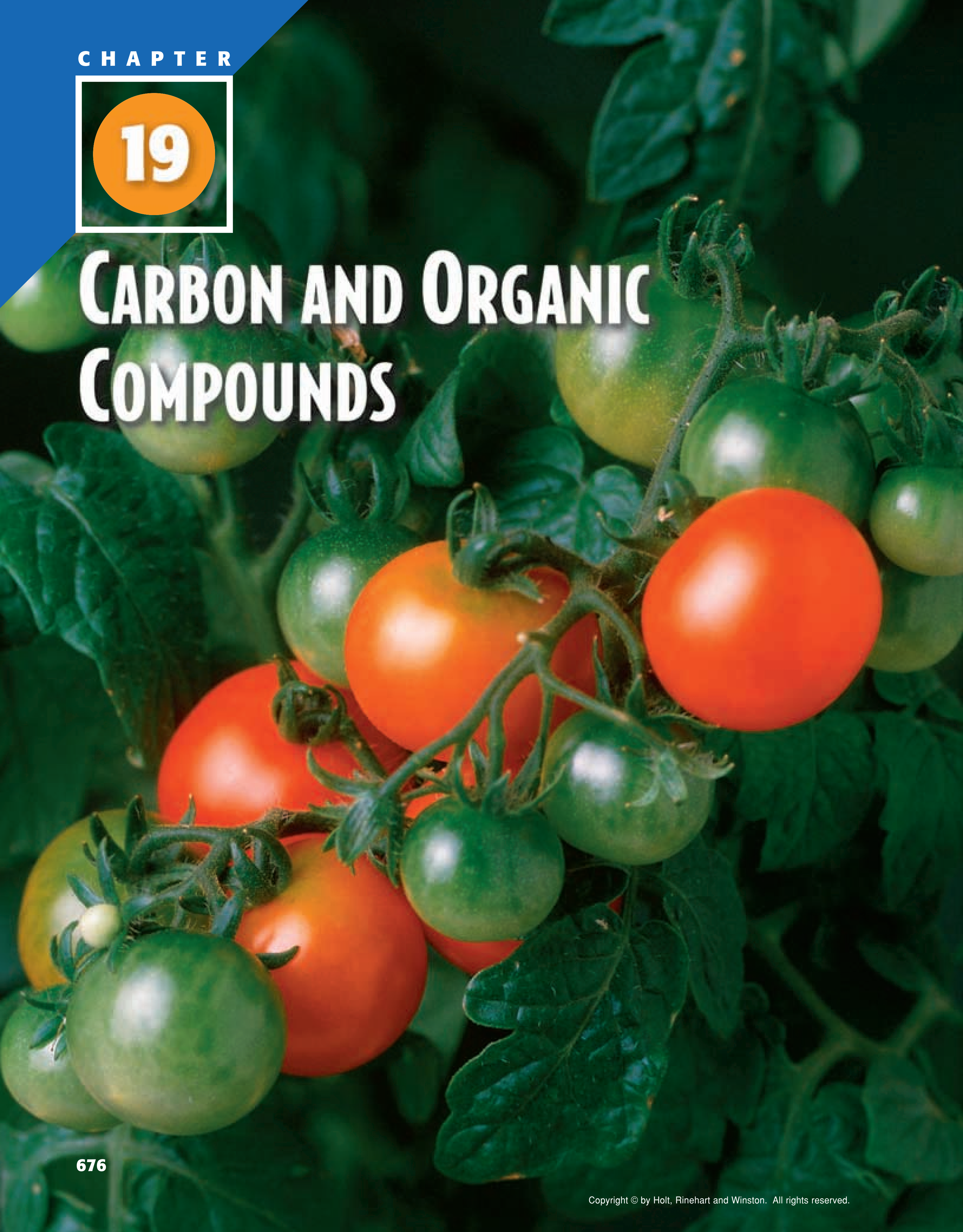
CHAPTER 19

Carbon and Organic Compounds



Tomatoes contain many compounds of carbon, including some that have properties that help people stay healthy. Two of these compounds are lycopene and beta-carotene. Lycopene gives tomatoes their red color and is believed to help prevent heart disease and some forms of cancer. In the human body, beta-carotene is converted to vitamin A, an essential nutrient .

Like the vine that supports the tomatoes in this picture, carbon forms the backbone for the chemicals that make up living organisms. In this chapter, you will learn about the nature of carbon and its many compounds.

START-UP ACTIVITY

Testing Plastics

PROCEDURE

1. Examine **two plastic samples** with a **magnifying lens** to look for any structural differences.
2. To test the rigidity of each sample, try to bend both pieces.
3. To test the hardness of each sample, press into each sample with your fingernail and try to make a permanent mark.
4. To test the strength of each sample, try tearing each plastic piece.

ANALYSIS

1. Which plastic sample would you use to hold liquids?
2. What physical differences did you observe between the two samples?
3. Why do you think most communities recycle only one of these plastics?

Pre-Reading Questions

1. **How many covalent bonds can a carbon atom form?**
2. **How does the structure of a compound affect its chemical reactivity?**
3. **What are two possible ways to show the structure of CH_4?**

CONTENTS 19

SECTION 1

Compounds of Carbon

KEY TERMS

- hydrocarbon
- alkane
- alkene
- alkyne
- aromatic hydrocarbon
- functional group
- isomer

OBJECTIVES

1. **Explain** the unique properties of carbon that make the formation of organic molecules possible.
2. **Relate** the structures of diamond, graphite, and other allotropes of carbon to their properties.
3. **Describe** the nature of the bonds formed by carbon in alkanes, alkenes, alkynes, aromatic compounds, and cyclic compounds.
4. **Classify** organic compounds such as alcohols, esters, and ketones by their functional groups.
5. **Explain** how the structural difference between isomers is related to the difference in their properties.

Properties of Carbon

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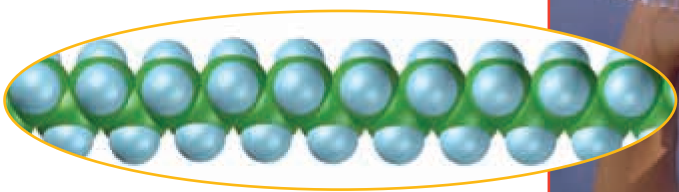
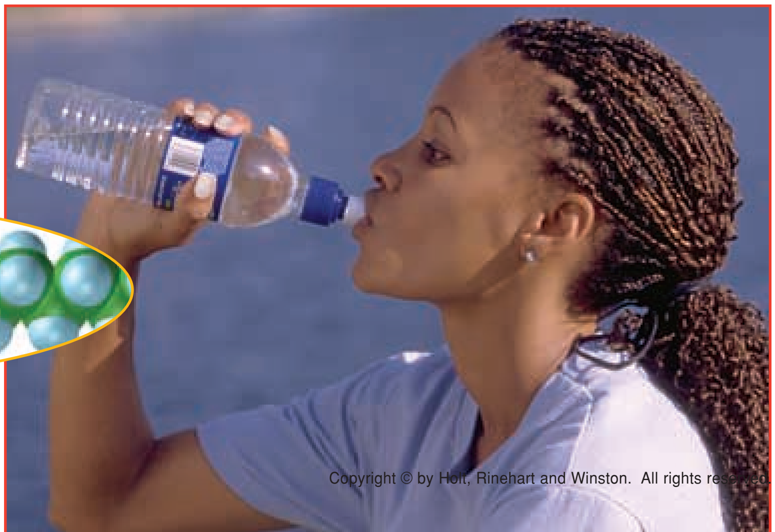
The water bottle shown in **Figure 1** is made of a strong but flexible plastic. These properties result from the bonds formed by the carbon atoms that make up the plastic. Carbon atoms nearly always form covalent bonds. Three factors make the bonds that carbon atoms form with each other unique.

First, even a single covalent bond between two carbon atoms is quite strong. In contrast, the single covalent bond that forms between two oxygen atoms, such as in hydrogen peroxide (HO—OH), is so weak that this compound decomposes at room temperature. Second, carbon compounds are not extremely reactive under ordinary conditions. Butane, C_4H_{10}, is stable in air, but tetrasilane, Si_4H_{10}, catches fire spontaneously in air. Third, because carbon can form up to four single covalent bonds, a wide variety of compounds is possible.

Figure 1
Carbon-carbon bonds within long-chained molecules, such as the polyethylene used to make water bottles, are very strong.





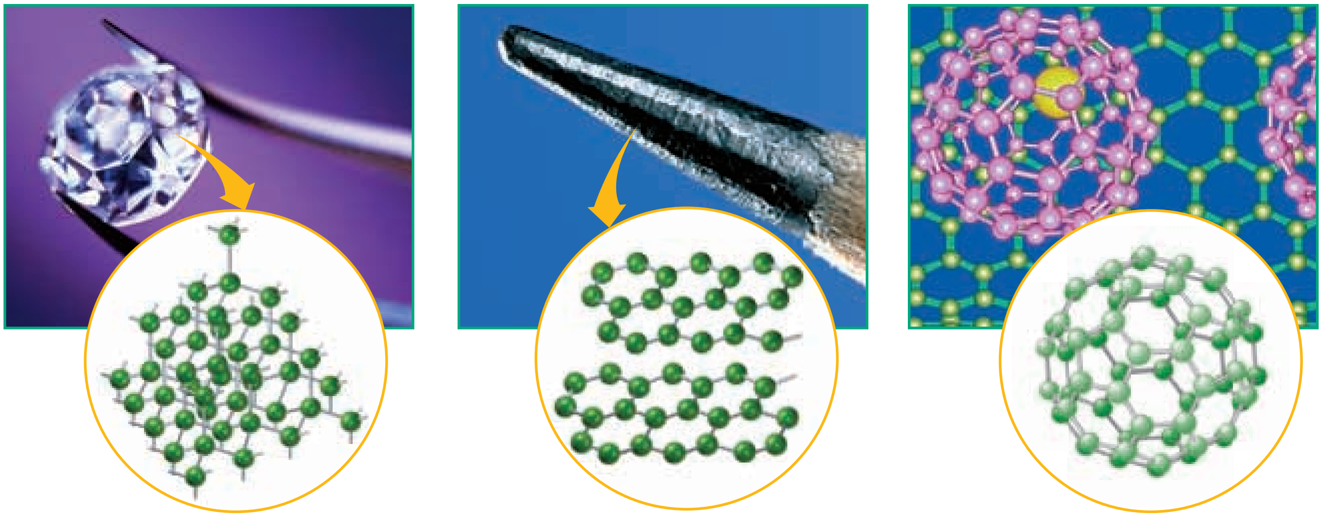


Figure 2
a Diamond is a carbon allotrope in which the atoms are densely packed in a tetrahedral arrangement.

b Graphite is a carbon allotrope in which the atoms form separate layers that can slide past one another.

c Buckminsterfullerene is a carbon allotrope in which 60 carbon atoms form a sphere.

Carbon Exists in Different Allotropes

As an element, carbon atoms can form different bonding arrangements, or *allotropes*. Three carbon allotropes are illustrated in **Figure 2.** As shown in **Figure 2a,** a diamond contains an enormous number of carbon atoms that form an extremely strong, tetrahedral network, which makes diamond the hardest known substance.

In contrast, graphite, another allotrope of carbon, is very soft. As illustrated in **Figure 2b,** the carbon atoms in graphite are bonded in a hexagonal pattern and lie in planes. The covalent bonds in each plane are very strong. However, weaker forces hold the planes together so that the planes can slip past each other. The sliding layers make graphite useful as a lubricant and as pencil lead. As you write with a pencil, the graphite layers slide apart, leaving a trail of graphite on the paper.

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Other Carbon Allotropes Include Fullerenes and Nanotubes

In the mid-1980s, another type of carbon allotrope, the fullerene, was discovered. As illustrated in **Figure 2c,** fullerenes consist of near-spherical cages of carbon atoms. The most stable of these structures is C_{60}, which is formed by 60 carbon atoms arranged in interconnecting rings. The discoverers of these allotropes named C_{60} *buckminsterfullerene* in honor of the architect and designer Buckminster Fuller, whose geodesic domes had a similar shape. These allotropes can be found in the soot that forms when carbon-containing materials burn with limited oxygen.

In 1991, yet another carbon allotrope was discovered. Hexagons of carbon atoms were made to form a hollow cylinder known as a *nanotube*. A nanotube has a diameter about 10 000 times smaller than a human hair. Despite its thinness, a single nanotube is between 10 and 100 times stronger than steel by weight. Scientists are currently experimenting to find ways in technology and industry to use the unique properties of nanotubes.

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Organic Compounds

Most compounds of carbon are referred to as *organic compounds*. Organic compounds contain carbon, of course, and most also contain atoms of hydrogen.

In addition to hydrogen, many other elements can bond to carbon. These elements include oxygen, nitrogen, sulfur, phosphorus, and the halogens. These bonded atoms are found in the different types of organic compounds found in living things, including proteins, carbohydrates, lipids (fats), and nucleic acids. In addition, these atoms are used to make a wide variety of synthetic organic compounds including plastics, fabrics, rubber, and pharmaceutical drugs. **Figure 3** shows examples of some natural and synthetic organic compounds.

