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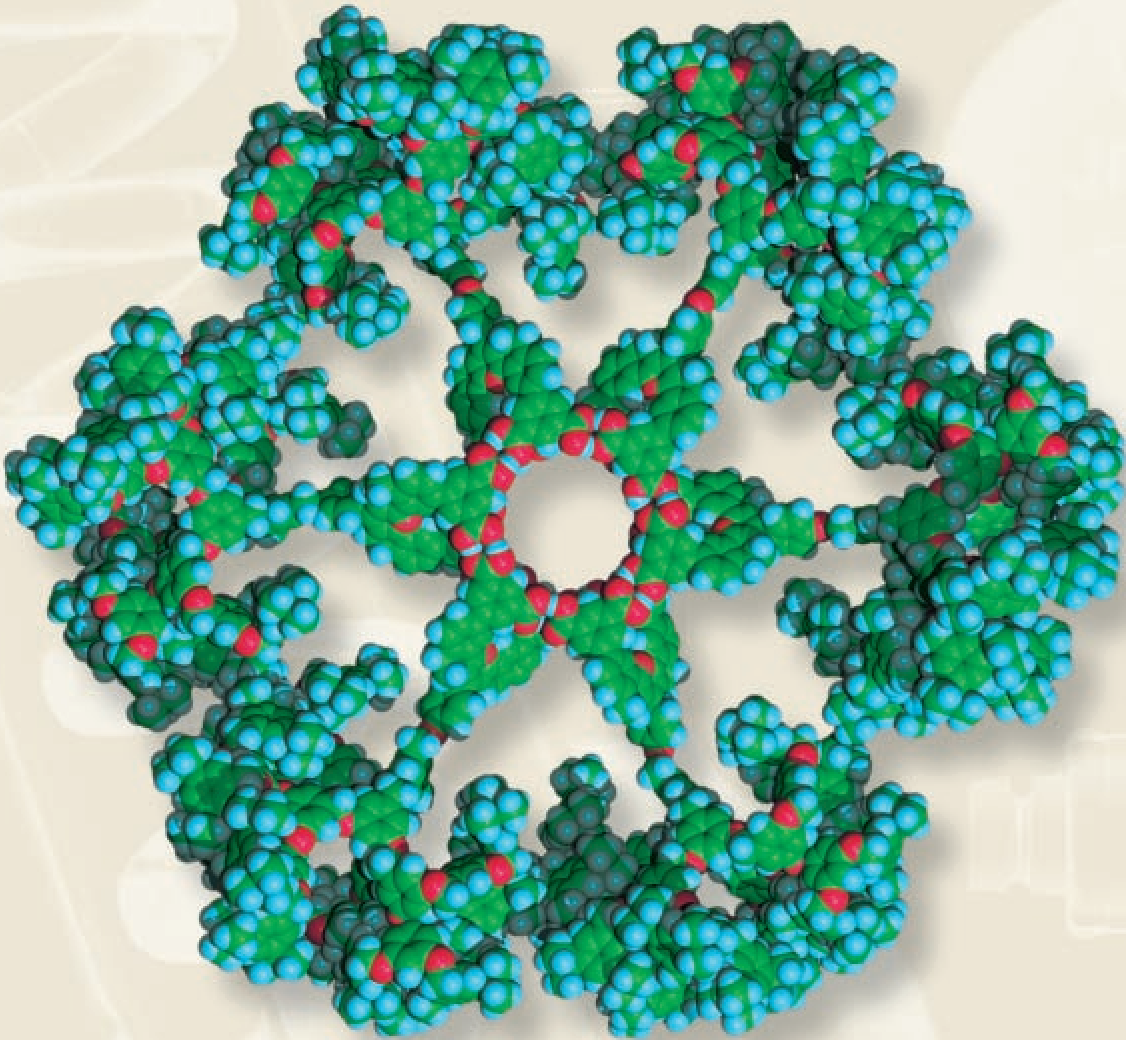
CHAPTER 20

Carbon and Hydrocarbons



Three-dimensional models help us visualize the shape of carbon compounds.

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SECTION 20-1

Abundance and Importance of Carbon

Objectives

- Relate the ability of a carbon atom to form covalent bonds to its atomic structure and hybrid orbitals.
- Identify the different allotropes of carbon and their structural differences.
- Explain how the different structures of carbon allotropes affect their properties.

Carbon is found in nature both as an element and in combined form. Although carbon ranks about 17th in abundance by mass among the elements in Earth's crust, it is exceedingly important because it is found in all living matter. Carbon is present in body tissues and in the foods you eat. It is also found in common fuels, such as coal, petroleum, natural gas, and wood.

Structure and Bonding of Carbon

Carbon, the first member of Group 14, has mostly nonmetallic properties. In its ground state, a carbon atom has an electronic configuration of $1s^22s^22p^2$. The two 1*s* electrons are tightly bound to the nucleus. The two 2*s* electrons and the two 2*p* electrons are the valence electrons. Carbon atoms show a very strong tendency to share electrons and form covalent bonds.

As was covered in Chapter 6, hybridization can be used to explain the bonding and geometry of most carbon compounds. Carbon atoms that form four single bonds have four sp^3 orbitals. These orbitals are directed toward the four corners of a regular tetrahedron, as shown in Figure 20-1. This results in the tetrahedral shape of methane, CH_4, and the zigzag pattern of molecules with multiple single-bonded carbon atoms, such as C_4H_{10}.

