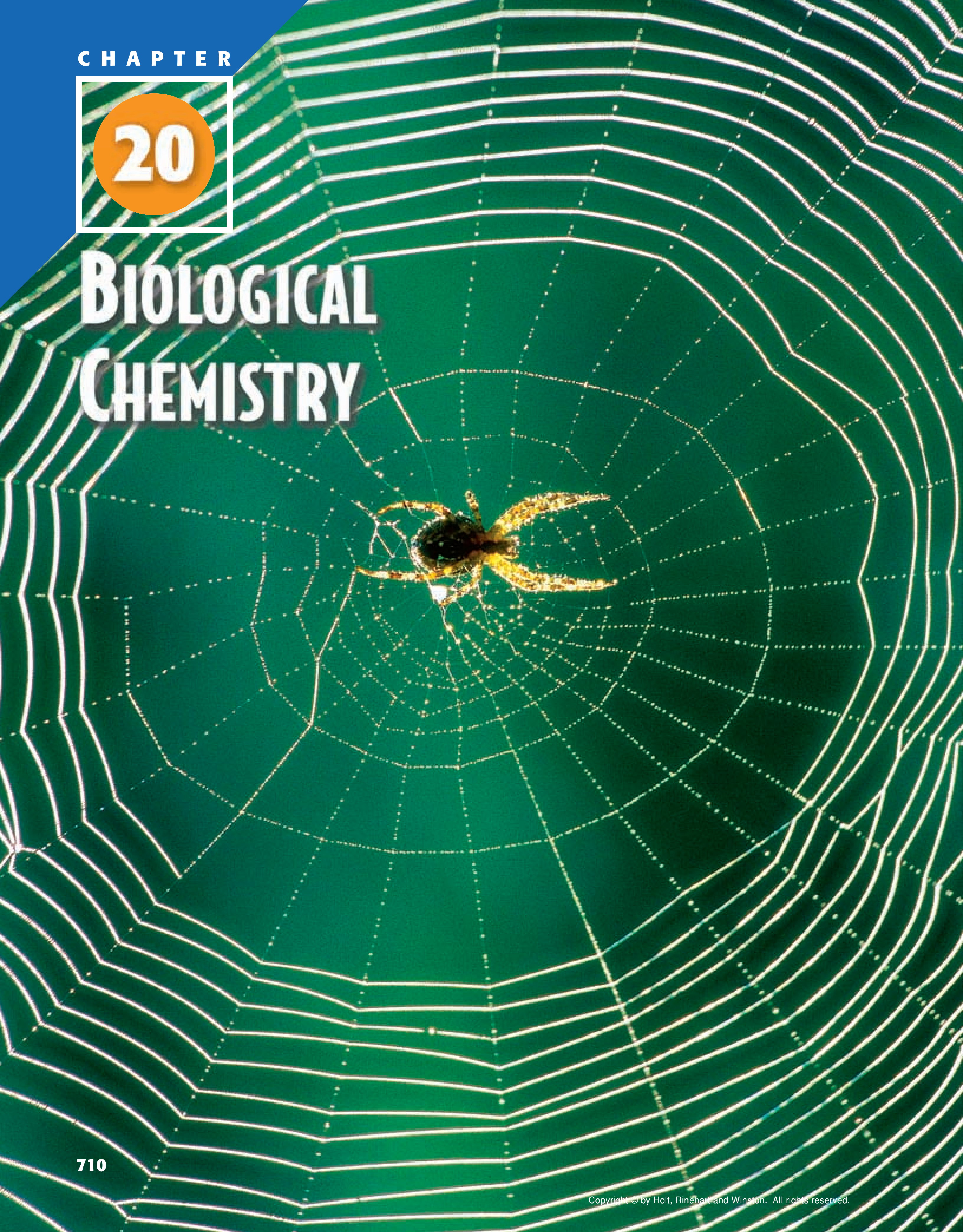
CHAPTER 20

BIOLOGICAL CHEMISTRY



A spider web can stop an insect that is flying at top speed, and a single thread of spider silk can hold the weight of a spider that is large in size. Scientists have marveled that a material as lightweight as spider silk can be so strong. The silk that spiders use to form their webs is made up of a biological chemical—a protein—called fibroin. Scientists are searching for ways to use fibroin to make building materials that are strong and lightweight, like spider silk. The study of spider silk is just one example of how biological chemists are looking to nature to solve problems in the industrial world.

START-UP ACTIVITY

SAFETY PRECAUTIONS

Exploring Carbohydrates

PROCEDURE

1. Measure out one-half teaspoon of **sugar** into a **small beaker.**
2. Measure out one-half teaspoon of **cornstarch** into a **second small beaker.**
3. Your teacher will provide you with a **slice of apple,** a **slice of potato,** and a **slice of turkey.**
4. Add a drop of **iodine solution** to all five samples.

ANALYSIS

1. In the presence of starch, iodine turns dark blue-black. Note which samples test positive for starch.
2. Explain your observations.

Pre-Reading Questions

1. **Describe at least one way that the laws of chemistry apply to living systems.**
2. **What biological molecule contains the information that determines your traits?**
3. **In chemical terms, what is the purpose of the food we eat?**

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SECTION

1 Carbohydrates and Lipids

KEY TERMS

- carbohydrate
- monosaccharide
- disaccharide
- polysaccharide
- condensation reaction
- hydrolysis
- lipid

OBJECTIVES

1. **Describe** the structure of carbohydrates.
2. **Relate** the structure of carbohydrates to their role in biological systems.
3. **Identify** the reactions that lead to the formation and breakdown of carbohydrate polymers.
4. **Describe** a property that all lipids share.

carbohydrate
any organic compound that is made of carbon, hydrogen, and oxygen and that provides nutrients to the cells of living things

monosaccharide
a simple sugar that is the basic subunit of a carbohydrate

disaccharide
a sugar formed from two monosaccharides

polysaccharide
one of the carbohydrates made up of long chains of simple sugars; polysaccharides include starch, cellulose, and glycogen

Carbohydrates in Living Systems

Most of the energy that you get from food comes in the form of **carbohydrates.** For most of us, starch, found in such foods as potatoes, bread, and rice, is our major carbohydrate source. Sugars—in fruit, honey, candy, and many packaged foods—are also carbohydrates. Plants make carbohydrates, such as the starch in potato tubers, shown in **Figure 1.**

Raw potato is difficult to digest because the starch is present in tight granules. Cooking bursts the granules, so that starch can be attacked by our digestive juices. During digestion, the starch is broken down into another carbohydrate called glucose, which—unlike starch—can be carried by the bloodstream.

Carbohydrates are compounds of carbon, hydrogen, and oxygen. They usually have the general formula $C_{6n}H_{10n+2}O_{5n+1}$. When $n = 1$ (6 C atoms), the carbohydrate is a **monosaccharide;** glucose is an example. A **disaccharide** is a carbohydrate with $n = 2$ (12 C atoms). Starch is an example of a **polysaccharide,** in which n can be many thousands.

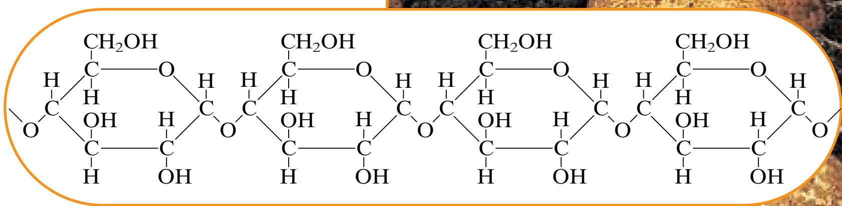

Figure 1
Potatoes have a lot of starch, a polysaccharide.

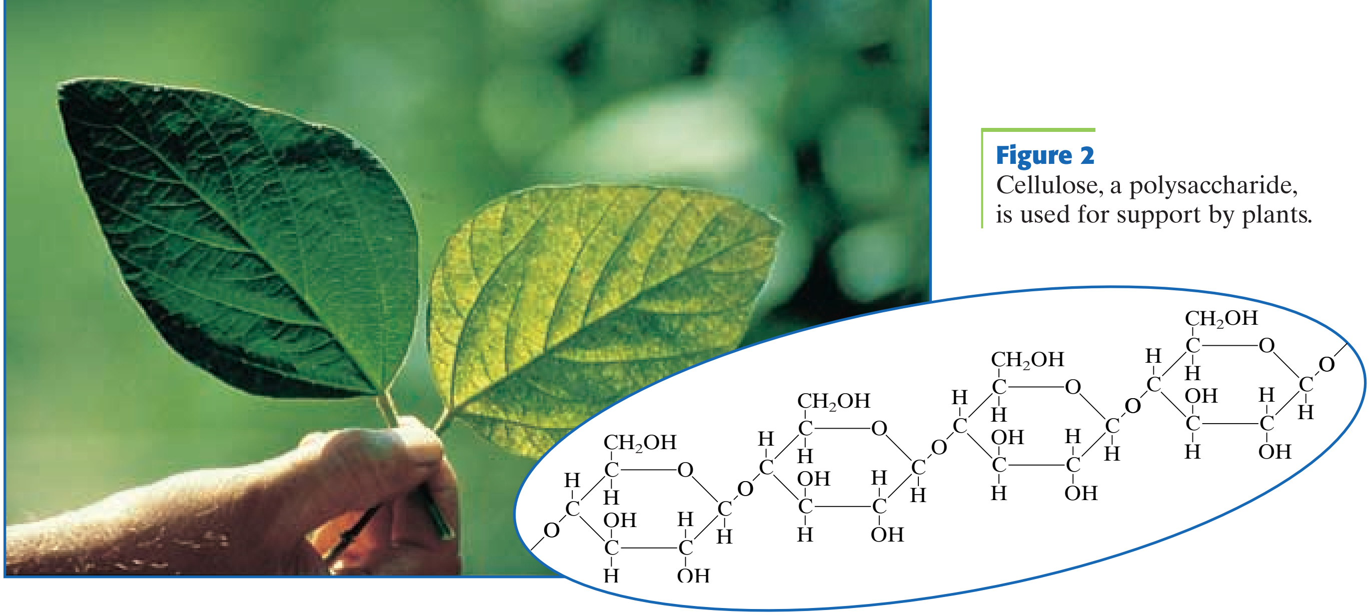

Figure 2
Cellulose, a polysaccharide, is used for support by plants.

Carbohydrates Have Many Functions

Starch is the polysaccharide that plants use for storing energy. Many animals make use of a similar energy-storage carbohydrate called *glycogen*. It is often stored in muscle tissue as an energy source.

Mammals rely on bones and muscles, which are made primarily of proteins, to give their bodies structure and support. However, insects and crustaceans, such as crabs and lobsters, rely on hard shells made of the polysaccharide chitin for structure.

The carbohydrate you come into contact with the most is the one you are looking at right now—cellulose, in paper, which comes from wood fiber. Cellulose is the most abundant organic compound on Earth. It is the polysaccharide that most plants use to give their structures rigidity. The leaves, stems, and roots of these plants are all made of cellulose, shown in **Figure 2.**

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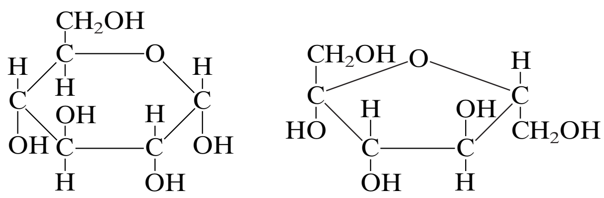
Structure of Simple Sugars