More than 12 million organic compounds are known, and thousands of new ones are discovered or synthesized each year. There are more known compounds of carbon than compounds of all the other elements combined. To make the study of these many organic compounds easier, chemists group those with similar characteristics. The simplest class of organic compounds are those that contain only carbon and hydrogen and are known as **hydrocarbons.** Hydrocarbons can be classified into three categories based on the type of bonding between the carbon atoms.

hydrocarbon

an organic compound composed only of carbon and hydrogen

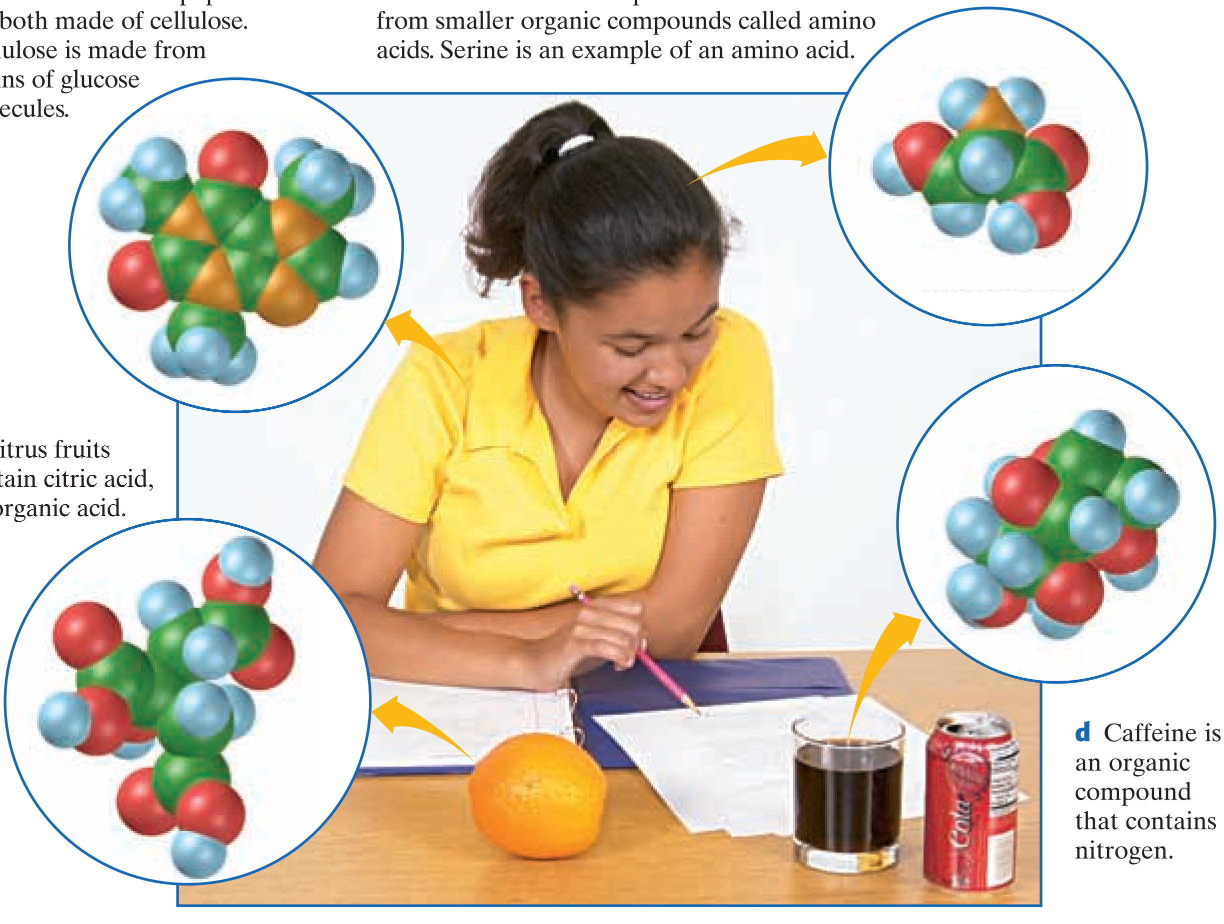


Figure 3
a This shirt and the paper are both made of cellulose. Cellulose is made from chains of glucose molecules.

b Your hair is made of proteins that are made from smaller organic compounds called amino acids. Serine is an example of an amino acid.

c Citrus fruits contain citric acid, an organic acid.

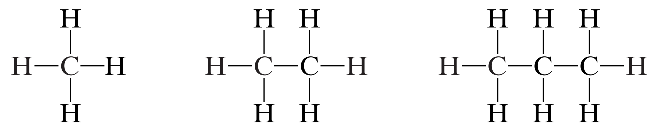
d Caffeine is an organic compound that contains nitrogen.

Alkanes Are the Simplest Hydrocarbons

The simplest hydrocarbons, **alkanes,** have carbon atoms that are connected only by single bonds. Three examples include methane, ethane, and propane. The structural formulas for each of these alkanes are drawn as follows.

alkane

a hydrocarbon characterized by a straight or branched carbon chain that contains only single bonds



methane, CH_4 ethane, C_2H_6 propane, C_3H_8

If you examine the structural formulas for these three alkanes, you will notice that each member of the series differs from the one before by one carbon atom and two hydrogen atoms. This difference is more obvious when you compare the molecular formulas of each compound. The molecular formulas of the alkanes fit the general formula C_nH_{2n+2}, where n represents the number of carbon atoms. If the alkane contains 30 carbon atoms, then its formula is $C_{30}H_{62}$.

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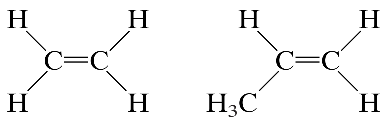
Many Hydrocarbons Have Multiple Bonds

The second class of hydrocarbons is the **alkenes,** which contain at least one double bond between two carbon atoms. The structural formulas for two alkenes are drawn as follows.

alkene

a hydrocarbon that contains one or more double bonds



ethene propene

Because alkenes with one double bond have twice as many hydrogen atoms as carbon atoms, their general formula is written C_nH_{2n}.

The third class of hydrocarbons is the **alkynes,** which contain at least one triple bond between two carbon atoms. The simplest alkyne is ethyne, C_2H_2, which is shown in **Figure 4.** The general formula for an alkyne with one triple bond is C_nH_{2n-2}.

alkyne

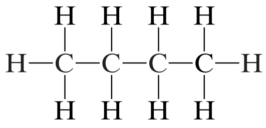
a hydrocarbon that contains one or more triple bonds

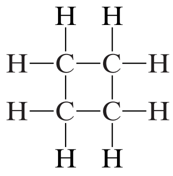
Figure 4
Ethyne, commonly called *acetylene,* is one of the very few alkynes that are of practical importance. This welder is using an acetylene torch.

$H-C\equiv C-H$

Carbon Atoms Can Form Rings

Carbon atoms that form covalent bonds with one another can be arranged in a straight line or in a ring structure. They can also be branched. For example, 4 carbon atoms and 10 hydrogen atoms can be arranged to form butane, C_4H_{10}, which has a linear structure. Four carbon atoms can also form a compound called cyclobutane, C_4H_8, which has a ring structure.


butane


cyclobutane

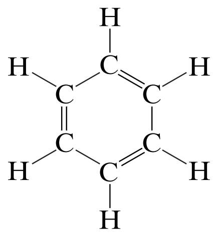
Notice that the prefix *cyclo-* is added to the name of the alkane to indicate that it has a ring structure.

Benzene Is an Important Ring Compound

A most important organic ring compound is the hydrocarbon benzene, C_6H_6. Benzene is the simplest member of a class of organic compounds known as **aromatic hydrocarbons.** These compounds have a variety of practical uses from insecticides to artificial flavorings. Benzene can be drawn as a six-carbon ring with three double bonds, as shown below.

aromatic hydrocarbon

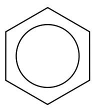
a member of the class of hydrocarbons (of which benzene is the first member) that consists of assemblages of cyclic conjugated carbon atoms and that is characterized by large resonance energies



However, experiments show that all the carbon-carbon bonds in benzene are the same. In other words, benzene is a molecule with resonance structures. **Figure 5** illustrates how the electron orbitals in benzene overlap to form continuous molecular orbitals known as delocalized clouds. The following structural formula is often used to show the ring structure of benzene.

Topic Link

Refer to the "Covalent Compounds" chapter for a discussion of resonance structures.



The hexagon represents the six carbon atoms, while the circle represents the delocalized electron clouds. The hydrogen atoms are not shown in this simplified structural formula.

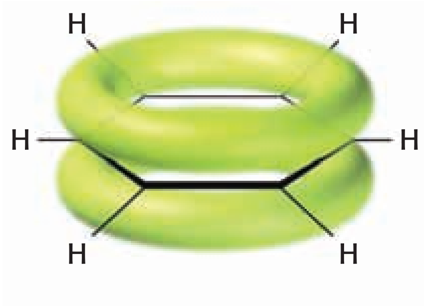


Figure 5
Electron orbitals in benzene overlap to form continuous orbitals that allow the delocalized electrons to spread uniformly over the entire ring.

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Other Organic Compounds

Hydrocarbons are only one class of organic compounds. The other classes of organic compounds include other atoms such as oxygen, nitrogen, sulfur, phosphorus, and the halogens along with carbon (and usually hydrogen).

Less than 200 years ago, scientists believed that organic compounds could be made only by living things. The word *organic* that is used to describe these compounds comes from this belief. Then in 1828 a German chemist named Friedrich Wöhler synthesized urea, an organic compound, from inorganic substances.

Many Compounds Contain Functional Groups

Like most organic compounds, urea contains a group of atoms that is responsible for its chemical properties. Such a group of atoms is known as a **functional group.** Many common organic functional groups can be seen in **Figure 6.** Because single bonds between carbon atoms are rarely involved in most chemical reactions, functional groups, which contain bonds between carbon atoms and atoms of other elements, are often responsible for how an organic compound reacts. Organic compounds are commonly classified by the functional groups they contain. **Table 1** on the next page provides an overview of some common classes of organic compounds and their functional groups.

functional group

the portion of a molecule that is active in a chemical reaction and that determines the properties of many organic compounds

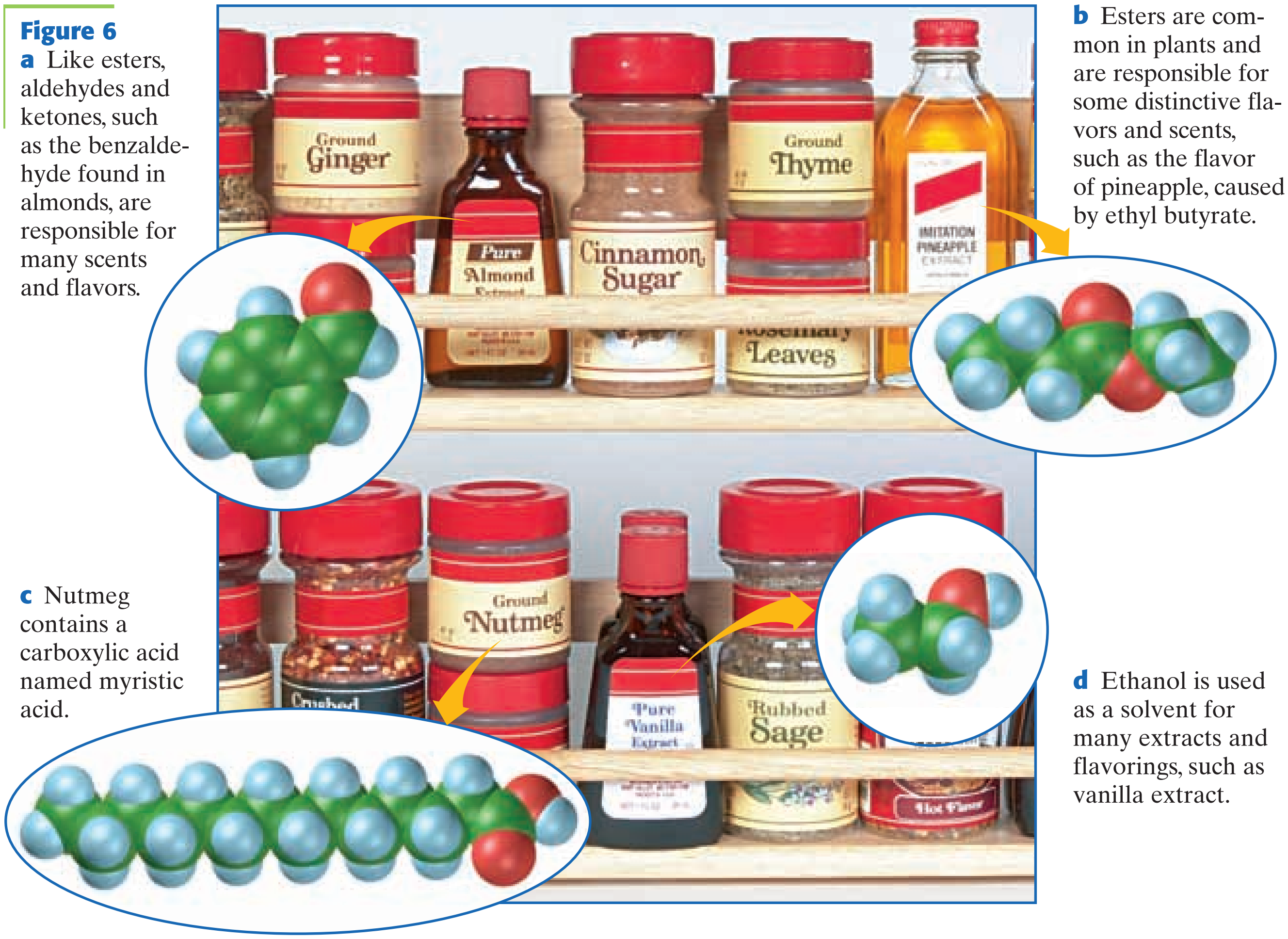


Figure 6

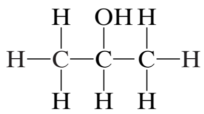
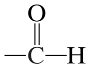
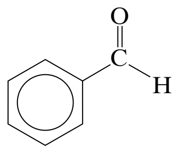
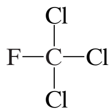
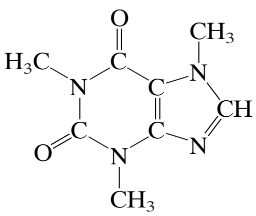
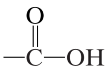
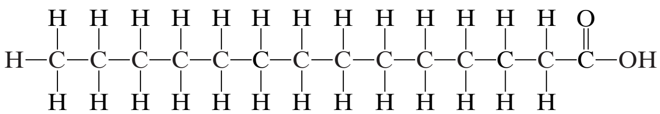
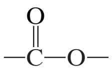
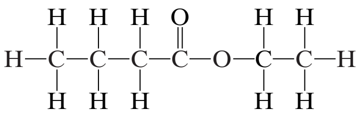
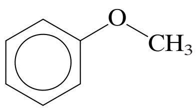
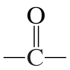
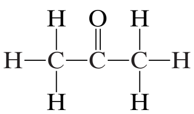
a Like esters, aldehydes and ketones, such as the benzaldehyde found in almonds, are responsible for many scents and flavors.

b Esters are common in plants and are responsible for some distinctive flavors and scents, such as the flavor of pineapple, caused by ethyl butyrate.

c Nutmeg contains a carboxylic acid named myristic acid.

d Ethanol is used as a solvent for many extracts and flavorings, such as vanilla extract.

Table 1 Classes of Organic Compounds

Class	Functional group	Example	Use
Alcohol	—OH	 2-propanol	disinfectant
Aldehyde		 benzaldehyde	almond flavor
Halide	—F, Cl, Br, I	 trichlorofluoromethane (Freon-11)	refrigerant
Amine		 caffeine	beverage ingredient
Carboxylic acid		 tetradecanoic acid (myristic acid)	soap-making ingredient
Ester		 ethyl butanoate	perfume ingredient
Ether	—O—	 methyl phenyl ether (anisole)	perfume ingredient
Ketone		 propanone (acetone)	solvent in nail-polish remover

Functional Groups Determine Properties

The presence of a functional group in an organic compound causes the compound to have properties that differ greatly from those of the corresponding hydrocarbon. In fact, while molecules of very different sizes with the same functional group will have similar properties, molecules of similar sizes with different functional groups will have very different properties.

