions.

- A **synthesis reaction** occurs when two or more chemical elements or compounds unite to form a more complex product. For example, nitrogen (N_2) and hydrogen (H_2) unite to form ammonia (NH_3):

$N_2 + 3\ H_2 \rightarrow 2\ NH_3$.

- A **decomposition reaction** occurs when a compound is broken down into smaller compounds or elements. For example, water (H_2O) breaks down into hydrogen (H_2) and oxygen (O_2):

$2\ H_2O \rightarrow 2\ H_2 + O_2$.

- A **substitution reaction** occurs when one element replaces another element in a compound. For example, sodium (Na^+) replaces hydrogen (H) in hydrochloric acid (HCl), producing sodium chloride (NaCl) and hydrogen gas (H_2):

$2\ Na^+ + 2\ HCl \rightarrow 2\ NaCl + H_2$.

Chemical Reactions and Energy

Some chemical reactions consume energy, whereas other chemical reactions release energy. Each of the energy changes that occur during a reaction are graphed in **Figure** 2.17. In the reaction on the left, energy is released. In the reaction on the right, energy is consumed.

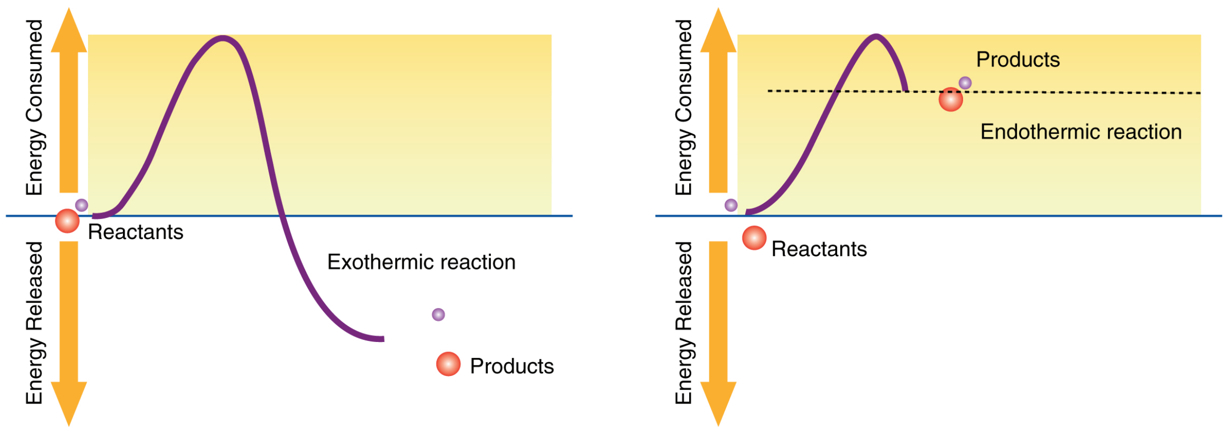

Figure 2.17: The reaction on the left releases energy. The reaction on the right consumes energy. (23)

Exothermic Reactions

Chemical reactions that release energy are called **exothermic reactions**. An example is the combustion of methane described at the beginning of this lesson. In organisms, exothermic reactions are called **catabolic reactions**. Catabolic reactions break down molecules into smaller units. An example is the breakdown of glucose molecules for energy. Exothermic reactions can be represented by the general chemical equation:

Reactants $\rightarrow$ Products + Heat.

Endothermic Reactions

Chemical reactions that consume energy are called **endothermic reactions**. An example is the synthesis of ammonia, described above. In organisms, endothermic reactions are called **anabolic reactions**. Anabolic reactions construct molecules from smaller units. An example is the synthesis of proteins from amino acids. Endothermic reactions can be represented by the general chemical equation:

Reactants + Heat $\rightarrow$ Products.

Activation Energy

Regardless of whether reactions are exothermic or endothermic, they all need energy to get started. This energy is called **activation energy**. Activation energy is like the push you need to start moving down a slide. The push gives you enough energy to start moving. Once you start, you keep moving without being pushed again. The concept of activation energy is illustrated in **Figure** 2.18.

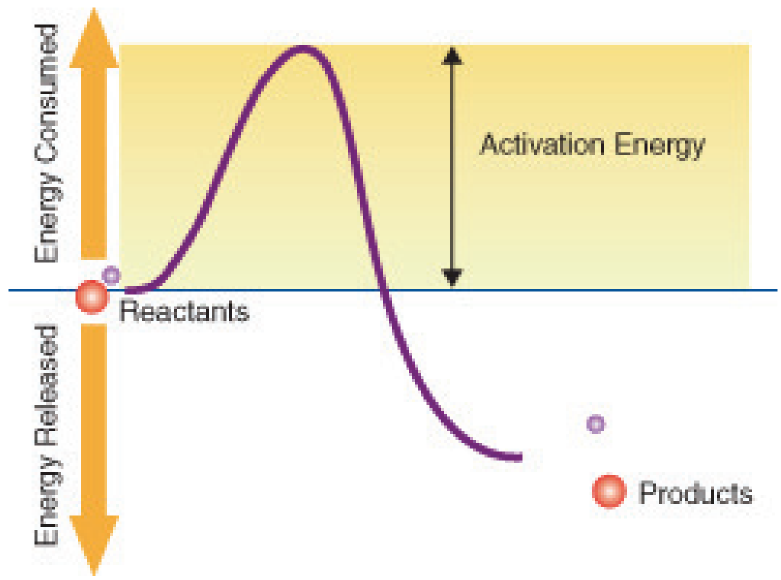

Figure 2.18: To start this reaction, a certain amount of energy is required, called the activation energy. How much activation energy is required depends on the nature of the reaction and the conditions under which the reaction takes place. (5)

Why do reactions need energy to get started? In order for reactions to occur, three things must happen, and they all require energy:

- Reactant molecules must collide. To collide, they must move, so they need kinetic energy.
- Unless reactant molecules are positioned correctly, intermolecular forces may push them apart. To overcome these forces and move together requires more energy.
- If reactant molecules collide and move together, there must be enough energy left for them to react.