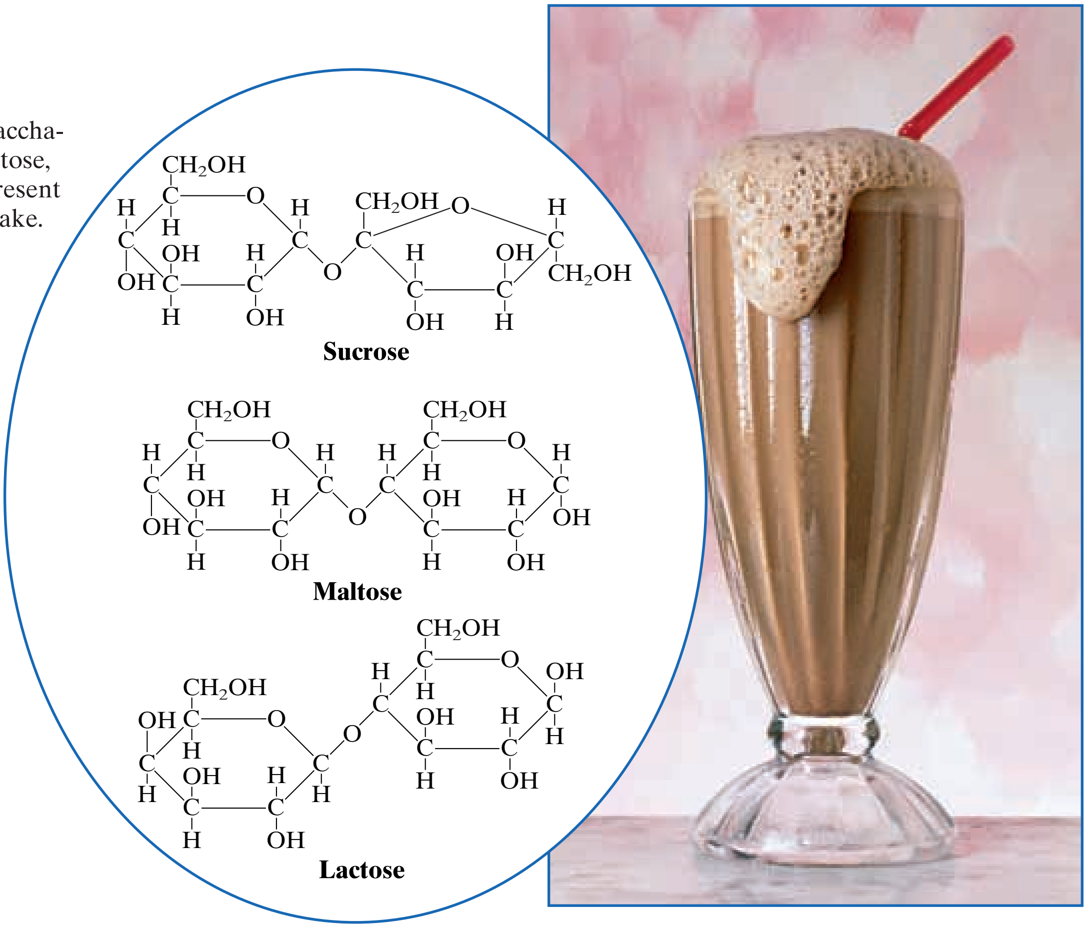
To a chemist, *sugar* is the name given to all monosaccharides and disaccharides. To a cook, *sugar* means one particular disaccharide, sucrose. The cyclic sugar glucose is important to the body because it is the chemical that the bloodstream uses to carry energy to every cell in the body. Shown below are the structures for glucose, $C_6H_{12}O_6$, and fructose, another sugar.



glucose **fructose**

The glucose molecule has a ring made of six atoms—five carbon atoms and one oxygen atom. A sixth carbon atom is part of a $-CH_2OH$ side chain. Four other hydroxyl, $-OH$, groups connect to the carbons in the ring, as do four H atoms. The fructose molecule has a ring of five atoms, four carbon and one oxygen. Fructose has two $-CH_2OH$ side chains. Fructose and glucose have the same molecular formula, $C_6H_{12}O_6$, even though they have very different structures.

Figure 3
Three different disaccharides—sucrose, maltose, and lactose—are present in a malted milk shake.



Sugars Combine to Make Disaccharides

Monosaccharides, such as glucose, have one ring. However, two can combine to form a double-ringed disaccharide. Three examples of disaccharides—lactose, maltose, and sucrose—are found in the malted milk shake shown in **Figure 3.** Notice that the disaccharides are each made up of two monosaccharides. Each molecule of maltose, the sugar that adds to the flavor of malted milk shakes, is made up of two glucose units. Each molecule of sucrose, the sugar you use to sweeten food, is made up of a glucose and a fructose unit.

Structure of Polysaccharides

Topic Link

Refer to the "Carbon and Organic Compounds" chapter for a discussion of polymers.

Just as two monosaccharides combine to form a disaccharide, many monosaccharides or disaccharides can combine to form a long chain called a polysaccharide. Polysaccharides may be represented by the general formula below or by structural models such as the ones shown in **Figures 1 and 2.**

$$\cdots O—(C_6H_{10}O_4)—O—(C_6H_{10}O_4)—O—(C_6H_{10}O_4)—O—(C_6H_{10}O_4)\cdots$$

Earlier, you learned about the linking together of small molecular units in a process known as *polymerization*. Polymerization is a series of synthesis reactions that link many monomers together to make a very large, chainlike molecule. The formation of polysaccharides is similar to polymerization. In fact, polysaccharides and other large, chainlike molecules found in living things are called *biological polymers*. Amylose, a biological polymer listed in **Table 1,** is a form of starch.

Table 1 Types of Carbohydrates

Type	Example	Role
Monosaccharides	fructose	sweetener found in fruits
	glucose	cell fuel
Disaccharides	sucrose	sweetener (table sugar)
Polysaccharides	chitin	insect exoskeleton, support, protection
	amylose	energy storage (plants)
	glycogen	energy storage (animals)

Carbohydrate Reactions

Photosynthesis and respiration, described later, are the main ways that carbohydrates are made and broken down in living systems. These processes are also the primary ways that living things capture and use energy. Thus, carbohydrate reactions play a major role in the chemistry of life.

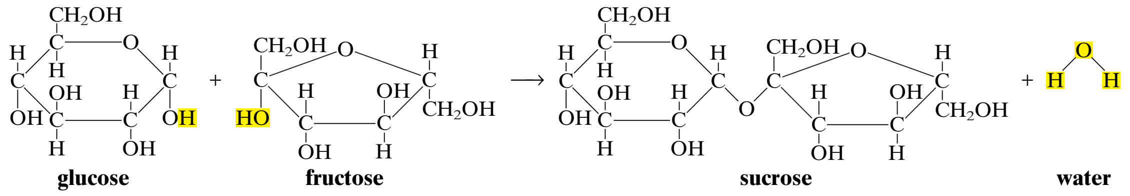
Formation of Disaccharides and Polysaccharides

Because glucose and other sugars dissolve easily in water, they are not useful for long-term energy storage. This is why living things change sugars to starch or glycogen, neither of which is soluble in water.

Disaccharides and polysaccharides are formed from sugars during **condensation reactions,** in which water is a byproduct. Though there are many more steps that are not shown here, the net equation below describes the formation of the disaccharide sucrose.

condensation reaction

a chemical reaction in which two or more molecules combine to produce water or another simple molecule

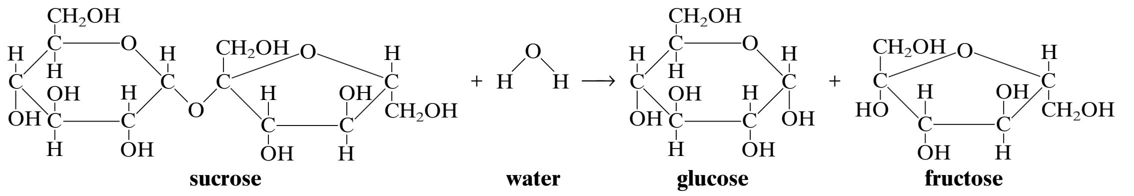


Breakdown of Carbohydrates

When an organism is ready to use energy that was previously stored as a polysaccharide, a different kind of reaction takes place. Polysaccharides are changed back to sugars during **hydrolysis** reactions. In these reactions, the decomposition of a biological polymer takes place along with the breakdown of a water molecule, as shown in the equation below.

hydrolysis

a chemical reaction between water and another substance to form two or more new substances

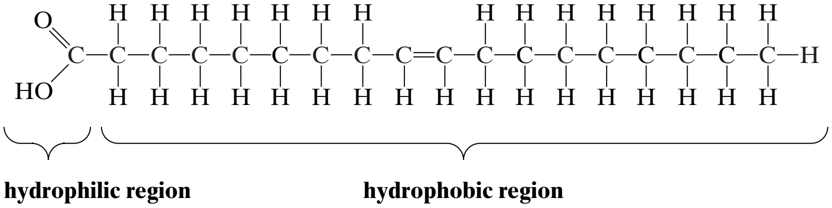


The reaction is the reverse of the condensation reaction by which sucrose formed. In humans, polysaccharides, such as starch and glycogen, and disaccharides, such as sucrose, are broken down in this way to make glucose.

Lipids

lipid
a type of biochemical that does not dissolve in water, including fats and steroids; lipids store energy and make up cell membranes

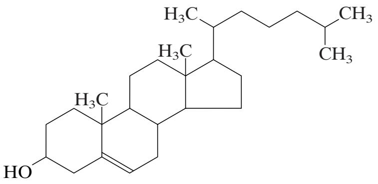
Lipids are a class of biological molecules that do not dissolve in water. However, they generally can have a polar, hydrophilic region at one end of the molecule. For example, the lipid shown below is oleic acid, which is found in the fat of some animals.



The hydrophilic region on the right side of the molecule allows it to interact with polar molecules. The hydrophobic region on the left side of the molecule allows it to interact with nonpolar molecules.

Lipids have a variety of roles in living systems. They are used in animals for energy storage as *fats.* Cell membranes are made up of lipids called *phospholipids. Steroids*—such as cholesterol, shown in **Figure 4**—are lipids used for chemical signaling. Waxes, such as those found in candles and beeswax are also lipids.

Figure 4
Like all steroids, cholesterol has a structure with four connected rings.



1 Section Review

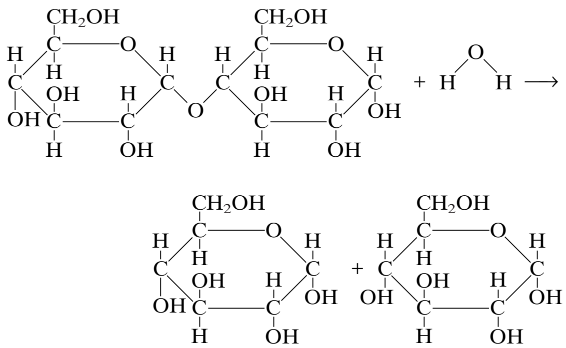
UNDERSTANDING KEY IDEAS

1. Describe the general chemical formula of carbohydrates.
2. What do chemists mean by a *sugar,* and what are the two principal classes of sugars?
3. What role do carbohydrates play in the survival of animals and plants?
4. Name several polysaccharides, and explain the biological role of each.
5. What is the molecular formula of glucose, and what is the role of this compound in human body systems?
6. What names are given to the reactions by which large carbohydrate molecules are built up and broken down?
7. How does the formation of a biological polymer compare to the formation of most manufactured polymers?
8. What property do all lipids share?

CRITICAL THINKING

9. What is the formula of the compound formed by the condensation of two disaccharides?
10. Why do we cook starchy foods?
11. Classify the following carbohydrates into monosaccharides, disaccharides, or polysaccharides: cellulose, glucose, lactose, starch, maltose, sucrose, chitin, and fructose.
12. Why is glycogen often called *animal starch*?
13. **a.** What type of reaction does the following equation describe?

    b. Name the reactants and the products.



SECTION

2 Proteins

KEY TERMS

- **protein**
- **amino acid**
- **polypeptide**
- **peptide bond**
- **enzyme**
- **denature**

OBJECTIVES

1. **Describe** the general amino acid structure.
2. **Explain** how amino acids form proteins through condensation reactions.
3. **Explain** the significance of amino-acid side chains to the three-dimensional structure and function of a protein.
4. **Describe** how enzymes work and how the structure and function of an enzyme is affected by changes in temperature and pH.

Amino Acids and Proteins

A **protein** is a biological polymer that is made up of nitrogen, carbon, hydrogen, oxygen, and sometimes other elements. Our bodies are mostly made out of proteins. For example, the most abundant protein in your body is collagen, which is found in skin and bones. Your hair has structural proteins, such as keratin, shown in **Figure 5.** Proteins in muscles allow your muscles to contract, making body movement possible.

Different proteins have different physical properties. Some—such as casein in milk, ovalbumin in egg whites, and hemoglobin in blood—are water-soluble. Others—such as keratin in hair, fibroin in spider silk, and collagen in connective tissue—are flexible solids.

What do all these proteins have in common? They are all made up of **amino acids.** In the same way that sugars are the building blocks of carbohydrates, amino acids are the building blocks of proteins.

protein
an organic compound that is made of one or more chains of amino acids and that is a principal component of all cells

amino acid
any one of 20 different organic molecules that contain a carboxyl and an amino group and that combine to form proteins

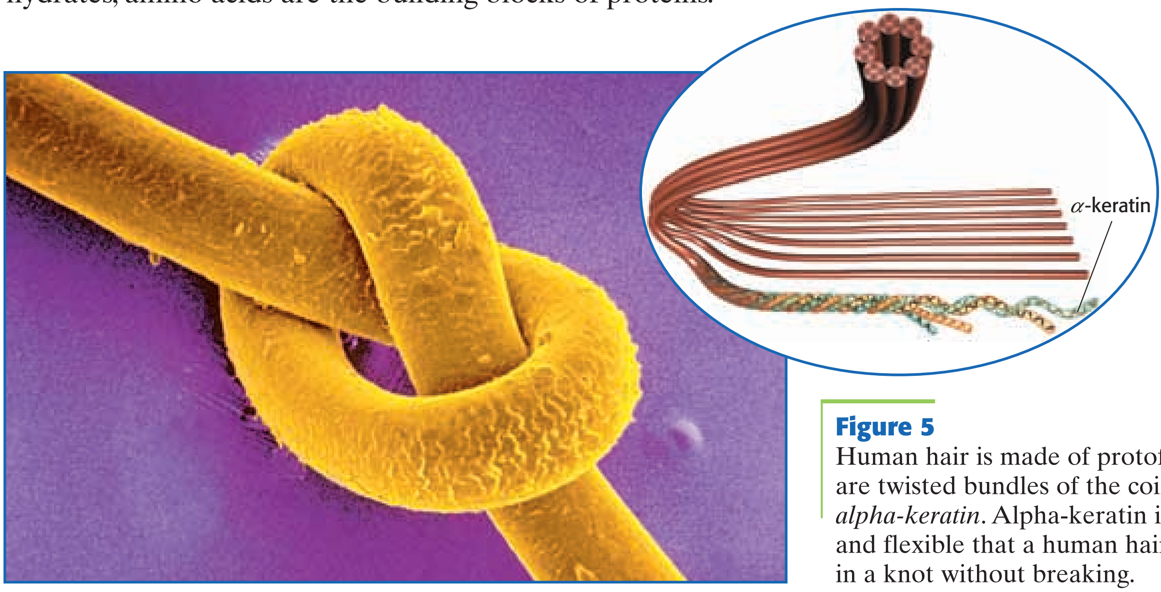
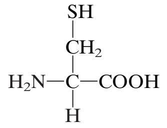
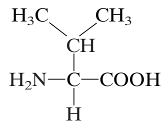
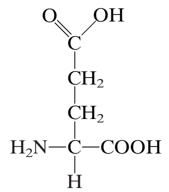
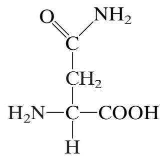
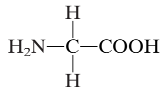
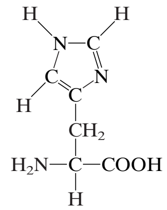


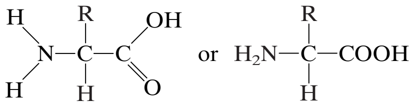
Figure 5
Human hair is made of protofibrils, which are twisted bundles of the coiled protein *alpha-keratin*. Alpha-keratin is so strong and flexible that a human hair can be tied in a knot without breaking.