Compare the structural formulas of the molecules shown in **Table 2.** Notice that each of these molecules consists of four carbon atoms joined to one another by a single bond and arranged in a linear fashion. Notice, however, that each molecule, with the exception of butane, has a different functional group attached to one or more of these carbon atoms. As a result, each molecule has properties that differ greatly from butane.

For example, compare the boiling point of butane with those of the other compounds in **Table 2.** Butane is a gas at room temperature. Because of the symmetrical arrangement of the atoms, butane is nonpolar. Because the intermolecular forces between butane molecules are weak, butane has very low boiling and melting points and a lower density than the other four-carbon molecules.

Next compare the structural formulas of butane and 1-butanol in **Table 2.** Notice that the only difference between these two molecules is the presence of the functional group —OH on one of the carbon atoms in 1-butanol. The presence of this functional group causes 1-butanol to exist as a liquid at room temperature with much higher melting and boiling points and a significantly greater density than butane.

Table 2 Comparing Classes of Organic Compounds

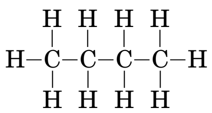
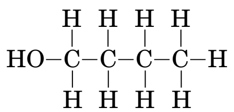
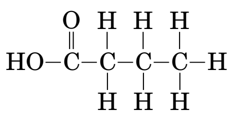
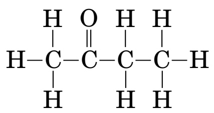
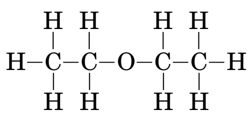
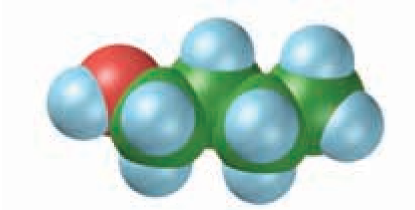
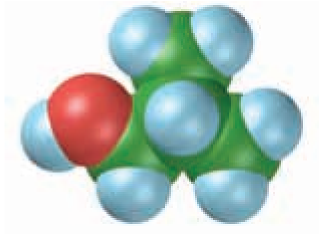
Name	Structural formula	Melting point (°C)	Boiling point (°C)	Density (g/mL)
Butane		–138.4	–0.5	0.5788
1-butanol		–89.5	117.2	0.8098
Butanoic acid		–4.5	163.5	0.9577
2-butanone		–86.3	79.6	0.8054
Diethyl ether		–116.2	34.5	0.7138

Figure 7
Both of these molecules are alcohols. They are isomers of each other because they both have the molecular formula $C_4H_{10}O$.



1-butanol



2-methyl-1-propanol
(isobutyl alcohol)

Different Isomers Have Different Properties

isomer
one of two or more compounds that have the same chemical composition but different structures

Examine the two molecules shown in **Figure 7.** Both have the same molecular formula: $C_4H_{10}O$. They differ, however, in the way in which their atoms are arranged. These two molecules are known as **isomers.** Isomers are compounds that have the same formula but differ in their chemical and physical properties because of the difference in the arrangement of their atoms. The greater the structural difference between two isomers, the more significant is the difference in their properties. Because the structural difference between the two isomers shown in **Figure 7** is minor, both molecules have similar boiling points and densities.

1 Section Review

UNDERSTANDING KEY IDEAS

1. List the three factors that make the bonding of carbon atoms unique.

2. What are allotropes?

3. How are alkanes, alkenes, and alkynes similar? How are they different from each other?

4. Draw the simplified representation of the resonance structure for benzene.

5. List four elements other than carbon and hydrogen that can bond to carbon in organic compounds.

6. What is an aromatic compound?

7. What is a functional group?

8. What is an isomer? What do two molecules that are isomers of each other have in common?

CRITICAL THINKING

9. Draw a structural formula for the straight-chain hydrocarbon with the molecular formula C_3H_6. Is this an alkane, alkene, or alkyne?

10. Can molecules with molecular formulas C_4H_{10} and $C_4H_{10}O$ be isomers of one another? Why or why not?

11. Draw a structural formula for an alkyne that contains seven carbon atoms.

12. Draw the structural formulas for two isomers of C_4H_{10}.

13. Why is benzene not considered a cycloalkene even though double bonds exist between the carbon atoms that are arranged in a ring structure?

14. Write the molecular formulas for an alkane, alkene, and alkyne with 5 carbon atoms each. Why are these three hydrocarbons not considered isomers?

15. Draw C_4H_6 as a cycloalkene.

SECTION

2 Names and Structures of Organic Compounds

Key Terms

- **saturated hydrocarbon**
- **unsaturated hydrocarbon**

Objectives

1. **Name** simple hydrocarbons from their structural formulas.
2. **Name** branched hydrocarbons from their structural formulas.
3. **Identify** functional groups from a structural formula, and assign names to compounds containing functional groups.
4. **Draw** and interpret structural formulas and skeletal structures for common organic compounds.

Naming Straight-Chain Hydrocarbons

Inorganic carbon compounds, such as carbon dioxide, are named by using a system of prefixes and suffixes. Organic compounds have their own naming scheme, which includes prefixes and suffixes that denote the class of organic compound. Learning just a few rules will help you decipher the names of most common organic compounds.

For example, the names of all alkanes end with the suffix *-ane*. The simplest alkane is methane, CH_4, the main component of natural gas. **Table 3** lists the names and formulas for the first 10 straight-chain alkanes. For alkanes that consist of five or more carbon atoms, the prefix comes from a Latin word that indicates the number of carbon atoms in the chain.

Table 3 Straight-Chain Alkane Nomenclature

Number of carbon atoms	Name	Formula
1	methane	CH_4
2	ethane	$CH_3—CH_3$
3	propane	$CH_3—CH_2—CH_3$
4	butane	$CH_3—CH_2—CH_2—CH_3$
5	pentane	$CH_3—CH_2—CH_2—CH_2—CH_3$
6	hexane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_3$
7	heptane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$
8	octane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$
9	nonane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$
10	decane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$

Naming Short-Chain Alkenes and Alkynes

The scheme used to name straight-chain hydrocarbons applies to both saturated and unsaturated compounds. A **saturated hydrocarbon** is a hydrocarbon in which each carbon atom forms four single covalent bonds with other atoms. The alkanes are saturated hydrocarbons. An **unsaturated hydrocarbon** is a hydrocarbon in which not all carbon atoms have four single covalent bonds. The alkenes and alkynes are unsaturated hydrocarbons.

saturated hydrocarbon

an organic compound formed only by carbon and hydrogen linked by single bonds

unsaturated hydrocarbon

a hydrocarbon that has available valence bonds, usually from double or triple bonds with carbon

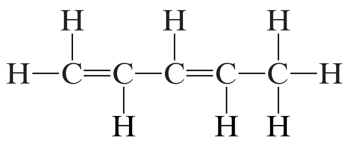
The rules for naming an unsaturated hydrocarbon with fewer than four carbon atoms are similar to those for naming alkanes. A two-carbon alkene is named *ethene,* with the suffix *-ene* indicating that the molecule is an alkene. A three-carbon alkyne is named *propyne,* with the suffix *-yne* indicating that the molecule is an alkyne.

Naming Long-Chain Alkenes and Alkynes

The name for an unsaturated hydrocarbon containing four or more carbon atoms must indicate the position of the double or triple bond within the molecule. First number the carbon atoms in the chain so that the first carbon atom in the double bond has the lowest number. Examine **Figure 8,** which shows structural formulas for two alkenes with five carbon atoms.

The correct name for the alkene shown on the left in **Figure 8** is *1-pentene*. The molecule is correctly numbered from left to right because the first carbon atom with the double bond must have the lowest number. The name *1-pentene* indicates that the double bond is present between the first and second carbon atoms. The alkene shown on the right in **Figure 8** is correctly named *2-pentene,* indicating that the double bond is present between the second and third carbon atoms. Note that 1-pentene and 2-pentene are the only possible pentenes, because 3-pentene would be the same molecule as 2-pentene and the lower numbering is preferred.

If there is more than one multiple bond in a molecule, number the position of each multiple bond, and use a prefix to indicate the number of multiple bonds. For example, the following molecule is called *1,3-pentadiene*. (Note the placement of the prefix *di-*.)



STUDY TIP

Preparing for Year-End Evaluations

As you approach the completion of your study of chemistry, you should start preparing for any final exams or standardized tests that you will be taking. The best way to begin is by developing a schedule for the remainder of the school year. Map out a schedule that involves spending more time on topics that you studied early in the course or ones that you found more difficult.

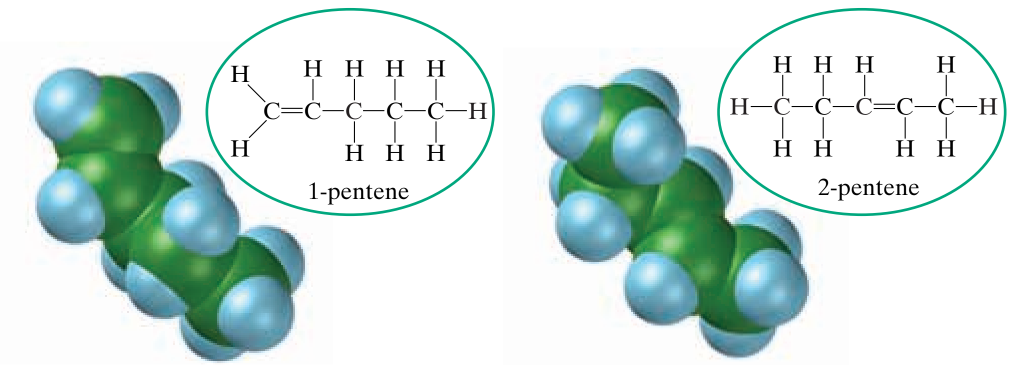
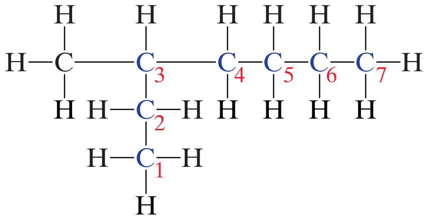


Figure 8
Both the names and structural formulas indicate the position of the double bond in each alkene. Notice that you cannot tell from the space-filling models where the double bond is located.

Naming Branched Hydrocarbons

When naming a hydrocarbon that is not a simple straight chain, first determine the number of carbon atoms in the longest chain. It can be named based on the corresponding alkane in **Table 3.** The longest chain may not appear straight in a structural formula, as in the example below.



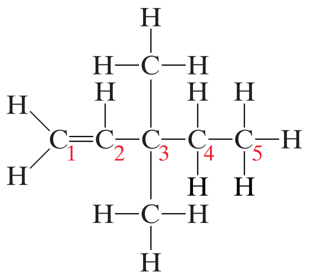
The "parent" chain in the compound shown above contains seven carbon atoms, so it is heptane. Next, number the carbon atoms on the parent chain so that any branches on the chain have the lowest numbers possible.

Name the Attached Groups and Indicate Their Positions

In the structural formula above, all the numbered carbon atoms, with one exception, are bonded only to hydrogen atoms. The one exception is the third carbon atom, which has a $—CH_3$ group attached. This group is known as a *methyl group,* because it is similar to a methane molecule, but with one less hydrogen atom. Because the methyl group is attached to the third carbon, the complete name for this branched alkane is *3-methylheptane*.

You can omit the numbers if there is no possibility of ambiguity. For example, a propane chain can have a methyl group only on its second carbon (if the methyl group were on the first or third carbon of propane, the molecule would be butane). So, what you might want to call *2-methylpropane* would be called *methylpropane.*

With unsaturated hydrocarbons that have attached groups, the longest chain containing the double bond is considered the parent compound. In addition, if more than one group is attached to the longest chain, the position of attachment of each group is given. Prefixes are used if the same group is attached more than once. Examine the following structural formula for a branched alkene.

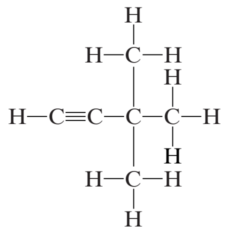


The chain containing the double bond has five carbon atoms. Therefore, the compound is a pentene. Notice that the first carbon atom has a double bond, making the chain 1-pentene. Because two methyl groups are attached to the third carbon atom, the correct name for this branched alkene is *3,3-dimethyl-1-pentene*.

SAMPLE PROBLEM A

Naming a Branched Hydrocarbon

Name the following hydrocarbon.



1 Gather information.

- The triple bond makes the branched hydrocarbon an alkyne.

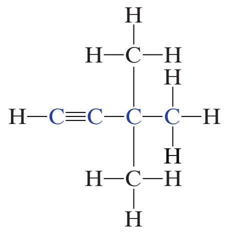
2 Plan your work.

- Identify the longest continuous chain (the "parent" chain), and name it.
- Number the parent chain so that the triple bond is attached to the carbon atom with the lowest possible number.
- Name the groups that make up the branches.
- Identify the positions that the branches occupy on the longest chain.

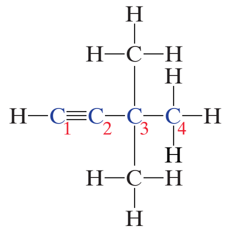
PRACTICE HINT

Many organic structural formulas look quite confusing, but keep in mind that the name will be based on one of the simple alkane names listed in **Table 3.**

3 Name the structure.



- The longest continuous chain has four carbon atoms.
- The parent chain is butyne.
- The numbering begins with the triple bond.
- Two methyl, $—CH_3$, groups are present.
- Both methyl groups are attached to the third carbon atom.
- The name of this branched hydrocarbon is *3, 3-dimethyl-1-butyne*.



4 Verify your results.

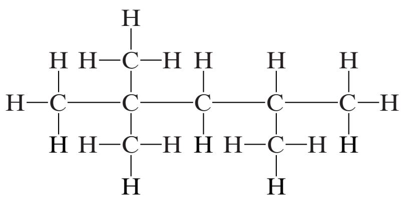
- The parent name *butyne* indicates that four carbon atoms are present in the longest chain. The *1-butyne* indicates that the first carbon atom has a triple bond. The *3,3-dimethyl-* indicates that two methyl groups, $—CH_3$, are attached to the third carbon atom in the longest chain.

PRACTICE

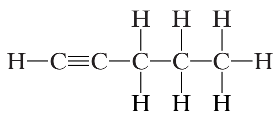
Name the following branched hydrocarbons.