Rates of Chemical Reactions

The rates at which chemical reactions take place in organisms are very important. Chemical reactions in organisms are involved in processes ranging from the contraction of muscles to the digestion of food. For example, when you wave goodbye, it requires repeated contractions of muscles in your arm over a period of a couple of seconds. A huge number of reactions must take place in that time, so each reaction cannot take longer than a few milliseconds. If the reactions took much longer, you might not finish waving until sometime next year.

Factors that help reactant molecules collide and react speed up chemical reactions. These factors include the concentration of reactants and the temperature at which the reactions occur.

- Reactions are usually faster at higher concentrations of reactants. The more reactant molecules there are in a given space, the more likely they are to collide and react.

- Reactions are usually faster at higher temperatures. Reactant molecules at higher temperatures have more energy to move, collide, and react.

Enzymes and Biochemical Reactions

Most chemical reactions within organisms would be impossible under the conditions in cells. For example, the body temperature of most organisms is too low for reactions to occur quickly enough to carry out life processes. Reactants may also be present in such low concentrations that it is unlikely they will meet and collide. Therefore, the rate of most biochemical reactions must be increased by a catalyst. A catalyst is a chemical that speeds up chemical reactions. In organisms, catalysts are called **enzymes**.

Like other catalysts, enzymes are not reactants in the reactions they control. They help the reactants interact but are not used up in the reactions. Instead, they may be used over and over again. Unlike other catalysts, enzymes are usually highly specific for particular chemical reactions. They generally catalyze only one or a few types of reactions.

Enzymes are extremely efficient in speeding up reactions. They can catalyze up to several million reactions per second. As a result, the difference in rates of biochemical reactions with and without enzymes may be enormous. A typical biochemical reaction might take hours or even days to occur under normal cellular conditions without an enzyme but less than a second with the enzyme. For an animation of a reaction in the presence or absence of an enzyme, see http://www.stolaf.edu/people/giannini/flashanimat/enzymes/prox-orien.swf.

How Enzymes Work

How do enzymes speed up biochemical reactions so dramatically? Like all catalysts, enzymes work by lowering the activation energy of chemical reactions. This is illustrated in **Figure** 2.19. The biochemical reaction shown in the figure requires about three times as much activation energy without the enzyme as it does with the enzyme. An animation of this process can be viewed at `http://www.stolaf.edu/people/giannini/flashanimat/enzymes/transition%20state.swf.`

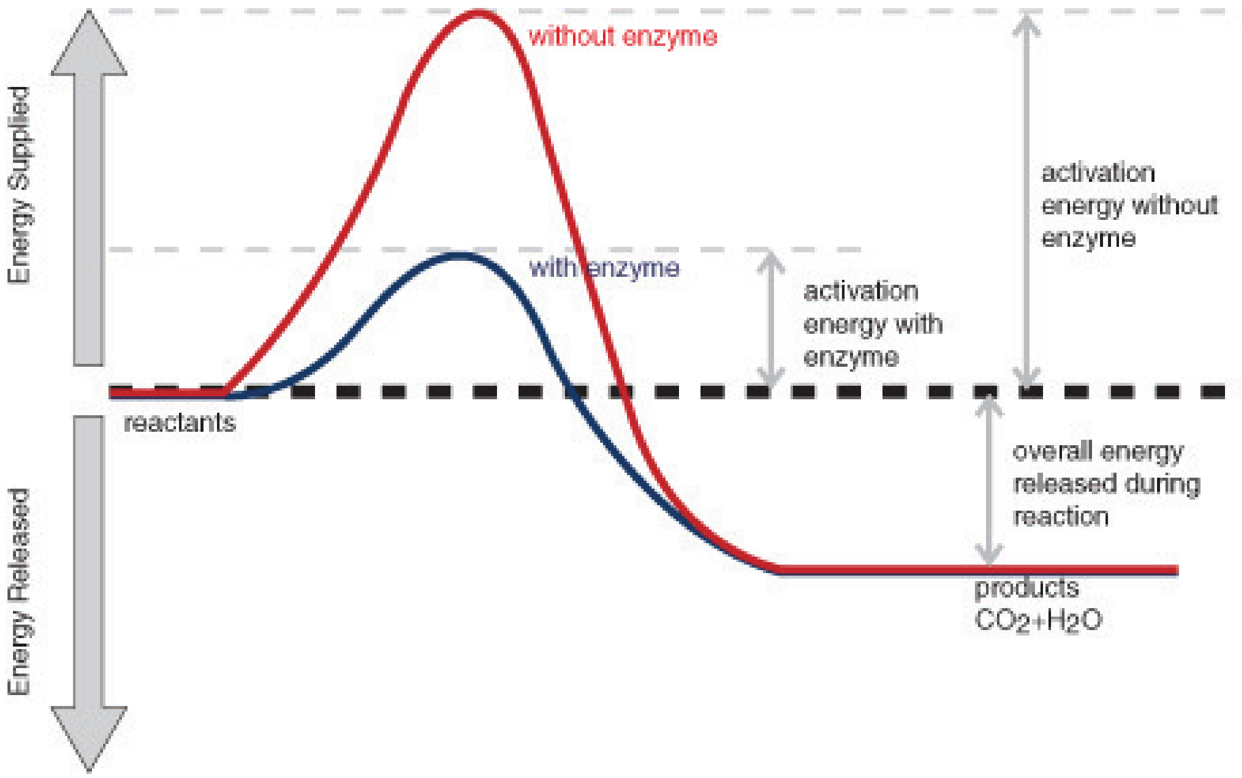

Figure 2.19: The reaction represented by this graph is a combustion reaction involving the reactants glucose ($C_6H_{12}O_6$) and oxygen (O_2). The products of the reaction are carbon dioxide (CO_2) and water (H_2O). Energy is also released during the reaction. The enzyme speeds up the reaction by lowering the activation energy needed for the reaction to start. Compare the activation energy with and without the enzyme. (14)

Enzymes generally lower activation energy by reducing the energy needed for reactants to come together and react. For example:

- Enzymes bring reactants together so they don't have to expend energy moving about until they collide at random. Enzymes bind both reactant molecules (called substrate), tightly and specifically, at a site on the enzyme molecule called the active site (**Figure** 2.20).