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Module 4: Chemical Bonding

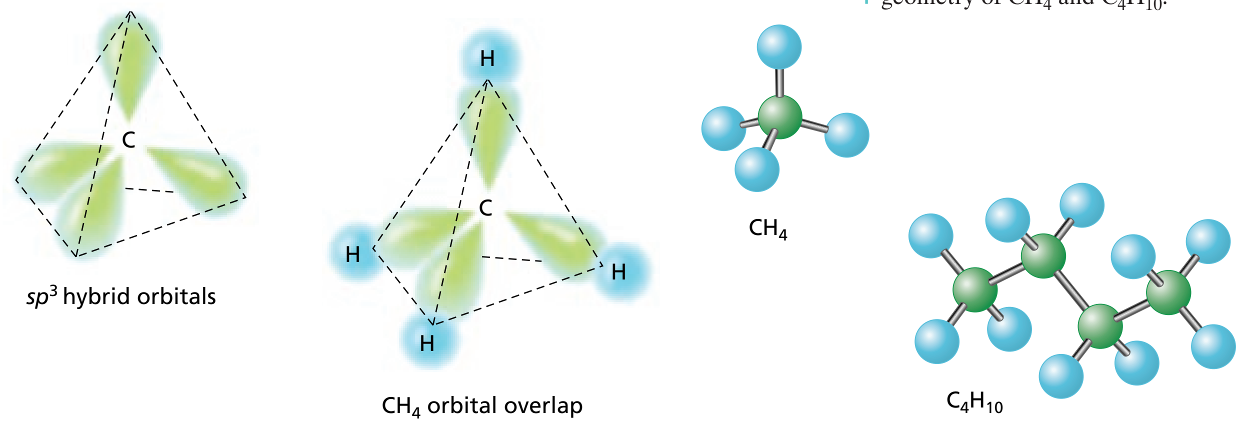

FIGURE 20-1 The orbital models show how the orientation of sp^3 hybrid orbitals relates to the geometry of CH_4 and C_4H_{10}.

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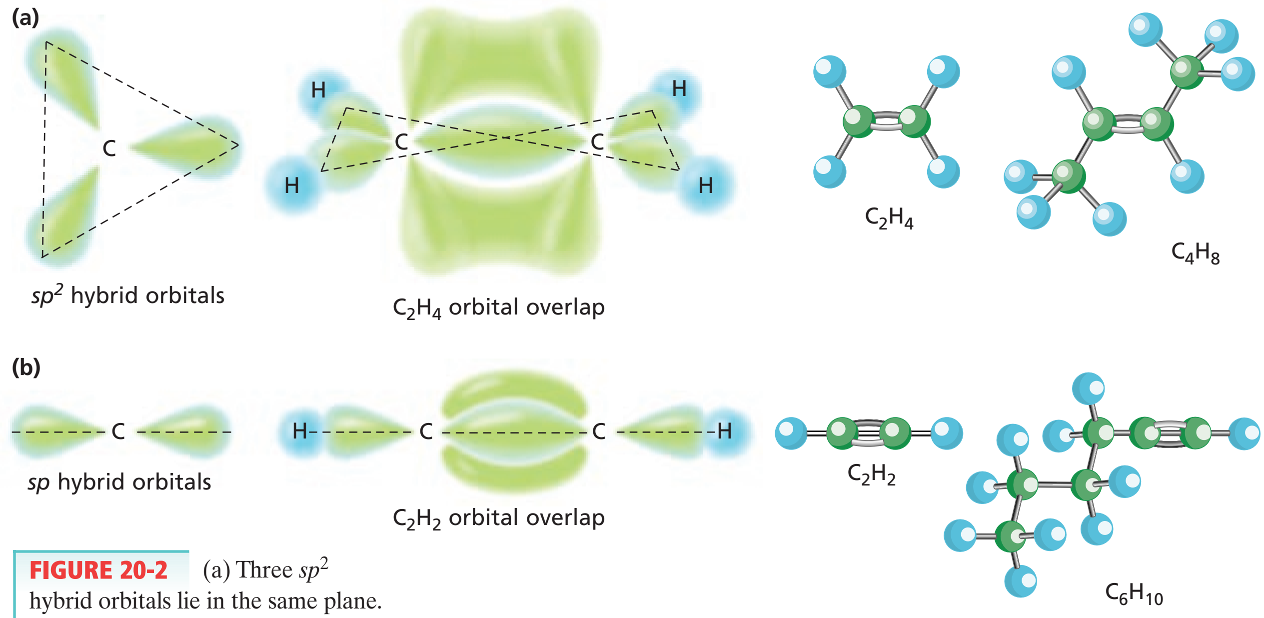

FIGURE 20-2 (a) Three sp^2 hybrid orbitals lie in the same plane. The C_2H_4 orbital overlap model shows the orientation of sp^2 hybrid orbitals in molecules that contain a double bond, such as C_2H_4 and C_4H_8. (b) The C_2H_2 orbital overlap model shows the orientation of *sp* hybrid orbitals in molecules that contain a triple bond, such as C_2H_2 and C_6H_{10}.

Carbon atoms form double bonds through sp^2 hybridization, as shown in Figure 20-2(a). When carbon atoms form double bonds, the sp^2 hybrid orbitals of both carbon atoms lie in the same plane, as shown in the orbital overlap model of ethene, C_2H_4. Because the hydrogen atoms of C_2H_4 also bond with carbon sp^2 orbitals, all six atoms lie in the same plane. The three-dimensional models of C_2H_4 and C_4H_8 show the geometry of molecules containing carbon-carbon double bonds.