PROBLEM SOLVING SKILL

1 **a.**

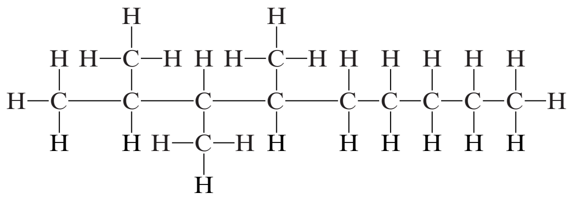


b.

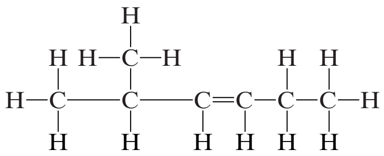


PRACTICE

1 **c.**

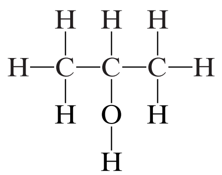


d.



Names of Compounds Reflect Functional Groups

Names for organic compounds with functional groups are based on the same system used for hydrocarbons with branched chains. First, the longest chain is named. Then a prefix or suffix indicating the functional group is added to the hydrocarbon name. **Table 4** lists the prefixes and suffixes for various functional groups. When necessary, the position of the functional group is noted in the same way that the position of hydrocarbon branches is noted. Consider the following structural formula.



Because the longest chain consists of three carbon atoms, the name for this compound is based on propane. From **Table 1,** you can see that the presence of the —OH functional group classifies this compound as an alcohol. Therefore, as indicated by **Table 4,** the name for this compound is *propanol,* whose suffix *-ol* indicates that this molecule is an alcohol. Because the functional group is attached to the second carbon atom, the correct name for this compound is *2-propanol*. A number of organic compounds are often referred to by their common names, even by chemists. The common name for 2-propanol is *isopropyl alcohol*.

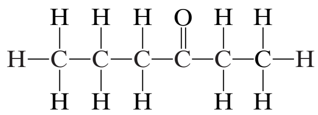
Table 4 Naming Compounds with Functional Groups

Class of compound	Suffix or prefix	Example
Alcohol	*-ol*	propanol
Aldehyde	*-al*	butanal
Amine	*-amine* or *amino-*	methylamine
Carboxylic acid	*-oic acid*	ethanoic acid
Ketone	*-one*	propanone

SAMPLE PROBLEM B

Naming a Compound with a Functional Group

Name the following organic compound.



1 Gather information.

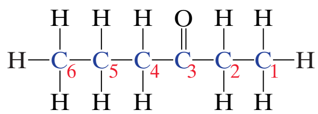
- Notice that the functional group indicates that this compound is a ketone.

2 Plan your work.

- Identify the longest continuous chain (the "parent" chain), and name it.
- Number the parent chain so that the functional group is attached to the carbon atom with the lowest possible number.
- Identify the position that the functional group occupies on the longest chain.
- Name the organic compound.

3 Name the structure.

- The longest continuous chain has six carbon atoms: the parent chain is hexane.
- The carbon atoms are numbered from right to left to give the ketone functional group the lowest number.



- The name of this organic compound is *3-hexanone*.

4 Verify your results.

- The name *3-hexanone* indicates that six carbon atoms are present in the parent chain. The suffix *-one* indicates that this compound is a ketone. The *3-* indicates that the functional group is attached to the third carbon atom in the parent chain.

PRACTICE HINT

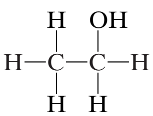
The steps to follow for naming organic compounds with functional groups are similar to those for naming branched hydrocarbons.

PRACTICE

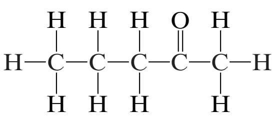
Name the following organic compounds.

PROBLEM SOLVING SKILL

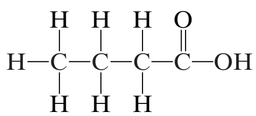
1 **a.**



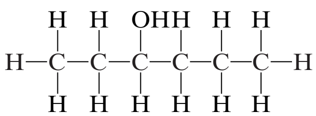
b.



c.



d.



Representing Organic Molecules

Table 5 shows four ways of representing the organic molecule cyclohexane. Each type of model used to represent an organic compound has both advantages and disadvantages. Each one highlights a different feature of the molecule, from the number and kinds of atoms in a chemical formula to the three-dimensional shape of the space-filling model. Keep in mind that a picture or model cannot fully convey the true three-dimensional shape of a molecule or show the motion within a molecule caused by the atoms' constant vibration.

Structural Formulas Can Be Simplified

Structural formulas are sometimes represented by what are called *skeletal structures,* which show bonds, but leave out some or even all of the carbon and hydrogen atoms. You have already seen the skeletal structure for benzene, which is a hexagon with a ring inside it.

A skeletal structure usually shows the carbon framework of a molecule only as lines representing bonds. These lines are often drawn in a zigzag pattern to indicate the tetrahedral arrangement of bonds between a carbon atom and other atoms. Carbon atoms are understood to be at each bond along with enough hydrogen atoms so that each carbon atom has four bonds. Atoms other than carbon and hydrogen are always shown, which highlights any functional groups present.

Table 5 Types of Molecular Models

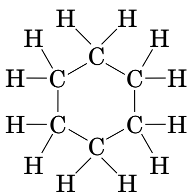
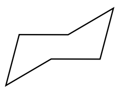
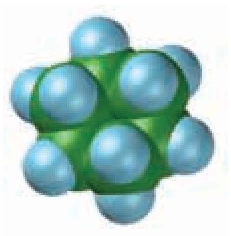
Type of model	Example	Advantages	Disadvantages
Chemical formula	C_6H_{12}	shows number of atoms in a molecule	does not show bonds, atom sizes, or shape
Structural formula		shows arrangement of all atoms and bonds in a molecule	does not show actual shape of molecule or atom sizes; larger molecules can be too complicated to draw easily
Skeletal structure		shows arrangements of carbon atoms; is simple	does not show actual shape or atom sizes; does not show all atoms or bonds
Space-filling model		shows three-dimensional shape of molecule; shows most of the space taken by electrons	uses false colors to differentiate between elements; bonds are not clearly indicated; parts of large molecules may be hidden

Figure 9
a The chemical name for aspirin is acetylsalicylic acid.

b Because the complete structural formula of acetylsalicylic acid is complex . . .

c . . . chemists usually draw its skeletal structure instead. The presence of a benzene ring indicates that it is an aromatic compound.

SAMPLE PROBLEM C

Drawing Structural and Skeletal Formulas

Draw both the structural formula and the skeletal structure for 1,2,3-propanetriol.

1 Gather information.

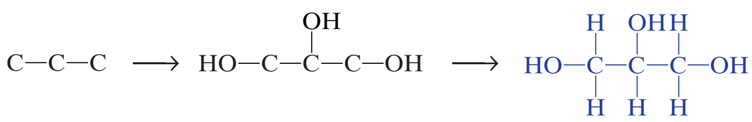
- The name *propanetriol* indicates that the molecule is an alcohol that consists of three carbon atoms making up the parent chain.
- The suffix *-triol* indicates that three alcohol groups are present.
- The *1,2,3-* prefix indicates that an alcohol group is attached to the first, second, and third carbon atoms.

2 Plan your work.

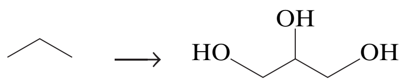
- Draw the carbon framework showing the parent chain.
- Add the alcohol groups to the appropriate carbon atoms.
- Add enough hydrogen atoms so that each carbon atom has four bonds.
- Show the carbon framework as a zigzag line.
- Include the functional groups as part of the skeletal structure.

3 Draw the structures.

Structural formula:



Skeletal formula:



4 Verify your results.

- The structural formula should show all bonds and atoms in the compound 1, 2, 3-propanetriol.
- The skeletal formula should show only carbon-carbon bonds plus any functional groups present in the molecule.

PRACTICE HINT

Unless it is a part of a functional group, hydrogen is not shown in a skeletal structure. In the sample, the hydrogens shown are part of the alcohol functional group. The other hydrogen atoms bonded to carbon are not shown.

PRACTICE

PROBLEM SOLVING SKILL

Draw both structural and skeletal formulas for each of the following compounds.

1. 2-octanone
2. butanoic acid
3. 1,1,1,2-tetrabromobutane
   (Hint: *Bromo*- indicates that a Br atom is attached to the parent chain.)
4. 2,2-dichloro-1,1-difluoropropane
   (Hint: Both Cl and F atoms are attached to the parent chain.)

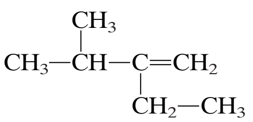
2 Section Review

UNDERSTANDING KEY IDEAS

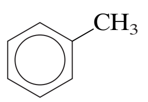
1. How does a saturated hydrocarbon differ from an unsaturated hydrocarbon?
2. What does the prefix *dec*- indicate about the composition of an organic compound?
3. What is the functional group for an aldehyde?
4. How are the carbon atoms in the parent chain numbered in a branched alkene or alkyne?
5. Which class of compounds forms the basis for naming most other carbon compounds?

PRACTICE PROBLEMS

6. Name the following branched hydrocarbon. (Hint: The $—CH_2—CH_3$ group is an ethyl group.)

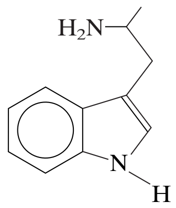


7. Name the following branched hydrocarbon.



8. Draw the structural formula for dichloromethane.
9. Draw the structural and skeletal formulas for 2-bromo-4-chloroheptane.
10. Write the molecular formula for the compound with the following skeletal structure.

    (Hint: Draw a full structural formula, and include all the carbon and hydrogen atoms in your count.)



CRITICAL THINKING

11. Why do the names of organic acids not contain any numbers to indicate the position of the functional group?
12. What is incorrect about the name *nonene*?
13. How is methanol different from methanal? How are they similar?
14. How many double bonds are present in 1,3-butadiene? Where are they located in the molecule?

SECTION

3 Organic Reactions

KEY TERMS

- substitution reaction
- addition reaction
- polymer
- condensation reaction
- elimination reaction

OBJECTIVES

1. **Describe** and distinguish between substitution and addition reactions.
2. **Describe** and distinguish between condensation and elimination reactions.

Substitution and Addition Reactions

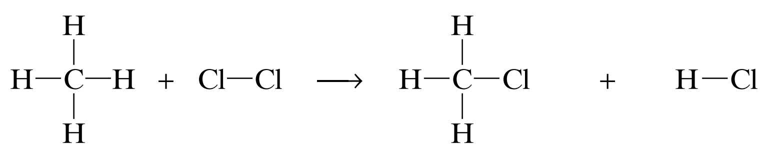
The single bonds between carbon and hydrogen atoms in organic compounds are not highly reactive. However, these compounds do participate in a variety of chemical reactions, one of which is called a *substitution reaction*. A **substitution reaction** is a reaction in which one or more atoms replace another atom or group of atoms in a molecule. Another type of reaction involving organic compounds is an **addition reaction** in which an atom or molecule is added to an unsaturated molecule and increases the saturation of the molecule.

substitution reaction
a reaction in which one or more atoms replace another atom or group of atoms in a molecule

addition reaction
a reaction in which an atom or molecule is added to an unsaturated molecule

Halogens Often Replace Hydrogen Atoms

As saturated hydrocarbons, the alkanes have the lowest chemical reactivity of organic compounds. However, under certain conditions these compounds can undergo substitution reactions, especially with the halogens. An example of such a reaction is that between an alkane, such as methane, and a halogen, such as chlorine. In this substitution reaction, a chlorine atom replaces a hydrogen atom on the methane molecule.



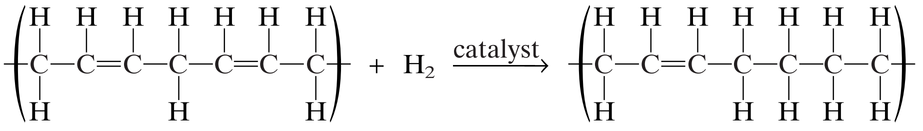
methane | chlorine | chloromethane | hydrogen chloride

The substitution reactions can continue, replacing the remaining hydrogen atoms in the methane molecule one at a time. The products are dichloromethane, trichloromethane, and tetrachloromethane. Trichloromethane is commonly known as *chloroform,* which was once used as an anesthetic. The common name for tetrachloromethane is carbon *tetrachloride,* which for many years was commonly used as a solvent.

Because the single covalent bonds are hard to break, catalysts are often added to the reaction mixture. For example, trichlorofluoromethane, CCl_3F, commonly known as *Freon-11,* was used as a refrigerant. It was made by a substitution reaction catalyzed by SbF_3.

Hydrogenation Is a Common Addition Reaction

A common type of addition reaction is hydrogenation, in which one or more hydrogen atoms are added to an unsaturated molecule. As a result of hydrogenation, the product of the reaction contains fewer double or triple bonds than the reactant. Hydrogenation is used to convert vegetable oils into fats. Vegetable oils are long chains of carbon atoms with many double bonds. When hydrogen gas is bubbled through an oil, double bonds between carbon atoms in the oil are broken and hydrogen atoms are added. Only a portion of the very long oil and fat molecules are shown in the following hydrogenation reaction.

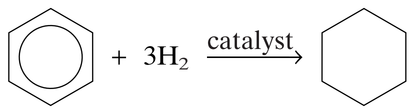


oil fat

Making Consumer Products by Hydrogenation

The margarine and vegetable shortening shown in **Figure 10** are two products made by the hydrogenation of oil. Although they contain double bonds, oils are still not very reactive. As a result, the hydrogenation of an oil requires the addition of a catalyst and temperatures of about 260°C.

Another application of hydrogenation is the manufacture of cyclohexane from benzene as shown by the following reaction.



benzene cyclohexane

Over 90% of the cyclohexane that is made is used in the manufacture of nylon. The rest is used mostly as a solvent for paints, varnish, and oils.

Figure 10 Hydrogenation is used to turn vegetable oil into solid margarine and butter.