- By binding reactants at the active site, enzymes also position reactants correctly, so they do not have to overcome intermolecular forces that would otherwise push them apart. This allows the molecules to interact with less energy.

- Enzymes may also allow reactions to occur by different pathways that have lower activation energy.

The activities of enzymes also depend on the temperature, ionic conditions, and the pH of the surroundings.

Some enzymes work best at acidic pHs, while others work best in neutral environments.

- Digestive enzymes secreted in the acidic environment (low pH) of the stomach help break down proteins into smaller molecules. The main digestive enzyme in the stomach is pepsin, which works best at a pH of about 1.5 (see the *Digestive and Excretory Systems* chapter). These enzymes would not work optimally at other pHs. Trypsin is another enzyme in the digestive system which break protein chains in the food into smaller parts. Trypsin works in the small intestine, which is not an acidic environment. Trypsin's optimum pH is about 8.

- Biochemical reactions are optimal at physiological temperatures. For example, most biochemical reactions work best at the normal body temperature of 98.6 ˚F. Many enzymes lose function at lower and higher temperatures. At higher temperatures, an enzyme's shape deteriorates and only when the temperature comes back to normal does the enzyme regain its shape and normal activity.

Importance of Enzymes

Enzymes are involved in most of the chemical reactions that take place in organisms. About 4,000 such reactions are known to be catalyzed by enzymes, but the number may be even higher. Needed for reactions that regulate cells, enzymes allow movement, transport materials around the body, and move substances in and out of cells.

In animals, another important function of enzymes is to help digest food. Digestive enzymes speed up reactions that break down large molecules of carbohydrates, proteins, and fats into smaller molecules the body can use (*See* Chapter: Digestive and Excretory Systems). Without digestive enzymes, animals would not be able to break down food molecules quickly enough to provide the energy and nutrients they need to survive.

Lesson Summary

- A chemical reaction is a process that changes some chemical substances into others. It involves breaking and forming chemical bonds. Types of chemical reactions include

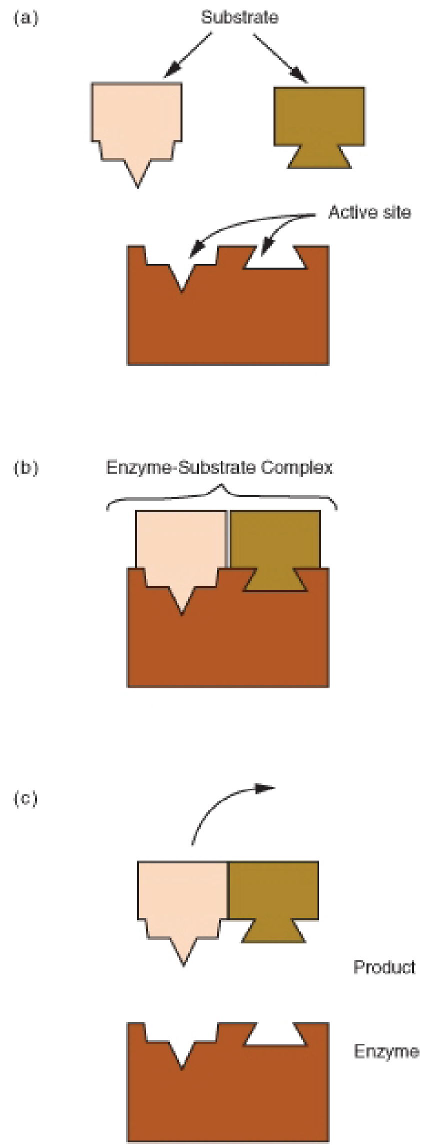

Figure 2.20: This enzyme molecule binds reactant molecules—called substrate—at its active site, forming an enzyme-substrate complex. This brings the reactants together and positions them correctly so the reaction can occur. After the reaction, the products are released from the enzyme's active site. This frees up the enzyme so it can catalyze additional reactions. (9)

synthesis reactions and decomposition reactions.

- Some chemical reactions are exothermic, which means they release energy. Other chemical reactions are endothermic, which means they consume energy. All chemical reactions require activation energy, which is the energy needed to get a reaction started.
- Rates of chemical reactions depend on factors such as the concentration of reactants and the temperature at which reactions occur. Both factors affect the ability of reactant molecules to react.
- Enzymes are needed to speed up chemical reactions in organisms. They work by lowering the activation energy of reactions.

Review Questions

1. Identify the roles of reactants and products in a chemical reaction.
2. What is the general chemical equation for an endothermic reaction?
3. State two factors, other than enzymes, that speed up chemical reactions.
4. How do enzymes work to speed up chemical reactions?
5. What is wrong with the chemical equation below? How could you fix it? $CH_4 + O_2 \rightarrow CO_2 + 2\ H_2O$
6. What type of reaction is represented by the following chemical equation? Explain your answer. $2\ Na + 2\ HCL \rightarrow 2\ NaCl + H_2$
7. Why do all chemical reactions require activation energy?
8. Explain why organisms need enzymes to survive.