Table 2 Structures and Roles of Several Amino Acids

Name	Structure	Role	Name	Structure	Role
Cysteine		cross-links to other cysteine units	Valine		contributes to hydrophobicity (nonpolar)
Glutamic acid		gives an acidic side chain	Asparagine		gives hydrogen-bonding sites (polar)
Glycine		acts as a spacer	Histidine		gives a basic side chain

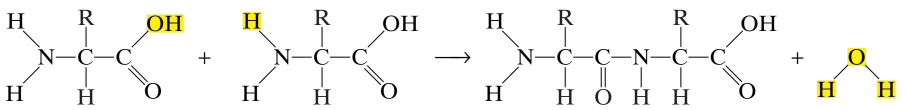
Amino-Acid Structure and Protein Synthesis

Amino refers to the $-NH_2$ group of atoms. Generally, organic acids have the carboxylic acid group, $-COOH$. Thus, *amino acids* are compounds that have both the basic $-NH_2$ and the acidic $-COOH$ groups. There are 20 amino acids from which natural proteins are made. All of them have the same basic structure shown below. The *R* represents a *side chain*.

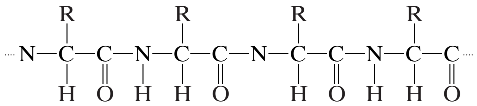


A side chain is a chemical group that differs from one amino acid to another. **Table 2** shows the detailed structure of six of these amino acids.

The reaction by which proteins are made from amino acids is similar to the condensation of carbohydrates. A water molecule forms from the $-OH$ of the carboxylic acid group of one amino acid and an $-H$ of the amino group of another. The condensation of amino acids is shown below.



The biological polymer that forms is called a **polypeptide.** The link that joins the N and C atoms of two different amino acids in a protein is called a **peptide bond.** In protein synthesis, hundreds of peptide bonds are formed one after another. This process makes a long polypeptide chain. The chain's backbone has the pattern –N–C–C–N–C–C–N–C–C–. Half the C atoms have side chains (R), as shown below.



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polypeptide
a long chain of several amino acids

peptide bond
the chemical bond that forms between the carboxyl group of one amino acid and the amino group of another amino acid

Properties and Interactions of Side Chains

The properties of a part of a polypeptide chain depend on the properties of the side chains present. For example, the side chain of glutamic acid is acidic. The side chain of histidine is basic. The side chains of asparagine and several other amino acids are strongly polar. On the other hand, amino acids with nonpolar side groups, such as valine, are nonpolar.

Some amino acid side chains can form ionic or covalent bonds with other side chains. Cysteine is a unique amino acid, because the –SH group in cysteine can form a covalent bond with other cysteine units. Two cysteine units, at different points on a protein molecule, can bond to form a *disulfide bridge,* shown in **Figure 6.** Such bonding can form a looped protein or link two separate polypeptides. In fact, curly hair is a result of the presence of disulfide bridges in hair protein. Some amino acid side chains can form ionic bonds with other amino acid side chains. These bonds also link different points on a protein. For example, glutamic acid can give up a proton to histidine. When this happens, an ionic bond will form between the two amino acids.

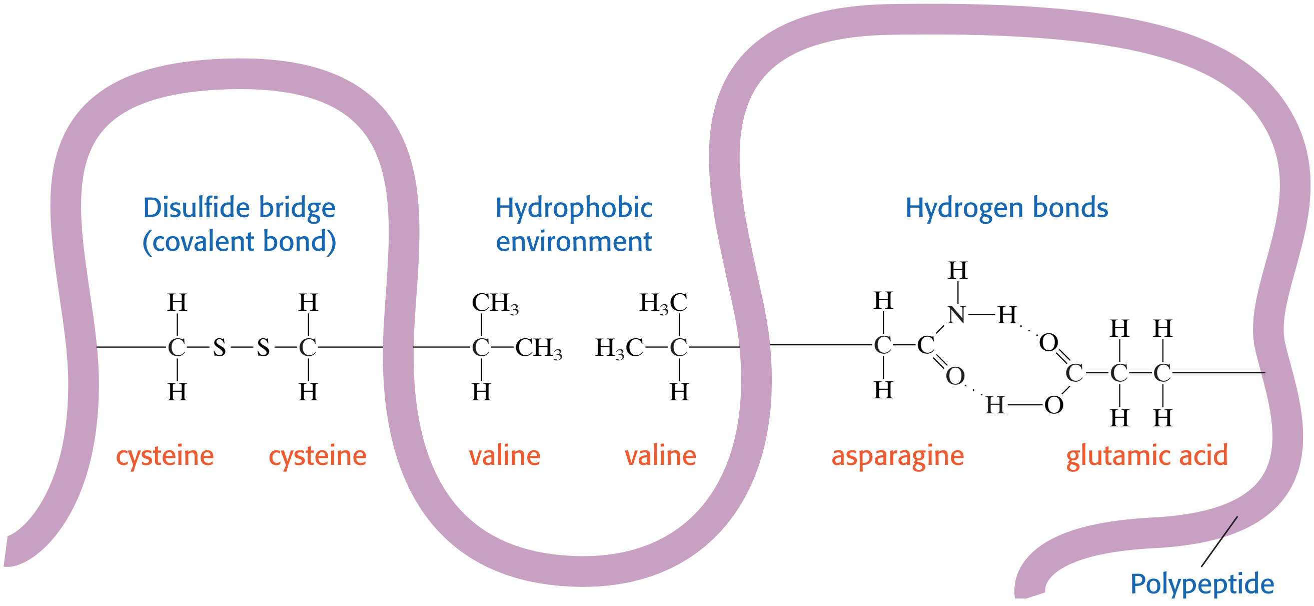
Also, weaker interactions can affect how segments of proteins interact with one another. You have read about these interactions in earlier chapters. Two are shown in **Figure 6.** One of these weak interactions is between the nonpolar hydrocarbon side chains present on many amino acids. These groups are hydrophobic and do not tend to be found in polar and ionic environments. Instead, nonpolar segments of a protein tend to be found with nonpolar molecules or with other nonpolar segments of the same protein.

The side chains of certain amino acids, such as asparagine, allow for another kind of interaction—hydrogen bonding. The hydrogen atoms on hydroxyl groups, –OH, and amino groups, $-NH_2$, are drawn to places where they can hydrogen bond to oxygen atoms, especially to carboxyl groups, –C=O, in the polypeptide backbone or in the side chains.

Topic Link

Refer to the "States of Matter and Intermolecular Forces" chapter for a discussion of intermolecular forces.

Figure 6
Four different kinds of interaction between side chains on a polypeptide molecule help to make the shape that a protein takes. Three are shown here.



Four Levels of Protein Structure

Proteins are not just long polypeptide chains. Because of the interactions of the side chains and other forces, each protein usually folds up into a unique shape. The three-dimensional shape that the chain forms gives characteristic properties to each protein. If a polypeptide chain folds into the wrong shape, it can function differently. It may also be unable to carry out its biological role. The levels of protein structure are shown in **Table 3.**

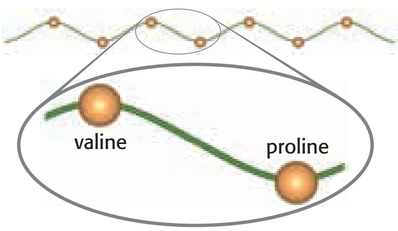
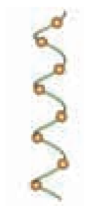
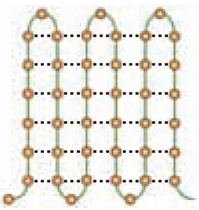
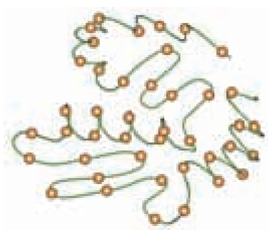
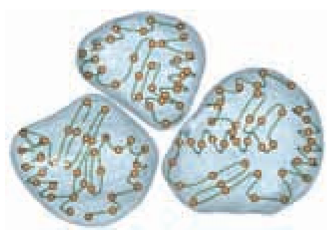
The amino-acid sequence of the polypeptide chain is said to be the *primary structure* of a protein. Thus, the primary structure of a protein is simply the order in which the amino acids bonded together.

Most proteins have segments in which the polypeptide chain is coiled or folded. These coils and folds are often held in place by hydrogen bonding. They give the protein its *secondary structure*. Two common kinds of secondary structures are the *alpha helix* and the *beta pleated sheet,* both of which are shown in the table. The alpha (α) helix is shaped like a coil with hydrogen bonds that form along a single segment of a polypeptide. The beta (β) pleated sheet is shaped like an accordion with hydrogen bonds that form between adjacent polypeptide segments.

In alpha-keratin, shown in **Figure 5,** the entire length of the protein has an α-helix structure. However, other proteins will have only sections that are α-helixes. Different sections of the same protein may have a pleated sheet secondary structure. These different sections of a protein can fold in different directions. These factors, combined with the intermolecular forces acting between side chains give each protein a distinct three-dimensional shape. This shape is the *tertiary structure* of the protein.

A *quaternary structure* arises when different polypeptide chains that have their own three-dimensional structure come together to form a larger protein. For example, four separate polypeptides make up a single molecule of hemoglobin, the protein that carries O_2 within red blood cells.

Table 3 Levels of Protein Structure

Primary structure	Secondary structure	Tertiary structure	Quaternary structure
	 α-helix  β-pleated sheet		

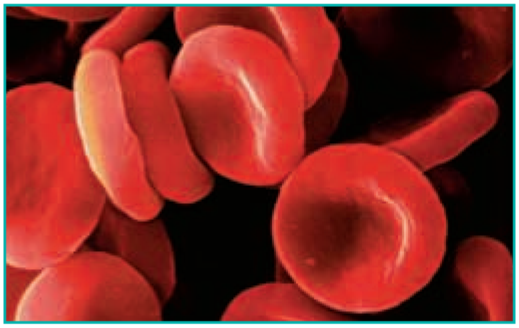
Amino-Acid Substitution Can Affect Shape

The sequence of amino acids—the primary structure—helps dictate the protein's final shape. A substitution of just one amino acid in the polypeptide sequence can have major effects on the final shape of the protein.

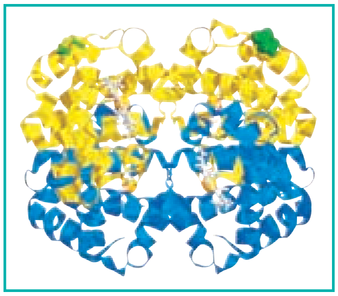
A hereditary blood cell disease called *sickle cell anemia* gives one example of the importance of amino-acid sequence. As the blood circulates, hemoglobin proteins in red blood cells pick up oxygen in the lungs and deliver it to all regions of the body. Normal red blood cells have the dimpled disk shape shown on the left in **Figure 7.** However, people with sickle cell anemia have blood cells with a crescent, or "sickle," shape. These cells are less efficient at carrying oxygen, which can cause respiration difficulties. Worse, the sickled cells tend to clump together in narrow blood vessels, causing clotting and sometimes death.

The cause of the sickle cell shape lies in the amino-acid sequence of the polypeptide. In sickle cell hemoglobin, the sixth amino acid in one of the polypeptide chains is valine. The sixth amino acid in healthy hemoglobin is glutamic acid. Because of the difference in only one amino acid, the entire shape of the hemoglobin is different in the unhealthy blood cells. This tiny change in the primary structure of the protein is enough to affect the health and life of people who have this disease.

