3

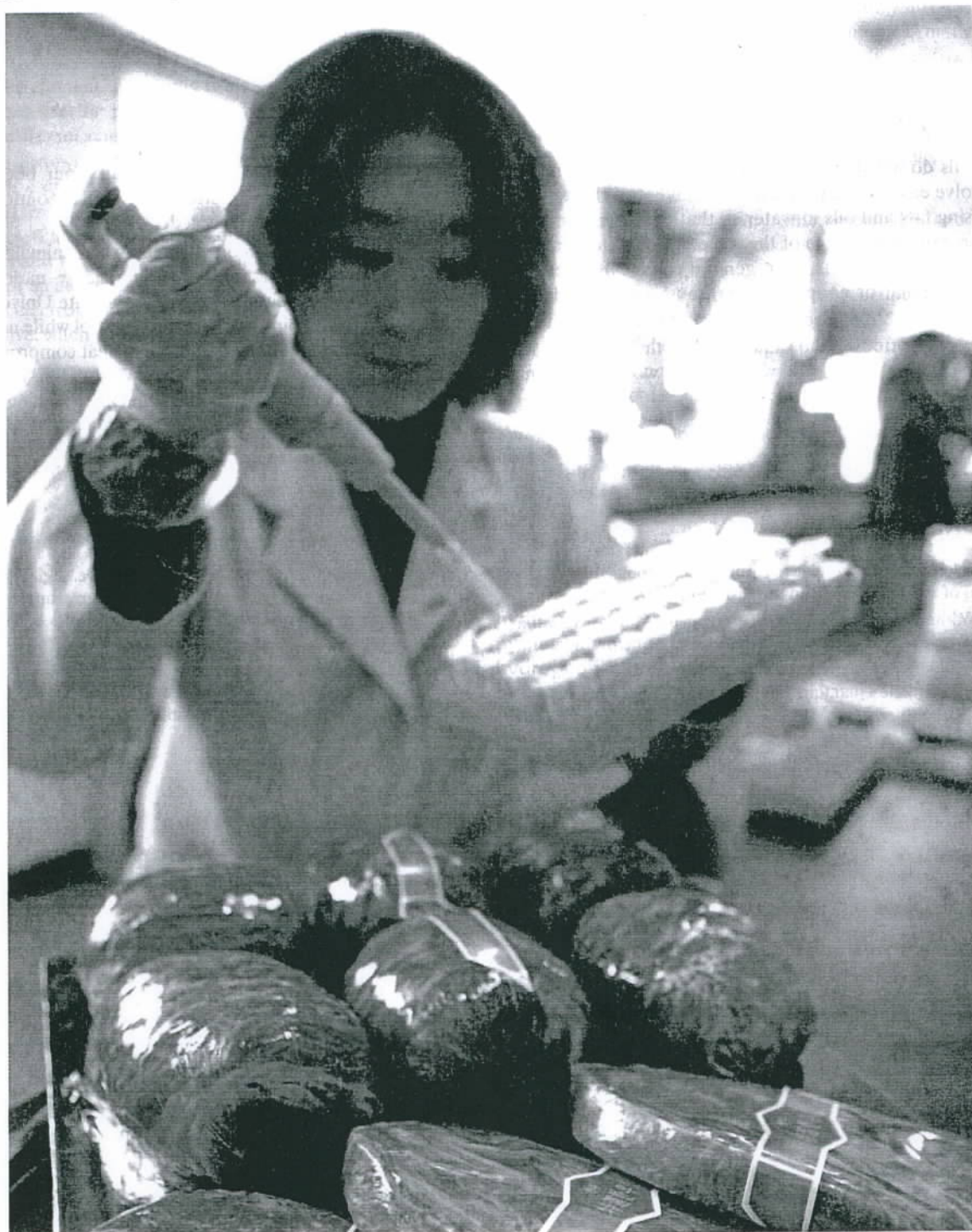# Biological Molecules

Meat in South Korea is tested to determine its origin after discovery of a case of mad cow disease in a U.S. herd.

CASE STUDY PUZZLING PROTEINS

"YOU KNOW, LISA, I think something is wrong with me," the vibrant, 22-year-old scholarship winner told her sister. It was 2001 and Charlene had been living in the United States for nine years when she began to lose her memory and experience mood swings. During the next year, her symptoms worsened; Charlene's hands shook, she was subject to uncontrollable episodes of biting and hitting, and she became unable to walk. Charlene was a victim of "mad cow disease," almost certainly contracted over 10 years earlier while she was residing in England. In June of 2004, having been bedridden and unable to swallow for two years, Charlene became the first U.S. resident to die of variant Creutzfeldt-Jakob disease (vCJD), the human form of mad cow disease (bovine spongiform encephalitis, or BSE). The daunting scientific name of mad cow disease refers to the spongy appearance of infected cow brains viewed under the microscope. The brains of human vCJD victims, usually young adults, are also riddled with microscopic holes. The human disease is so named because it resembles a long-recognized

malady called Creutzfeldt-Jakob disease. Both CJD and vCJD are always fatal.

Why did cattle suddenly begin to die from BSE? For centuries, it was known that sheep could suffer from a "spongiform encephalitis" called scrapie, which was not transmitted to humans or other livestock. Because the symptoms of BSE strongly resemble scrapie, scientists now believe that a mutated form of scrapie became capable of infecting cattle, perhaps in the early 1980s. The since-discontinued practice of supplementing cattle feed with bone and protein supplements derived from sheep and other livestock probably transmitted the mutated form of scrapie from sheep to cattle. Since BSE was first identified in British cattle in 1986, over 180,000 cattle have been diagnosed with the disease; and millions were slaughtered and their bodies burned as a precaution. It was not until the mid-1990s, about the time that the cattle outbreak was controlled, that officials recognized that the disease could be spread to people who ate meat from infected cattle. Although millions of people are likely to have eaten beef from infected cattle before the danger was

recognized, only about 155 people have died of vCJD worldwide. There is no evidence of transmission between people, except by blood transfusion or organ donation from an infected donor.

Fatal infectious diseases are common—so why does mad cow disease fascinate scientists? In the early 1980s, Dr. Stanley Prusiner, a researcher at the University of California in San Francisco, startled the scientific world by providing evidence that a protein with no genetic material was the cause of scrapie, and that this protein could transmit the disease to experimental animals in the laboratory. He dubbed the infectious proteins "prions" (pronounced PREE-ons), short for "proteinacious infectious particles." Because no infectious agent had ever been identified that lacked all genetic material (DNA or RNA), Prusiner's findings were greeted with enormous skepticism from his fellow scientists.

What are proteins? How do they differ from DNA and RNA? How can a protein with no hereditary material infect another organism and then increase in numbers, resulting in disease?

3.1   WHY IS CARBON SO IMPORTANT IN BIOLOGICAL MOLECULES?

You have probably seen "organic" fruits and vegetables in your grocery store. To a chemist, this phrase is redundant; all produce is organic because it is formed from biological molecules. In chemistry, the term **organic** describes molecules that have a carbon skeleton and contain some hydrogen atoms. The word *organic* is derived from the ability of living *organisms* to synthesize and use this general type of molecule. **Inorganic** molecules include carbon dioxide and all molecules without carbon, such as water and salt.

The versatile carbon atom is the key to the tremendous variety of organic molecules. This variety, in turn, allows the diversity of structures within single organisms and even within individual cells. A carbon atom has four electrons in its outermost shell, with room for eight. Therefore, a carbon atom can become stable by bonding with up to four other atoms, and they can also form double or even triple bonds. Molecules with many carbon atoms can assume complex shapes, including chains, branches, and rings—the basis for an amazing diversity of molecules.
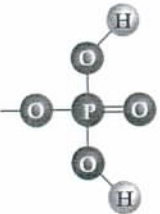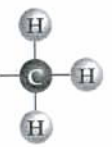
Organic molecules are much more than just complicated skeletons of carbon atoms, however. Attached to the carbon backbone are **functional groups**, groups of atoms that determine the characteristics and chemical reactivity of the molecules. Functional groups are far less stable than the carbon backbone and are more likely to participate in chemical reactions. The common functional groups found in biological molecules are shown in Table 3-1.

The similarity among organic molecules from all forms of life is a consequence of two main features: the use of the same basic set of functional groups in virtually all organic molecules in all types of organisms, and the "modular approach" of synthesizing large organic molecules.

3.2   HOW ARE ORGANIC MOLECULES SYNTHESIZED?

In principle, there are two ways to manufacture a large, complex molecule: by combining atom after atom following an extremely detailed blueprint, or by preassembling smaller molecules and hooking them together. Just as trains are made by coupling engines to various train cars, life also

Table 3-1 Important Functional Groups in Biological Molecules

Group	Structure	Properties	Found In
Hydrogen ($-H$)	$-H$	Polar or nonpolar, depending on which atom hydrogen is bonded to; involved in dehydration and hydrolysis reactions	Almost all organic molecules
Hydroxyl ($-OH$)	$-O-H$	Polar; involved in dehydration and hydrolysis reactions	Carbohydrates, nucleic acids, alcohols, some acids, and steroids
Carboxylic acid ($-COOH$)	$-C\big(\!\!\begin{smallmatrix}O\\O-H\end{smallmatrix}$	Acidic; involved in peptide bonds	Amino acids, fatty acids
Amino ($-NH_2$)	$-N\big(\!\!\begin{smallmatrix}H\\H\end{smallmatrix}$	Basic; may bond an additional H^+, becoming positively charged; involved in peptide bonds	Amino acids, nucleic acids
Phosphate ($-H_2PO_4$)	$-O-P(-O)(O)-O-H$	Acidic; links nucleotides in nucleic acids; energy-carrier group in ATP	Nucleic acids, phospholipids
Methyl ($-CH_3$)	$-C(H)(H)-H$	Nonpolar; tends to make molecules hydrophobic	Many organic molecules; especially common in lipids

takes a "modular approach." Small organic molecules (for example, sugars) are used as subunits that combine to form longer molecules (for example, starches)—like cars in a train. The individual subunits are often called **monomers** (from Greek words meaning "one part"); long chains of monomers are called **polymers** ("many parts").

Biological Molecules Are Joined Together or Broken Apart by Removing or Adding Water

In Chapter 2, you learned some of the reasons that water is so important to life. But water also plays a central role in reactions that break down biological molecules to liberate subunits that the body can use. In addition, when complex biological molecules are synthesized in the body, water is often produced as a by-product.

The subunits that make up large biological molecules almost always join together by means of a chemical reaction called **dehydration synthesis** (literally, "to form by removing water"). In dehydration synthesis, a hydrogen ion (H^+) is removed from one subunit and a hydroxyl ion (OH^-) is removed from a second subunit, creating openings in the outer electron shells of atoms in the two subunits. These openings are filled when the subunits share electrons, creating a covalent bond that links them. The hydrogen ion and the hydroxyl ion then combine to form a molecule of water (H_2O)(**FIG. 3-1**).
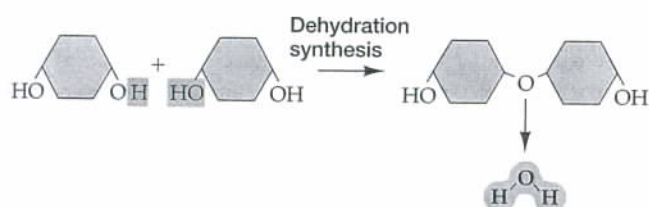

FIGURE 3-1 Dehydration synthesis

The reverse reaction, **hydrolysis** ("to break apart with water"), splits the molecule back into its original subunits (**FIG. 3-2**).
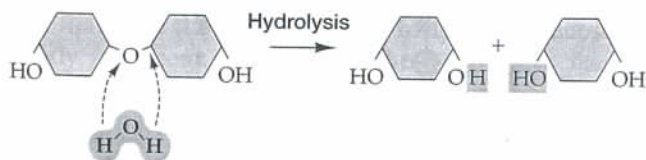

FIGURE 3-2 Hydrolysis

Hydrolysis is the major way our digestive enzymes break down food. For example, the starch in a cracker is composed of a series of glucose (simple sugar) molecules (see Fig. 3-8). Enzymes in our saliva and small intestines promote hydrolysis of the starch into individual sugar molecules that can be absorbed into the body.