Some Addition Reactions Form Polymers

polymer

a large molecule that is formed by more than five monomers, or small units

The addition reactions you have examined so far involve adding atoms to a molecule. Some addition reactions involve joining smaller molecules together to make larger ones. The smaller molecules are known as *monomers*. The larger molecule that is made by the addition reaction is called a **polymer.**

Consider how polyethylene is made. Polyethylene is a strong but flexible plastic used to make a variety of consumer products, including the water bottle shown at the beginning of this chapter. The monomer from which polyethylene is made is ethene, C_2H_4. Because ethene is commonly known as *ethylene,* the polymer it forms is often called *polyethylene*. The following equation shows how a portion of the polymer forms. Notice that these are condensed formulas that show all the atoms but not the bonds between the carbon and hydrogen atoms.

$$CH_2{=}CH_2 + CH_2{=}CH_2 \longrightarrow -CH_2-CH_2-CH_2-CH_2-$$

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Monomers Can Be Added in Different Ways

Notice the open single bonds at each end of the product in the reaction shown above. An ethene molecule can be added at each end. The process of adding ethene molecules, one at each end, continues until polyethylene is eventually produced. Polyethylene is a very long alkane polymer chain. These chains form a product that is strong yet flexible.

Occasionally, monomers are added so that a chain branches. For example, an ethene monomer is sometimes added to form a side chain. A polymer with many side chains remains flexible. Such polymers are used to manufacture the plastic that wraps a variety of consumer products such as those shown in **Figure 11.**

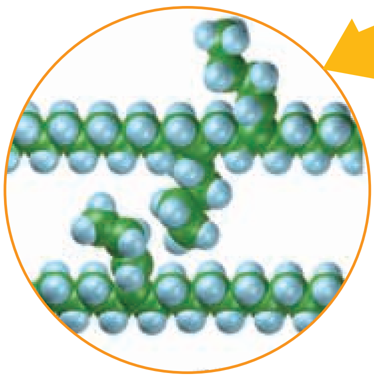


Figure 11
Plastic wrap is used to protect foods from spoiling. It is flexible because the side chains in the polymer prevent side-by-side molecules from packing together rigidly.

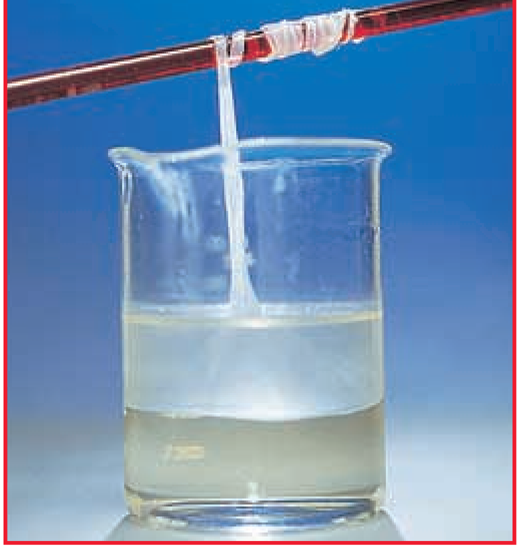


Figure 12
Nylon 66, shown here being wound onto a stirring rod, is one of the most widely used of all synthetic polymers.

Condensation and Elimination

Polymers can also be formed by a **condensation reaction** in which two molecules combine, usually accompanied by the loss of a water molecule. The formation of water as a reaction product is the reason for the name of this type of reaction. In some instances, hydrochloric acid is formed as a byproduct of a condensation reaction.

Another type of reaction that produces water is known as an *elimination reaction*. An **elimination reaction** is a reaction in which a simple molecule is removed from adjacent carbon atoms on the same organic molecule. Another simple molecule that can be a product of an elimination reaction is ammonia.

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

elimination reaction
a reaction in which a simple molecule, such as water or ammonia, is removed and a new compound is produced

Condensation Reactions Produce Nylon

Figure 12 shows a polymer being formed in a condensation reaction. The bottom layer in the beaker shown in **Figure 12** is hexanediamine, an organic molecule with an amine group at each end. The top layer in the beaker is adipic acid, an organic molecule with a carboxyl group at each end. The condensation reaction takes place between an amine group on hexanediamine and a carboxyl group on adipic acid as shown below.

$$\underbrace{H{-}N(H){-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}N(H){-}H}_{\text{hexanediamine}} + \underbrace{HO{-}C({=}O){-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}C({=}O){-}OH}_{\text{adipic acid}} \longrightarrow$$

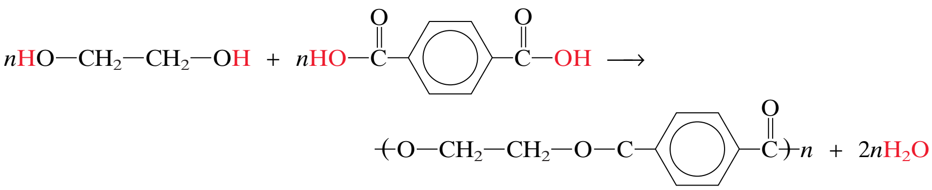
$$H{-}N(H){-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}N(H){-}C({=}O){-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}C({=}O){-}OH + \underbrace{H_2O}_{\text{water}}$$

Notice that a water molecule is eliminated when an H atom from the amine group and an —OH group from the carboxyl group are removed. Another adipic acid molecule is then added to the amine group shown on the left, while another hexanediamine molecule is added to the carboxyl group shown on the right. This process continues, linking hundreds of reactants to form a product called *nylon 66*.

Figure 13
These colorful threads are made from polyester that can be woven into fabrics to make many types of clothing.

Many Polymers Form by Condensation Reactions

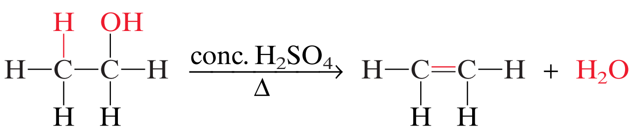
In addition to nylon 66, many other polymers are made by condensation reactions. The polymer shown in **Figure 13** is polyethylene terephthalate, abbreviated PET, which is used to make permanent-press clothing and soda bottles. The following formulas show how two monomers are combined in this condensation reaction.



Notice that the first reactant shown is an alcohol because it contains two —OH groups. The second reactant shown is an organic acid because it contains two —COOH groups. When PET is made, water is formed from an —H from the alcohol and an —OH from the acid. The two monomers then bond. The functional group present in the product shown above classifies this molecule as an ester. Therefore, PET is a polyester.

Elimination Reactions Often Form Water

An elimination reaction involves the removal of a small molecule from two adjacent carbon atoms, as shown below.



ethanol ethene water

The acid catalyzes a reaction that eliminates water from the ethanol molecule, which leaves a double bond.

Figure 14
An elimination reaction occurs when sucrose and concentrated sulfuric acid are mixed. Water is formed, which leaves a product that is mostly carbon.

Figure 14 shows another example of an elimination reaction; one whose results can be seen easily. When sucrose reacts with concentrated sulfuric acid, water is eliminated, which leaves behind mostly carbon. Carbon is the black substance you can see forming in the photos and rising out of the beaker on the far right.

3 Section Review

UNDERSTANDING KEY IDEAS

1. Explain why an addition reaction increases the saturation of a molecule.
2. What molecule is often a product of both condensation and elimination reactions?
3. What kind of organic reaction can form fluoromethane, CH_3F, from methane?
4. Give an example of a polymer, and tell what monomers it consists of.
5. How does a condensation reaction get its name?
6. Name the type of organic reaction that results in the formation of a double bond.

CRITICAL THINKING

7. Explain why alkanes do not undergo addition reactions.
8. Explain how an elimination reaction can be considered the opposite of an addition reaction.
9. Draw the skeletal structure of part of a polyethylene molecule consisting of eight monomers.
10. Can two different monomers be involved in an addition reaction? Why or why not?
11. Why is a molecule with only one functional group unable to undergo a condensation reaction to form a polymer?
12. Why does a substitution reaction involving an alkane and a halogen not increase the saturation of the organic compound?

CONSUMER FOCUS

Recycling Codes for Plastic Products

More than half the states in the United States have enacted laws that require plastic products to be labeled with numerical codes that identify the type of plastic used in them.

Sorting your plastics

Used plastic products can be sorted by the codes shown in **Table 6** and properly recycled or processed. Only Codes 1 and 2 are widely accepted for recycling. Codes 3 and 6 are rarely recycled. Find out what types of plastics are recycled in your area. If you know what the codes mean, you will have an idea of how successfully a given plastic product can be recycled. This information may affect your decision to buy or not buy particular items.

Questions

1. What do the recycling codes on plastic products indicate?
2. Why is it important to sort plastics before recycling them?

Table 6 Recycling Codes for Plastic Products

Recycling code	Type of plastic	Physical properties	Examples	Uses for recycled products
1	polyethylene terephthalate (PET)	tough, rigid; can be a fiber or a plastic; solvent resistant; sinks in water	soda bottles, clothing, electrical insulation, automobile parts	backpacks, sleeping bags, carpet, new bottles, clothing
2	high density polyethylene (HDPE)	rough surface; stiff plastic; resistant to cracking	milk containers, bleach bottles, toys, grocery bags	furniture, toys, trash cans, picnic tables, park benches, fences
3	polyvinyl chloride (PVC)	elastomer or flexible plastic; tough; poor crystallization; unstable to light or heat; sinks in water	pipe, vinyl siding, automobile parts, clear bottles for cooking oil, bubble wrap	toys, playground equipment
4	low density polyethylene (LDPE)	moderately crystalline, flexible plastic; solvent resistant; floats on water	shrink wrapping, trash bags, dry-cleaning bags, frozen-food packaging, meat packaging	trash cans, trash bags, compost containers
5	polypropylene (PP)	rigid, very strong; fiber or flexible plastic; lightweight; heat-and-stress-resistant	heatproof containers, rope, appliance parts, outdoor carpet, luggage, diapers, automobile parts	brooms, brushes, ice scrapers, battery cable, insulation, rope
6	polystyrene (P/S, PS)	somewhat brittle, rigid plastic; resistant to acids and bases but not organic solvents; sinks in water, unless it is a foam	fast-food containers, toys, videotape reels, electrical insulation, plastic utensils, disposable drinking cups, CD jewel cases	insulated clothing, egg cartons, thermal insulation

CHAPTER HIGHLIGHTS 19

KEY TERMS

KEY IDEAS

SECTION ONE Compounds of Carbon

hydrocarbon
alkane
alkene
alkyne
aromatic hydrocarbon
functional group
isomer

- The properties of carbon allotropes depend on the arrangement of the atoms and how they are bonded to each other.
- The simplest organic compounds are the hydrocarbons, which consist of only carbon and hydrogen atoms.
- Alkanes, alkenes, and alkynes are hydrocarbons. Organic compounds containing one or more rings with delocalized electrons are aromatic hydrocarbons.
- Organic compounds are classified by their functional groups.

SECTION TWO Names and Structures of Organic Compounds

saturated hydrocarbon
unsaturated hydrocarbon

- The names of the alkanes form the basis for naming most other organic compounds.
- When an organic compound is named, the parent chain is identified, and the carbon atoms are numbered so that any branches or multiple bonds have the lowest possible numbers.
- Organic molecules can be represented in various ways, and each model has advantages and disadvantages.

SECTION THREE Organic Reactions

substitution reaction
addition reaction
polymer
condensation reaction
elimination reaction

- In a substitution reaction, an atom or group of atoms is replaced.
- In an addition reaction, an atom or group of atoms is added to replace a double or triple bond.
- Polymers are very long organic molecules formed by successive addition of monomers and are used in plastics.
- In a condensation reaction, two molecules or parts of the same molecule combine, which usually forms water.
- In an elimination reaction, a molecule, usually water, is formed by combining atoms from adjacent carbon atoms.

KEY SKILLS

Naming a Branched Hydrocarbon
Sample Problem A p. 690

Naming a Compound with a Functional Group
Sample Problem B p. 692

Drawing Structural and Skeletal Formulas
Sample Problem C p. 694

19 CHAPTER REVIEW

USING KEY TERMS

1. The benzene ring is the simplest member of what class of organic compounds?

2. Two compounds may have the same molecular formulas but different structural formulas. Each of these compounds is known as a(n) ____________.

3. What class of organic compounds includes all saturated hydrocarbons?

4. If an element exists in more than one bonding pattern, what term is used for each of these forms?

5. What type of reaction involves the replacement of a hydrogen atom by a halogen atom?

6. The chemical and physical properties of an organic compound are largely determined by the presence of a(n) ______________.

7. Which two types of organic reactions usually form small molecules such as water?

8. What type of molecule results when many smaller units are joined in addition reactions?

9. The hexagon and circle often used to depict a benzene molecule is an example of what kind of structure?

UNDERSTANDING KEY IDEAS

Compounds of Carbon

10. Explain why alkynes are more reactive than alkanes.

11. a. Why is diamond so hard and strong?
b. Why is graphite so soft and easy to break apart?

12. How are fullerenes and nanotubes alike? How are they different?

13. What is the molecular formula for the alkane that contains 14 carbon atoms?

14. Draw the two possible resonance structures for benzene.

15. Explain the connection between the strength of the carbon-carbon single bond and the ability of carbon to be the basis of large molecules.

16. How does pentane differ from cyclopentane?

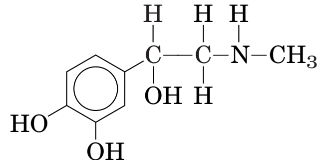
17. Explain why isomers have different chemical and physical properties.

18. Explain why the properties of butane differ from those of butanol.

Names and Structures of Organic Compounds

19. Use **Table 4** to identify the functional group from the name for each of the following organic compounds.
a. propanol
b. ethanoic acid
c. propanal
d. hexanone

20. What functional groups are present in a molecule of adrenaline, whose structural formula is shown below?



21. What group of organic compounds forms the basis for naming the other organic compounds?

22. What rule must be followed when the carbon atoms in an alkene or alkyne is numbered?

23. How does a skeletal structure differ from a structural formula? How are they the same?

24. Why is the name *pentyne* not completely correct?

25. What information does the name *1-aminobutane* provide about the structure of this organic compound?

26. List the main advantage and disadvantage of using a skeletal structure as a model.

Organic Reactions

27. What are two reactions by which polymers can be formed?

28. Compare substitution and addition reactions.

29. What is the structural requirement for a molecule to be a monomer in an addition reaction?

30. Explain what hydrogenation is.

31. How does adding monomers as branches to a parent chain affect the properties of a polymer?

32. What is the difference between condensation and elimination?

33. Why are catalysts added to substitution reactions involving alkanes?

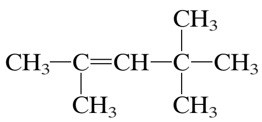
34. What is the chemical difference between an oil and a fat?

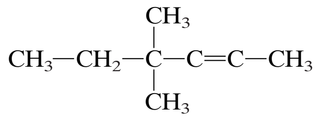
35. How are a nylon and polyethylene similar? How are they different?