Carbon triple bonds are linear due to the linear arrangement of two *sp* hybrid orbitals, as shown in Figure 20-2(b). This can be seen in the orbital overlap model for ethyne, C_2H_2. The three-dimensional models of C_2H_2 and C_6H_{10} show the geometry of molecules containing carbon-carbon triple bonds.

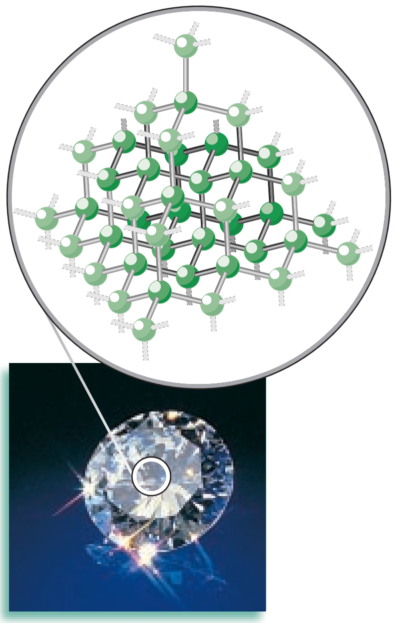

FIGURE 20-3 In diamond, the carbon atoms are densely packed because each carbon atom is bonded to four tetrahedrally oriented carbon atoms.

Allotropes of Carbon

Carbon occurs in several solid allotropic forms that have dramatically different properties. **Diamond** *is a colorless, crystalline, solid form of carbon.* **Graphite** *is a soft, black, crystalline form of carbon that is a fair conductor of electricity.* **Fullerenes** *are dark-colored solids made of spherically networked carbon-atom cages.*

Diamond

Diamond is the hardest material known. It is the most dense form of carbon—about 3.5 times more dense than water. It also has an extremely high melting point (greater than 3500°C). These properties of diamond can be explained by its structure. The model in Figure 20-3 shows carbon atoms in diamond bonded covalently in a network fashion. Each

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carbon atom is tetrahedrally oriented to its four nearest neighbors. The distance between the carbon-atom nuclei has been measured to be 154 pm. Because of diamond's extreme hardness and high melting point, its major industrial uses are for cutting, drilling, and grinding. Diamonds used in industry are not of gem quality.

Another property of diamond is its ability to conduct heat. A diamond crystal conducts heat more than five times more readily than silver or copper, which are the best metallic conductors. In diamond, heat is conducted by the transfer of energy of vibration from one carbon atom to the next. In a diamond crystal, this process is very efficient because the carbon atoms have a small mass. The forces holding the atoms together are strong and can easily transfer vibratory motion among the atoms. However, unlike metals, diamond does not conduct electricity. Because all the valence electrons are used in forming localized covalent bonds, none of the electrons can migrate.

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TOPIC: Diamond/graphite
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Graphite

Graphite is nearly as remarkable for its softness as diamond is for its hardness. It feels greasy and crumbles easily, characteristics that are readily explained by its structure. The carbon atoms in graphite are arranged in layers that form thin hexagonal plates, as shown by the model in Figure 20-4.

The distance between the nuclei of adjacent carbon atoms within a layer has been measured to be 142 pm. This distance is less than the distance between adjacent carbon atom nuclei in diamond. However, the distance between the nuclei of atoms in adjacent layers measures 335 pm. Because the average distance between carbon atoms in graphite is greater than the average distance in diamond, graphite has a lower density.

The layers of carbon atoms in graphite are too far apart to be held together by covalent bonds. Only weak London dispersion forces hold the layers together. Because of the weak attraction, the layers can slide across one another. This property allows graphite to be used as a lubricant and in pencil "lead."

Within each layer, each carbon atom is bonded to only three other carbon atoms. These bonds are examples of resonance hybrid bonds, which were discussed in Chapter 6. The bonding electrons of resonance hybrid bonds can be thought of as delocalized. **Delocalized electrons** *are electrons shared by more than two atoms.*

Graphite is a fairly good conductor of electricity, even though it is a nonmetal, because the delocalized electrons move freely within each layer. Like diamond, graphite has a high melting point (3652°C). This is because the structure created by delocalized electrons results in a strongly bonded covalent network. Another use of graphite is in graphite fibers. Graphite fibers are stronger and stiffer than steel, but less dense. The strength of the bonds within a layer makes graphite difficult to pull apart in the direction parallel to the surface of the layers. The strength and light weight of graphite fiber have led to its use in products such as sporting goods and aircraft.

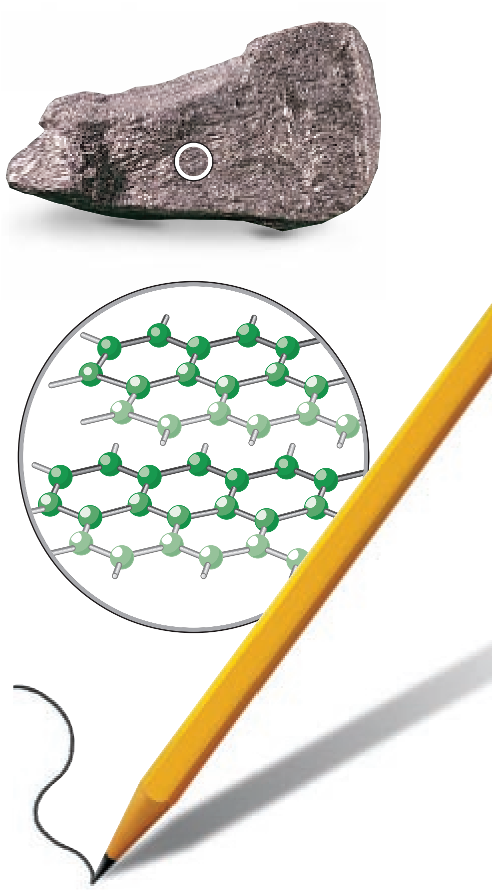

FIGURE 20-4 Notice the space between layers in the ball-and-stick model of graphite. Graphite pencils mark on paper because adjacent layers can slide past each other.