Considering how complicated living things are, it might surprise you to learn that nearly all biological molecules fall into one of only four general categories: *carbohydrates, lipids, proteins,* and *nucleic acids* (Table 3-2).

3.3 WHAT ARE CARBOHYDRATES?

Carbohydrate molecules are composed of carbon, hydrogen, and oxygen in the approximate ratio of 1:2:1 or CH_2O. This formula explains the origin of the word "carbohydrate," which literally means "carbon plus water." All carbohydrates are either small, water-soluble **sugars** or polymers of sugar, such as starch. If a carbohydrate consists of just one sugar molecule, it is called a **monosaccharide** (Greek for "single sugar"). When two monosaccharides are linked, they form a **disaccharide** ("two sugars"), and a polymer of many monosaccharides is called a **polysaccharide** ("many sugars"). While sugars and starches are used to store energy in many organisms, other carbohydrates provide support. Various types of carbohydrates strengthen plant, fungal, and bacterial cell walls, or form a supportive armor over the bodies of insects, crabs, and their relatives.

The hydroxyl groups of sugars are polar and form hydrogen bonds with water, making sugars water soluble. **FIGURE 3-3** illustrates how a monosaccharide (glucose) forms hydrogen bonds with water molecules.
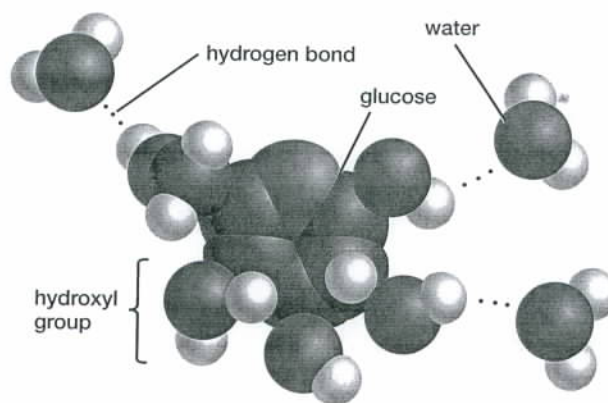
FIGURE 3-3 Sugar dissolving

There Are Several Monosaccharides with Slightly Different Structures

Monosaccharides usually have a backbone of three to seven carbon atoms. Most of these carbon atoms have both a hydrogen $(—H)$ and a hydroxyl group $(—OH)$ attached to them; therefore, carbohydrates generally have the approximate chemical formula $(CH_2O)_n$ (n is the number of carbons in the backbone). When dissolved in water, such as in the cytosol of a cell, the carbon backbone of a sugar usually forms a ring. Sugars in ring form can link together to make disaccharides (see Fig. 3-7) and polysaccharides (see

Table 3-2 The Principal Biological Molecules

| Class of Molecule	Principal Subtypes	Example	Function
Carbohydrate: Usually contains carbon, oxygen, and hydrogen, in the approximate formula $(CH_2O)_n$	*Monosaccharide:* Simple sugar with the formula $C_6H_{12}O_6$	Glucose	Important energy source for cells; subunit of polysaccharides
	Disaccharide: Two monosaccharides bonded together	Fructose	Energy-storage molecule in fruits and honey
		Sucrose	Principal sugar transported throughout bodies of land plants
	Polysaccharide: Many monosaccharides (usually glucose) bonded together	Starch	Energy storage in plants
		Glycogen	Energy storage in animals
		Cellulose	Structural material in plants
Lipid: Contains high proportion of carbon and hydrogen; usually nonpolar and insoluble in water	*Triglyceride:* Three fatty acids bonded to glycerol	Oil, fat	Energy storage in animals, some plants
	Wax: Variable numbers of fatty acids bonded to long-chain alcohol	Waxes in plant cuticle	Waterproof covering on leaves and stems of land plants
	Phospholipid: Polar phosphate group and two fatty acids bonded to glycerol	Phosphatidylcholine	Component of cell membranes
	Steroid: Four fused rings of carbon atoms with functional groups attached	Cholesterol	Common component of membranes of eukaryotic cells; precursor for other steroids such as testosterone, bile salts
Protein: Chains of amino acids; contains carbon, hydrogen, oxygen, nitrogen, and sulfur	*Peptide:* Short chain of amino acids	Keratin	Helical protein, principal component of hair
		Silk	Beta-pleated sheet protein produced by silk moths and spiders
	Polypeptide: Long chain of amino acids; also called "protein"	Hemoglobin	Globular protein composed of four subunit peptides; transport of oxygen in vertebrate blood
Nucleic acid: Made of nucleotide subunits containing carbon, hydrogen oxygen, nitrogen, and phosphorus. May consist of a single nucleotide or long chain of nucleotides.	*Long-chain nucleic acids:* polymer of nucleotide subunits	Deoxyribonucleic acid (DNA)	Genetic material of all living cells
		Ribonucleic acid (RNA)	Genetic material of some viruses; in cells, essential in transfer of genetic information from DNA to protein
	Single nucleotides	Adenosine triphosphate (ATP)	Principal short-term energy carrier molecule in cells
		Cyclic adenosine monophosphate (cyclic AMP)	Intracellular messenger

Fig. 3-8). **FIGURES 3-3** and **3-4** show various ways of depicting the chemical structure of the common sugar **glucose.** In many figures, we will use the simplified versions of molecules. Keep in mind that every unlabeled "joint" in a ring is actually a carbon atom.

FIGURE 3-4 Glucose structure
Chemists can represent the same molecule in a variety of ways; glucose is shown here in linear (straight) form and in two different versions of its ring form. Glucose forms a ring when dissolved in water. Notice that each unlabeled joint in a ring structure is a carbon atom.
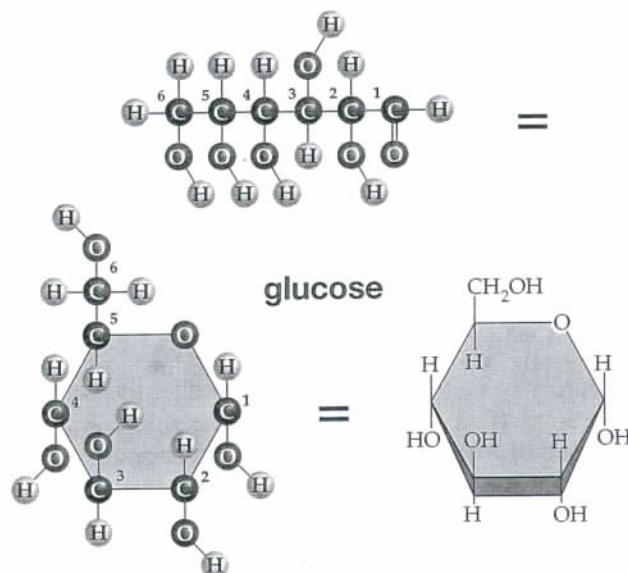
LINKS TO LIFE   Fake Food?

In societies blessed with an overabundance of food, obesity is a serious health problem. One goal of food scientists is to modify biological molecules to make them noncaloric; sugar and fat are prime candidates. Several artificial sweeteners such as aspartame (Nutrasweet™) and sucralose (Splenda™) add a sweet taste to foods, while providing few or no calories. The artificial oil called olestra is completely indigestible, ensuring that potato chips made with olestra have no fat calories and far fewer total calories than normal chips (**FIG. E3-1**).

How are these "nonbiological molecules" made? Aspartame is a combination of two amino acids: aspartic acid and phenylalanine (see Fig. 3-19). For unknown reasons, aspartame is far more effective than sugar in stimulating the sweet taste receptors on our tongues. Sucralose is a modified sucrose molecule in which three of its hydroxyl groups are replaced with chlorine atoms (**FIG. E3-2**).

Sucralose activates our sweet taste receptors 600 times as effectively as sucrose, but our enzymes cannot digest it, so it provides no calories. Sucralose is gaining in popularity because it is more stable than other artificial sweeteners and can be used in baked goods, as well as in ice cream, diet drinks, and tabletop sweetener packets.

To understand olestra, look at Figure 3-13 and you will see that oils combine a glycerol backbone with three fatty acid chains. Olestra, however, contains a sucrose backbone with six to eight fatty acids attached. Apparently, the large number of fatty acid chains prevents digestive enzymes from reaching the digestible sucrose backbone of the olestra molecule. Since the molecule is not broken into absorbable fragments, it is not digested; but it adds the same appealing feel and flavor to foods that oil does.

FIGURE E3-1 Artificial "foods"
The sucralose in Splenda™ and the olestra in WOW™ potato chips are synthetic, indigestible versions of sugar and oil that are intended to help people lose weight.
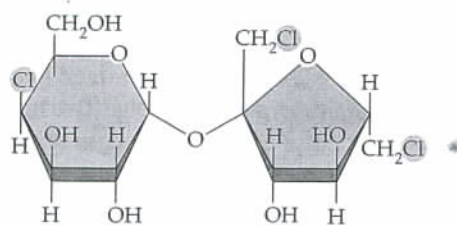
FIGURE E3-2 The structure of Splenda™

Glucose is the most common monosaccharide in living organisms and is a subunit of many polysaccharides. Glucose has six carbons, so its chemical formula is $C_6H_{12}O_6$. Many organisms synthesize other monosaccharides that have the same chemical formula as glucose but slightly different structures. These include *fructose* ("fruit sugar" found in corn syrup, fruits, and honey) and *galactose* (part of lactose, or "milk sugar")(**FIG. 3-5**).

Other common monosaccharides, such as *ribose* and *deoxyribose* (found in DNA and RNA) have five carbons (**FIG. 3-6**).

FIGURE 3-6 Ribose sugars

Disaccharides Consist of Two Single Sugars Linked by Dehydration Synthesis

Monosaccharides may be broken down in cells to free their chemical energy for use in various cellular activities or may be linked together by dehydration synthesis to

FIGURE 3-5 Monosaccharides

FIGURE 3-7 Synthesis of a disaccharide
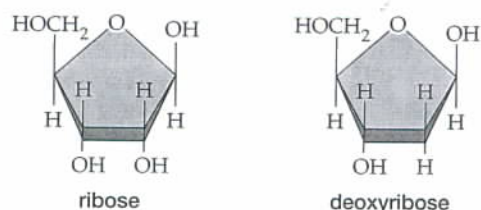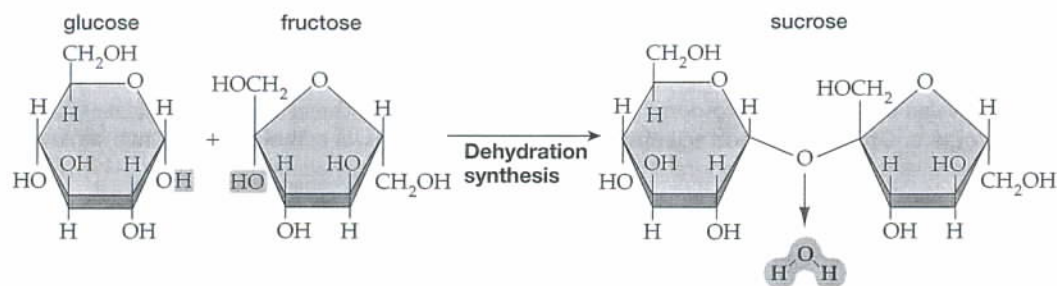The disaccharide sucrose is synthesized by dehydration synthesis reaction in which a hydrogen (—H) is removed from glucose and a hydroxyl group (—OH) is removed from fructose. A water molecule (H—O—H) is formed in the process, leaving the two monosaccharide rings joined by single bonds to the remaining oxygen atom. Hydrolysis of sucrose is just the reverse of its synthesis—that is, water is split and added to the monosaccharides.

form disaccharides or polysaccharides (**FIG. 3-7**). Disaccharides are often used for short-term energy storage, especially in plants. When energy is required, the disaccharides are broken apart into their monosaccharide subunits by hydrolysis (see Fig. 3-2). Many foods we eat contain disaccharides. Perhaps you had toast and coffee with cream and sugar at breakfast. You stirred **sucrose** (glucose plus fructose, used as an energy storage molecule in sugarcane and sugar beets) into your coffee; added milk containing **lactose** (milk sugar: glucose plus galactose). The disaccharide **maltose** (glucose plus glucose) is rare in nature, but it is formed as enzymes (such as those in your digestive tract) attack and hydrolyze starches such as those in your toast. Digestive enzymes then hydrolyze each maltose into two glucose molecules that

your body can absorb and enzymes in your cells can break down to liberate energy.