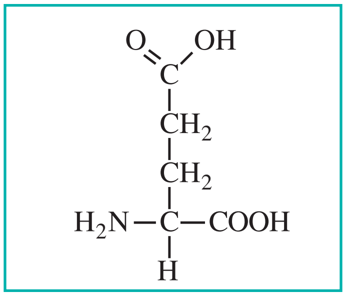
Figure 7



a The round, flat shape of healthy red blood cells shows they have normal hemoglobin molecules.

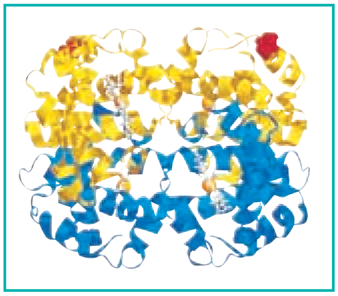


b Hemoglobin consists of four polypeptide chains; a fragment of one chain is shown in green.

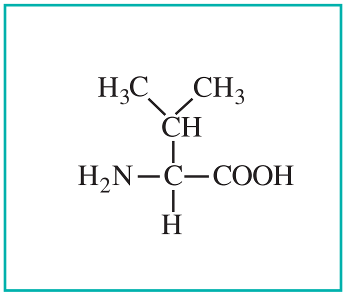


c Each of the chains is a polymer of 141 or 146 amino acid units, such as the glutamic acid monomer shown here.

d Because of their shape, sickle cells clog small blood vessels.



e A genetic mutation causes one glutamic acid to be replaced by valine in the hemoglobin molecules, as shown in red.



f The sickle shape of the cell comes from the different shape of the hemoglobin caused by the valine substitution.

Enzymes

enzyme

a type of protein that speeds up metabolic reactions in plant and animals without being permanently changed or destroyed

An **enzyme** is a protein that catalyzes a chemical reaction. Almost all of the chemical reactions in living systems take place with the help of enzymes. In fact, some biochemical processes would not take place at all without enzymes.

Enzymes have remarkable catalytic power. For example, blood cells change carbon dioxide, CO_2, to carbonic acid, H_2CO_3, which is easily carried to the lungs. Once in the lungs, carbonic acid decomposes back into carbon dioxide so that the CO_2 can be exhaled by the lungs. The reaction described by the equation below takes place in our lungs and tissues.

$$CO_2(aq) + H_2O(l) \rightleftarrows H_2CO_3(aq)$$

Topic Link

Refer to the "Reaction Rates" chapter for a discussion of catalysis.

The enzyme *carbonic anhydrase* allows this reaction to take place 10 million times faster than it normally would. The forward and reverse processes are accelerated equally. Hence the reaction's equilibrium constant is unaffected by the enzyme's presence. Enzymes are very efficient. A single molecule of carbonic anhydrase can cause 600 000 carbon dioxide molecules to react each second.

How Enzymes Work

In the late 19th century, the German chemist Emil Fischer proposed that enzymes work like a lock and key. That is, only an enzyme of a specific shape can fit the reactants of the reaction that it is catalyzing. A model of an enzyme mechanism is shown in **Figure 8.** Only a small part of the enzyme's surface, known as the *active site,* is believed to make the enzyme active. In reactions that use an enzyme, the reactant is called a *substrate*. The substrate has bumps and dips that fit exactly into the dips and bumps of the active site, much like three-dimensional puzzle pieces. Also, the active site has groups of side chains that form hydrogen bonds and other interactions with parts of the substrate. While the enzyme and the substrate hold this position, the bond breaking (or bond formation) takes place and the products are released. Once the products are released, the enzyme is available for a new substrate.

Figure 8

a The enzyme reacts with the substrate in a fast, reversible reaction.

b The substrate-enzyme complex can either revert to the reactants or . . .

c . . . proceed to the products.

Scientists have added to Fischer's idea and suggested that some enzymes are flexible structures. An enzyme might wrap its active site around the substrate as the substrate approaches. Further flexing of the enzyme causes some bonds in the substrate to break and frees the products. Whatever the actual mechanism of an enzyme, its shape is very important to its ability to catalyze a reaction. Because protein function depends so much on the shape of the protein, changing a protein's shape can inactivate a protein.

Denaturing an Enzyme Destroys Its Function

You do not have to change the primary structure of an enzyme to inactivate it. You can **denature** a protein. To denature a protein means to cause it to lose its tertiary and quaternary structures so that the polypeptide becomes a random tangle. Mild changes, such as shifts in solvent, temperature, pH, or salinity, may be enough to denature the enzyme. For example, the enzymatic ability to decompose hydrogen peroxide is lost by plant and animal cells when they are heated.

denature

to change irreversibly the structure or shape—and thus the solubility and other properties—of a protein by heating, shaking, or treating the protein with acid, alkali, or other species

Of course, many proteins other than enzymes can also be easily denatured. When you prepare protein foods for meals you are usually denaturing proteins. For example, when you cook an egg, the egg white changes from runny and clear to firm and white, because the proteins are denatured by the change in temperature. Denaturing is the reason you can "cook" some foods without heating them. For example, when you make a dish called *ceviche* (suh VEE CHAY), you denature the proteins in raw fish by changing the pH of the protein's environment. By marinating the fish in acidic lime juice, you are denaturing the proteins much in the same way as if you heated the fish. Some recipes for pickled herring work in the same way, using vinegar (acetic acid) to denature the raw fish proteins.

Quick LAB

SAFETY PRECAUTIONS

Denaturing an Enzyme

PROCEDURE

1. Get **15 potato cubes** from your teacher. Place one potato cube on a **paper plate.**
2. Using a **dropper,** drop **hydrogen peroxide solution** onto the potato cube. Note the amount of bubbling (the enzymatic activity). Let this amount of bubbling count as a score of 10.
3. Place the remaining potato cubes in a **beaker of water** at room temperature. Place the beaker on a preheated **hot plate** that remains switched on.
4. Using **tongs,** remove one cube every 30 s, and test its enzymatic activity, assigning a score between 0 and 10 based on the amount of bubbling.

ANALYSIS

1. Graph the enzymatic activity score versus heating time.
2. What happens to the enzymatic activity of a potato with heating? Explain.

Curbing Enzyme Action

Enzymes can be too strong by themselves. One example of an overly strong enzyme is a *proteolytic* (or protein-splitting) enzyme called *trypsin,* which plays a part in the digestion of protein food. Trypsin is used in the small intestine to help break down proteins into amino acids through hydrolysis. However, the small intestine is itself made of proteins, which can also be broken down by trypsin! Rather than producing trypsin that will destroy its own organs, the body makes an inactive form of trypsin, a protein called *trypsinogen*.

Trypsinogen is stored in the pancreas. It is added to semidigested food as it passes through the small intestine. Small amounts of another protein, *enteropeptidase,* which is enzymatically active, are also added. When an enteropeptidase molecule meets a molecule of trypsinogen, enteropeptidase attacks one of the bonds in trypsinogen. When this bond is broken, one of the products is trypsin. Thus, this strong enzyme is made only at a time and place when it can break down food with the fewest dangerous side effects.

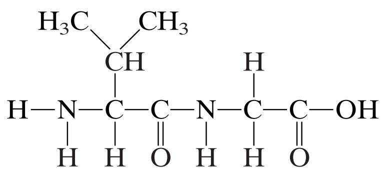
2 Section Review

UNDERSTANDING KEY IDEAS

1. Describe the meaning of the two parts of the name *amino acid*.
2. Draw the general structure of an amino acid.
3. What is a peptide bond, and what name is given to enzymes that catalyze its hydrolysis?
4. **a.** Identify three side chains found in amino acids.
   b. Draw the three amino acids that have these side chains.
   c. What property does each of these chains give to a polypeptide chain?
5. What causes sickle cell anemia?
6. Describe the secondary structure of proteins.
7. What is meant by *denaturing* an enzyme, and what changes in conditions might bring it about?
8. Briefly describe how enzymes are believed to work to catalyze a reaction.

CRITICAL THINKING

9. What do condensation of sugars and condensation of amino acids have in common?
10. What different meanings do the words *polypeptide* and *protein* have?
11. List four different ways in which one part of a polypeptide chain may interact with another part. List them in the order that reflects *decreasing* strength of the interaction. (Hint: Apply what you have learned in previous chapters about the strength of different types of bonds and intermolecular forces.)
12. Proteolytic enzymes catalyze the hydrolysis of polypeptides. Predict the products if you carried out the hydrolysis of the following molecule, a dipeptide.



SECTION

3 Nucleic Acids

KEY TERMS

- **nucleic acid**
- **DNA**
- **gene**
- **DNA fingerprint**
- **clone**
- **recombinant DNA**

OBJECTIVES

1. **Relate** the structure of nucleic acids to their function as carriers of genetic information.
2. **Describe** how DNA uses the genetic code to control the synthesis of proteins.
3. **Describe** important gene technologies and their significance.

Nucleic Acids and Information Storage

You are probably like one or both of your parents in personality or physical features. Some traits may be due to the environment you grew up in, but many traits you inherited from your parents. Before you were born, you began as a single cell that had equal amounts of information from your mother and father about *their* hereditary characteristics. As that cell divided and redivided, that information was duplicated and now resides in every cell of your body.

Hereditary information is not just about the shape and color of your eyes, but also about the very fact that you have eyes—and that you are a human and not a snail or a cabbage. All that information, including the "construction plans" for building your body, is stored chemically in compounds called **nucleic acids.**

nucleic acid

an organic compound, either RNA or DNA, whose molecules are made up of one or two chains of nucleotides and carry genetic information

Nucleic-Acid Structure

Like polysaccharides and polypeptides, nucleic acids are biological polymers. Nucleic acids are formed from equal numbers of three chemical units: a sugar, a phosphate group, and one of several nitrogenous bases. The "backbone" of the nucleic acid is a -sugar-phosphate-sugar-phosphate-chain, with various nitrogenous bases connected to the sugar units. **Figure 9** shows the structures of the four most common nitrogenous bases.

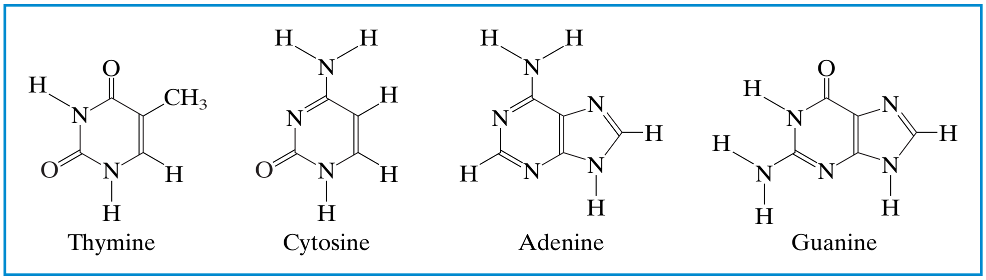


Figure 9 There are four common nitrogenous bases of nucleic acids. Thymine and cytosine bases have a single six-membered ring. Adenine and guanine bases have connected six- and five-membered rings.

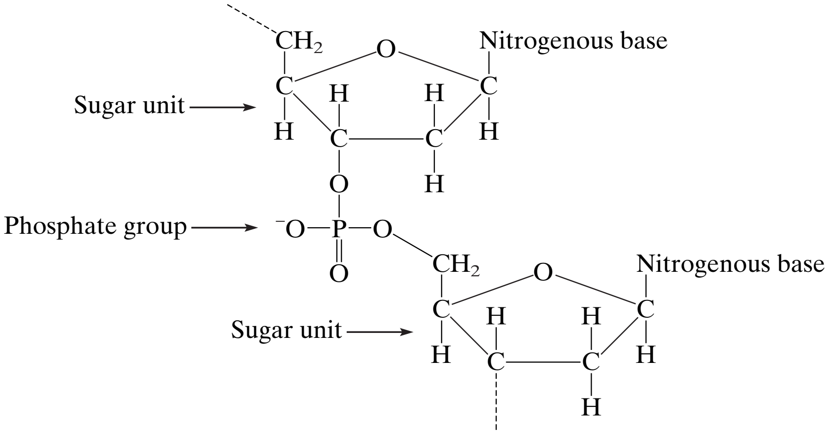
Deoxyribonucleic Acid, or DNA

DNA

deoxyribo**n**ucleic **a**cid, the material that contains the information that determines inherited characteristics

Deoxyribonucleic acid is the full name of the most famous nucleic acid, which is usually known by the abbreviation **DNA.** DNA acts as the biochemical storehouse of genetic information in the cells of all living things.

The sugar in DNA is *deoxyribose,* which has a ring in which four of the atoms are carbon and the fifth atom is oxygen. The phosphate group comes from phosphoric acid, $(HO)_3PO$. Two of the –OH groups from the phosphoric acid condense with the –OH groups on two different sugar molecules, linking all three together as shown below.



The nitrogenous bases connect to the sugar units in the backbone. There is one base per sugar unit. Any one of the four bases—adenine, guanine, thymine, and cytosine—is connected along the strand at the sugar units. All genetic information is encoded in the sequence of the four bases, which are abbreviated to A, G, T, and C. Just as history is written in books using a 26-letter alphabet, heredity is written in DNA using a 4-letter alphabet.