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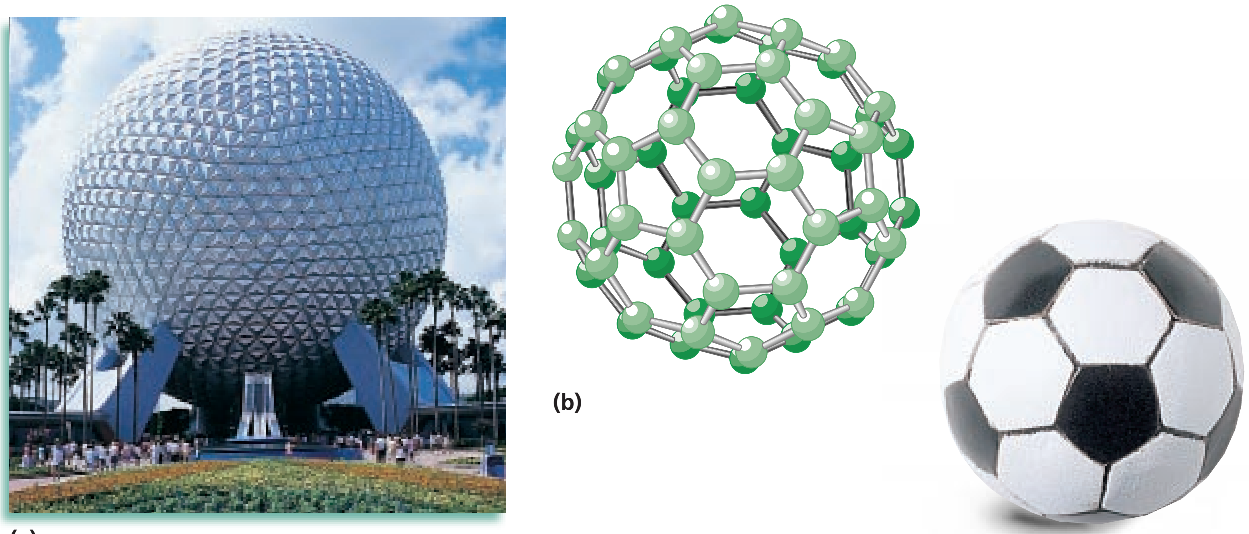

(a) (b) (c)

FIGURE 20-5 (a) Buckminsterfullerene was named after Buckminster Fuller, who invented geodesic domes like the one shown here. (b) The structure of buckminsterfullerene resembles the pattern of a soccer ball (c).

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Fullerenes

In the mid-1980s a new allotropic form of carbon was discovered. The 1996 Nobel Prize in chemistry was awarded to Richard E. Smalley, Robert F. Curl, and Harold W. Kroto, leaders of the research teams that discovered this class of compounds, fullerenes.

Fullerenes are part of the soot that forms when carbon-containing materials are burned with limited oxygen. Their structures consist of near-spherical cages of carbon atoms. The most stable of these is C_{60}, shown in Figure 20-5. C_{60} is formed by 60 carbon atoms arranged in interconnected five- and six-membered rings.

Because of its structural resemblance to geodesic domes, Richard Smalley and his co-workers at Rice University named C_{60} "buckminsterfullerene" in honor of the geodesic-dome architect, Buckminster Fuller. The whole family of carbon-atom cages, which have a wide range in the number of carbon atoms, are therefore called fullerenes. Because the structure of C_{60} also resembles the design of a soccer ball, C_{60} is also known less formally as buckyball. Scientists are currently trying to find practical uses for these substances.

SECTION REVIEW

1. What makes carbon an important element in the study of chemistry?
2. What type of hybrid orbital is found in carbon double bonds? In carbon triple bonds?
3. How does the structure of graphite relate to its properties and uses?
4. a. How are the structures of different fullerenes similar?
   b. How do they differ?

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Organic Compounds

SECTION 20-2

Objectives

- Explain how the structure and bonding of carbon lead to the diversity and number of organic compounds.
- Explain the importance and limitations of molecular and structural formulas.
- Compare structural and geometric isomers.

All organic compounds contain carbon atoms. However, not all carbon-containing compounds are classified as organic. There are a few exceptions, such as Na_2CO_3, CO, and CO_2, that are considered inorganic. **Organic compounds,** then, can be defined as *covalently bonded compounds containing carbon, excluding carbonates and oxides*. Figure 20-6 shows a few familiar items that contain organic compounds.

Carbon Bonding and the Diversity of Organic Compounds

The diversity of organic compounds results from the uniqueness of carbon's structure and bonding. Carbon's electronic structure allows it to bind to itself to form chains and rings, to bind covalently to other elements, and to bind to itself and other elements in different arrangements.

FIGURE 20-6 Aspirin, polyethylene in plastic bags, citric acid in fruit, and amino acids in animals are all examples of organic compounds.