If you are on a diet, you may have used an artificial "sugar substitute" such as Splenda™ or Equal™ in your coffee. These interesting molecules are described in "Links to Life: Fake Food?"

Polysaccharides Are Chains of Single Sugars

Try chewing a cracker for a long time. Does it taste sweeter the longer you chew? It should, because over time, enzymes in saliva cause hydrolysis of the **starch** (a polysaccharide) in crackers into its component glucose sugar molecules (monosaccharides), which taste sweet. While plants often
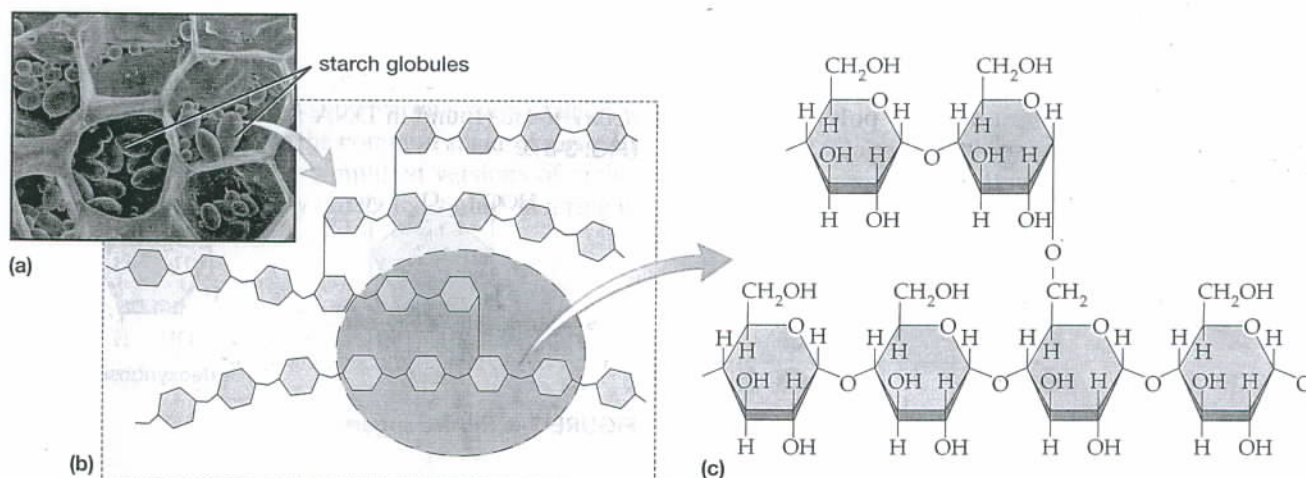
FIGURE 3-8 Starch is an energy-storage polysaccharide made of glucose subunits
(a) Starch globules inside individual potato cells. Most plants synthesize starch, which forms water-insoluble globules consisting of many starch molecules. (b) A small section of a single starch molecule, which occurs as branched chains of up to half a million glucose subunits. (c) The precise structure of the blue highlighted portion of the starch molecule in (b). Notice the linkage between the individual glucose subunits for comparison with cellulose (see Fig. 3-9).

use starch (FIG. 3-8) as an energy-storage molecule, animals commonly store **glycogen**. Both substances consist of polymers of glucose subunits. Starch is commonly formed in roots and seeds—in your cracker, from wheat seeds. Starch often takes the form of branched chains of up to half a million glucose subunits. Glycogen, stored as an energy source in the liver and muscles of animals (including ourselves), is a much shorter chain of glucose subunits with many branches, which probably make it easy to split off the glucose subunits for quick energy release.

Many organisms also use polysaccharides as structural materials. One of the most important structural polysaccharides is **cellulose**, which makes up most of the cell walls of plants, the fluffy white bolls of a cotton plant, and about half the bulk of a tree trunk (FIG. 3-9). When you imagine the vast fields and forests that blanket much of our planet, it may not surprise you to learn that there is probably more cellulose on Earth than all other organic molecules combined. Ecologists estimate that about 1 trillion tons of cellulose are synthesized on Earth each year.

Cellulose, like starch, is a polymer of glucose. However, while most animals can easily digest starch, only a few microbes—such as those in the digestive tracts of cows or termites—can digest cellulose. Why is this the case, given that both starch and cellulose consist of glucose? The orientation of the bonds between subunits differs between the two polysaccharides. In cellulose, every other glucose is "upside down" (compare Fig. 3-8c with Fig. 3-9d). This arrangement prevents animals' digestive enzymes from attacking the bonds between glucose subunits. Certain microbes, however, synthesize enzymes that can break these bonds and consume cellulose as food. But for most animals, cellulose passes undigested through the digestive tract. While it serves a valuable function as fiber that prevents constipation, we don't derive any nutrients from it.
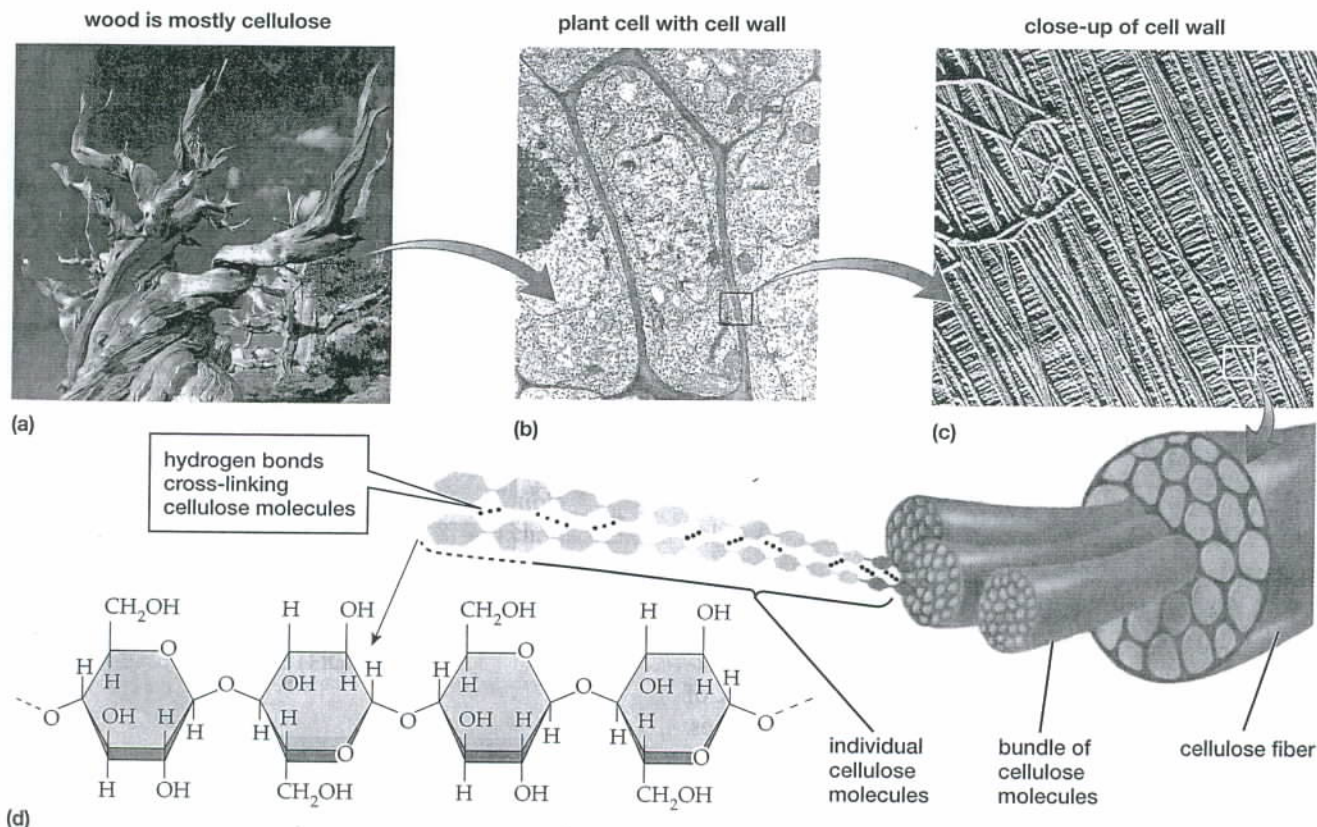
FIGURE 3-9 Cellulose structure and function
Cellulose can be incredibly tough. **(a)** Wood in this 3000-year-old bristlecone pine is primarily cellulose. **(b)** Cellulose forms the cell wall that surrounds each plant cell. **(c)** Plant cell walls often consist of cellulose fibers in layers that run at angles to each other and resist tearing in both directions. **(d)** Cellulose is composed of glucose subunits. Compare this structure with Fig. 3-8c and notice that every other glucose molecule in cellulose is "upside down." QUESTION Many types of plastic are composed of molecules derived from cellulose, but engineers are working hard to develop plastics based on starch molecules. Why might starch-based plastics be an improvement over existing types of plastic?

FIGURE 3-10 Chitin: A unique polysaccharide
Chitin has the same bonding configuration of glucose molecules as cellulose does. In chitin, however, the glucose subunits have a nitrogen-containing functional group (yellow) instead of a hydroxyl group. Tough, flexible chitin supports the otherwise soft bodies of arthropods (insects, spiders, and their relatives) and certain fungi, such as this mushroom.

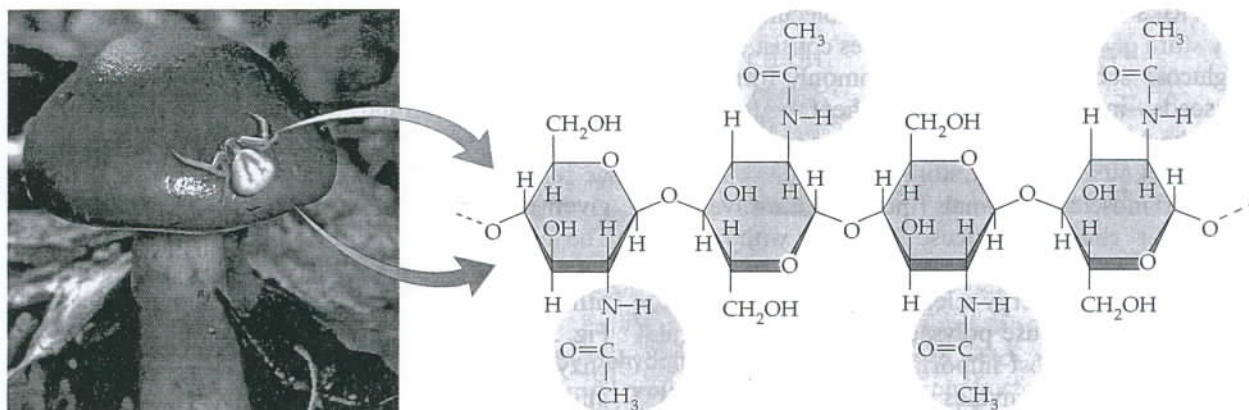The hard outer coverings (exoskeletons) of insects, crabs, and spiders are made of **chitin**, a polysaccharide in which the glucose subunits bear a nitrogen-containing functional group (**FIG. 3-10**). Interestingly, chitin also stiffens the cell walls of many fungi, including mushrooms. Other types of polysaccharides are found in the cell walls of bacteria, in fluids that lubricate our joints, and in the transparent corneas of our eyes.