Living things vary in the size and number of DNA molecules in their cells. Cells may have just one or many molecules of DNA. Some bacteria cells have a single molecule of DNA that has about 8 million bases. Human cells have 46 molecules of DNA that have a total of about 6 billion bases.

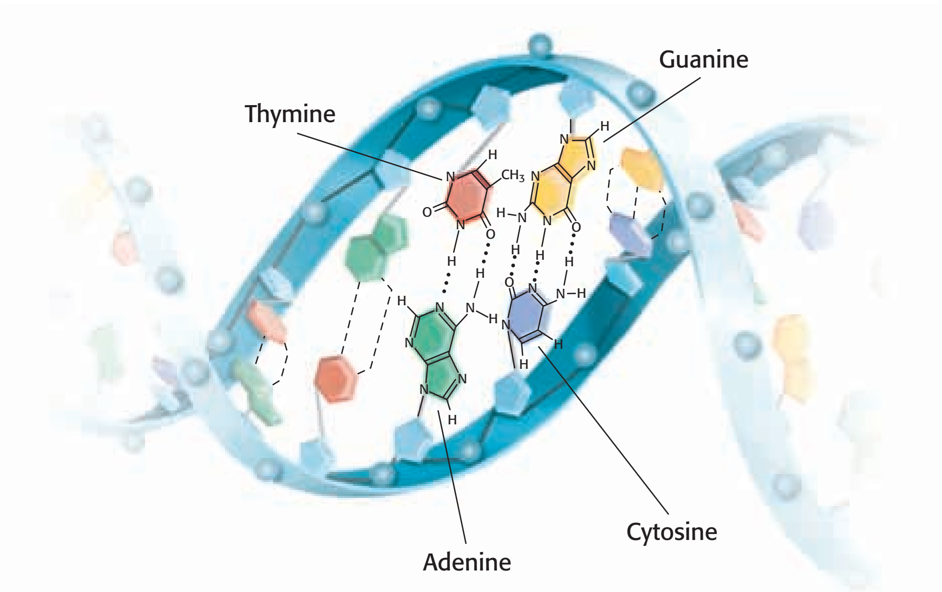
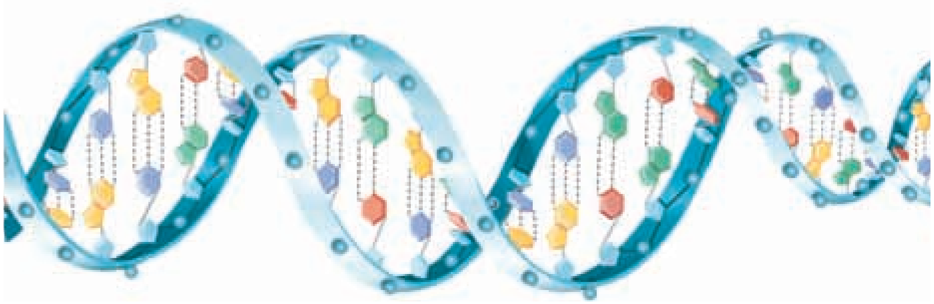


Figure 10
The three-dimensional structure of DNA is made stable by hydrogen bonding between base pairs.



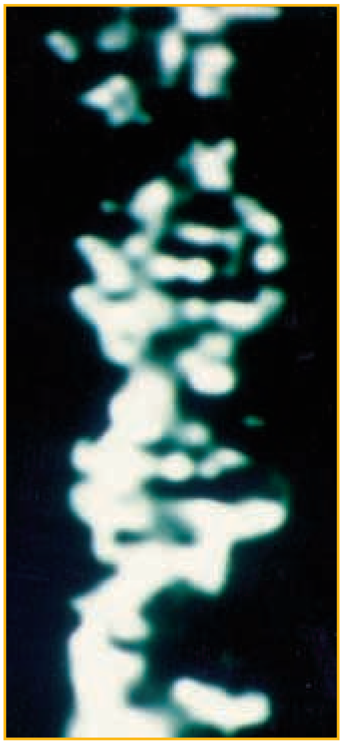


Figure 11
The double helix of DNA can be seen by scanning-tunneling microscopy (above) or shown as a molecular model (above left).

DNA's Three-Dimensional Structure

There are single strands of DNA, but the biological polymer is mostly found as a double helix in which two DNA strands spiral around each other as shown in **Figure 11.** The two strands are not duplicates of each other. Instead, they are complementary. This means that where an adenine (A) is found in one strand, thymine (T) is found in the other. Likewise, a guanine (G) in one strand is matched with a cytosine (C) in the other.

The reason for the complementary nature of DNA can be seen in **Figure 10.** When A and T are lined up opposite each other, the two bases are ideally placed for forming two hydrogen bonds, which bond the two strands together. Likewise, G and C can easily form three hydrogen bonds between themselves. No other pairing can form the right hydrogen bonds to keep the strands together. Thus, the three-dimensional configuration of DNA looks like a twisted ladder or spiral staircase, with A–T and G–C base pairs providing the rungs or steps.

Quick LAB

Isolation of Onion DNA

SAFETY PRECAUTIONS

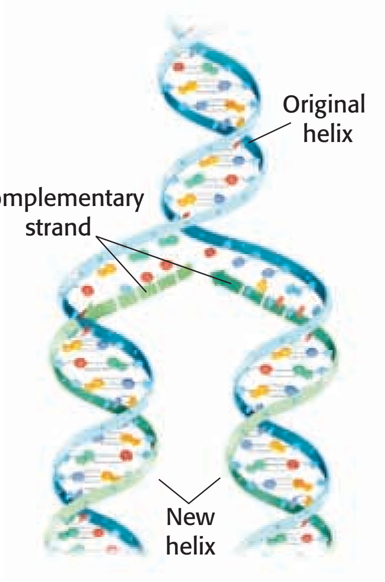
PROCEDURE

1. Place **5 mL of onion extract** in a **test tube.** The extract was taken from whole onions that were processed in a laboratory.
2. Hold the test tube at a 45° angle. Use a **pipet** to add **5 mL of ice-cold ethanol** to the tube one drop at a time. Note: Allow the ethanol to run slowly down the side of the tube so that it forms a distinct layer.
3. Let the test tube stand for 2–3 min.
4. Insert a **glass stirring rod** into the boundary between the onion extract and ethanol. Gently twirl the stirring rod by rolling the handle between your thumb and finger.
5. Remove the stirring rod from the liquids, and examine any material that has stuck to it. You are looking at onion DNA. Touch the DNA to the lip of the test tube, and observe how it acts as you try to remove it.

ANALYSIS

1. Why do you think the DNA is now visible?
2. How has the DNA changed from when it was undisturbed in the onion's cells?

Figure 12
DNA replicates by building complementary strands on the single strands that form as the original helix unwinds.



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Topic: DNA Replication
SciLinks code: HW4044
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gene
a segment of DNA that is located in a chromosome and that codes for a specific hereditary trait

DNA Replication

There is a copy of your DNA in each cell in your body, because DNA is able to replicate itself efficiently. To begin replication, a part of the double helix unwinds, providing two strands. Each strand acts as a template for the making of a new strand. New nucleic acid units made by the cell meet up one by one with their complementary bases on the template. Hydrogen bonds form between the correct base pairs: A to T, T to A, C to G, and G to C. As the nucleic acid units line up on the template strand, covalent bonds form between the sugars and phosphate groups of neighboring units or the complementary strand, as shown in **Figure 12.** Eventually, the original double helix is replaced by two perfect copies.

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RNA and Protein Synthesis

Our proteins determine what our cells do. However, our DNA determines what these proteins are made of. A **gene** is a segment of DNA that has the code for the amino acid sequence to build a polypeptide. The way that the gene is translated into an amino-acid sequence is elaborate. It uses many proteins and another nucleic acid, *ribonucleic acid,* or RNA.

Protein synthesis begins with the cell making an RNA strand that codes for a specific protein. The DNA double helix unwinds and RNA units match up with the DNA bases. The process is similar to DNA replication. However, instead of using DNA units, the cell uses RNA units, which differ from DNA by an oxygen on the sugar unit and in one of the bases. RNA has the base *uracil,* shown in **Figure 13,** instead of thymine. The uracil bases hydrogen-bond with the adenine on the DNA strand, as in the following base sequence.

DNA strand: C C C C A C C C T A C G G T G
RNA strand: G G G G U G G G A U G C C A C

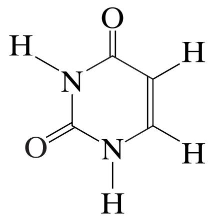
The cell then uses the RNA strand as instructions for building a protein. Amino acids line up according to the sequence of bases in the RNA. The polypeptide chain grows as bonds form between the amino acids.

The Genetic Code

There are 20 different amino acids but only four RNA bases. Thus, a single base cannot specify a single amino acid. In fact, a group of three, or a *triplet* of bases in RNA indicates a particular amino acid. For example, the sequence of bases GUC causes valine to be added to a growing polypeptide. The complete *genetic code* lists the RNA triplets and their corresponding amino acids. You can use **Skills Toolkit 1** to decode RNA sequences to their corresponding amino acid sequences, as shown below.

RNA strand:	GGG	GUG	GGA	UGC	CAC
amino acid:	glycine	valine	glycine	cysteine	histidine

Because there are $4^3 = 64$ triplet combinations of the four bases, most of the 20 amino acids are encoded by more than one triplet. Almost all living things use the same code to translate their proteins.



Uracil

Figure 13
Uracil is a nitrogenous base that is unique to RNA. Uracil pairs with adenine.

SKILLS Toolkit 1

Using the Genetic Code

This table shows the triplet codes of RNA that specify each of the 20 amino acids. The triplets UAA, UAG, UGA, and AUG signal the end of the gene and the start of the next gene.

1. Find the first base of the RNA triplet along the left side of the table.
2. Follow that row to the right until you are beneath the second base triplet.
3. Move up or down in that section until you are even, on the right side of the chart, with the third base of the triplet.

The Genetic Code

First base	Second base U	Second base C	Second base A	Second base G	Third base
U	UUU Phenylalanine	UCU Serine	UAU Tyrosine	UGU Cysteine	U
	UUC	UCC	UAC	UGC	C
	UUA Leucine	UCA	UAA Stop	UGA—Stop	A
	UUG	UCG	UAG	UGG—Tryptophan	G
C	CUU Leucine	CCU Proline	CAU Histidine	CGU Arginine	U
	CUC	CCC	CAC	CGC	C
	CUA	CCA	CAA Glutamine	CGA	A
	CUG	CCG	CAG	CGG	G
A	AUU Isoleucine	ACU Threonine	AAU Asparagine	AGU Serine	U
	AUC	ACC	AAC	AGC	C
	AUA	ACA	AAA Lysine	AGA Arginine	A
	AUG—Start	ACG	AAG	AGG	G
G	GUU Valine	GCU Alanine	GAU Aspartic acid	GGU Glycine	U
	GUC	GCC	GAC	GGC	C
	GUA	GCA	GAA Glutamic acid	GGA	A
	GUG	GCG	GAG	GGG	G

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Gene Technology

After learning the role that DNA plays in life, biological chemists have gone on to research ways of using DNA that differ from natural processes. These efforts have many benefits and promise many more to come. But at the same time, gene technology has raised fears about the possibilities of misuse or mistake, as well as ethical issues about the uniqueness and sanctity of life.

Mapping and Identifying DNA

There are thought to be about 30 000 genes in human DNA. However, genes are only a tiny part of our DNA. There are large parts of our DNA that either have no function or have functions that have not been found yet.

Both the coding and noncoding base sequences differ from person to person. Unless you have an identical twin, the chance that someone else shares your DNA pattern is next to zero. Because no one else has the same DNA as you, your DNA pattern gives a unique "fingerprint" of you and your cells. Scientists use a technique called **DNA fingerprinting** to identify where a sample of DNA comes from. In DNA fingerprinting, scientists compare *autoradiographs* of DNA samples, such as those shown in **Figure 14.** Autoradiographs are images that show the DNA's pattern of nitogenous bases.

DNA fingerprint

the pattern of bands that results when an individual's DNA sample is fragmented, replicated, and separated

You may have heard that DNA fingerprinting is used in forensics to prove whether a suspect can be linked to a crime. There are other applications. Two people who are closely related to each other have DNA patterns that are more similar than the DNA of two unrelated people, so DNA is useful in identifying a person's family members and tracing heredity. Likewise, because species that share a common extinct ancestor have similar DNA patterns, scientists can track presumed evolutionary links.

Figure 14
Scientists study images called autoradiographs, which show the pattern of nitrogenous bases in the DNA of an organism.

Identifying DNA from Small Samples

It takes a lot of DNA to make a DNA fingerprint. However, forensic applications of DNA fingerprinting can make use of a single hair, or the smallest trace of blood. Scientists can use small samples of DNA because they can rapidly copy, or "amplify," DNA strands. By making many copies of a tiny sample of DNA, a scientist can make enough DNA to see the pattern of bases.