FIGURE 20-7 Compare the shape of a fatty acid found in cream with that of fructose, found in fruit. In the fatty acid, the carbon atoms are in chains. In fructose, carbon atoms form a ring.

Carbon-Carbon Bonding

Carbon atoms are unique in their ability to form long chains and rings of covalently bonded atoms. This type of bonding is known as **catenation,** *the covalent binding of an element to itself to form chains or rings*. This produces a multitude of chain, branched-chain, and ring structures. In addition, carbon atoms in these structures can be linked by single, double, or triple covalent bonds. Examples of molecules containing carbon-atom rings and chains are shown in Figure 20-7.

Carbon Bonding to Other Elements

Besides binding to other carbon atoms, carbon atoms bind readily to elements with similar electronegativities. Organic compounds consist of carbon and these other elements. **Hydrocarbons** *are composed of only carbon and hydrogen; they are the simplest organic compounds.* Other organic compounds contain hydrocarbon backbones to which other elements, primarily O, N, S, and the halogens, are attached. Figure 20-8 shows a molecule in which carbon atoms are bound to other elements.

Arrangement of Atoms

The bonding capabilities of carbon also allow for different arrangements of atoms. This means that some compounds may contain the same atoms but have different properties because the atoms are arranged differently. For example, the molecular formula C_2H_6O represents both ethanol and dimethyl ether. *Compounds that have the same molecular formula but different structures are called* **isomers.** As the number of carbon atoms in a molecular formula increases, the number of possible isomers increases rapidly. For example, there are 18 isomers with the molecular formula C_8H_{18}, 35 with the molecular formula C_9H_{20}, and 75 with the molecular formula $C_{10}H_{22}$. For the molecular formula of just 40 carbon atoms and 82 hydrogen atoms, $C_{40}H_{82}$, there are theoretically 69 491 178 805 831 isomers. To distinguish one from another, more information than just the molecular formula is needed.

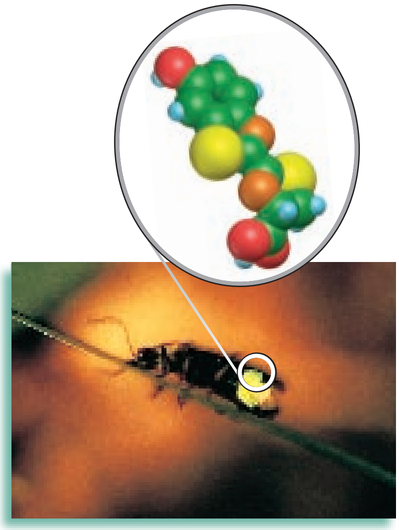
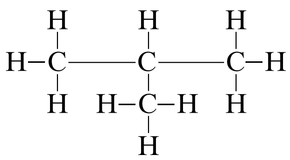


FIGURE 20-8 In firefly luciferin, carbon atoms bind to hydrogen, oxygen, nitrogen, and sulfur. Luciferin is responsible for the light emitted from the tail of a firefly.

Structural Formulas

For this reason, organic chemists use structural formulas to represent organic compounds. *A* **structural formula** *indicates the number and types of atoms present in a molecule and also shows the bonding arrangement of the atoms.* For example, one possible structural formula for an isomer of C_4H_{10} is the following.



Structural formulas are sometimes condensed to make them easier to read. In one type of condensed structure, hydrogen single covalent bonds are not shown. The hydrogen atoms are understood to bind to the

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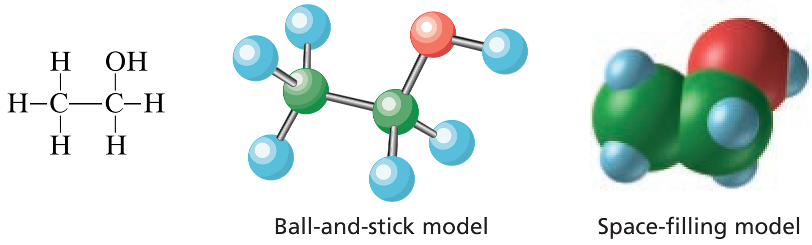
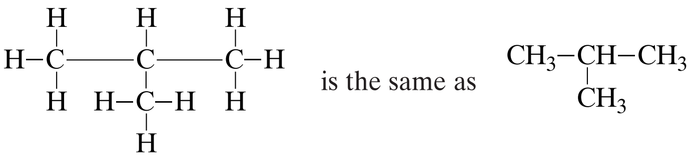


FIGURE 20-9 The structure of ethanol can be represented in different ways. Ball-and-stick and space-filling models represent the three-dimensional shape of the molecule.

atom they are written beside. The following structural and condensed structural formulas represent the same molecule.



Remember that the structural formula does not accurately show the three-dimensional shape of the molecule. Three-dimensional shape is depicted with drawings or models, as shown for ethanol in Figure 20-9.

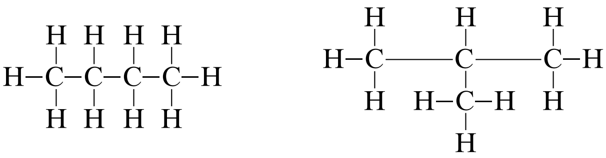
As you continue your study, you may find that the use of dashes can be eliminated by writing in a horizontal row the symbols and subscripts for the groups of carbon and hydrogen atoms that appear in a molecule. For example, ethane is written as CH_3CH_3 and propane as $CH_3CH_2CH_3$.

Isomers

You have learned that isomers are compounds that have the same molecular formula but different structural formulas. Isomers can be further classified by structure and geometry.