Further Reading / Supplemental Links

- Peter Atkins and Julio De Paula, *Physical Chemistry for the Life Sciences.* Oxford University Press, 2006.
- Rita Elkins, *Digestive Enzymes.* Woodland Publishing, 2007.
- James Keeler and Peter Wothers, *Why Chemical Reactions Happen.* Oxford University Press, 2003.
- George W. Roberts, *Chemical Reactions and Chemical Reactors.* Wiley, 2008.
- http://en.wikipedia.org

Summary Animations

- http://www.stolaf.edu/people/giannini/flashanimat

Vocabulary

activation energy Energy needed for a chemical reaction to get started.

anabolic reaction Endothermic reaction that occurs in organisms.

catabolic reaction Exothermic reaction that occurs in organisms.

chemical reaction Process that changes some chemical substances into other chemical substances.

combustion reaction Type of chemical reaction in which a compound or element burns in oxygen.

decomposition reaction Type of chemical reaction in which a compound is broken down into smaller compounds or elements.

endothermic reaction Any chemical reaction that consumes energy.

enzyme Chemical that speeds up chemical reactions in organisms.

exothermic reaction Any chemical reaction that releases energy.

product Substance that forms as a result of a chemical reaction.

reactant Substance involved in a chemical reaction that is present at the beginning of the reaction.

substitution reaction Type of chemical reaction in which one element replaces another element in a compound.

synthesis reaction Type of chemical reaction in which elements or compounds unite to form a more complex product.

Points to Consider

Most chemical reactions in organisms take place in an environment that is mostly water.

- What do you know about water?
- Are you aware that water has unique properties?
- Do you know how water behaves differently from most other substances on Earth?
- Do you know why water is necessary for life?

2.4 Lesson 2.4: Water

Lesson Objectives

- Describe the distribution of Earth's water, and outline the water cycle.
- Identify the chemical structure of water, and explain how it relates to water's unique properties.
- Define solution, and describe water's role as a solvent.
- State how water is used to define acids and bases, and identify the pH ranges of acids and bases.
- Explain why water is essential for life processes.

Introduction

Water, like carbon, has a special role in biology because of its importance to organisms. Water is essential to all known forms of life. Water, H_2O, such a simple molecule, yet it is this simplicity that gives water its unique properties and explains why water is so vital for life.

Water, Water Everywhere

Water is a common chemical substance on Earth. The term water generally refers to its liquid state. Water is a liquid over a wide range of standard temperatures and pressures. However, water can also occur as a solid (ice) or gas (water vapor).

Where Is All the Water?

Of all the water on Earth, about two percent is stored underground in spaces between rocks. A fraction of a percent exists in the air as water vapor, clouds, or precipitation. Another fraction of a percent occurs in the bodies of plants and animals. So where is most of Earth's water? It's on the surface of the planet. In fact, water covers about 70 percent of Earth's surface. Of water on Earth's surface, 97 percent is salt water, mainly in the ocean. Only 3 percent is freshwater. Most of the freshwater is frozen in glaciers and polar ice caps. The remaining freshwater occurs in rivers, lakes, and other freshwater features.

Although clean freshwater is essential to human life, in many parts of the world it is in short supply. The amount of freshwater is not the issue. There is plenty of freshwater to go around, because water constantly recycles on Earth. However, freshwater is not necessarily located where it is needed, and clean freshwater is not always available.

How Water Recycles

Like other matter on Earth, water is continuously recycled. Individual water molecules are always going through the water cycle (see the *Principles of Ecology* chapter). In fact, water molecules on Earth have been moving through the water cycle for billions of years. In this cycle, water evaporates from Earth's surface (or escapes from the surface in other ways), forms clouds, and falls back to the surface as precipitation. This cycle keeps repeating. Several processes change water from one state to another during the water cycle. They include:

- **Evaporation**—Liquid water on Earth's surface changes into water vapor in the atmosphere.
- **Sublimation**—Snow or ice on Earth's surface changes directly into water vapor in the atmosphere.
- **Transpiration**—Plants give off liquid water, most of which evaporates into the atmosphere.
- **Condensation**—Water vapor in the atmosphere changes to liquid water droplets, forming clouds or fog.
- **Precipitation**—Water droplets in clouds are pulled to Earth's surface by gravity, forming rain, snow, or other type of falling moisture.

Chemical Structure and Properties of Water

You are probably already familiar with many of water's properties. For example, you no doubt know that water is tasteless, odorless, and transparent. In small quantities, it is also colorless. However, when a large amount of water is observed, as in a lake or the ocean, it is actually light blue in color. These and other properties of water depend on its chemical structure.

The transparency of water is important for organisms that live in water. Because water is transparent, sunlight can pass through it. Sunlight is needed by water plants and other water organisms for photosynthesis (see *Biomes, Ecosystems, and Communities* chapter).

Chemical Structure of Water

Each molecule of water consists of one atom of oxygen and two atoms of hydrogen, so it has the chemical formula H_2O. The arrangement of atoms in a water molecule, shown in **Figure** 2.21, explains many of water's chemical properties. In each water molecule, the nucleus of the oxygen atom (with 8 positively charged protons) attracts electrons much more strongly than do the hydrogen nuclei (with only one positively charged proton). This results in a negative electrical charge near the oxygen atom (due to the "pull" of the negatively charged electrons toward the oxygen nucleus) and a positive electrical charge near the hydrogen atoms. A difference in electrical charge between different parts of a molecule is called **polarity**. A polar molecule is a molecule in which part of the molecule is positively charged and part of the molecule is negatively charged.