Scientists use a method called *polymerase chain reaction,* or PCR, which replicates a short "targeted" sequence of double-stranded DNA. Large amounts of the four monomeric components of DNA are added to a solution that has the DNA, an enzyme, and *primers*. A primer is a short length of single-stranded DNA that has the complementary sequence of the first few bases of the target. The solution is then subjected to a number of heating-cooling cycles. Heating denatures the DNA and separates the double strands. Cooling causes the primer to connect to the end of the target. The enzyme then replicates the DNA using the primer as a starting point. In this way, the amount of DNA is doubled during each cooling. After 20 cycles, the amount of DNA increases by a factor of 2^{20}, or more than 1 million.

Figure 15
a Each of these identical twins has the same genetic information as her sister.

b Growers can produce many orchids by artificial cloning of the meristem tissue of a single orchid plant.

c The kitten at left is an artificial clone of an adult calico cat.

Cloning

Identical twins arise from the chance splitting of a group of embryonic cells early in the growth of a human baby. Each cell of a very young embryo can grow into a complete organism, but this ability is lost as an embryo grows larger and its cells become more specialized.

Undifferentiated cells are cells that have not yet specialized to become part of a specific tissue in the body. These cells include *stem cells* in animals and *meristem* cells in plants, which may be cultured artificially so they grow into complete organisms. These organisms are genetically identical to the organisms from which the cells were harvested and are **clones** of their "parent." Cloning a mammal is a difficult task. However, it was accomplished in 1997 by Scottish scientist Ian Wilmut. His work produced a sheep named Dolly. Dolly's genes were taken from the mammary cell of one sheep and placed in the enucleated, or empty, egg cell of another sheep. Dolly's embryo was then raised in the uterus of a third sheep. Scientists have artificially cloned many other living things—not only sheep, but plants, such as orchids, and other animals, such as the kitten shown in **Figure 15.**

clone
an organism that is produced by asexual reproduction and that is genetically identical to its parent; to make a genetic duplicate

Recombinant DNA

recombinant DNA

DNA molecules that are artificially created by combining DNA from different sources

The greatest advances in gene technology have come from *recombinant DNA technology*. Making use of proteins that cut and reconnect DNA molecules, scientists have learned to insert genes from one species into the DNA of another. When this **recombinant DNA** is placed in a cell, the cell is able to make the protein coded by the foreign gene.

The earliest success was in redesigning the DNA of bacteria to make human insulin, a protein that people with diabetes lack. Many proteins can be made in this way, and drug companies are rapidly finding ways to cure diseases and make life-saving drugs using recombinant DNA.

Bacteria are not the only living things that have been treated with recombinant DNA. Plants have been made more resistant to insects and frost damage. Spiders do not make large quantities of spider silk proteins, which may be used as strong building materials, so genetically changed goats with spider genes make milk that has these potentially useful proteins. This very active scientific field has grown much since the late 1900s.

Though genetically changed organisms offer new solutions to many difficult problems, many people worry about the drawbacks of using such technologies. For example, a genetically changed organism may thrive so well in an ecosystem that natural organisms cannot compete and are wiped out. Also, some people object to products that come from recombinant DNA because of ethical issues about the creation of new life forms for human use.

3 Section Review

UNDERSTANDING KEY IDEAS

1. From what three components is DNA made?
2. Describe the three-dimensional shape of DNA.
3. Describe how DNA uses the genetic code to control the synthesis of proteins.
4. Why is a very small trace of blood enough for DNA fingerprinting?
5. What was the first protein to be made commercially by recombinant DNA technology?

PRACTICE PROBLEMS

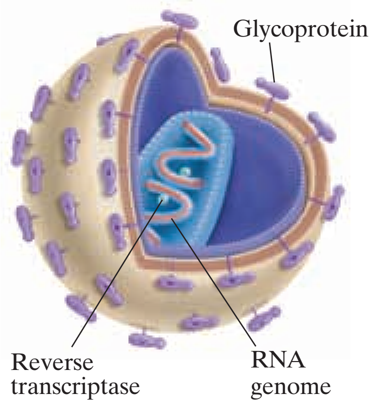
6. For what sequence of amino acids does the RNA base sequence AUGAAGUUGGCUAA code?
7. A segment of a DNA strand has the base sequence ACGTTGGCT.
   a. What is the base sequence in a complementary strand of RNA?
   b. What is the corresponding amino acid sequence?
   c. What is the base sequence in a complementary strand of DNA?

CRITICAL THINKING

8. Why might identical twins be called clones?
9. What features of the four base pairs make them ideal for holding DNA strands together?
10. Is it possible to specify the 20 amino acids using only two base pairs as the code? Explain.

SCIENCE AND TECHNOLOGY

Protease Inhibitors



HIV Virus

HIV, or human immunodeficiency virus, is the virus that causes AIDS by severely weakening the human immune system. Since the discovery of HIV in 1983, scientists have searched for drugs that will combat the growth of the virus in human cells. Protease inhibitors are one of the newest classes of drugs to be developed.

Viruses are not living cells. They are bits of genetic material (RNA or DNA) combined with protein molecules. Viruses enter (infect) cells and release their genetic material. The cell uses this genetic material as a code to make more viruses.

The HIV virus is a *retrovirus,* a virus that contains RNA, which it carries into the cell along with an enzyme called *reverse transcriptase*. The HIV virus uses the reverse transcriptase enzyme to make a DNA copy of the RNA genetic pattern. The DNA segment enters the cell's nucleus, where it becomes a part of the cell's genes. There, it causes the cell to make all of the parts needed to make new viruses. The new viruses assemble and leave the cell to infect new cells. The cell is usually destroyed in the process.

Inhibiting Viral Reproduction

Most of the drugs that have been used to treat HIV infections are compounds that inhibit the reverse transcriptase enzyme, in turn preventing the RNA from forming a DNA copy. The new drugs, protease inhibitors, do their work after the parts of the virus have been made. The polypeptides that are needed to put together new viruses must be cut apart into the individual proteins. Protease is an enzyme that breaks the polypeptides in the right places. Inhibiting protease keeps many of the new viruses from forming.

Questions

1. Research to find out more about HIV. Identify the kind of cells the virus attacks, and describe how the viral infection leads to AIDS.
2. Find out more about other retroviruses. How are drugs used to combat infections caused by these retroviruses?

CAREER APPLICATION

Nurse Practitioner

A nurse practitioner does all of the things that registered nurses in hospitals or physicians' offices do. In fact, most nurse practitioners (NPs) begin as nurses and, after a few years of experience, study to become a nurse practitioner. Nurse practitioners have some of the same responsibilities as physicians. NPs can do extensive diagnoses of disease, carry out medical tests, counsel families, and in some cases, prescribe medicine. They often have specialties, such as pediatrics, mental health, or geriatrics. For some families, the NP is the primary health care provider.

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SECTION 4

Energy in Living Systems

KEY TERMS

- **photosynthesis**
- **respiration**
- **ATP**

OBJECTIVES

1. **Explain** how plants use photosynthesis to gather energy.
2. **Explain** how plants and animals use energy from respiration to carry out biological functions.

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Obtaining Energy

Moving our muscles is one way in which we use energy, but many other ways that we use energy are harder to see. We use energy in digesting our food, in pumping our blood, in keeping warm, and in making the many compounds that our bodies need to function and grow. Energy is needed for every action of every organ in our bodies. All living things need energy to build and repair themselves and to fuel their activities. With rare exceptions, all forms of life on Earth draw energy ultimately from sunlight. Green plants get energy directly from the sun's rays through the process of **photosynthesis.** Other living things rely on plants, directly or indirectly, as their source of energy.

photosynthesis
the process by which plants, algae, and some bacteria use sunlight, carbon dioxide, and water to produce carbohydrates and oxygen

The flow of energy throughout an ecosystem is related to the carbon cycle. The carbon cycle follows carbon atoms as they become part of one compound and then another. The reactions that involve these carbon compounds, shown in **Figure 16,** give plants and animals the energy that they need.

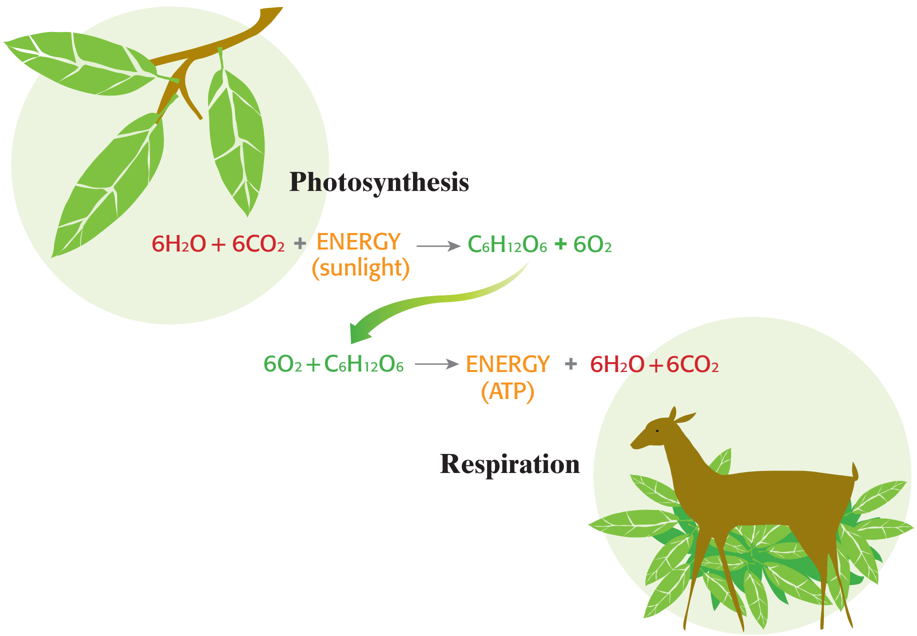


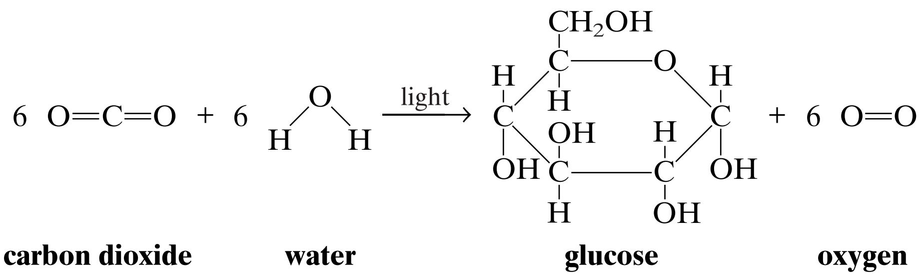
Figure 16
Plants use carbon dioxide, water, and sunlight to produce oxygen and glucose. Glucose is used by plants and animals to produce chemical energy in the form of a substance called *ATP*.

Plants Use Photosynthesis as a Source of Carbohydrates

Look at the diagram of the carbon cycle shown in **Figure 16.** Notice that the reactants needed for the second equation—glucose and oxygen—are produced in the first equation, photosynthesis. And the reactants and conditions needed for the first equation—carbon dioxide, water, and energy—are produced in the second equation, although the energy is in a different form.

Most plants use *chlorophyll,* a magnesium-containing organic molecule, to capture the energy of sunlight. The light absorbed by the chlorophyll is mostly from the red and the blue regions of the visible spectrum. What is reflected is green light, from the central region of the spectrum, which accounts for the color of most plants.

The overall chemistry of photosynthesis, which takes place in green plants and many other living things, such as the algae in **Figure 17,** is described by the following endothermic equation.



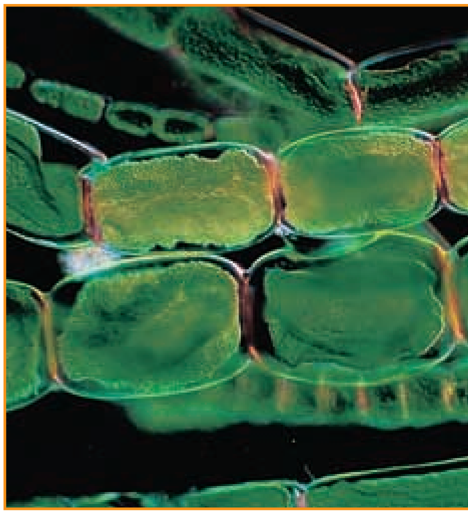


Figure 17
Green plants and algae have chlorophyll, a multiringed compound that contains magnesium.

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Animals Consume Carbohydrates as a Source of Energy

The carbohydrates that plants make by photosynthesis are used as a source of energy, not only by plants themselves, but also by animals.

Both plants and animals need carbohydrates for energy, and both plants and animals store simple carbohydrates by making them into larger carbohydrate polymers, such as starch and glycogen. Because animals cannot make carbohydrates directly from the sun's energy as plants do, animals eat plants or other animals to obtain the carbohydrates that plants have made. **Figure 18** shows one way that we get plant carbohydrates. Once an animal eats a plant, it breaks the plant's larger carbohydrates down into simpler carbohydrates, such as glucose. Glucose, which is soluble in blood, can be carried to the rest of the body for energy use.

Figure 18
Carbohydrates, such as the starch found in this baked potato, are the main energy source for most humans.