Structural Isomers

Structural isomers *are isomers in which the atoms are bonded together in different orders.* For example, the atoms of the molecular formula C_4H_{10} can be arranged in two different ways.



butane methylpropane

Notice that the formula for butane shows a continuous chain of four carbon atoms. The chain may be bent or twisted, but it is continuous. The formula of methylpropane shows a continuous chain of three carbon atoms, with the fourth carbon atom attached to the second carbon atom of the chain.

TABLE 20-1 Physical Properties of the Structural Isomers Butane and Methylpropane

	Melting point (°C)	Boiling point (°C)	Density at 20°C (g/mL)
butane	–138.4	–0.5	0.5788
methylpropane	–159.4	–11.633	0.549

Structural isomers can have different physical or chemical properties. For example, butane and methylpropane have different melting points, boiling points, and densities, as shown in Table 20-1.

Geometric Isomers

Geometric isomers *are isomers in which the order of atom bonding is the same but the arrangement of atoms in space is different.* Consider the molecule 1,2-dichloroethene, which contains a double bond. The double bond prevents free rotation and holds groups to either side of the molecule. This means there can be two different 1,2-dichloroethene geometric isomers as shown below.

cis *trans*

Because the two chlorine atoms are on the same side of the molecule in the first structure, it is called *cis*. In the second molecule, the two chlorine atoms are on opposite sides of the molecule, and so the molecule is called *trans*. Notice that in both molecules the bonding order of the atoms is the same: each carbon atom in the double bond is also bound to one chlorine atom and one hydrogen atom.

Now consider the molecule 1,2-dichloroethane. Atoms attached to the carbon atoms can rotate freely around the single carbon-carbon bond, as shown in Figure 20-10. There are no geometric isomers of 1,2-dichloroethane. *In order for geometric isomers to exist, there must be a rigid structure in the molecule to prevent free rotation around a bond.*

Now consider two apparent structures for another molecule with a double bond, chloroethene.

Although these structures may appear different at first glance, they are actually the same. In *both* structures, two hydrogen atoms are on one side of the molecule, and one chlorine atom and one hydrogen atom are on the other. *A molecule can have a geometric isomer only if two carbon atoms in a rigid structure each have two different groups attached.*

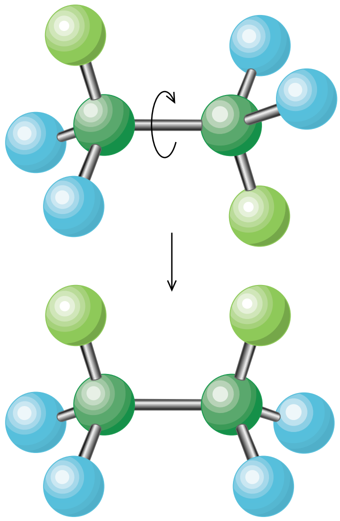
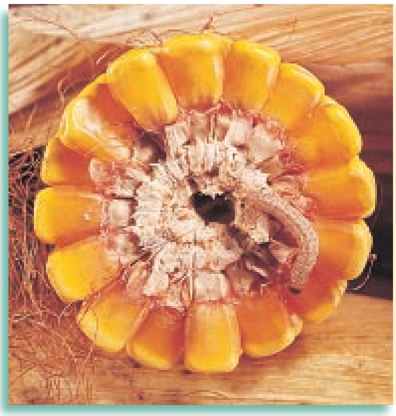
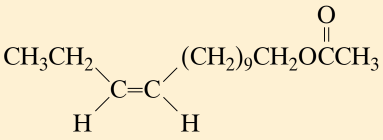
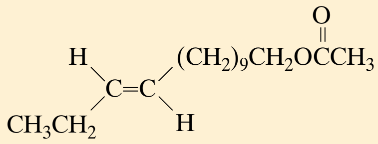


FIGURE 20-10 Unlike double bonds, single bonds allow free rotation within a molecule. Groups attached to the carbon atoms are not held to one side of the molecule, so there are no geometric isomers.





cis-11-tetradecenyl acetate

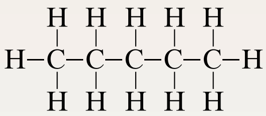
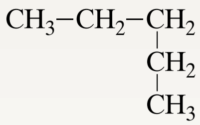


trans-11-tetradecenyl acetate

FIGURE 20-11 Males of the Iowa strain of the European corn borer respond most strongly to mixtures of the female sex attractant pheromone that are 96% *cis* isomer. But males of the New York strain respond most strongly to mixtures containing 97% *trans* isomer.

Like structural isomers, geometric isomers differ in physical and chemical properties. Some geometric isomers are known to differ in physiological behavior as well. For example, insects can communicate by chemicals called pheromones and may distinguish between the geometric isomers of pheromones. One geometric isomer of a pheromone may be physiologically active, while the other will be only slightly active or not at all. The European corn borer, shown in Figure 20-11, distinguishes between isomers of its sex-attractant pheromone. Another example of differences between geometric isomers is found in fatty acids. Natural unsaturated fatty acids are primarily *cis*-fatty acids. Hydrogenation is used to convert vegetable oil, which contains unsaturated fatty acids, into a solid fat, such as margarine or vegetable shortening. During hydrogenation *trans*-fatty acids are produced. Research has shown that there may be health risks associated with diets high in *trans*-fatty acids.