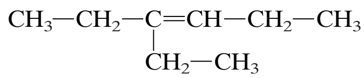
PRACTICE PROBLEMS

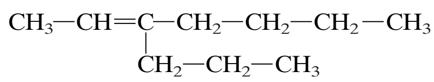
PROBLEM SOLVING SKILL

36. Name the following compounds.

a. 

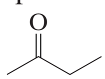
b. 

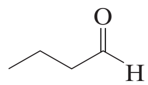
c. 

d. 

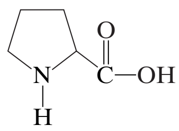
37. Draw the structural formulas for each of the following compounds.
a. 1,4-dichlorohexane
b. 2-bromo-4-chloroheptane

38. Name the following organic compounds, and then write the molecular formula for each compound.

a. 

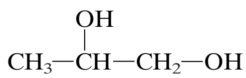
b. 

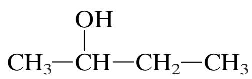
39. The skeletal structure for proline, an amino acid, is shown below. Draw its structural formula.

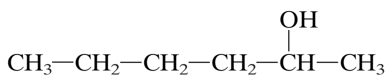


40. Name the following alcohols.

a. CH_3-OH

b. 

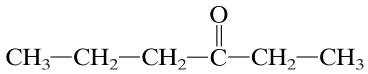
c. 

d. 

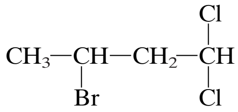
41. Draw skeletal structures for the following organic compounds.
a. 2,3,4-trichloropentane
b. 2,2 dichloro-1,1-difluoropropane

42. Name the following compounds.

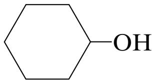
a.



b.



c.



CRITICAL THINKING

43. Explain why some alcohols and organic acids are soluble in water, whereas hydrocarbons are virtually insoluble.

44. Copolymers are made from two different monomers. For example, some plastic food wrap is an addition polymer made from 1,1-dichloroethene and chloroethene. Draw a possible structure for this copolymer showing a structure that is four monomers in length.

45. When propyne reacts with H_2 under the proper conditions, the triple bond is broken and hydrogen atoms are added to the alkyne to form an alkane.

a. Draw the structural formula for the alkane product.

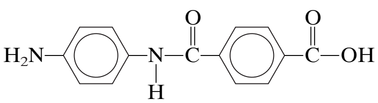
b. What is the name of this alkane?

46. When 2-methylpropene is mixed with HI, 2-iodo-2-methylpropane is produced.

a. Draw the structural formula for the organic reactant.

b. Draw the structural formula of the product.

47. The Kevlar™ that is used in bulletproof vests is a condensation polymer that can be made from the following monomer.

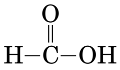


Draw a portion of a Kevlar™ polymer showing four molecules of a monomer that have combined.

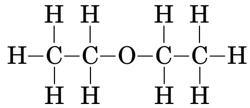
48. Draw two structural formulas for an alcohol with the molecular formula C_3H_8O.

49. Classify the organic compounds shown below by their functional groups.

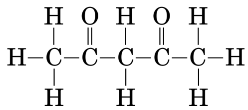
a.



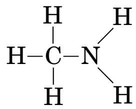
b.



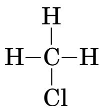
c.



d.



e.



ALTERNATIVE ASSESSMENT

50. Dimethyl mercury is an organic compound that poses a serious environmental threat to all living things. Research how this compound affects living things. Include information on whether dimethyl mercury poses a threat to your local environment. If so, determine what is being done to eliminate this problem.

51. Environmental concerns have led to the development of plastics that are labeled "biodegradable." Devise a set of experiments to study how well biodegradable plastics break down. If your teacher approves your plan, carry out your experiments on various consumer products labeled "biodegradable."

CONCEPT MAPPING

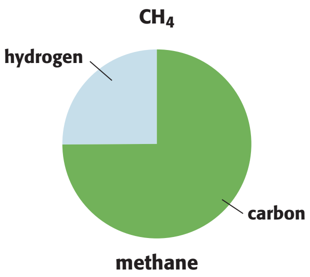
52. Use the following terms to create a concept map: *organic reactions, substitution, addition, condensation, hydrogen, halogen,* and *water*.

FOCUS ON GRAPHING

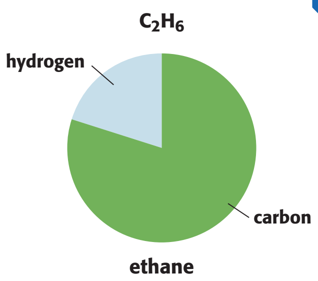
Study the graph below, and answer the questions that follow.
For help in interpreting graphs, see Appendix B, "Study Skills for Chemistry."

53. a. Determine the percentage composition by weight of hexane, C_6H_{14}.

b. Using the charts to the right as a model, make a pie chart for hexane using a protractor to draw the correct sizes of the pie slices. (Hint: A circle has 360°. To draw the correct angle for each slice, multiply each percentage by 360°.)



carbon	74.9%
hydrogen	25.1%



carbon	79.9%
hydrogen	20.1%

54. a. Compare the charts for methane, ethane, and hexane. In which of these three charts is the slice for carbon the largest?

b. In which of the three charts is the slice for carbon the smallest?

55. Based on your answers to the previous item, complete the following statement:
For saturated hydrocarbons, as the number of carbon atoms in the molecule increases, the percentage of carbon in the molecule will ____________.

56. a. Determine the percentage composition of hexene, C_6H_{12}.

b. Using the charts above as a model, make a pie chart for hexene.

c. Compare the charts for hexane and hexene. Which of these charts shows a larger slice for carbon?

TECHNOLOGY AND LEARNING

57. Graphing Calculator

Hydrocarbon formulas

The graphing calculator can run a program that can tell you the formula of any straight-chain hydrocarbon, provided you indicate the number of carbons and the number of double bonds in the compound.

Go to Appendix C. If you are using a TI-83 Plus, you can download the program HYDROCAR and run the application as directed. If you are using another calculator, your teacher will provide you with keystrokes and data sets to use. At the prompts, enter the number of carbon atoms and the number of double bonds in the molecule. Run the program as needed to answer the following questions.

a. Dodecane is an alkane with 12 carbons and no double bonds. What is its formula?

b. The name 1,5-hexadiene describes a molecule with six carbons (hexa–) and two double bonds (–diene). What is its formula?

c. What is the formula for 1, 3, 5-hexatriene?

d. What is the formula for 3-nonene?

e. What is the formula for 1,3,5,7-octatetraene?

f. What is the formula for 2,4,6-octatriene?

19 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. Which of these formulas represents a saturated hydrocarbon?
   A. C_2H_2
   B. C_4H_{10}
   C. C_5H_{10}
   D. C_6H_6

2. Which of these is the product of the hydrogenation of benzene?
   F. benzyl hydride
   G. cyclohexane
   H. hexane
   I. 1-hexanol

3. Which of the following occurs during an addition reaction?
   A. The saturation of a molecule is increased.
   B. Single bonds are replaced by double bonds.
   C. A number of monomers react to form a polymer.
   D. One or more atoms replace another atom or group of atoms.

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

4. Why is ethyne, also known as acetylene, used in welding torches instead of ethane which also has two carbon atoms?

5. Why does a hydrogenation reaction never include an alkane as a reactant?

6. Sunflower oil contains polyunsaturated fat molecules. What does polyunsaturated mean?

READING SKILLS

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

In the early part of the nineteenth century, chemists were unable to synthesize most carbon-containing compounds, unless they started with a material that had been produced by a living organism. The predominant theory was that there was a force inherent in living organisms that had to be used to make these compounds. In 1828 a German chemist, Friedrich Wöhler, succeeded in making an organic compound, urea, starting with inorganic chemicals. Although many chemists did not immediately accept that there was no living force involved in making organic molecules, the results prompted other scientists to perform experiments that led to synthesis of a variety of carbon compounds from inorganic sources and eventually new chemical theories.

7. Why did Wöhler's synthesis of urea from inorganic compounds mean that the theory about organic materials had to be reevaluated?
   F. It showed that other chemists were wrong.
   G. It proved that urea is not an organic compound.
   H. New data was not consistent with the existing theory.
   I. There is no special force existant that organisms use to make compounds.

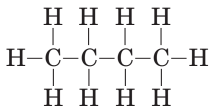
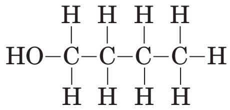
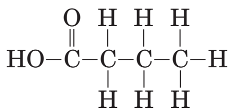
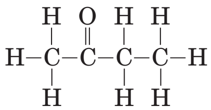
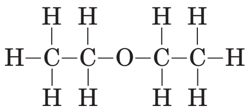
8. Why wasn't the theory that living organisms contributed special characteristics to organic compounds immediately replaced in the scientific community as soon as Wöhler announced his results?

INTERPRETING GRAPHICS

***Directions (9–12):* For *each* question below, record the correct answer on a separate sheet of paper.**

Use the table below to answer questions 9 through 12.

Comparing Classes of Organic Compounds

Name	Structural formula	Melting point (°C)	Boiling point (°C)	Density (g/mL)
Butane		–138.4	–0.5	0.5788
1-butanol		–89.5	117.2	0.8098
Butanoic acid		–4.5	163.5	0.9577
2-butanone		–86.3	79.6	0.8054
Diethyl ether		–116.2	34.5	0.7138

9 Which of the following statements is supported by the data in the table?

A. The density of an organic molecule is primarily a function of the number of carbons it contains.

B. A double bond between carbon and oxygen increases the boiling point more than a single bond.

C. The increase in melting and boiling points of organic compounds is related to the polarity of functional groups.

D. The increase in melting and boiling points of oxygen-containing organic molecules compared to hydrocarbons is primarily due to the polarity of the oxygen-hydrogen bond.

10 What is the main reason that the melting point of 2-butanone differs from that of butane?

F. the loss of a hydrogen atom

G. the increase in molecular size

H. the increase in intermolecular forces

I. the presence of oxygen in the molecule

11 Identify two pairs of isomeric compounds among those in the table.

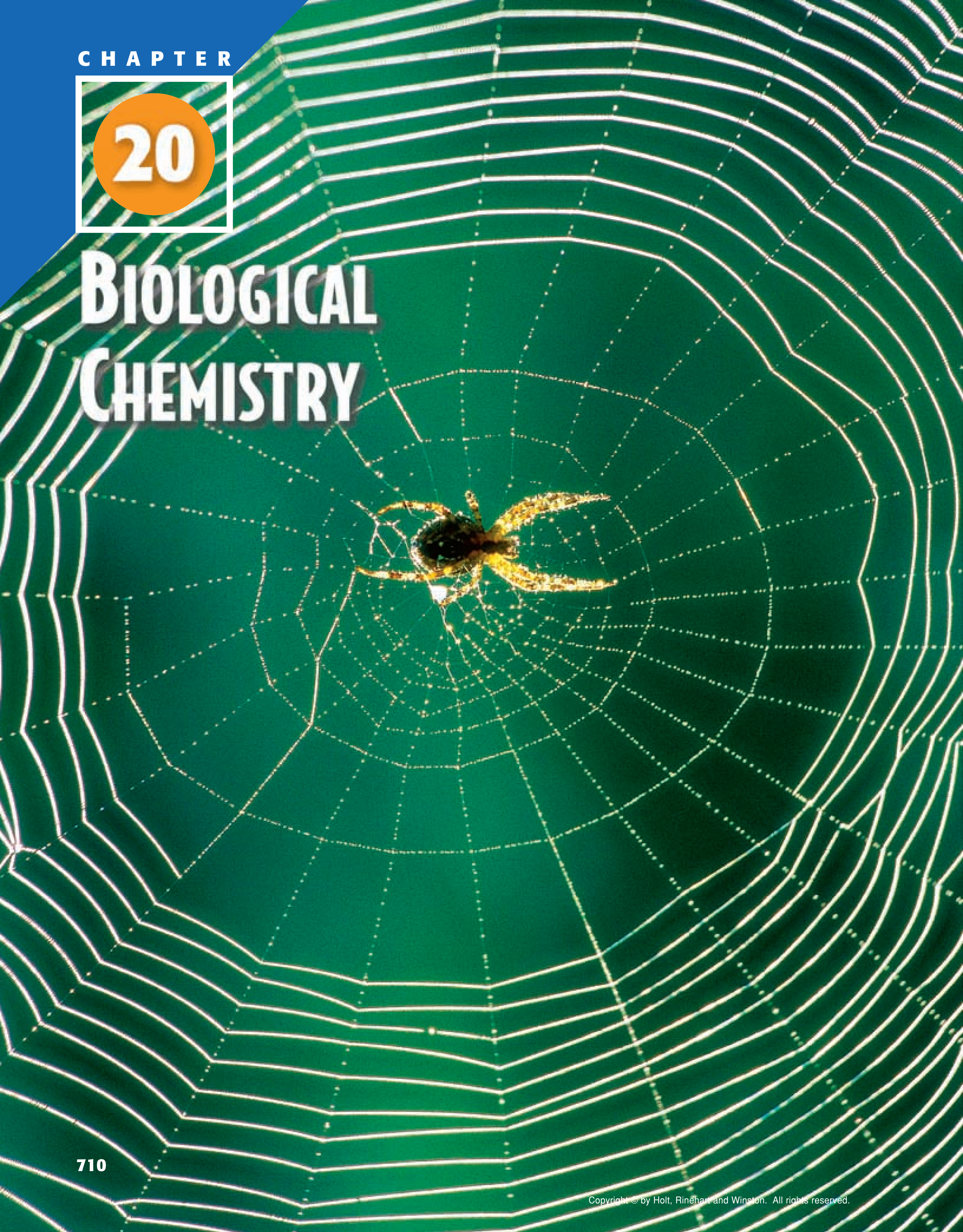
12 In °C, by how much does the introduction of a hydroxyl group on the end carbon of the butane molecule increase the melting point?

Test TIP

For questions requiring an extended response, make an outline listing the key points of your response before you begin writing.

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

Exploring Carbohydrates

SAFETY PRECAUTIONS

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?**

CONTENTS 20

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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.