A variety of other molecules—including mucus, some chemical messengers called *hormones*, and many molecules in the plasma membrane that surrounds each cell—consist, in part, of carbohydrate. Perhaps the most interesting of these molecules are the nucleic acids (containing sugars) that carry hereditary information. We will discuss these molecules later in this chapter.

3.4 WHAT ARE LIPIDS?

Lipids form a diverse group of molecules with two important features. First, lipids contain large regions composed almost entirely of hydrogen and carbon, with nonpolar carbon–carbon or carbon–hydrogen bonds. Second, these nonpolar regions make lipids hydrophobic and insoluble in water. Lipids serve a wide variety of functions. Some are energy-storage molecules, some form waterproof coverings on plant or animal bodies, some make up the bulk of all the membranes of a cell, and still others are hormones.

Lipids are classified into three major groups: (1) oils, fats, and waxes, which are similar in structure and contain only carbon, hydrogen, and oxygen; (2) phospholipids, which are structurally similar to oils but also contain phosphorus and nitrogen; and (3) the "fused-ring" family of steroids.

Oils, Fats, and Waxes Are Lipids Containing Only Carbon, Hydrogen, and Oxygen

Oils, fats, and waxes are related in three ways. First, they contain only carbon, hydrogen, and oxygen. Second, they contain one or more **fatty acid** subunits, which are long

chains of carbon and hydrogen with a *carboxylic acid group* (—COOH) at one end. Finally, most do not have ring structures. **Fats** and **oils** are formed by dehydration synthesis from three fatty acid subunits and one molecule of **glycerol**, a short, three-carbon molecule (**FIG. 3-11**). This structure gives fats and oils their chemical name: **triglycerides**. Notice that a double bond between two carbons in the fatty acid subunit creates a kink in the chain.
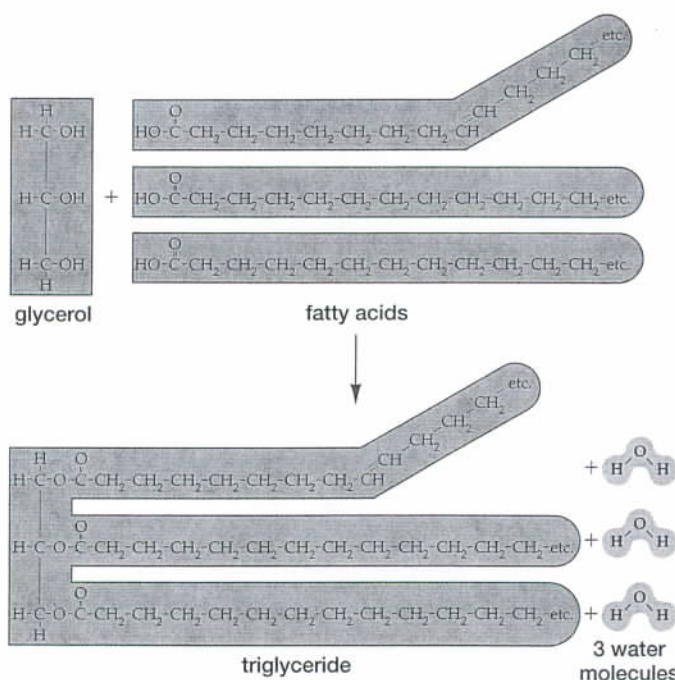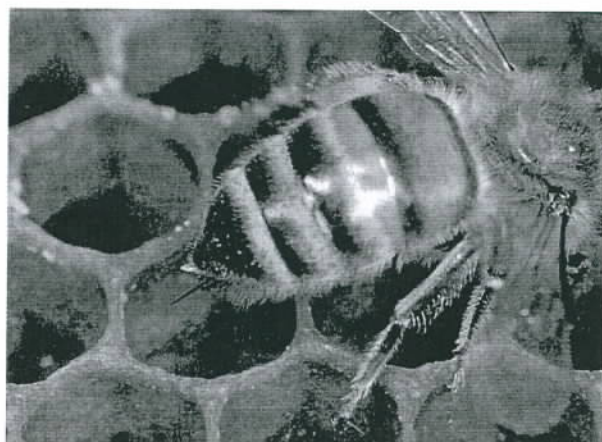

FIGURE 3-11 Synthesis of a triglyceride
Dehydration synthesis links a single glycerol molecule with three fatty acids to form a triglyceride and three water molecules.
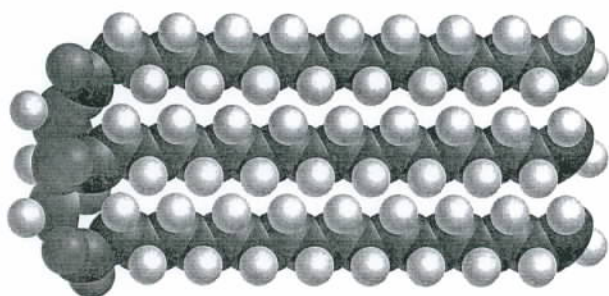
(a) Fat   (b) Wax

FIGURE 3-12 Lipids
(a) A fat European brown bear ready to hibernate. If this bear stored the same amount of energy in car-bohydrates instead of fat, she probably would be unable to walk! (b) Wax is a highly saturated lipid that remains very firm at normal outdoor temperatures. Its rigidity allows it to be used to form the strong but thin-walled hexagons of this honeycomb.

Fats and oils contain over twice as many calories per gram as do sugars and proteins, making them very efficient energy-storage molecules for both plants and animals, such as the bear in **FIGURE 3-12a**. People who want to avoid looking like this bear may turn to foods manufactured with fat substitutes such as olestra, described in "Links to Life: Health Food?" Most of the saturated fat in the human diet, such as butter and bacon fat, comes from animals. The difference between a fat (such as beef fat), which is a solid at room temperature, and an oil (such as those used to make potato chips or french fries) lies in their fatty acids. Fats have fatty acids with all single bonds in their carbon chains. Hydrogens occupy all the other bond positions on the carbons. The resulting fatty acid is said to be **saturated**, because it has as many hydrogen atoms as possible. Lacking double bonds between carbons, the carbon chain of the fatty acid is straight. The straight carbon chains of saturated fatty acids of fats (such as the beef fat molecule illustrated below) can nestle closely together, forming solid lumps at room temperature (**FIG. 3-13**).

If there are double bonds between some of the carbons, and consequently fewer hydrogens, the fatty acid is said to be **unsaturated**. Oils have mostly unsaturated fatty acids. We get most of our unsaturated oils from the seeds of plants, where they are stored for the plants' developing embryos. Corn oil, peanut oil, and canola oil are all examples. The double bonds in the unsaturated fatty acids of oils produce kinks in the fatty acid chains, as illustrated by the linseed oil molecule (**FIG. 3-14**).
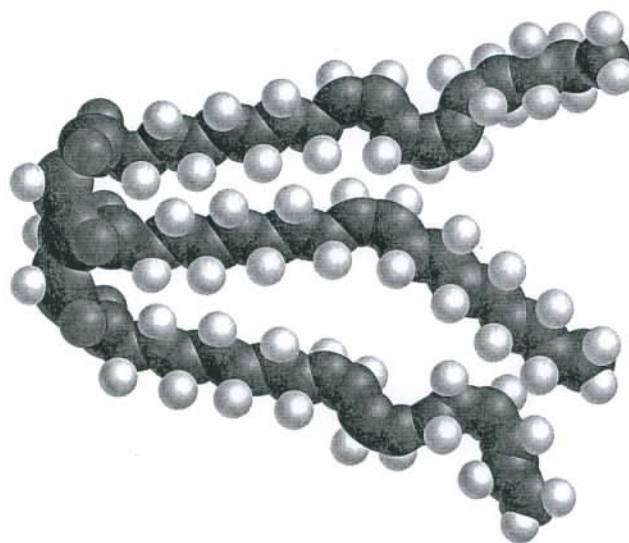
FIGURE 3-14 Linseed oil is unsaturated

FIGURE 3-13 Beef fat is saturated

The kinks caused by the double bonds in unsaturated fatty acids keep oil molecules apart; as a result, oil is liquid at room temperature. An oil can be converted to a fat by
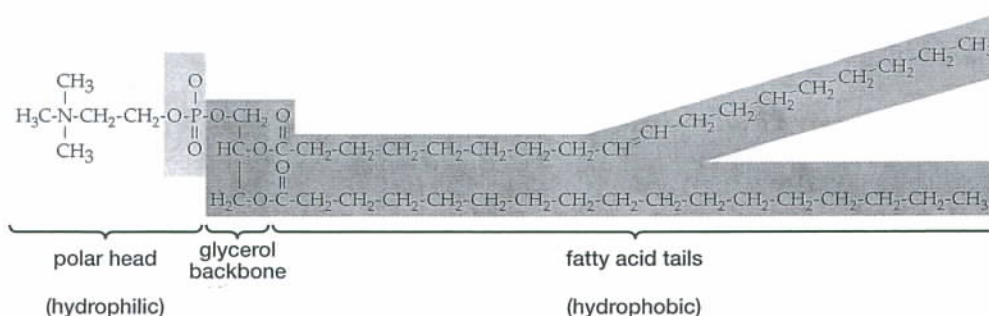
FIGURE 3-15 Phospholipids
Phospholipids have two fatty acid tails attached to the glycerol backbone. The third position on glycerol is occupied by a polar "head" consisting of a phosphate group to which a second (usually nitrogen-containing) functional group is attached. The phosphate group bears a slight negative charge, and the nitrogen-containing group bears a slight positive charge, making the heads hydrophilic.

breaking some of the double bonds between carbons, replacing them with single bonds, and adding hydrogens to the remaining bond positions. The resulting substance is the "hydrogenated oil" that causes the oil to be solid at room temperature. The partial hydrogenation process results in a configuration of double and single bonds, called the *trans* configuration, that is rare in nature. In this configuration, the carbon chain bends in a zigzag shape that allows adjacent fatty acids to stack together: the "zigs" of one strand nestle within the "zags" of adjacent strands. This resembles the packing that occurs between the straight-chain fatty acids in saturated fats, and it allows the *trans fats* to assemble into a solid, as do saturated fats. These artificially produced trans fats are found in many commercial food products, including margarine, cookies, crackers, and french fries. Recently, however, researchers have become concerned about our consumption of trans fats (see "Health Watch: Cholesterol—Friend and Foe"). As a result, many manufacturers have made efforts to reduce the use of these substances in processed food.

Although **waxes** are chemically similar to fats, they are not a food source; people and most other animals do not have the appropriate enzymes to break them down. Waxes are highly saturated and therefore solid at normal outdoor temperatures. Waxes form a waterproof coating over the leaves and stems of land plants. Animals synthesize waxes as waterproofing for mammalian fur and insect exoskeletons and, in a few cases, use waxes to build elaborate structures such as beehives (see Fig. 3-12b).

Phospholipids Have Water-Soluble "Heads" and Water-Insoluble "Tails"

The plasma membrane that surrounds each cell contains several types of **phospholipids**. A phospholipid is similar to an oil, except that one of the three fatty acids is replaced by a phosphate group with a short, polar functional group (typically containing nitrogen) attached to the end (**FIG. 3-15**). A phospholipid has two dissimilar ends: two nonpolar fatty acid "tails," which are insoluble in water, and one phosphate–nitrogen "head" that is polar and water soluble.