SECTION REVIEW

1. What are three characteristics of carbon that contribute to the diversity of organic compounds?
2. Define the term *isomer,* and distinguish between structural and geometric isomers.
3. Which of the following types of molecular representations can be used to show differences between isomers? Explain why each can or cannot.
   a. molecular formula
   b. structural formula
   c. three-dimensional drawing or model
4. Write the formula for methylpropane (shown at the right on page 631) in a horizontal row.
5. Which of the following can represent the same molecule?
   a. 
   b. $CH_3-CH_2-CH_2-CH_3$
   c. 
   d. C_5H_{12}

SECTION 20-3

Saturated Hydrocarbons

Objectives

- Recognize the important structural feature of saturated hydrocarbons, alkanes.
- Be able to name and write structural formulas for alkanes.
- Explain how structures of alkanes relate to their properties and how those properties affect the uses of specific alkanes.

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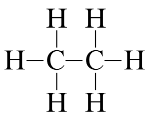
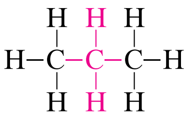
Hydrocarbons are grouped mainly by the type of bonding between carbon atoms. **Saturated hydrocarbons** *are hydrocarbons in which each carbon atom in the molecule forms four single covalent bonds with other atoms.*

Alkanes

Hydrocarbons that contain only single bonds are **alkanes.** In Table 20-2, the molecular formulas, structural formulas, and space-filling models are given for alkanes with one to four carbon atoms. If you examine the molecular formulas for successive alkanes in Table 20-2, you will see a clear pattern. Each member of the series differs from the preceding one by one carbon atom and two hydrogen atoms. For example, propane, C_3H_8, differs from ethane, C_2H_6, by one carbon atom and two hydrogen atoms, a $-CH_2-$ group.


ethane


propane

Compounds that differ in this fashion belong to a homologous series. A **homologous series** *is one in which adjacent members differ by a constant unit.* It is not necessary to remember the molecular formulas for all members of a homologous series. Instead, a general molecular formula can be used to determine the formulas. Look at the molecular formulas for ethane and propane, C_2H_6 and C_3H_8. They both fit the formula C_nH_{2n+2}. For ethane, $n = 2$, so there are two carbon atoms and $(2 \times 2) + 2 = 6$ hydrogen atoms. For propane, $n = 3$, so there are three carbon atoms and $(2 \times 3) + 2 = 8$ hydrogen atoms. Now consider a molecule for which we do not know the molecular formula. Suppose a member of this series has 30 carbon atoms in its molecules. Then $n = 30$, and there are $(2 \times 30) + 2 = 62$ hydrogen atoms. The formula is $C_{30}H_{62}$.

Notice that for alkanes with three or fewer carbon atoms, only one molecular structure is possible. However, in alkanes with more than three carbon atoms, the chains can be straight or branched. Thus,

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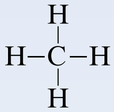
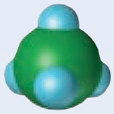
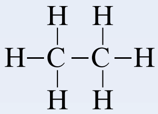
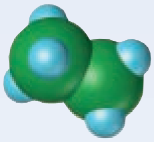
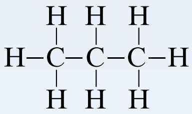
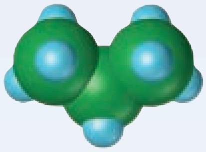
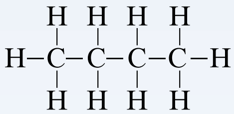
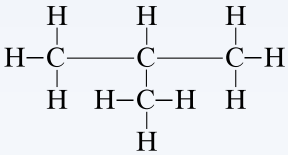
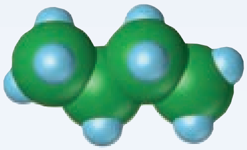
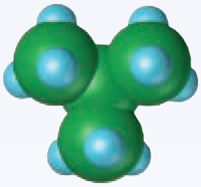
TABLE 20-2 *Alkanes with One to Four Carbon Atoms*

Molecular formulas	Structural formulas	Space-filling models
CH_4	 methane	
C_2H_6	 ethane	
C_3H_8	 propane	
C_4H_{10}	 butane  methylpropane	 

alkanes with four or more carbon atoms have structural isomers. There are two possible structural isomers for alkanes with four carbon atoms, butane and methylpropane.

Cycloalkanes

Cycloalkanes *are alkanes in which the carbon atoms are arranged in a ring, or cyclic, structure.* The structural formulas for cycloalkanes are often drawn in a simplified form. It is understood that there is a carbon

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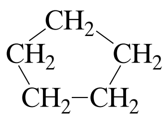
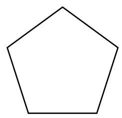
atom at each corner and enough hydrogen atoms to complete the four bonds to each carbon atom.

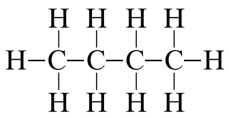


or

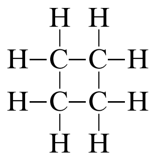


cyclopentane | cyclopentane

Because there are no free ends where a carbon atom is attached to three hydrogen atoms, there are two fewer hydrogen atoms in cycloalkanes than in noncyclic alkanes.



butane
C_4H_{10}



cyclobutane
C_4H_8

The general structure for cycloalkanes, C_nH_{2n}, shows that they have $2 \times n$ hydrogen atoms. This is two fewer hydrogen atoms than noncyclic alkanes, C_nH_{2n+2}, which have $(2 \times n) + 2$ hydrogen atoms.