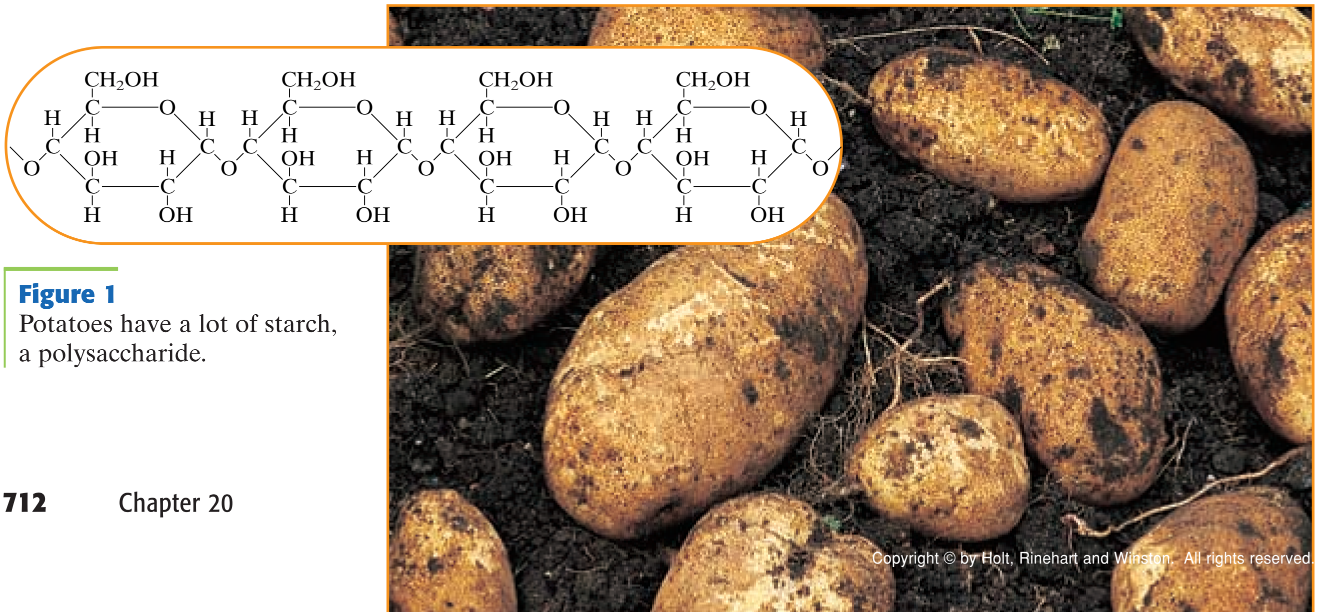

Figure 1
Potatoes have a lot of starch, a polysaccharide.

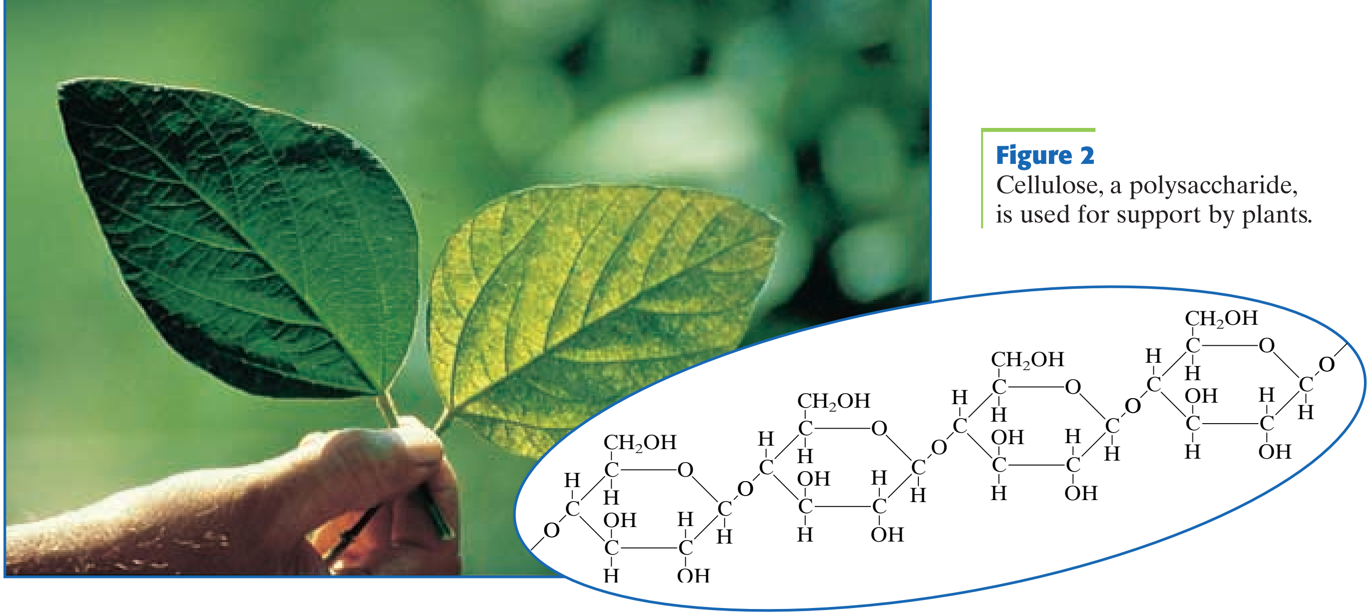

Figure 2
Cellulose, a polysaccharide, is used for support by plants.

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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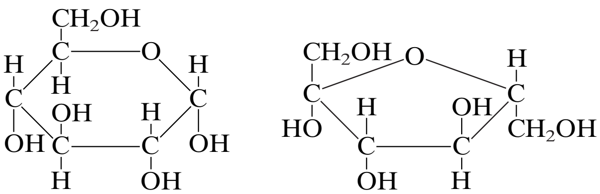
Structure of Simple Sugars

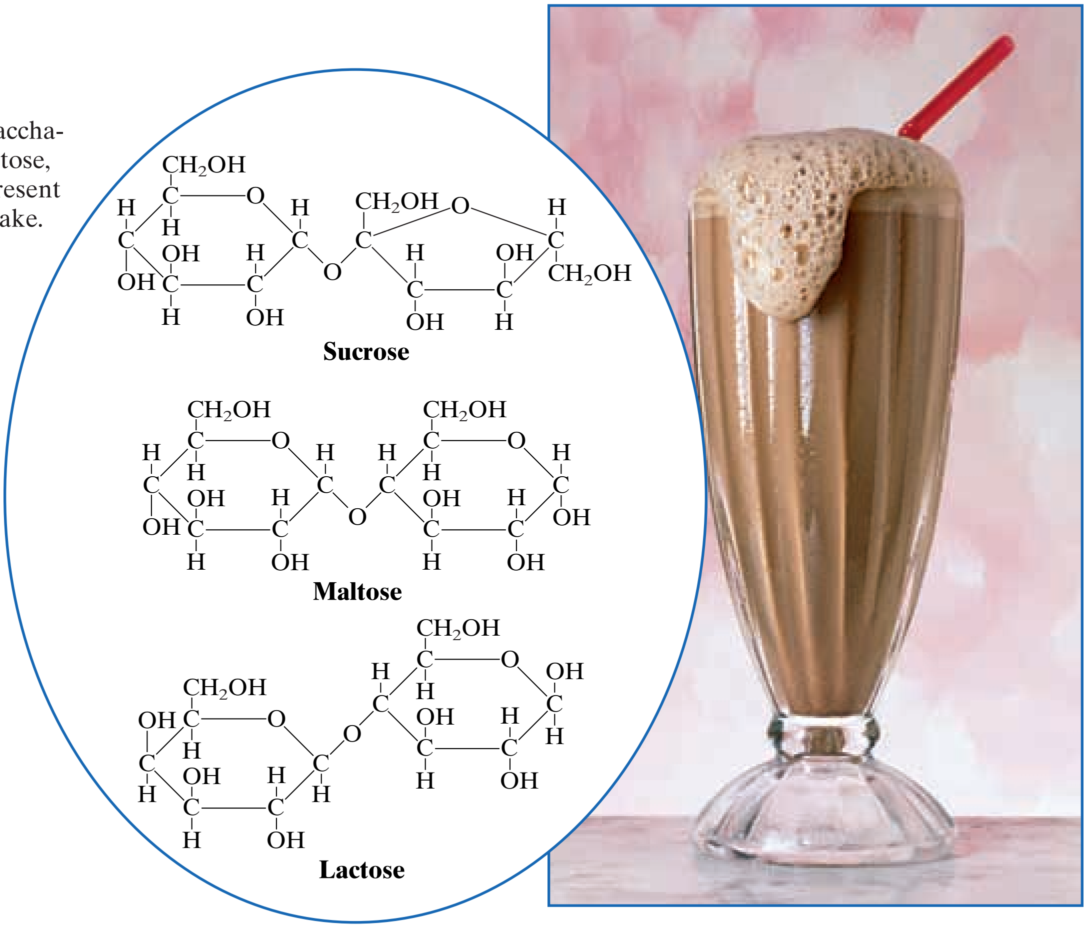
To a chemist, *sugar* is the name given to all monosaccharides and disaccharides. To a cook, *sugar* means one particular disaccharide, sucrose. The cyclic sugar glucose is important to the body because it is the chemical that the bloodstream uses to carry energy to every cell in the body. Shown below 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.**

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

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.

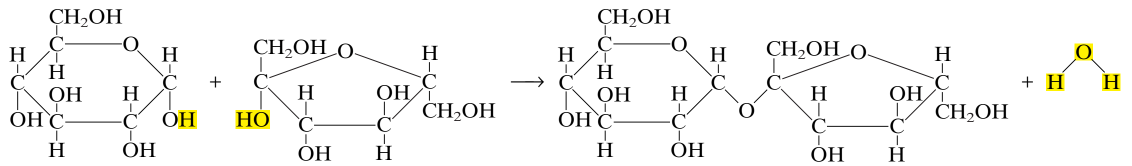
Formation of Disaccharides and Polysaccharides

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



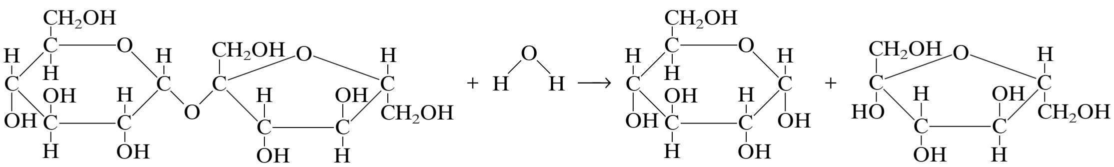
glucose **fructose** **sucrose** **water**

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



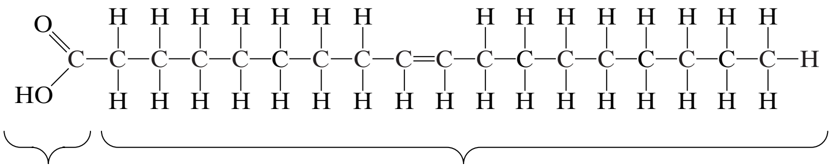
sucrose **water** **glucose** **fructose**

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

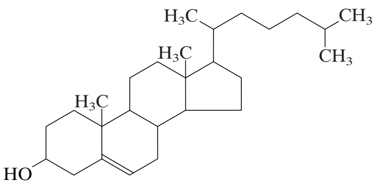
lipid
a type of biochemical that does not dissolve in water, including fats and steroids; lipids store energy and make up cell membranes

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.



hydrophilic region **hydrophobic region**

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



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.

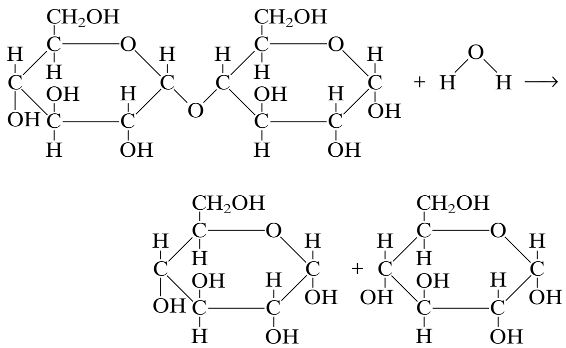
1 Section Review

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

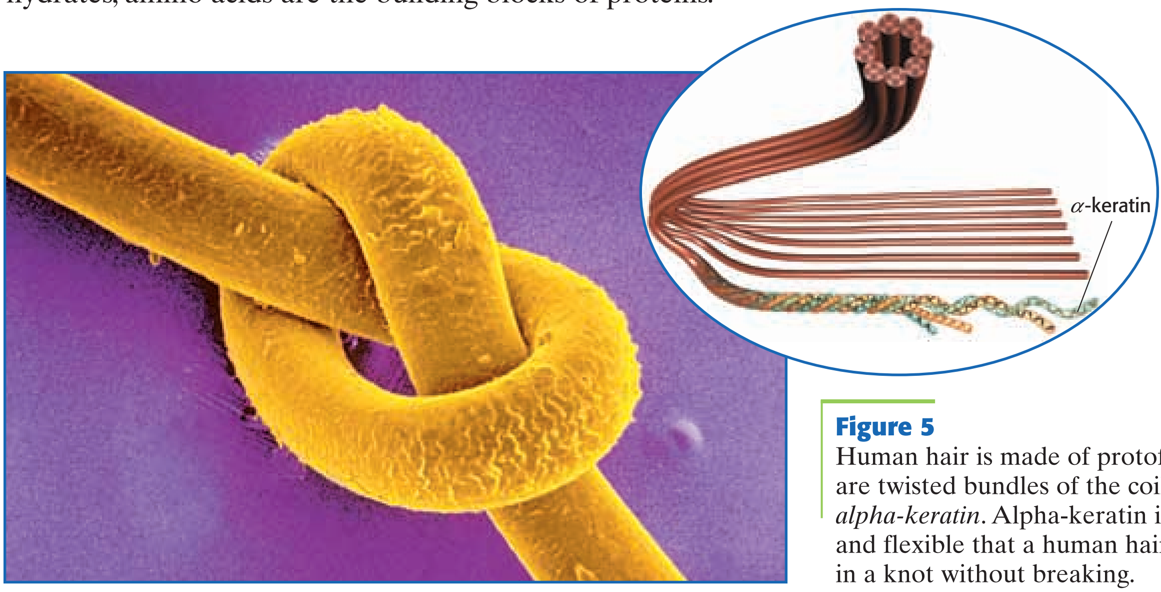
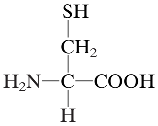
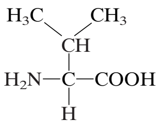
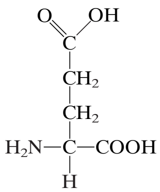
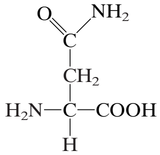
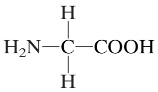
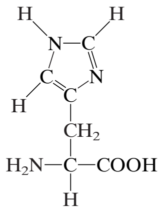


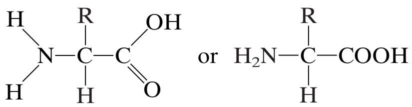
Figure 5
Human hair is made of protofibrils, which are twisted bundles of the coiled protein *alpha-keratin*. Alpha-keratin is so strong and flexible that a human hair can be tied in a knot without breaking.