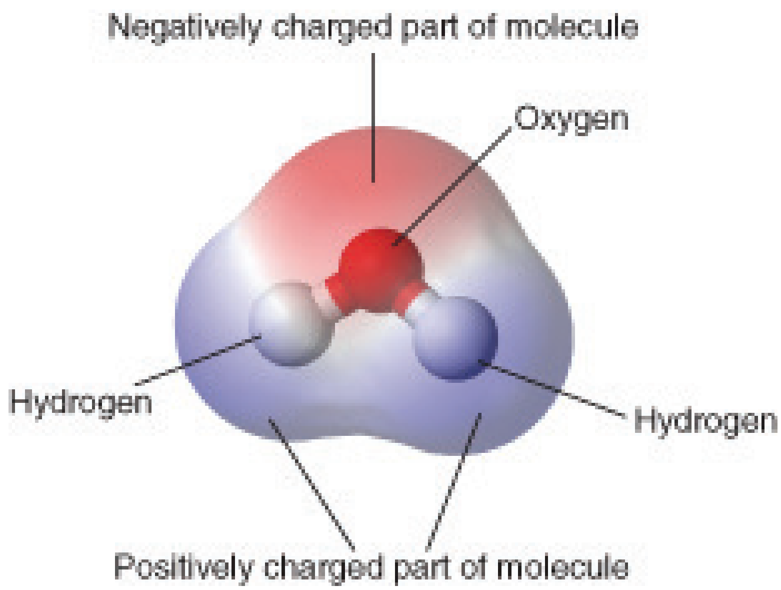

Figure 2.21: This model shows the arrangement of oxygen and hydrogen atoms in a water molecule. The nucleus of the oxygen atom attracts electrons more strongly than do the hydrogen nuclei. As a result, the middle part of the molecule near oxygen has a negative charge, and the other parts of the molecule have a positive charge. In essence, the electrons are "pulled" toward the nucleus of the oxygen atom and away from the hydrogen atom nuclei. Water is a polar molecule, with an unequal distribution of charge throughout the molecule. (21)

Opposite electrical charges attract one another other. Therefore, the positive part of one water molecule is attracted to the negative parts of other water molecules. Because of this attraction, bonds form between hydrogen and oxygen atoms of adjacent water molecules, as demonstrated in **Figure** 2.22. This type of bond always involves a hydrogen atom, so it is called a **hydrogen bond**. Hydrogen bonds are bonds between molecules, and they are not as strong as bonds within molecules. Nonetheless, they help hold water molecules together.

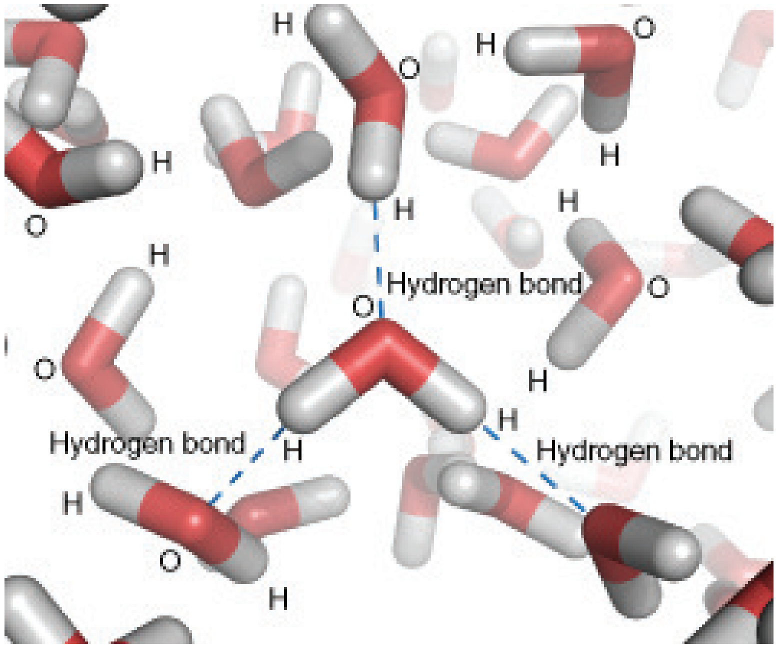

Figure 2.22: Hydrogen bonds form between positively and negatively charged parts of water molecules. The bonds hold the water molecules together. (12)

Hydrogen bonds can also form within a single large organic molecule (see the *Organic Compounds* lesson). For example, hydrogen bonds that form between different parts of a protein molecule bend the molecule into a distinctive shape, which is important for the protein's functions. Hydrogen bonds also hold together the two nucleotide chains of a DNA molecule.

Sticky, Wet Water

Water has some unusual properties due to its hydrogen bonds. One property is the tendency for water molecules to stick together. For example, if you drop a tiny amount of water onto a very smooth surface, the water molecules will stick together and form a droplet, rather than spread out over the surface. The same thing happens when water slowly drips from a leaky faucet. The water doesn't fall from the faucet as individual water molecules but as droplets of water. The tendency of water to stick together in droplets is also illustrated by the dew drops in **Figure** 2.23.

Hydrogen bonds also explain why water's boiling point (100° C) is higher than the boiling points of similar substances without hydrogen bonds. Because of water's relatively high boiling point, most water exists in a liquid state on Earth. Liquid water is needed by all living organisms. Therefore, the availability of liquid water enables life to survive over much of the planet.

Figure 2.23: Droplets of dew cling to a spider web, demonstrating the tendency of water molecules to stick together because of hydrogen bonds. (19)

Density of Ice and Water

The melting point of water is 0° C. Below this temperature, water is a solid (ice). Unlike most chemical substances, water in a solid state has a lower density than water in a liquid state. This is because water expands when it freezes. Again, hydrogen bonding is the reason. Hydrogen bonds cause water molecules to line up less efficiently in ice than in liquid water. As a result, water molecules are spaced farther apart in ice, giving ice a lower density than liquid water. A substance with lower density floats on a substance with higher density. This explains why ice floats on liquid water, whereas many other solids sink to the bottom of liquid water.