As you will learn in Chapter 5, the dual nature of phospholipids is crucial to the structure and function of the plasma membrane.

Steroids Consist of Four Carbon Rings Fused Together

Steroids are structurally different from all other lipids. In contrast to other lipids that lack rings, all steroids are composed of four rings of carbon, fused together, with various functional groups protruding from them (**FIG. 3-16**). One type of steroid is *cholesterol*. Cholesterol is a vital component of the membranes of animal cells and is also used by cells to synthesize other steroids, including the male sex
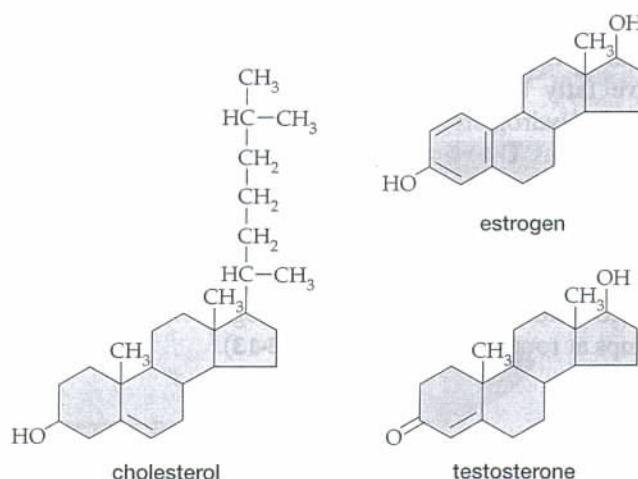
FIGURE 3-16 Steroids
Steroids are synthesized from cholesterol. All steroids have a similar, nonpolar molecular structure (compare the carbon rings). Differences in steroid function result from differences in functional groups attached to the rings. Notice the similarity between the male sex hormone testosterone and the female sex hormone estradiol (estrogen). QUESTION Why are steroid hormones, after traveling in the bloodstream, able to penetrate plasma membranes and nuclear membranes of cells to exert their effects?

HEALTH WATCH   Cholesterol—Friend and Foe

Why are so many foods advertised as "cholesterol free" or "low in cholesterol"? Although cholesterol is crucial to life, medical researchers have found that individuals with high levels of cholesterol in their blood are at increased risk for heart attacks and strokes. Cholesterol contributes to the formation of obstructions in arteries, called *plaques* (**FIG. E3-3**), which in turn can promote the formation of blood clots. If a clot breaks loose and blocks an artery supplying the heart muscle, it can cause a heart attack. If the clot blocks an artery to the brain, it may cause stroke.

Cholesterol comes from animal-derived foods: egg yolks are a particularly rich source; sausages, bacon, whole milk, and butter contain it as well. Perhaps you have heard of "good" and "bad" cholesterol. Because cholesterol molecules are nonpolar, they do not dissolve in blood (which is mostly water). Thus, clusters of cholesterol molecules, surrounded by polar protein carrier molecules and phospholipids, are transported in the blood. These packets of cholesterol plus carriers are called *lipoproteins* (lipids plus proteins). If these lipoproteins have more protein and less lipid, they are described as "high-density lipoproteins," or HDL, because protein is denser than lipid. The HDL form of cholesterol packet is the good kind; these are transported to the liver, where the cholesterol is removed from circulation and further metabolized (used in bile synthesis, for example). In contrast, bad cholesterol is transported in low-density lipoprotein packets ("LDL cholesterol"), which have less protein and more cholesterol. The LDL cholesterol circulates to cells throughout the body and can be deposited in artery walls. A high ratio of HDL ("good") to LDL ("bad") is correlated with a reduced risk of heart disease. A complete cholesterol screening test will distinguish between these two forms in your blood.

Perhaps you've also heard about trans fatty acids as dietary villains. These are not found in nature, but are produced when oils are artificially hardened to make them solid at room temperature. Research has revealed that these trans fatty acids are not metabolized normally and can both increase LDL cholesterol and decrease HDL cholesterol, suggesting that they may place consumers at a higher risk of heart disease. The U.S. Food and Drug Administration now requires food labels to include the trans fat content. In response to

health concerns, many food manufacturers and fast-food chains are reducing or eliminating trans fats in their products.

Animals, including people, can synthesize all the cholesterol their bodies require. Roughly 85 percent of the cholesterol in human blood is synthesized by the body, and the other 15 percent comes from diet. Lifestye choices also play a role; exercise tends to increase HDL cholesterol, while obesity and smoking increase LDL levels. Because of genetic differences, some people's bodies manufacture more cholesterol than do others. Studies of identical twins indicate that genetics also influences how much effect diet has on cholesterol levels. Some people's bodies can compensate for a high-cholesterol diet by manufacturing less. Other people compensate poorly, and their diet strongly influences cholesterol levels. Pairs of identical twins share these compensating or non-compensating traits.

People with high cholesterol (about 25 percent of all adults in the United States) are advised to switch to a diet low in cholesterol and saturated fats, to maintain a healthy weight, and to exercise. For people with dangerous levels of cholesterol who are unable to reduce it adequately through lifestyle changes, doctors often prescribe cholesterol-reducing drugs.
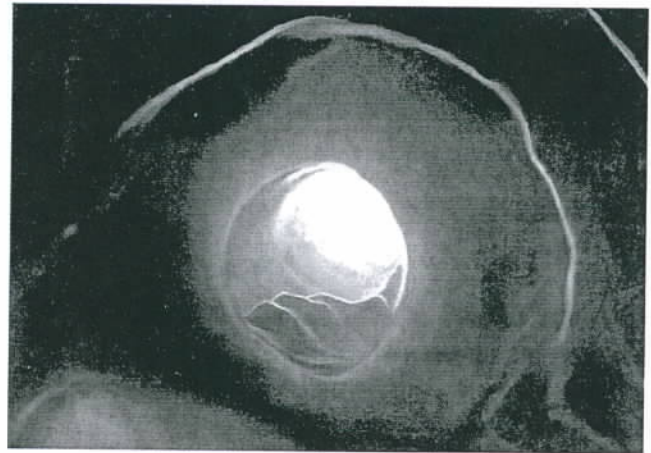
FIGURE E3-3 Plaque
A plaque deposit (ripply structure) partially blocks a carotid artery.

---

hormone testosterone, the female sex hormone estrogen, and bile that assists in fat digestion. However, cholesterol can also contribute to heart disease, as explained in "Health Watch: Cholesterol—Friend and Foe."

3.5 WHAT ARE PROTEINS?

Proteins are molecules composed of one or more chains of *amino acids*. Proteins perform many functions; this diversity of function is made possible by the diversity of protein structures (Table 3-3). Most cells contain hundreds of different **enzymes**, which are proteins that guide

Table 3-3 Functions of Proteins

Function	Example
Structure	Collagen in skin; keratin in hair, nails, horns
Movement	Actin and myosin in muscle
Defense	Antibodies in bloodstream
Storage	Albumin in egg white
Signaling	Growth hormone in bloodstream
Catalyzing reactions	Enzymes (Ex.: amylase digests carbohydrates; ATP synthase makes ATP)

(a) Hair

(b) Horn

(c) Silk

FIGURE 3-17 Structural proteins
Common structural proteins include keratin, which is the predominant protein found in (a) hair, (b) horn, and (c) the silk of a spider web.

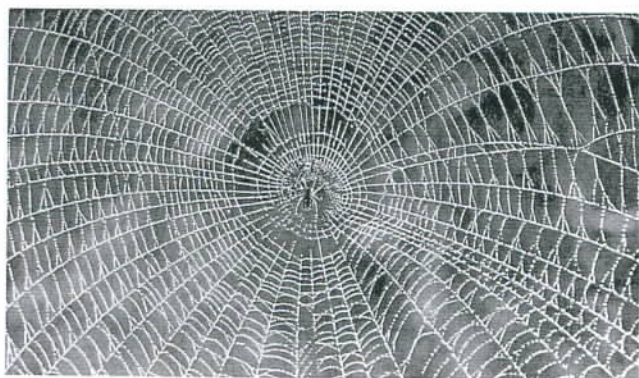almost all the chemical reactions occurring inside cells, as you will learn in Chapter 6. Other types of proteins are used for structural purposes. These include *elastin*, which gives skin its elasticity; *keratin*, the principal protein of hair, horns, nails, scales, and feathers; and the silk

of spider webs and silk moth cocoons (FIG. 3-17). Still other proteins provide a source of amino acids for developing young animals, such as *albumin* protein in egg white and *casein* protein in milk. The protein *hemoglobin* transports oxygen in the blood, while contractile proteins, such as those in muscle, allow both individual cells and entire animal bodies to move. Some hormones, including insulin and growth hormone, are proteins, as are *antibodies* (which help fight disease and infection) and many poisons (such as rattlesnake venom) produced by animals.

Proteins Are Formed from Chains of Amino Acids

Proteins are polymers of **amino acids**. All amino acids have the same fundamental structure (FIG. 3-18), consisting of a central carbon bonded to four different functional groups: a nitrogen-containing amino group ($-NH_2$); a carboxylic acid group ($-COOH$); a hydrogen; and a group that varies among different amino acids (R).
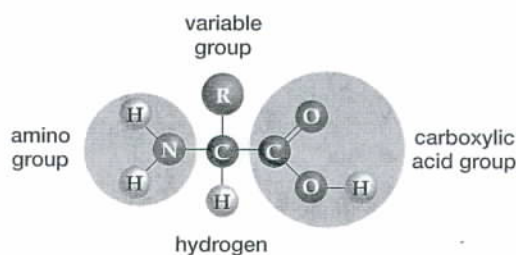
FIGURE 3-18 Amino acid structure

The R group gives each amino acid its distinctive properties (FIG. 3-19). Twenty amino acids are commonly found in the proteins of organisms. Some amino acids are hydrophilic and water soluble because their R groups are polar. Others are hydrophobic, with nonpolar R groups that are insoluble in water. The R group of one amino acid, cysteine (Fig. 3-19c), contains sulfur that can form covalent bonds with the sulfur in other cysteines; these bonds are called **disulfide bridges**. Disulfide bridges can link different chains of amino acids to one another or connect different parts of the same amino acid chain, causing the protein to bend or fold. For example, disulfide bridges link chains in the keratin protein of hair, making it curly or straight (see "A Closer Look: A Hairy Subject").

Amino acids differ in their chemical and physical properties—size, water solubility, electrical charge—because of their different R groups. Therefore, the sequence of amino acids largely determines the properties and function of each protein—whether it is water soluble and whether it is an enzyme, a hormone, or a structural protein. In some cases, just one wrong amino acid can cause a protein to function incorrectly.