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

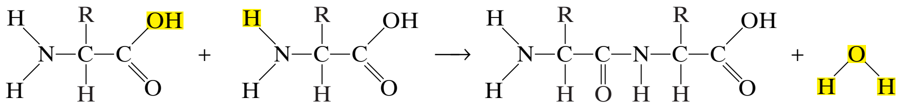
Amino-Acid Structure and Protein Synthesis

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*.

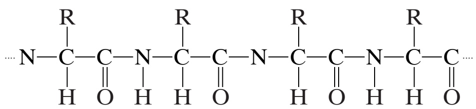


A side chain is a chemical group that differs from one amino acid to another. **Table 2** shows the detailed structure of six of these amino acids.

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.



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.

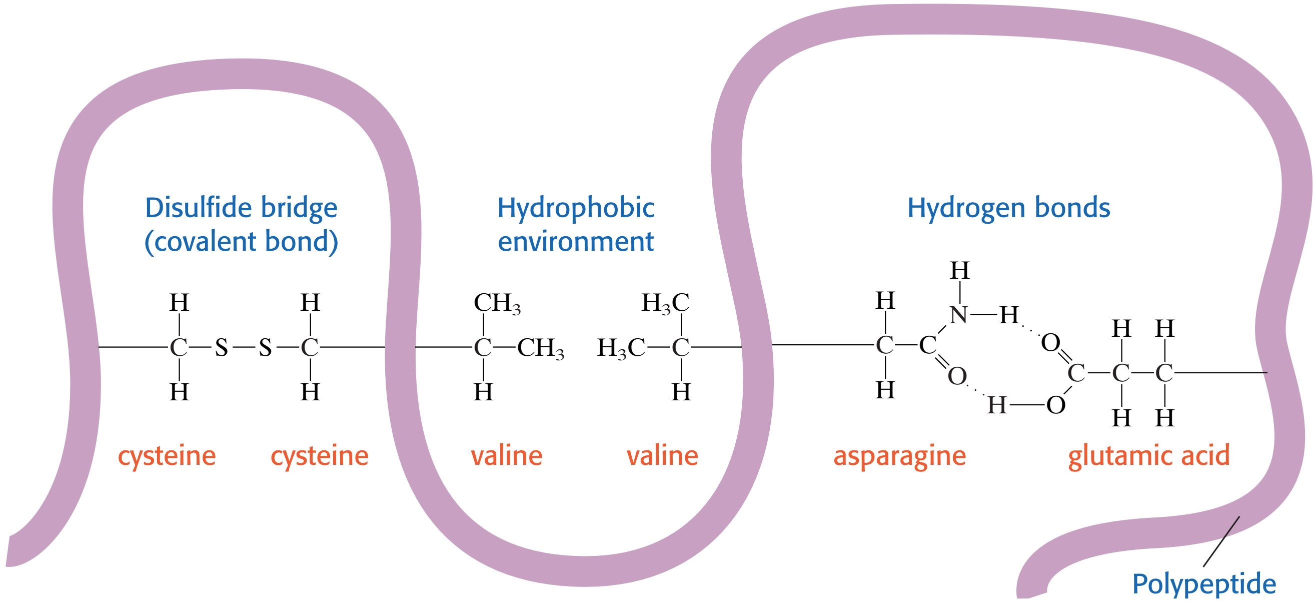
Also, weaker interactions can affect how segments of proteins interact with one another. You have read about these interactions in earlier chapters. Two are shown in **Figure 6.** One of these weak interactions is between the nonpolar hydrocarbon side chains present on many amino acids. These groups 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.**

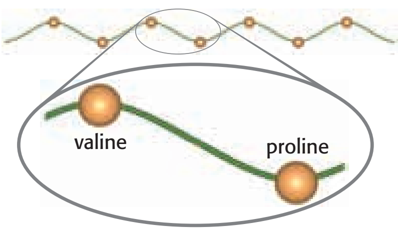
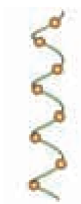
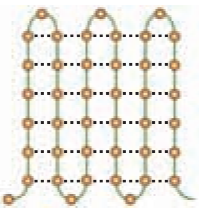
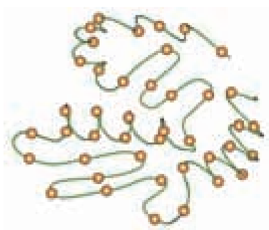
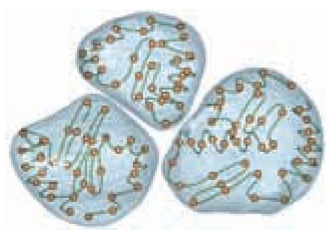
The amino-acid sequence of the polypeptide chain is said to be the *primary structure* of a protein. Thus, the primary structure of a protein is simply the order in which the amino acids bonded together.

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		

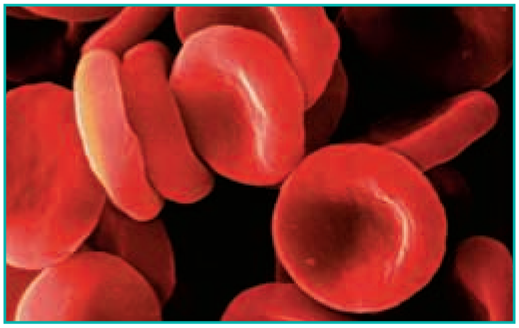
Amino-Acid Substitution Can Affect Shape

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.

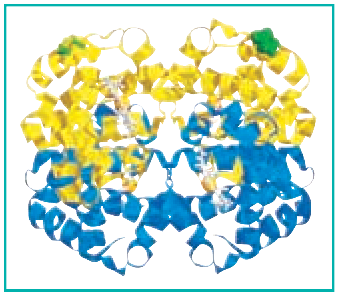
A hereditary blood cell disease called *sickle cell anemia* gives one example of the importance of amino-acid sequence. As the blood circulates, hemoglobin proteins in red blood cells pick up oxygen in the lungs and deliver it to all regions of the body. Normal red blood cells have the dimpled disk shape 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.

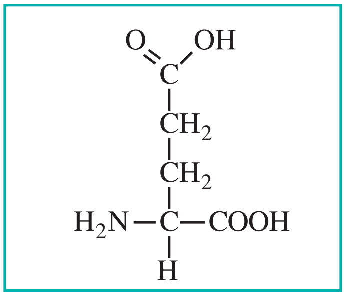
Figure 7



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

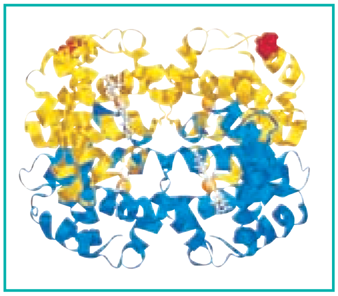


b Hemoglobin consists of four polypeptide chains; a fragment of one chain is shown in green.

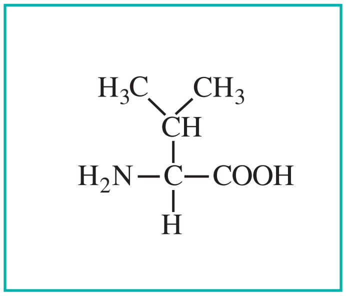


c Each of the chains is a polymer of 141 or 146 amino acid units, such as the glutamic acid monomer shown here.

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.

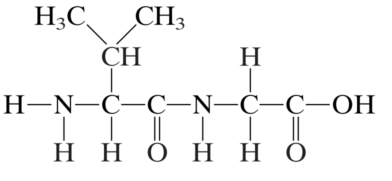
CRITICAL THINKING

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.

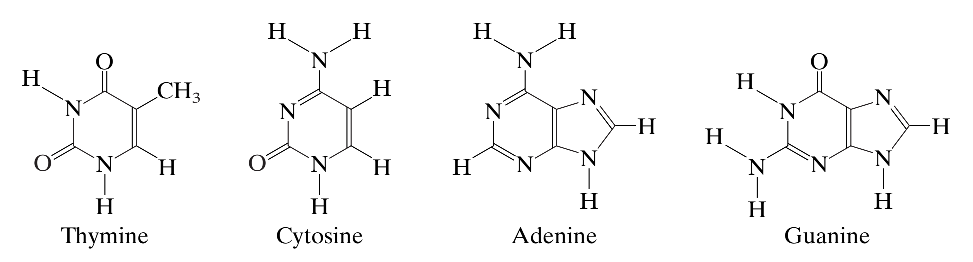


Figure 9
There are four common nitrogenous bases of nucleic acids. Thymine and cytosine bases have a single six-membered ring. Adenine and guanine bases have connected six- and five-membered rings.

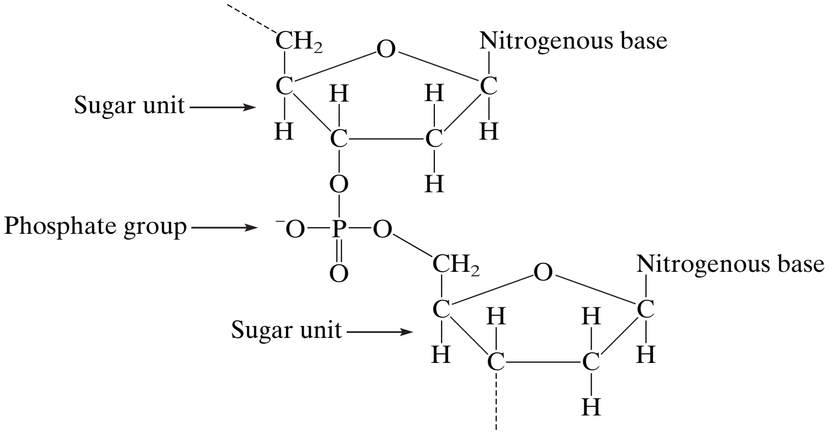
Deoxyribonucleic Acid, or DNA

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.

DNA

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

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.

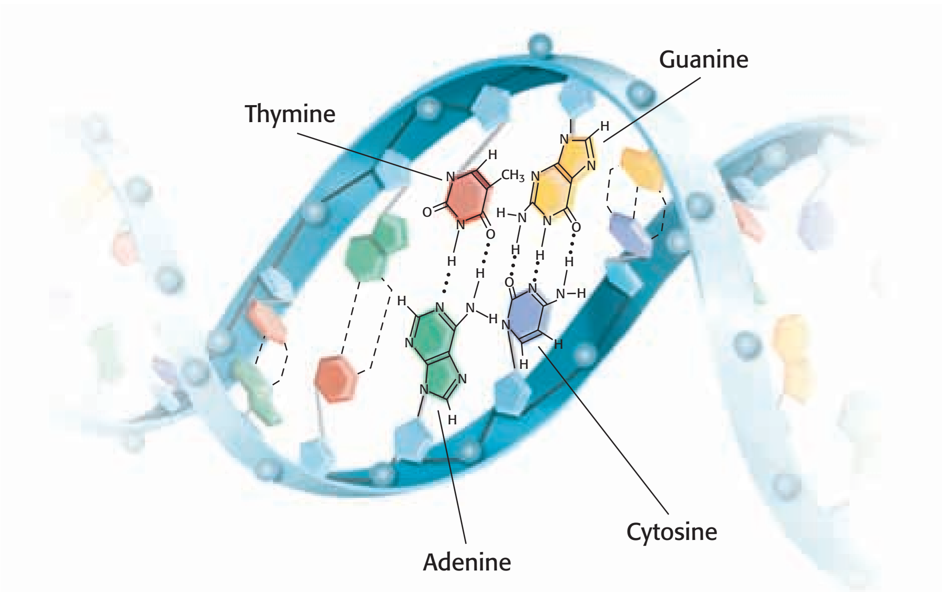
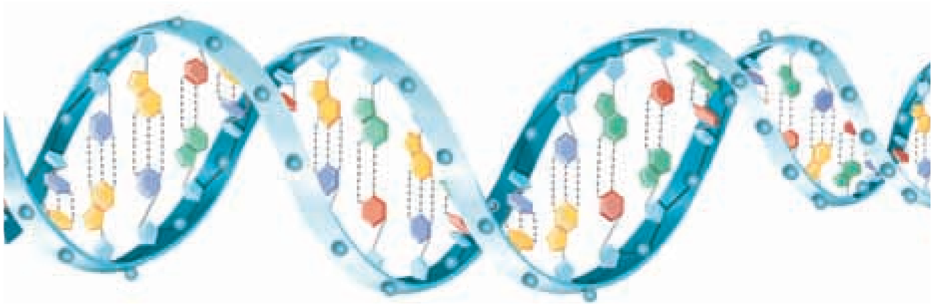


Figure 10 The three-dimensional structure of DNA is made stable by hydrogen bonding between base pairs.



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.

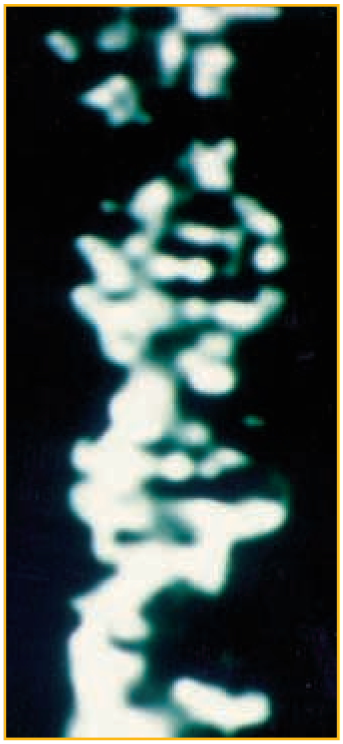


Figure 11
The double helix of DNA can be seen by scanning-tunneling microscopy (above) or shown as a molecular model (above left).

Quick LAB

Isolation of Onion DNA

SAFETY PRECAUTIONS

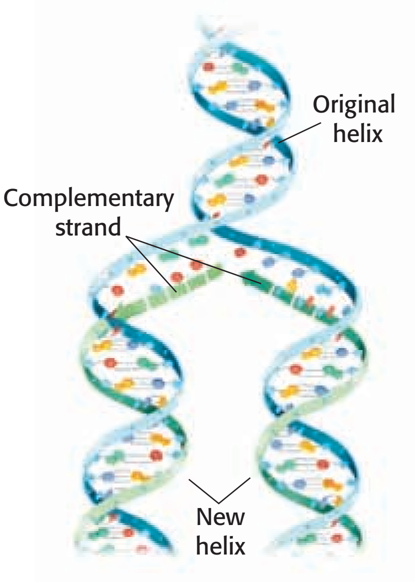
PROCEDURE

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.



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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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

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.

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