In a large body of water, such as a lake or the ocean, the water with the greatest density always sinks to the bottom. Water is most dense at about 4° C. As a result, the water at the bottom of a lake or the ocean usually has temperature of about 4° C. In climates with cold winters, this layer of 4° C water insulates the bottom of a lake from freezing temperatures. Lake organisms such as fish can survive the winter by staying in this cold, but unfrozen, water at the bottom of the lake.

Solutions

Water is one of the most common ingredients in solutions. A **solution** is a homogeneous mixture composed of two or more substances. In a solution, one substance is dissolved in another substance, forming a mixture that has the same proportion of substances throughout. The dissolved substance in a solution is called the **solute**. The substance in which is it dissolved is called the **solvent**. An example of a solution in which water is the solvent is salt water. In this solution, a solid—sodium chloride—is the solute. In addition to a solid dissolved in a liquid, solutions can also form with solutes and solvents in other states of matter. Examples are given in **Table 1**.

Table 2.3:

Solvent	Gas	Liquid	Solid
Gas	Oxygen and other gases in nitrogen (air)		
Liquid	Carbon dioxide in water (carbonated water)	Ethanol (an alcohol) in water	Sodium chloride in water (salt water)
Solid	Hydrogen in metals	Mercury in silver and other metals (dental fillings)	Iron in carbon (steel)

(*Source:* http://en.wikipedia.org/wiki/Solute, *License:* Creative Commons)

The ability of a solute to dissolve in a particular solvent is called **solubility**. Many chemical substances are soluble in water. In fact, so many substances are soluble in water that water is called the universal solvent. Water is a strongly polar solvent, and polar solvents are better at dissolving polar solutes. Many organic compounds and other important biochemicals are polar, so they dissolve well in water. On the other hand, strongly polar solvents like water cannot dissolve strongly nonpolar solutes like oil. Did you ever try to mix oil and water? Even after being well shaken, the two substances quickly separate into distinct layers.

Acids and Bases

Water is the solvent in solutions called acids and bases. To understand acids and bases, it is important to know more about pure water, in which nothing is dissolved. In pure water (such as distilled water), a tiny fraction of water molecules naturally breaks down, or dissociates, to form ions. An **ion** is an electrically charged atom or molecule. The dissociation of pure water into ions is represented by the chemical equation:

$2\ H_2O \rightarrow H_3O^+ + OH^-$.

The products of this reaction are a hydronium ion (H_3O^+) and a hydroxide ion (OH^-). The hydroxide ion is negatively charged. It forms when a water molecule donates, or gives up, a positively charged hydrogen ion. The hydronium ion, modeled in **Figure** 2.24, is positively charged. It forms when a water molecule accepts a positively charged hydrogen ion (H^+).

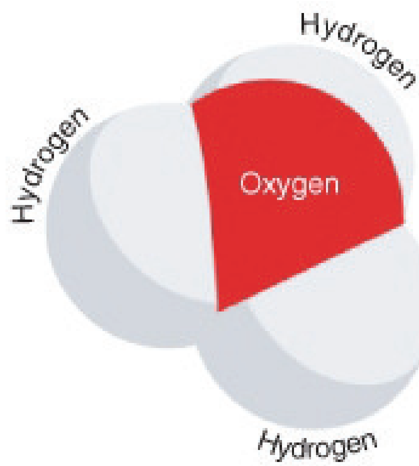

Figure 2.24: A hydronium ion has the chemical formula H_3O^+. The plus sign ($^+$) indicates that the ion is positively charged. How does this molecule differ from the water molecule in **Figure** 2.21? (8)

Acidity and pH

Acidity refers to the hydronium ion concentration of a solution. It is measured by **pH**. In pure water, the hydronium ion concentration is very low. Only about one in ten million water molecules naturally dissociates to form a hydronium ion in pure water. This gives water a pH of 7. The hydronium ions in pure water are also balanced by hydroxide ions, so pure water is neutral (neither an acid nor a base).

Because pure water is neutral, any other solution with the same hydronium ion concentration and pH is also considered to be neutral. If a solution has a higher concentration of hydronium ions and lower pH than pure water, it is called an **acid**. If a solution has a lower concentration of hydronium ions and higher pH than pure water, it is called a **base**. Several acids and bases and their pH values are identified on the pH scale, which ranges from 0 to 14, in **Figure** 2.25.