(a)

hydrophilic functional groups

glutamic acid (glu)

aspartic acid (asp)

(b)

hydrophobic functional groups

phenylalanine (phe)

leucine (leu)

(c)

sulfur-containing functional group (can form disulfide bridges)
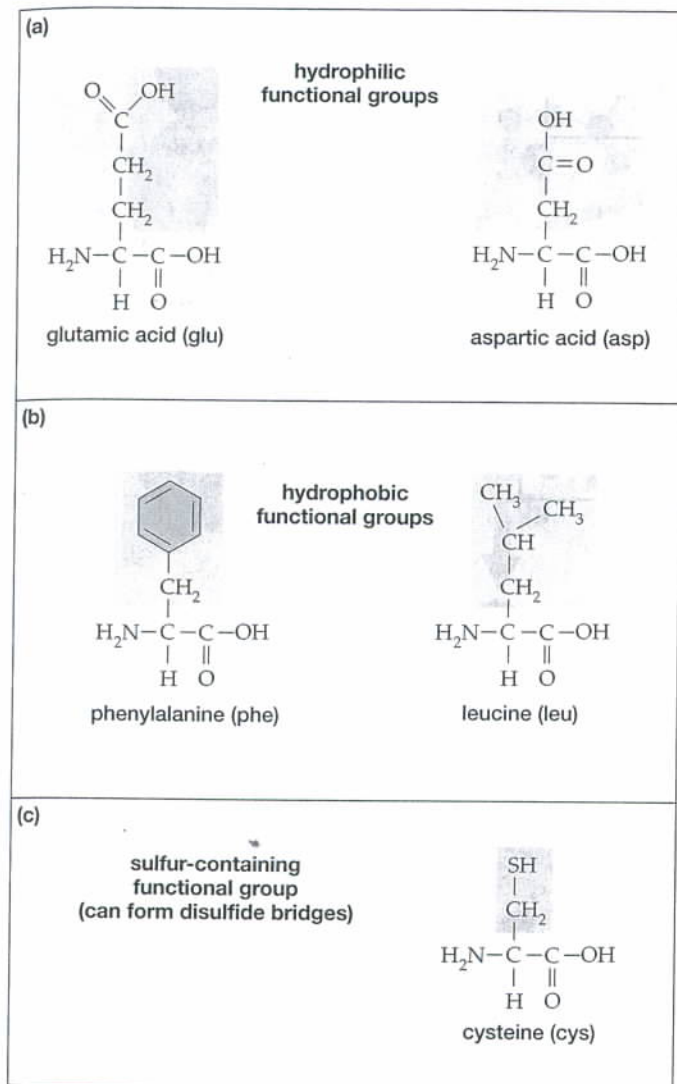
cysteine (cys)

FIGURE 3-19 Amino acid diversity
The diversity of amino acids is a consequence of the variable R group (colored blue), which may be hydrophilic or hydrophobic. The R group of cysteine is unique in possessing a sulfur atom, which can form covalent bonds with the sulfur in other cysteines, creating disulfide bridges that can bend a protein or link adjacent polypeptide chains.

Amino Acids Are Joined to Form Chains by Dehydration Synthesis

Like lipids and polysaccharides, proteins are formed by dehydration synthesis. The nitrogen in the amino group ($-NH_2$) of one amino acid is joined to the carbon in the carboxylic acid group ($-COOH$) of another amino acid by a single covalent bond (FIG. 3-20). This bond is called a peptide bond, and the resulting chain of two amino acids is called a peptide. More amino acids are added, one by one, until the protein is complete. Amino acid chains in living cells vary in length from three to thousands of amino acids. The term *protein* or *polypeptide* is often reserved for long chains—say, 50 or more amino acids in length—and the term *peptide* refers to shorter chains.

A Protein Can Have Up to Four Levels of Structure

Proteins come in many shapes, and biologists recognize four levels of organization in protein structure. A single molecule of hemoglobin, the oxygen-carrying protein in red blood cells, illustrates all four structural levels (FIG. 3-21). The primary structure refers to the sequence of amino acids that make up the protein (see Fig. 3-21a). This sequence is specified by genes within molecules of DNA. Different types of proteins have different sequences of amino acids.

Polypeptide chains can exhibit two types of simple, repeating secondary structures. You may recall that hydrogen bonds can form between parts of polar molecules that have slight negative and slight positive charges, which attract one another (see Chapter 2). Hydrogen bonds between amino acids produce the secondary structures of proteins. Many proteins, such as keratin in hair and the subunits of the hemoglobin molecule (see Fig. 3-21b) have a coiled, springlike secondary structure called a helix. Hydrogen bonds that form between the oxygens of $-C=O$ in the carboxylic acid groups (which have a partial negative charge) and the hydrogens of the $-N-H$ in the amino groups (which have a partial positive charge) hold the turns of the coils together. Other proteins, such as silk, consist of polypeptide chains that repeatedly fold back

amino acid   amino acid   peptide   water

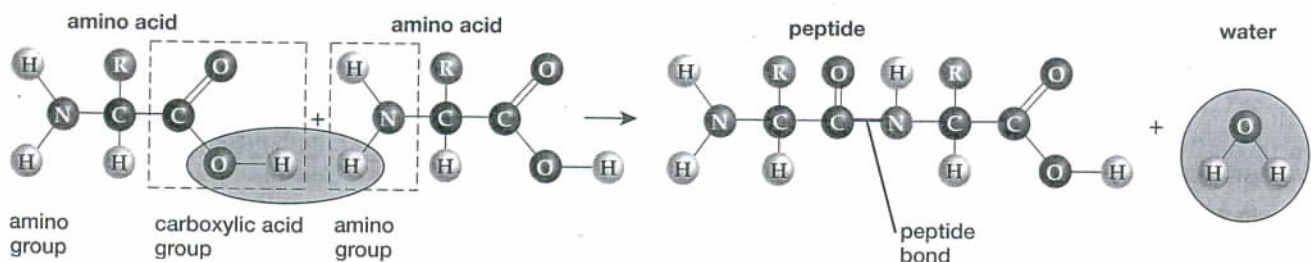amino group   carboxylic acid group   amino group   peptide bond

FIGURE 3-20 Protein synthesis
In protein synthesis, a dehydration reaction joins the carbon of the carboxylic acid group of one amino acid to the nitrogen of the amino group of a second amino acid, releasing water. The resulting covalent bond between amino acids is called a *peptide bond*.
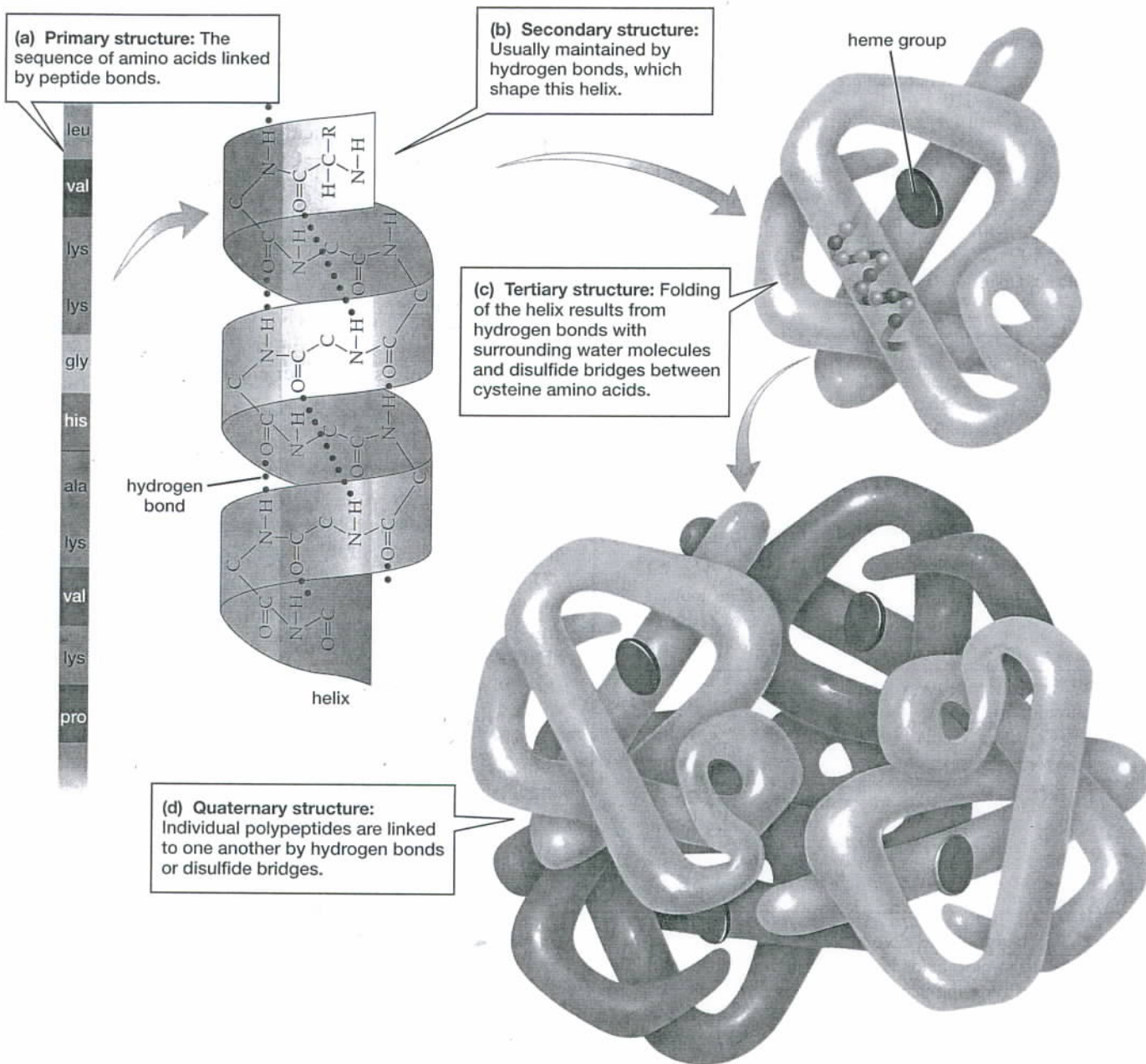
(a) **Primary structure:** The sequence of amino acids linked by peptide bonds.

(b) **Secondary structure:** Usually maintained by hydrogen bonds, which shape this helix.

heme group

(c) **Tertiary structure:** Folding of the helix results from hydrogen bonds with surrounding water molecules and disulfide bridges between cysteine amino acids.

hydrogen bond

helix

leu
val
lys
lys
gly
his
ala
lys
val
lys
pro

(d) **Quaternary structure:** Individual polypeptides are linked to one another by hydrogen bonds or disulfide bridges.

FIGURE 3-21 The four levels of protein structure
Levels of protein structure are represented here by hemoglobin, the oxygen-carrying protein in red blood cells (red discs represent the iron-containing heme group that binds oxygen). Levels of protein structure are generally determined by the amino acid sequence of the protein, interactions among the R groups of the amino acids, and interactions between the R groups and their surroundings. QUESTION Why do most proteins, when heated, lose their ability to function?

upon themselves, with hydrogen bonds holding adjacent segments of the polypeptide together in a **pleated sheet** arrangement (**FIG. 3-22**).

In addition to their secondary structures, proteins assume complex, three-dimensional **tertiary structures** that determine the final configuration of the polypeptide (see Fig. 3-21c). Probably the most important influence on the tertiary structure of a protein is its cellular environment—specifically, whether the protein is dissolved in the watery

cytoplasm within a cell, in the lipids of cellular membranes, or spanning a cell membrane and thus straddling the two environments. Hydrophilic amino acids can form hydrogen bonds with nearby water molecules, whereas hydrophobic amino acids cannot. Therefore, a protein dissolved in water folds in a way that exposes its hydrophilic amino acids to the watery environment outside and causes its hydrophobic amino acids to cluster together in the center of the molecule. Disulfide bridges can also contribute to tertiary
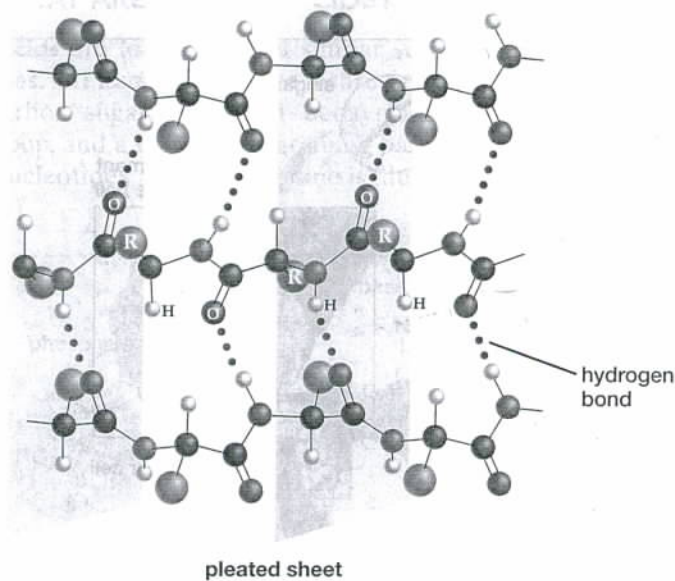
FIGURE 3-22 The pleated sheet is an example of protein secondary structure In a pleated sheet, a single polypeptide chain is folded back upon itself repeatedly (connecting portions not shown). Adjacent segments of the folded polypeptide are linked by hydrogen bonds (dotted lines), creating a sheetlike configuration. The R groups (green) project alternately above and below the sheet. Despite its accordion-pleated appearance, produced by bonding patterns between adjacent amino acids, each peptide chain is in a fully extended state and cannot easily be stretched farther. For this reason, pleated sheet proteins such as silk are not elastic.

pleated sheet

structure by linking cysteine amino acids from different regions of the polypeptide. In keratin (**FIG. 3-23**), disulfide bridges within individual helical polypeptides can distort them, creating a tertiary structure that makes hair kinky or curly (see "A Closer Look: A Hairy Subject").
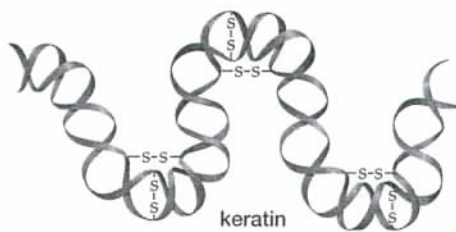
FIGURE 3-23 Keratin structure

Individual polypeptides are sometimes linked together, forming a fourth level of protein organization called **quaternary structure**. Hemoglobin consists of four polypeptide chains (two pairs of very similar peptides) held together by hydrogen bonds (see Fig. 3-21d). Each of the four peptides holds an iron-containing organic molecule called a *heme* (red disks in Fig. 3-21c, d), which can bind one molecule (two atoms) of oxygen.