Figure 19
Muscular activity leads to an increase in respiration rate.

respiration

the process by which cells produce energy from carbohydrates; atmospheric oxygen combines with glucose to form water and carbon dioxide

Using Energy

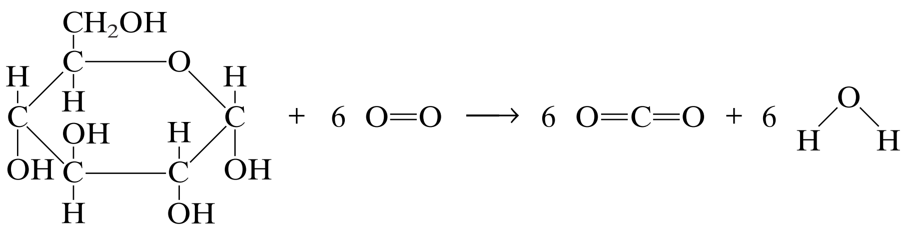
Glucose itself is changed into a more readily available source of energy through *respiration*. The equation for chemical respiration is shown in **Figure 16.** In everyday speech, *respiration* means getting gases into and out of the lungs. In biological chemistry, **respiration** refers to the entire process of getting oxygen into body tissues and allowing it to react with glucose to generate energy.

Respiration Requires Oxygen and Glucose

You may have noticed that you breathe more heavily when you exercise, as does the runner in **Figure 19.** This is because you need to get more oxygen into your system and you need to remove carbon dioxide more rapidly from your system.

The lungs move oxygen from the air into the blood as oxygen-carrying hemoglobin. The lungs also move carbon dioxide out of the blood—where it is present as $HCO_3^-(aq)$ and $H_2CO_3(aq)$—and into the air. The bloodstream carries oxygen and glucose to all the cells of your body for respiration. The bloodstream must also remove the products of respiration. That is, it takes carbon dioxide to the lungs, and it takes water to the kidneys.

Chemical respiration, or *cellular respiration,* takes place in the cells of a plant or animal and is fueled by glucose and oxygen. The overall process is the opposite of the photosynthesis reaction, as shown in the following equation.



glucose **oxygen** **carbon dioxide** **water**

For every molecule of glucose that is broken down by respiration, six molecules of oxygen, O_2, are consumed. The overall process produces six molecules of carbon dioxide, CO_2, and six molecules of water.

Respiration Is Exothermic

While photosynthesis takes in energy, respiration gives off energy. The thermodynamic values for the equation below show that the reaction is very exothermic ($\Delta H = -1273$ kJ) and highly spontaneous ($\Delta G = -2880$ kJ).

$$C_6H_{12}O_6(aq) + 6O_2(g) \longrightarrow 6CO_2(g) + 6H_2O(l)$$

However, the goal of cellular respiration is not to liberate energy as heat or light but to produce chemical energy in the form of special polyatomic ions, as discussed next.

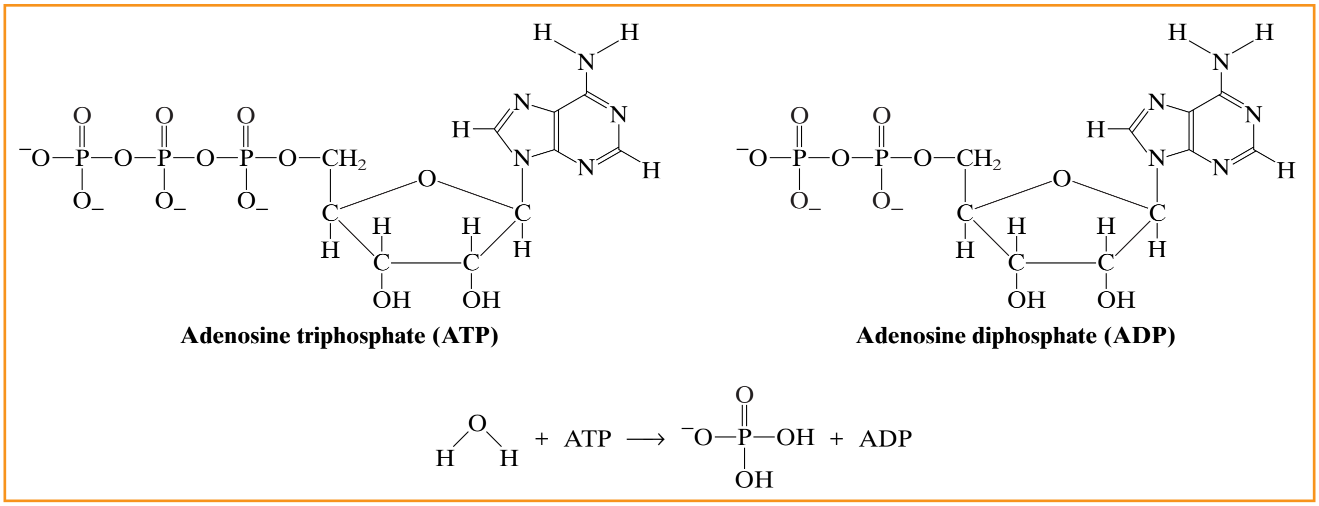


Figure 20
The hydrolysis of ATP produces ADP and releases energy.

Adenosine Triphosphate and Adenosine Diphosphate

Adenosine triphosphate, **ATP,** and adenosine diphosphate, ADP, are the high-energy and low-energy forms of a chemical that acts as energy "cash" in biological systems. The structures of ATP and ADP are shown in **Figure 20.** The main structural difference between them is that ATP has an extra phosphate group, $-PO_3^-$.

The hydrolysis of ATP to ADP is exothermic ($\Delta H = -20$ kJ) and spontaneous, as the following equation shows.

$$ATP(aq) + H_2O(l) \longrightarrow ADP(aq) + H_2PO_4^-(aq) \qquad \Delta G = -31 \text{ kJ}$$

Many reactions in a cell would not take place spontaneously if left alone. These reactions can "use" the spontaneity of ATP hydrolysis to take place by coupling with the ATP ⟶ ADP reaction. ATP hydrolysis thus allows these other nonspontaneous reactions to take place.

ATP

adenosine **trip**hosphate, an organic molecule that acts as the main energy source for cell processes; composed of a nitrogenous base, a sugar, and three phosphate groups

The Two Stages of Cellular Respiration

Cellular respiration has two stages. Both stages produce ATP. The first stage of cellular respiration includes *glycolysis*. The name means "glucose-splitting," which makes sense because the six-carbon glucose is split into two molecules of pyruvic acid, $CH_3COCOOH$ or $C_3H_4O_3$. The glycolysis reaction has about a dozen steps. Other products react further to make more ATP. The net gain of eight ATP is shown in the following equation.

$$C_6H_{12}O_6 + O_2 + 8ADP + 8H_2PO_4^- \longrightarrow 2C_3H_4O_3 + 8ATP + 10H_2O$$

The second stage of cellular respiration, called the *Kreb's cycle,* also has several steps. The overall result is the oxidation of pyruvic acid to form CO_2, as shown in the following equation.

$$2C_3H_4O_3 + 5O_2 + 30ADP + 30H_2PO_4^- \longrightarrow 6CO_2 + 30ATP + 34H_2O$$

The two stages together produce 38 ATP ions per glucose molecule. The reaction for glucose has an enthalpy change of −1273 kJ. Thus, (38 × −20 kJ)/(−1273 kJ) or 60% of the energy of glucose has been stored as ATP. The remaining energy helps to keep the body warm.

Table 4 Approximate "Cost" of Daily Activities

Activity (for 30 min)	Energy required (kJ)	ATP required (mol)
Running	1120	56
Swimming	840	42
Bicycling	1400	70
Walking	560	28

ATP Is Energy Currency

The conversion of ATP to ADP gives the energy needed for many cellular activities. So, ATP represents energy that is immediately available in the cell. Also, ATP is continuously resynthesized by cellular respiration as long as an organism is alive.

On the molecular level, there are three kinds of work that a cell does, and ATP gives the energy needed for them all. ATP gives the energy needed for *synthetic work,* making compounds that do not form spontaneously because they are accompanied by a positive ΔG. By coupling the reaction to the ATP $\longrightarrow$ ADP conversion, the overall process becomes spontaneous. ATP also gives the energy needed for *mechanical work*. The ATP $\longrightarrow$ ADP conversion changes the shape of muscle cells, which allows muscles to flex and move. Finally, the ATP $\longrightarrow$ ADP conversion fuels *transport work,* carrying solutes across a membrane. Again, the ATP $\longrightarrow$ ADP conversion is harnessed to allow specific proteins in the membrane to pump ions into or out of the cell. **Table 4** shows just how much ATP is needed for some daily activities.

4 Section Review

UNDERSTANDING KEY IDEAS

1. What are two reactions that involve carbon and together give plants energy?

2. Write the chemical reaction representing the photosynthesis of glucose.

3. What role does the bloodstream play in respiration?

4. Write the net equation for the reaction that makes ATP and pyruvic acid from glucose during cellular respiration.

5. Briefly, what biological role is played by ATP?

CRITICAL THINKING

6. To some small extent, plants make some ATP during photosynthesis. Why can't plants use photosynthesis as an energy source all the time instead of making carbohydrates?

7. In what sense is it true to say that sunlight fills the energy needs of a cheetah?

8. Explain the roles of glycogen, glucose, and ATP as energy sources in animals.

9. For chemical reactions, Gibbs energy is a more important quantity than enthalpy. Show that the efficiency of the glucose to ATP conversion in terms of ΔG is only 41%.

10. Explain how nonspontaneous biochemical reactions can take place with the help of ATP.

Where is Mg?

Earth's crust
2.5% by mass

Sea water
0.13% by mass

Element Spotlight

12
Mg
Magnesium
24.3050
$[Ne]3s^2$

Magnesium: An Unlimited Resource

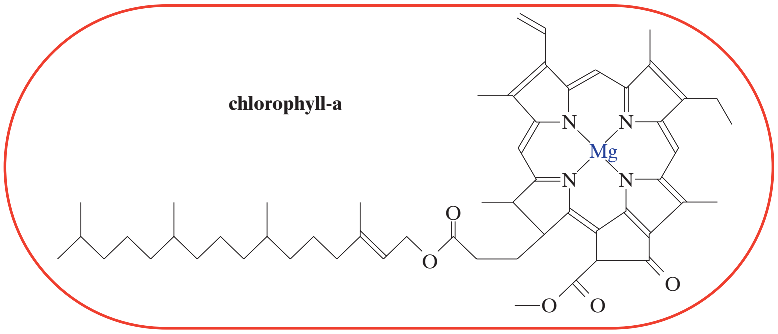
Extracting magnesium from sea water is an efficient and economical process. Sea water is mixed with lime, CaO, from oyster shells to form insoluble magnesium hydroxide, $Mg(OH)_2$, which can be easily filtered out. Hydrochloric acid is added to the solid to form magnesium chloride. The electrolysis of molten magnesium chloride will produce pure magnesium metal.

Spinach is a good source of dietary magnesium. Magnesium is the central atom in the green plant pigment chlorophyll.

Industrial Uses

- Magnesium oxide, MgO, is used in paper manufacturing, as well as in fertilizers, medicine, and household cleaners.
- Aqueous magnesium hydroxide, $Mg(OH)_2$, is known as *milk of magnesia,* an antacid.
- Magnesium alloys are used in aircraft fuselages, engine parts, missiles, luggage, optical and photo equipment, lawn mowers, and portable tools.

Real-World Connection If 90 million metric tons of magnesium were extracted per year for 1 million years, the magnesium content of the oceans would drop by 0.01%.



A Brief History

1700 — 1800 — 1900

1808: Humphry Davy discovers that the compound magnesia alba is the oxide of a new metal.

1828: A.A.B. Bussy obtains the first pure magnesium metal.

1833: Michael Faraday makes magnesium metal through the electrolysis of molten magnesium chloride.

1852: Robert Bunsen designs an electrolytic cell that allows molten Mg to be collected without burning when it makes contact with the air.

1944: L. M. Pidgeon discovers how to extract magnesium from its ore, dolomite.

Questions

1. Find out more about chlorophyll. How is chlorophyll's structure important to its role in photosynthesis?
2. Magnesium is used to make fireworks. Find out what property makes this substance useful in fireworks.

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20 CHAPTER HIGHLIGHTS

KEY IDEAS

SECTION ONE Carbohydrates and Lipids

- Carbohydrates are compounds of carbon, hydrogen, and oxygen made by living things for energy storage and support. They can be ringed and have many –OH groups.
- Carbohydrates are classified into monosaccharides, disaccharides, or polysaccharides according to the number of rings present. The smaller carbohydrates are called *sugars*.
- Sugars combine by condensation, a reaction in which a water molecule is formed. The reverse reaction, hydrolysis, breaks down polysaccharides into smaller carbohydrate units.
- Lipids are nonpolar molecules that include fats, phospholipids, steroids, and waxes.

SECTION TWO Proteins

- The 20 amino acids from which proteins are formed all have the formula H_2N-CHR-COOH. They differ in the identity of *R,* which stands for different side chains.
- Proteins are formed by condensation of amino acids.
- The form and function of a protein depends on its three-dimensional shape, which itself depends on the amino acid sequence in the polypeptide chain.