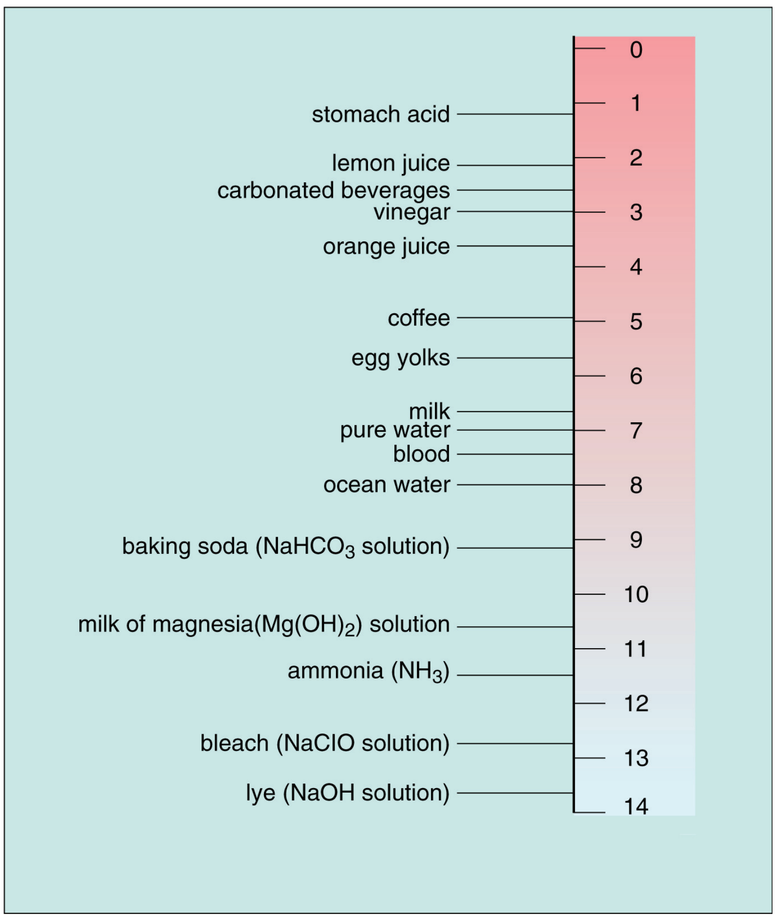

Figure 2.25: **Acidity and the pH Scale** Water has a pH of 7, so this is the point of neutrality on the pH scale. Acids have a pH less than 7, and bases have a pH greater than 7. (1)

The pH scale is a negative logarithmic scale. Because the scale is negative, as the ion concentration increases, the pH value decreases. In other words, the more acidic the solution, the lower the pH value. Because the scale is logarithmic, each one-point change in pH reflects a ten-fold change in the hydronium ion concentration and acidity. For example, a solution with a pH of 6 is ten times as acidic as pure water with a pH of 7.

Acids

An acid can be defined as a hydrogen ion donor. The hydrogen ions bond with water molecules, leading to a higher concentration of hydronium ions than in pure water. For example, when hydrochloric acid (HCl) dissolves in pure water, it donates hydrogen ions (H^+) to water molecules, forming hydronium ions (H_3O^+) and chloride ions (Cl^-). This is represented by the chemical equation:

$HCl + H_2O \rightarrow Cl^- + H_3O^+$.

Strong acids can be harmful to organisms and damaging to materials. Acids have a sour taste and may sting or burn the skin. Testing solutions with litmus paper is an easy way to identify acids. Acids turn blue litmus paper red.

Bases

A base can be defined as a hydrogen ion acceptor. It accepts hydrogen ions from hydronium ions, leading to a lower concentration of hydronium ions than in pure water. For example, when the base ammonia (NH_3) dissolves in pure water, it accepts hydrogen ions (H^+) from hydronium ions (H_3O^+) to form ammonium ions (NH_4^+) and hydroxide ions (OH^-). This is represented by the chemical equation:

$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$.

Like strong acids, strong bases can be harmful to organisms and damaging to materials. Bases have a bitter taste and feel slimy to the touch. They can also burn the skin. Bases, like acids, can be identified with litmus paper. Bases turn red litmus paper blue.

Neutralization

What do you think would happen if you mixed an acid and a base? If you think the acid and base would "cancel each other out," you are right. When an acid and base react, they form a neutral solution of water and a salt (a molecule composed of a positive and negative ion). This type of reaction is called a **neutralization** reaction. For example, when the base sodium hydroxide (NaOH) and hydrochloric acid (HCl) react, they form a neutral solution of water and the salt sodium chloride (NaCl). This reaction is represented by the chemical equation:

$NaOH + HCl \rightarrow NaCl + H_2O$.

In this reaction, hydroxide ions (OH^-) from the base combine with hydrogen ions (H^+) from the acid to form water. The other ions in the solution (Na^+) and (Cl^-) combine to form sodium chloride.

Acids and Bases in Organisms

Enzymes are needed to speed up biochemical reactions. Most enzymes require a specific range of pH in order to do their job. For example, the enzyme pepsin, which helps break down proteins in the human stomach, requires a very acidic environment in order to function. Strong acid is secreted into the stomach, allowing pepsin to work. Once the contents of the stomach enter the small intestine, where most digestion occurs, the acid must be neutralized. This is because enzymes that work in the small intestine need a basic environment. An organ near the small intestine, called the pancreas, secretes bicarbonate ions (HCO_3^-) into the small intestine to neutralize the stomach acid.

Bicarbonate ions play an important role in neutralizing acids throughout the body. Bicarbonate ions are especially important for protecting tissues of the central nervous system from changes in pH. The central nervous system includes the brain, which is the body's control center. If pH deviates too far from normal, the central nervous system cannot function properly. This can have a drastic effect on the rest of the body.

Water and Life

Humans are composed of about 70 percent water (not counting water in body fat). This water is crucial for normal functioning of the body. Water's ability to dissolve most biologically significant compounds—from inorganic salts to large organic molecules—makes it a vital solvent inside organisms and cells.

Water is an essential part of most metabolic processes within organisms. **Metabolism** is the sum total of all body reactions, including those that build up molecules (anabolic reactions) and those that break down molecules (catabolic reactions). In anabolic reactions, water is generally removed from small molecules in order to make larger molecules. In catabolic reactions, water is used to break bonds in larger molecules in order to make smaller molecules.

Water is central to two related, fundamental metabolic reactions in organisms: photosynthesis (*Photosynthesis* chapter) and respiration (*Cellular Respiration* chapter). All organisms depend directly or indirectly on these two reactions.

- In photosynthesis, cells use the energy in sunlight to change water and carbon dioxide into glucose and oxygen. This is an anabolic reaction, represented by the chemical equation:

$6\ CO_2 + 6\ H_2O + \text{energy} \rightarrow C_6H_{12}O_{6,} + 6\ O_2$.