The Functions of Proteins Are Linked to Their Three-Dimensional Structures

Within a protein, the exact type, position, and number of amino acids bearing specific R groups determine both the structure of the protein and its biological function. In hemoglobin, for example, certain amino acids bearing specific R groups must be present in precisely the right places to hold the iron-containing heme group that binds oxygen. In contrast, the amino acids on the outside of a hemoglobin molecule serve mostly to keep it dissolved in the cytoplasm of a red blood cell. Therefore, as long as they are hydrophilic, changes in these amino acids will not alter the protein's function. As you will see in Chapter 12, replacing a hydrophilic amino acid with a hydrophobic amino acid can have catastrophic effects on the solubility of the hemoglobin molecule. Such a substitution is the molecular cause of a painful and sometimes life-threatening disorder called sickle-cell anemia.

For an amino acid to be in the proper location within a protein, the amino acids must be in their proper sequence, and the protein must have the correct secondary and tertiary structures. For example, enzymes, such as those in your digestive system that break down starch into glucose molecules, are proteins that rely on a precise three-dimensional shape to function properly. The infectious prion protein described in our Case Study has a tertiary structure different from the normal, noninfectious version. If the secondary and tertiary structures of a protein are altered (leaving the peptide bonds between amino acids intact), the protein is said to be **denatured**, and it will no longer perform its function. Although scientists do not yet know what causes the shape change of infectious prions, there are many ways to denature proteins in everyday life. In a fried egg, for example, the heat of the frying pan causes so much movement of the atoms in the albumin protein that hydrogen bonds are ripped apart. Due to the loss of its secondary structure, the egg white changes from clear to white and its texture changes from liquid to solid. Sterilization using heat or ultraviolet rays denatures the proteins of bacteria or viruses and causes them to lose their function. Salty, acidic solutions can denature bacterial proteins, killing the bacteria—dill pickles are preserved from bacterial attack in this way. When hair is permed, the disulfide bridges of keratin are altered, denaturing the natural protein.

A CLOSER LOOK   A Hairy Subject

Pull out a strand of hair, and notice the root or follicle that was embedded in the scalp. Hair is composed mostly of a helical protein called *keratin*. Living cells in the hair follicle produce new keratin at the rate of 10 turns of the protein helix every second. The keratin proteins in a hair entwine around one another, held together by disulfide bridges (**FIG. E3-4**). If you pull gently on the hair, you will find it to be both strong and stretchy. When hair stretches, hydrogen bonds that create the helical structure of keratin are broken, allowing the strand of protein to be extended. Most of the covalent disulfide bonds, in contrast, are distorted by stretching but do not break. When tension is released, these disulfide bridges return the hair to its normal length, and the hydrogen bonds reform. Now wet the hair and notice how limp it becomes. In wet hair, the hydrogen bonds of the helices are broken and replaced by hydrogen bonds between the hair amino acids and the water molecules surrounding them, so the protein is denatured and the helices collapse. Notice that the hair is now both longer and easier to stretch, as well. If you roll the wet hair around a curler and allow it to dry, the hydrogen bonds will re-form in slightly different places, holding the hair in a curl. However, the slightest moisture (even humid air) allows these hydrogen bonds to rearrange into their natural configuration.

If your hair is naturally curly (because of the particular sequence of amino acids specified by your genes), the disulfide bridges within and between the individual keratin helices form at locations that bend the keratin molecules, producing a curl (**FIG. E3-5**).

In straight hair, the disulfide bridges occur in places that do not distort the keratin (as shown in Fig. E3-4). When straight hair is given a "permanent wave," two lotions are applied. The first lotion breaks disulfide bonds, denaturing the protein. After the hair is rolled tightly onto curlers, a second solution is applied that re-forms the disulfide bridges.
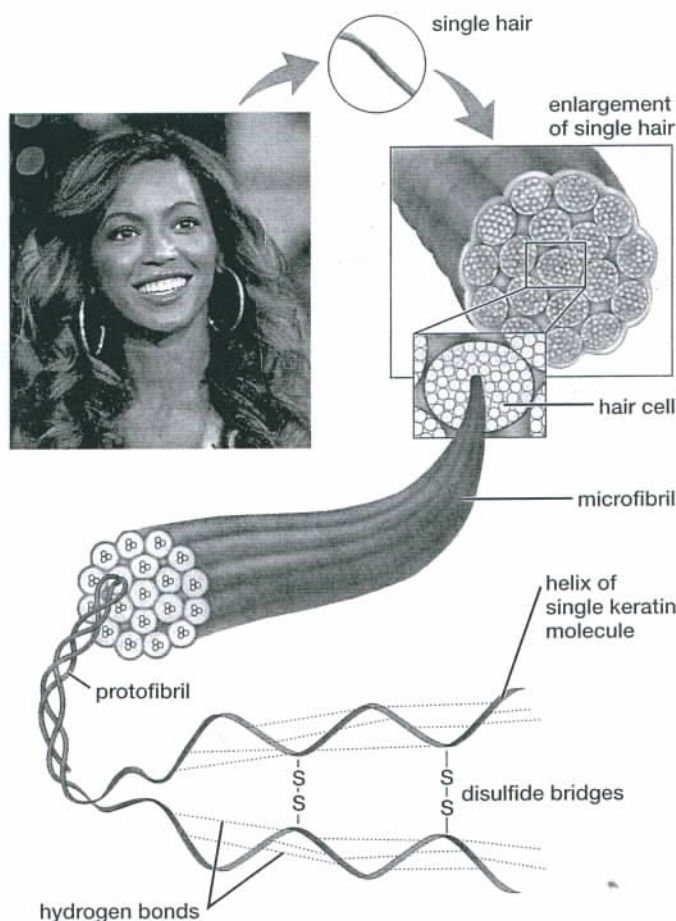

FIGURE E3-4 The structure of hair
At the microscopic level, a single hair is organized into bundles of "protofibrils" within larger bundles called "microfibrils." Each protofibril consists of keratin molecules held in a helical shape by hydrogen bonds, with different keratin strands cross-linked by disulfide bridges. These bonds give hair both elasticity and strength.

The new disulfide bridges reconnect the keratin helices at new positions determined by the curler, as in the curly hair shown in Figure E3-5. These new bridges are permanent, transforming genetically straight hair into "biochemically curly" hair.
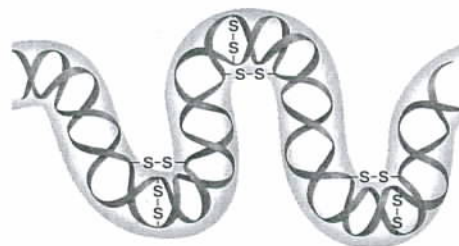

FIGURE E3-5 Curly hair

3.6 WHAT ARE NUCLEIC ACIDS?

Nucleic acids are long chains of similar subunits called **nucleotides**. All nucleotides have a three-part structure: a five-carbon sugar (ribose or deoxyribose), a phosphate group, and a nitrogen-containing base that differs among nucleotides; the base adenine is illustrated below (FIG. 3-24).
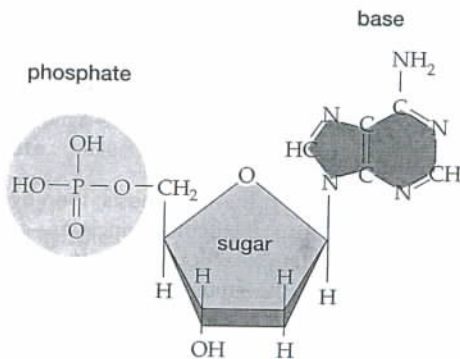
FIGURE 3-24 Deoxyribose nucleotide

There are two types of nucleotides: ribose nucleotides (containing the 5-carbon sugar ribose) and deoxyribose nucleotides (containing the sugar deoxyribose, which has one fewer oxygen than ribose has). The base component of a deoxyribose nucleotide can be adenine, guanine, cytosine, or thymine. Like the adenine molecule in Fig. 3-24, these all have carbon- and nitrogen-containing rings. In adenine and guanine the rings are double, while cytosine and thymine have single-ring structures.

Nucleotides may be strung together in long chains (FIG. 3-25), forming nucleic acids. In nucleic acids, the phosphate group of one nucleotide is covalently bonded to the sugar of another.
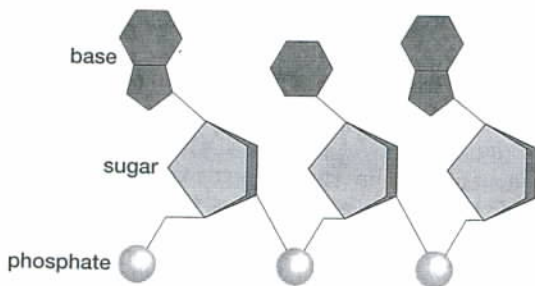
FIGURE 3-25 Nucleotide chain