SECTION THREE Nucleic Acids

- Nucleic acids are made of -phosphate-sugar-phosphate-sugar- chains with nitrogenous bases connected to the sugar units.
- DNA uses four bases and forms a double helix by specific A–T and G–C pairing. Replication can take place only when the helix splits apart.
- The arrangement of base triplets on DNA encodes genetic information by dictating the synthesis of proteins.
- Gene technologies involve working with DNA and include DNA fingerprinting, cloning, and recombinant DNA.

SECTION FOUR Energy in Living Systems

- Green plants use solar energy, carbon dioxide, and water to synthesize glucose during photosynthesis.
- The reverse of photosynthesis is respiration, in which glucose is broken down into carbon dioxide and water. Energy is harvested in the process by the production of about 38 ATP ions per glucose molecule.
- Through the release of energy during the breaking of its third phosphate bond, ATP fuels life's processes: motion, synthesis, and transport.

KEY TERMS

carbohydrate
monosaccharide
disaccharide
polysaccharide
condensation reaction
hydrolysis
lipid

protein
amino acid
polypeptide
peptide bond
enzyme
denature

nucleic acid
DNA
gene
DNA fingerprint
clone
recombinant DNA

photosynthesis
respiration
ATP

KEY SKILLS

Using the Genetic Code
Skills Toolkit 1 p. 729

CHAPTER REVIEW 20

USING KEY TERMS

1. What do all carbohydrates have in common?
2. How are carbohydrates classified?
3. What type of reaction changes sugars into polysaccharides?
4. Where are peptide bonds found?
5. Describe and name the four different levels of protein structure.
6. What is an enzyme, and what is a proteolytic enzyme?
7. Contrast the terms nucleic acid, DNA, and gene.
8. Name three examples of gene technologies.
9. Describe how green plants use sunlight.
10. What does *respiration* mean in everyday language, and what larger meaning does it have in biological chemistry?
11. Describe the role of ATP and what the name *ATP* stands for.

UNDERSTANDING KEY IDEAS

Carbohydrates and Lipids

12. What different roles do the polysaccharides starch and cellulose play in plant systems?
13. Both cholesterol and oleic acid are lipids. What property do they have in common?

Proteins

14. List the four groups attached to the central carbon of an amino acid.
15. What are the products of protein synthesis?
16. How is a disulfide bridge formed?
17. What is the *lock-and-key* model of enzyme action?

Nucleic Acids

18. Describe the structure of a DNA molecule and what the name *DNA* stands for.
19. In DNA replication, why is a G on the original strand partnered by a C on the complementary strand, and not by an A, a T, or a G?
20. What is the genetic code? Give an example of how it is used.
21. What is recombinant DNA technology?
22. Describe the procedure for DNA amplification by polymerase chain reaction (PCR).

Energy in Living Systems

23. Identify the specialized molecule that absorbs light in photosynthesis.
24. Write the balanced chemical equation that describes the overall process in photosynthesis.
25. Explain why plants are generally green.
26. What is glycolysis?
27. How are living things able to respond immediately to energy-demanding situations?

PRACTICE PROBLEMS

PROBLEM SOLVING SKILL

Skills Toolkit 1 **Using the Genetic Code**

28. What sequence of amino acids do the following RNA base sequences code?
    a. AAG AUU GGA CAC
    b. AUG UCU UCG AGU UCA UAG

29. A segment of a DNA strand has the base sequence TACACACGTTGGATT.
   a. What is the base sequence in a complementary strand of RNA?
   b. What is the corresponding amino acid sequence?

30. a. Write one possible RNA sequence that codes for the following amino acids: aspartic acid-glutamine-tryptophan.
   b. What is the sequence in a complementary strand of DNA?

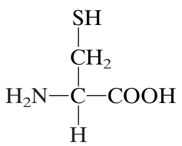
MIXED REVIEW

31. Imagine that you have created a very short polypeptide from the following RNA sequence: GACGAAGGAGAG.
   a. What is the amino acid sequence of the polypeptide?
   b. What property does the polypeptide have?

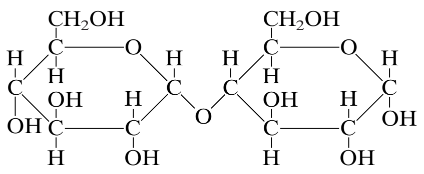
32. Write balanced chemical equations to describe the following metabolic processes: (a) starch ⟶ glucose; (b) glucose ⟶ carbon dioxide; (c) ATP ⟶ ADP.

33. Identify each of the following structures as a carbohydrate, an amino acid, or a nitrogenous base.

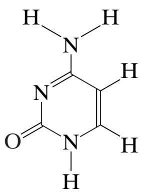
   a.



   b.



   c.



CRITICAL THINKING

34. Explain how a similar reaction forms three kinds of biological polymers: polysaccharides, polypeptides, and nucleic acids.

35. How is it possible to denature a protein without breaking the polypeptide chain?

36. Why is a special molecule, hemoglobin, needed to move oxygen *from* the lungs, while no molecule is needed to move carbon dioxide *to* the lungs?

37. Compare the advantages and disadvantages of DNA fingerprinting compared with literal fingerprints as a forensic tool.

38. A lab technician sweeps his hair back while he prepares a sample for polymerase chain reaction (PCR). Later, the DNA fingerprinting tests of the sample indicate that the lab technician was at the scene of the crime. What other explanation is there for the results of the DNA test?

39. Explain how all of the following statements can be true: "Many plants use *starch* to provide energy"; "Energy is supplied by *glucose* in both plants and animals"; and "*ATP* is the energy source in all living cells."

ALTERNATIVE ASSESSMENT

40. News reports about gene technology are sometimes one-sided, stressing the advantages but ignoring the dangers, or vice versa. Find such a report and write "the other side of the story."

41. Research to find out more about the structure of phospholipids and the properties that make them ideal for the construction of cell membranes.

CONCEPT MAPPING

42. Use the following terms to create a concept map: *DNA, polypeptides, amino acids, nucleic acids,* and *carbohydrates*.

FOCUS ON GRAPHING

Study the graph below, and answer the questions that follow.
For help in interpreting graphs, see Appendix B, "Study Skills for Chemistry."

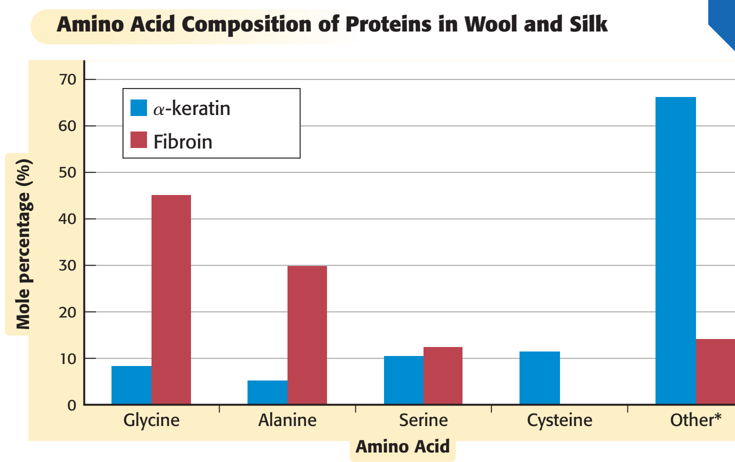
43. What characteristic of the two proteins in this bar graph is being compared?

44. The two proteins compared are α-keratin in wool and fibroin in spider silk. Which color represents the protein found in wool?

45. According to the graph, what is significant about spider fibroin protein?

46. What are the mole percentages of alanine in α-keratin and fibroin?

47. Why do you think the mole percentages of all of the amino acids are not shown?



48. Spider fibroin protein is a much stronger material than α-keratin in wool. Violet would like to create a strong protein for manufacturing fishing line. What amino acids might she decide to use to build the protein? Use the graph to support your answer.

TECHNOLOGY AND LEARNING

49. Graphing Calculator

Polypeptides and Amino Acids

Go to Appendix C. If you are using a TI-83 Plus, you can download the program PEPTIDE and run the application as directed. If you are using another calculator, your teacher will provide you with keystrokes to use. There are 20 amino acids that occur in proteins found in nature. The program will prompt you to input a number of amino acids. After you do, press ENTER. The program will respond with the number of different straight-chain polypeptides possible given that number of amino acid units.

a. Aspartame is an artificial sweetener that is a dipeptide, a protein made of two amino acids. How many possible dipeptides are there?

b. Enkephalins produced in the brain serve to help the body deal with pain. Several of them are pentapeptides. That is, they are polypeptides made of five amino acids. How many different pentapeptides are there?

c. The calculator uses the following equation:

$$\text{number of polypeptides} = 20^{(\text{number of amino acids})}$$

This equation can also be expressed as:

$$\text{number of polypeptides} = (2^{(\text{number of amino acids})})(10^{(\text{number of amino acids})})$$

Given this equation, estimate how many possible polypeptides there are that are made of 100 amino acids? (Hint: The answer is too large for your calculator. However, you can use the graphing calculator to find the value of $2^{(\text{number of amino acids})}$.)

20 STANDARDIZED TEST PREP

UNDERSTANDING CONCEPTS

***Directions (1–3):* For *each* question, write on a separate sheet of paper the letter of the correct answer.**

1. During enzyme catalysis, to which of these does a substrate bind?
   - **A.** DNA
   - **B.** an active site
   - **C.** a disulfide bridge
   - **D.** a monosaccharide

2. Why don't lipids dissolve in water?
   - **F.** One end of the molecule is hydrophilic.
   - **G.** A large portion of the molecule is hydrophobic.
   - **H.** The molecule contains one or more double bonds.
   - **I.** Lipid molecules have no functional groups, so they do not interact with water.

3. What is the function of the conversion of ATP to ADP in cellular respiration?
   - **A.** It absorbs excess energy for later use.
   - **B.** It catalyzes the breaking apart of a glucose molecule.
   - **C.** It provides the energy needed to allow nonspontaneous reactions to occur.
   - **D.** It produces the oxygen necessary for the reactions involved in the Kreb's cycle.

***Directions (4–6):* For *each* question, write a short response.**

4. In terms of energy, how do photosynthesis and cellular respiration differ?

5. In addition to the polysaccharide, what two substances are required for the reaction that converts polysaccharides into sugars inside cells?

6. For the hydrolysis of ATP, $\Phi H = -21$ kJ/mol. What information does this ΦH value provide about the reaction?

READING SKILLS

***Directions (7–8):* Read the passage below. Then answer the questions.**

In 1953 James Watson and Francis Crick proposed a model for the structure of the DNA molecule, based on data about the size and function of the molecule. They built a physical model of their proposed structure in order to help them understand how the molecule functions. Their proposed structure, which consisted of a double helix of two complementary polymer chains, enabled them to predict how DNA replicates.

7. Why is the double helix structure important to the function of DNA molecules?
   - **F.** The bases could not link together in the correct order in any other form.
   - **G.** DNA molecules would be too large if they did not form a double helix.
   - **H.** The double helix allows two complementary, but separable, sequences to exist.
   - **I.** The double helix shape is the only arrangement that allows the two strands to join together with covalent bonds.

8. Why could PCR techniques not be developed until after the current model of DNA had been proposed?
   - **A.** Until the model was developed, scientists could not identify the components of DNA.
   - **B.** People objected to using DNA on ethical grounds.
   - **C.** DNA molecules are too small to see with a conventional microscope.
   - **D.** The replication process can only be understood in the context of the arrangement of the components of DNA.

INTERPRETING GRAPHICS

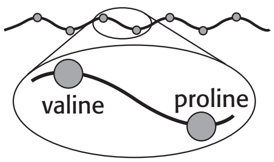
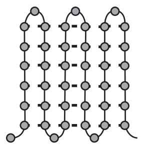
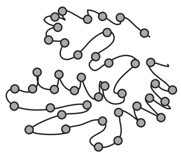
***Directions (9–13):* For *each* question below, record the correct answer on a separate sheet of paper.**

9 Which of the following statements about enzyme catalysis is true?

F. The enzyme molecule is used only once.
G. The reactant binds to an active site on the enzyme.
H. The enzyme must be denatured before it can participate in a reaction.
I. Reaction energy must be supplied to cause the enzyme to form the proper shape.

The table below shows three levels of protein structure. Use it to answer questions 10 through 13.

Levels of Protein Structure

Primary structure	Secondary structure	Tertiary structure
	 β-pleated sheet	

10 What is considered the primary structure of a protein molecule?

A. the sequence of amino acids held together by covalent bonds
B. a chain of sugar molecules held together in a long polymeric chain
C. groups of amino acids held into a rigid structure by hydrogen bonding
D. a three-dimensional model of the monomers involved in forming the protein molecule

11 Which of these bond types is primarily responsible for defining the secondary structure of a protein?

F. covalent
G. hydrogen
H. ionic
I. metallic

12 What forces are primarily responsible for the secondary structure of a protein?

A. covalent bonds that form a bridge across sections of the chain
B. interactions between parts of the protein that have partial electric charges
C. the grouping of several different protein chains to form a large superstructure
D. attractive and repulsive forces of molecules around the protein such as water and fats

13 How can the substitution of a single amino acid by a different amino acid in a protein molecule affect the protein's function?

Test TIP

If you come upon a word you do not know, try to identify its prefix, suffix, or root. Sometimes knowing even one part of the word will help you answer the question.

LABORATORY PROGRAM