- In cellular respiration, cells break down glucose in the presence of oxygen and release energy, water, and carbon dioxide. This is a catabolic reaction, represented by the chemical equation:

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy}$

Two other types of reactions that occur in organisms and involve water are dehydration and hydration reactions. A dehydration reaction occurs when molecules combine to form a single, larger molecule and also a molecule of water. (If some other small molecule is formed instead of water, the reaction is called by the more general term, condensation reaction.) It is a type of catabolic reaction. An example of a dehydration reaction is the formation of peptide bonds between amino acids in a polypeptide chain. When two amino acids bond together, a molecule of water is lost. This is shown in **Figure** 2.26.

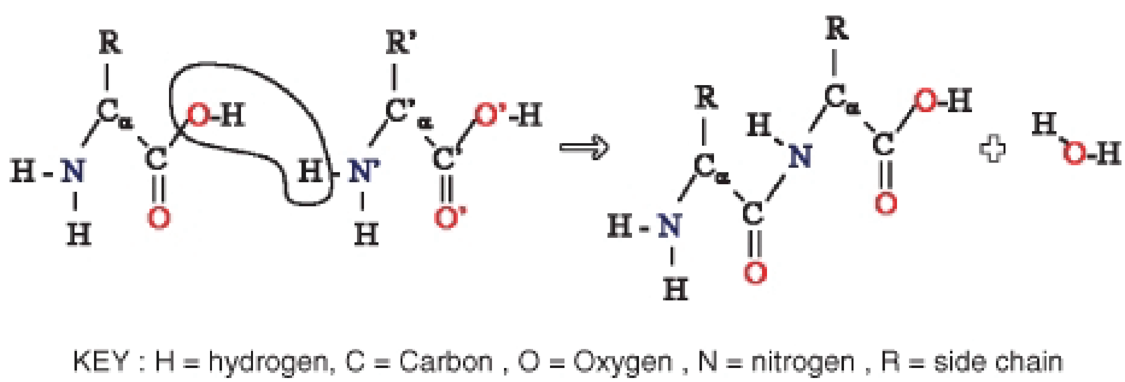

Figure 2.26: In this dehydration reaction, two amino acids form a peptide bond. A water molecule also forms. (20)

A hydration reaction is the opposite of a dehydration reaction. A hydration reaction adds water to an organic molecule and breaks the large molecule into smaller molecules. Hydration reactions occur in an acidic water solution. An example of hydration reaction is the breaking of peptide bonds in polypeptides. A hydroxide ion (OH-) and a hydrogen ion (H+) (both from a water molecule) bond to the carbon atoms that formed the peptide bond. This breaks the peptide bond and results in two amino acids.

Water is essential for all of these important chemical reactions in organisms. As a result, virtually all life processes depend on water. Clearly, without water, life as we know it could not exist.

Lesson Summary

- Most of Earth's water is salt water located on the planet's surface. Water is constantly recycled through the water cycle.
- Water molecules are polar, so they form hydrogen bonds. This gives water unique properties, such as a relatively high boiling point.
- A solution is a homogeneous mixture in which a solute dissolves in a solvent. Water is a very common solvent, especially in organisms.
- The ion concentration of neutral, pure water gives water a pH of 7 and sets the standard for defining acids and bases. Acids have a pH lower than 7, and bases have a pH higher than 7.
- Water is essential for most life processes, including photosynthesis, cellular respiration, and other important chemical reactions that occur in organisms.

Review Questions

1. Where is most of Earth's water?
2. What is polarity, and why is water polar?
3. Define solution, and give an example of a solution.
4. What is the pH of a neutral solution? Why?
5. Draw a circle diagram to represent the water cycle. Identify the states of water and the processes in which water changes state throughout the cycle.
6. What type of reaction is represented by the chemical equation below? Defend your answer. $KOH + HCl \rightarrow KCl + H_2O$
7. Explain how hydrogen bonds cause molecules of liquid water to stick together.
8. Summarize how metabolism in organisms depends on water.

Further Reading / Supplemental Links

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- Robert A. Copeland, Enzymes: A Practical Introduction to Structure, Mechanisms, and Data Analysis. Wiley, 2000.
- Peter Swanson, Water: The Drop of Life. Cowles Creative Publishing, 2001.
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Vocabulary

acid Solution with a higher hydronium ion concentration than pure water and a pH lower than 7.

acidity Hydronium ion concentration of a solution.

base Solution with a lower hydronium ion concentration than pure water and a pH higher than 7.

condensation Process in which water vapor changes to water droplets, forming clouds or fog.

evaporation Process in which liquid water changes into water vapor.

hydrogen bond Bond that forms between a hydrogen atom in one molecule and a different atom in another molecule.

ion Electrically charged atom or molecule.

metabolism Sum total of all body reactions, including those that build up molecules (anabolic reactions) and those that break down molecules (catabolic reactions).

neutralization Chemical reaction in which an acid and a base react to form a neutral solution of water and a salt.

pH Measure of the acidity, or hydronium ion concentration, of a solution.

polarity Difference in electrical charge between different parts of a molecule.

precipitation Rain, snow, sleet, or other type of moisture that falls from clouds.

solubility Ability of a solute to dissolve in a particular solvent.

solute Substance in a solution that is dissolved by the other substance (the solvent).

solution Homogeneous mixture in which one substance is dissolved in another.

solvent Substance in a solution that dissolves the other substance (the solute).

sublimation Process in which snow or ice changes directly into water vapor.

transpiration Process in which plants give off water, most of which evaporates.

Points to Consider

Most life processes take place within cells. You probably know that cells are the microscopic building blocks of organisms.

- What do you think you would see if you could look inside a cell?
- What structures might you see?
- What processes might you observe?

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