DNA and RNA, the Molecules of Heredity, Are Nucleic Acids

Deoxyribose nucleotides form chains millions of units long, called **deoxyribonucleic acid**, or **DNA**. DNA is found in the chromosomes of all living things. Its sequence of nucleotides, like the dots and dashes of a biological Morse code, spells out the genetic information needed to construct
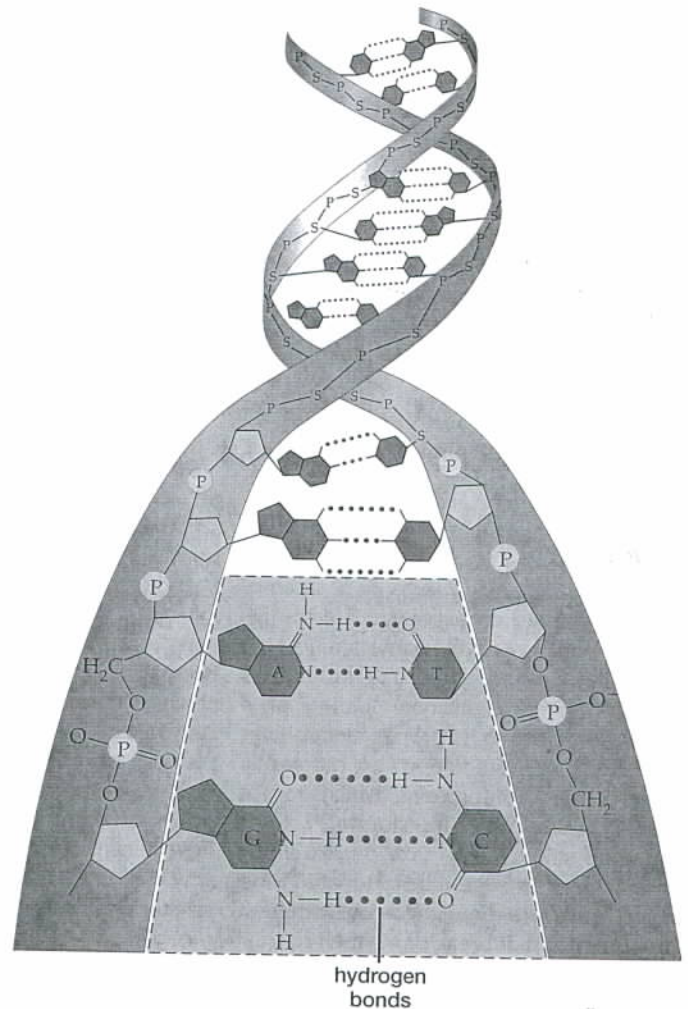
FIGURE 3-26 DNA
Like a twisted ladder, the double helix of DNA is formed by helical strands of nucleotides that spiral around one another. The two strands are held together by hydrogen bonds linking the bases of nucleotides in opposing strands, which form the "rungs" of the ladder.

the proteins of each organism. Each DNA molecule consists of two chains of nucleotides entwined in the form of a double helix. The nucleotides on the opposing strands form hydrogen bonds with one another, linking the two strands (FIG. 3-26). Chains of ribose nucleotides, called **ribonucleic acid**, or **RNA**, are copied from the DNA in the nucleus of each cell. The RNA carries DNA's genetic code into the cell's cytoplasm and directs the synthesis of proteins. DNA and RNA are described in detail in Chapters 9 and 10.

Other Nucleotides Act as Intracellular Messengers and Energy Carriers

Not all nucleotides are part of nucleic acids. Some exist singly in the cell or occur as parts of other molecules. Some, such as the nucleotide *cyclic AMP*, are intracellular messengers that carry chemical signals within a cell.

Other nucleotides have additional phosphate groups. These diphosphate and triphosphate nucleotides, such as **adenosine triphosphate (ATP)**, are unstable molecules that carry energy from place to place within a cell, storing the energy in bonds between the phosphate groups (**FIG. 3-27**).

Nucleotides such as ATP can release energy to drive energy-demanding reactions (to synthesize a protein, for example). Other nucleotides (NAD^+ and FAD) are known as "electron carriers" that transport energy in the form of high-energy electrons. You will learn more about these nucleotides in Chapters 6, 7, and 8.
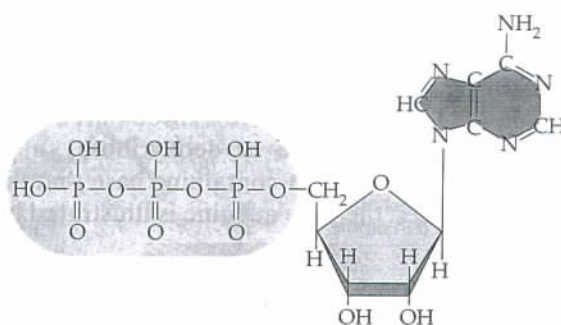

FIGURE 3-27 The energy-carrier molecule ATP

CASE STUDY REVISITED PUZZLING PROTEINS

Prusiner and his associates identified a protein found normally throughout the animal kingdom as the culprit in scrapie, and now in mad cow disease. But the infectious prions, with the same amino acid sequence, were different. You now know that the three-dimensional folding of a protein is crucial to its proper functioning. Infectious prions are folded very differently from normal prion proteins, which do not cause disease. Like Transformer™ toys, the same structure can take on extremely different appearances. Unfortunately, the infectious prions resist attack by both heat and enzymes that break down their normal counterparts. How does the infectious prion "reproduce" itself? Prusiner and other researchers have strong experimental evidence supporting a radical hypothesis: the misfolded protein interacts with normal proteins and causes them to change configuration, misfolding into the infectious form. The new misfolded "converts" then go on to transform additional normal proteins in an ever-expanding chain reaction. As in Charlene's case, it can be years after infection that enough of the proteins have been transformed to cause disease symptoms. Scientists are investigating how the abnormal folding occurs, how it can induce more misfolding, and why misfolded prions cause disease.

Stanley Prusiner's efforts led to the recognition of a totally new disease process. A major strength of the scientific method is that hypotheses can be tested experimentally. If repeated experiments support the hypothesis, then even well-established scientific principles—for example, that an infectious agent must have genetic material—must be redefined. Although some scientists still insist that proteins can't be infectious, Prusiner's efforts have been so convincing to the scientific community that he was awarded a Nobel Prize in 1997.

Consider This A disorder called "chronic wasting disease" has been reported among both wild and captive elk and deer populations in several western states in the United States. Like scrapie and BSE, wasting disease is a fatal brain disorder caused by prions. No human cases have been confirmed. If you were a hunter in an affected region, would you eat deer or elk meat? Explain why or why not.

CHAPTER REVIEW

SUMMARY OF KEY CONCEPTS

3.1 Why Is Carbon So Important in Biological Molecules?
Organic molecules are so diverse because the carbon atom is able to form many types of bonds. This ability, in turn, allows organic molecules (molecules with a backbone of carbon) to form many complex shapes, including chains, branches, and rings. The presence of functional groups, shown in Table 3-1, produces further diversity among biological molecules.

3.2 How Are Organic Molecules Synthesized?
Most large biological molecules are polymers synthesized by linking together many smaller subunits, or monomers. The subunits are connected by covalent bonds through dehydration synthesis; the chains may be broken apart by hydrolysis reactions. The most important organic molecules fall into one of four classes: carbohydrates, lipids, proteins, and nucleic acids. Their major characteristics are summarized in Table 3-2.

Web Tutorial 3.1 Dehydration Synthesis and Hydrolysis

3.3 What Are Carbohydrates?
Carbohydrates include sugars, starches, chitin, and cellulose. Sugars (monosaccharides and disaccharides) are used for temporary storage of energy and for the construction of other molecules. Starches and glycogen are polysaccharides that provide longer-term energy storage in plants and animals, respectively. Cellulose forms the cell walls of plants, and chitin strengthens the exoskeletons of many invertebrates and many types of fungi. Other types of polysaccharides form the cell walls of bacteria.

Web Tutorial 3.2 Carbohydrate Structure and Function

3.4 What Are Lipids?
Lipids are nonpolar, water-insoluble molecules of diverse chemical structure. Lipids include oils, fats, waxes, phospholipids, and steroids. Lipids are used for energy storage (oils and fats), as waterproofing for the outside of many plants and animals (waxes), as the principal component of cellular membranes (phospholipids), and as hormones (steroids).

Web Tutorial 3.3 Lipid Structure and Function

3.5 What Are Proteins?
Proteins are chains of amino acids that possess primary, secondary, tertiary, and sometimes quaternary structure. Both the

structure and the function of a protein are determined by the sequence of amino acids in the chain as well as by how these amino acids interact with their surroundings and with each other. Proteins can be enzymes (which promote and guide chemical reactions), structural molecules (hair, horn), hormones (insulin), or transport molecules (hemoglobin).

Web Tutorial 3.4 Protein Structure

3.6 What Are Nucleic Acids?

The nucleic acid molecules deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) are chains of nucleotides. Each nucleotide is composed of a phosphate group, a sugar group, and a nitrogen-containing base. Molecules formed from single nucleotides include intracellular messengers, such as cyclic AMP, and energy-carrier molecules, such as ATP.

Web Tutorial 3.5 The Structure of DNA

KEY TERMS

adenosine triphosphate (ATP) *page 54*
amino acid *page 48*
carbohydrate *page 39*
cellulose *page 43*
chitin *page 44*
dehydration synthesis *page 39*
denatured *page 51*
deoxyribonucleic acid (DNA) *page 53*
disaccharide *page 39*
disulfide bridge *page 48*
enzyme *page 47*

fat *page 44*
fatty acid *page 44*
functional group *page 38*
glucose *page 40*
glycerol *page 44*
glycogen *page 43*
helix *page 49*
hydrolysis *page 39*
inorganic *page 38*
lactose *page 42*
lipid *page 44*
maltose *page 42*
monomer *page 39*
monosaccharide *page 39*

nucleic acid *page 53*
nucleotide *page 53*
oil *page 44*
organic *page 38*
peptide *page 49*
peptide bond *page 49*
phospholipid *page 46*
pleated sheet *page 50*
polymer *page 39*
polysaccharide *page 39*
primary structure *page 49*
protein *page 47*
quaternary structure *page 51*

ribonucleic acid (RNA) *page 53*
saturated *page 45*
secondary structure *page 49*
starch *page 42*
steroid *page 46*
sucrose *page 42*
sugar *page 39*
tertiary structure *page 50*
triglyceride *page 44*
unsaturated *page 45*
wax *page 46*

THINKING THROUGH THE CONCEPTS

1. Which elements are common components of biological molecules?

2. List the four principal types of biological molecules and give an example of each.

3. What roles do nucleotides play in living organisms?

4. One way to convert corn oil to margarine (a solid at room temperature) is to add hydrogen atoms, decreasing the number of double bonds in the molecules of oil. What is this process called? Why does it work?

5. Describe and compare dehydration synthesis and hydrolysis. Give an example of a substance formed by each chemical reaction, and describe the specific reaction in each instance.

6. Distinguish among the following: monosaccharide, disaccharide, and polysaccharide. Give two examples of each, and list their functions.

7. Describe the synthesis of a protein from amino acids. Then describe primary, secondary, tertiary, and quaternary structures of a protein.

8. Most structurally supportive materials in plants and animals are polymers of special sorts. Where would we find cellulose? Chitin? In what way(s) are these two polymers similar? Different?

9. Which kinds of bonds or bridges between keratin molecules are altered when hair is (a) wet and allowed to dry on curlers and (b) given a permanent wave?

APPLYING THE CONCEPTS

1. A preview question for Chapter 4: In Chapter 2, you learned that hydrophobic molecules tend to cluster when immersed in water. In this chapter, you read that a phospholipid has a hydrophilic head and hydrophobic tails. What do you think would be the configuration of phospholipids that are immersed in water?

2. Fat contains twice as many calories per unit weight as carbohydrate does, so fat is an efficient way for animals, who must move about, to store energy. Compare the way fat and carbohydrates interact with water, and explain why this interaction also gives fat an advantage for weight-efficient energy storage.

FOR MORE INFORMATION

Burdick, A., "Cement on the Half Shell." *Discover*, February 2003. Mussels produce a protein polymer that is waterproof and incredibly strong.

Gorman J. "Trans Fat." *Science News*, November 10, 2001. Reviews the structure and origin of trans fats and studies that implicate it in heart disease.

Hill, J. W., and Kolb, D. K. *Chemistry for Changing Times*. 10th ed. Upper Saddle River, NJ: Prentice Hall, 2004. A chemistry textbook for nonscience majors that is both clearly readable and thoroughly enjoyable.

King, J., Haase-Pettingell, C., and Gossard, D. "Protein Folding and Misfolding." *American Scientist*, September–October 2002. Protein folding holds the key to diverse functions.

Kunzig, R., "Arachnomania." *Discover*, September 2001. Researchers work to unravel the mystery of spider silk, and develop a process to synthesize it.

Prusiner, S. B. "Detecting Mad Cow Disease." *Scientific American*, July, 2004. A clear discussion of prions, mad cow disease, and techniques for detection and possible future treatments, written by the discoverer of prions.