Systematic Names of Alkanes

Historically, the names of many organic compounds were derived from the sources in which they were found. As more organic compounds were discovered, a systematic naming method became necessary. The systematic method used primarily in this book was developed by the International Union of Pure and Applied Chemistry, IUPAC.

The basic part of the systematic name of an organic compound is the name of the longest carbon chain, or parent hydrocarbon, in the molecule. Table 20-3 gives the names of the prefixes for carbon-atom chains up to 10 carbon atoms long. Beginning with *pent-*, the prefixes are Greek or Latin numerical prefixes.

TABLE 20-3 *Carbon-Atom Chain Prefixes*

Number of carbon atoms	Prefix
1	meth-
2	eth-
3	prop-
4	but-
5	pent-
6	hex-
7	hept-
8	oct-
9	non-
10	dec-

Unbranched-Chain Alkane Nomenclature

To name an unbranched alkane, find the prefix in Table 20-3 that corresponds to the number of carbon atoms in the chain of the hydrocarbon. Then add the suffix *-ane* to the prefix. An example is shown below.

$$\overset{1}{CH_3}-\overset{2}{CH_2}-\overset{3}{CH_2}-\overset{4}{CH_2}-\overset{5}{CH_2}-\overset{6}{CH_2}-\overset{7}{CH_3}$$

heptane

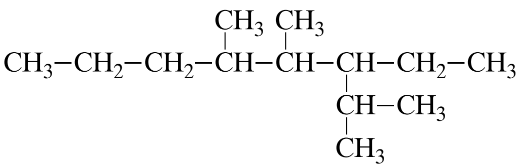
The molecule has a chain seven carbon atoms long, so the prefix *hept-* is added to the suffix *-ane* to form *heptane*.

TABLE 20-4 Some Straight-Chain Alkyl Groups

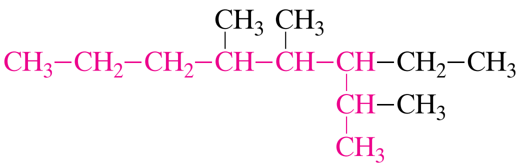
Alkane	Name	Alkyl group	Name
CH_4	methane	$-CH_3$	methyl
CH_3-CH_3	ethane	$-CH_2-CH_3$	ethyl
$CH_3-CH_2-CH_3$	propane	$-CH_2-CH_2-CH_3$	propyl
$CH_3-CH_2-CH_2-CH_3$	butane	$-CH_2-CH_2-CH_2-CH_3$	butyl
$CH_3-CH_2-CH_2-CH_2-CH_3$	pentane	$-CH_2-CH_2-CH_2-CH_2-CH_3$	pentyl

Branched-Chain Alkane Nomenclature

The naming of branched-chain alkanes also follows a systematic method. The hydrocarbon branches of alkanes are alkyl groups. **Alkyl groups** *are groups of atoms that are formed when one hydrogen atom is removed from an alkane molecule*. Alkyl groups are named by replacing the suffix *-ane* of the parent alkane with the suffix *-yl*. Some examples are shown in Table 20-4. Alkyl group names are used when naming branched-chain alkanes. We will only present the method for naming simple branched-chain alkanes with only straight-chain alkyl groups. Consider the following molecule.



To name this molecule, locate the parent hydrocarbon. The parent hydrocarbon is the longest continuous chain that contains the most straight-chain branches. In this molecule, there are two chains that are eight carbon atoms long. The parent hydrocarbon is the chain that contains the most straight-chain branches. Do not be tricked by the way the molecule is drawn. The longest chain may be shown bent.



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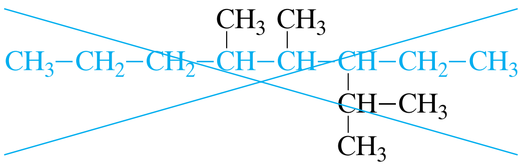

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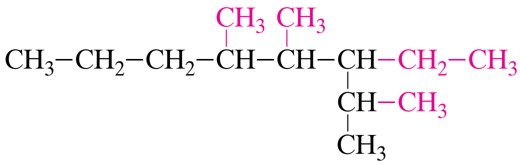
To name the parent hydrocarbon, add the suffix *-ane* to the prefix *oct-* (for a carbon-atom chain with eight carbon atoms) to form *octane.* Now identify and name the alkyl groups.



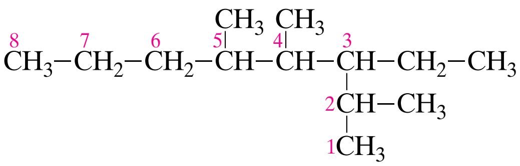
The three $-CH_3$ groups are methyl groups. The $-CH_2-CH_3$ group is an ethyl group. Arrange the names in alphabetical order in front of the name of the parent hydrocarbon.

ethyl methyloctane

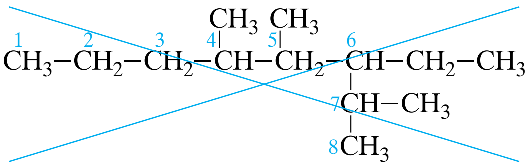
To show that there are three methyl groups present, attach the prefix *tri-* to the name *methyl* to form *trimethyl*.

ethyl **tri**methyloctane

Now we need to show the locations of the alkyl groups on the parent hydrocarbon. Number the octane chain so that the alkyl groups have the lowest numbers possible.



NOT



Place the location numbers of *each* of the alkyl groups in front of its name. Separate the numbers from the names of the alkyl groups with hyphens. The ethyl group is on carbon *3*.

3-ethyl trimethyloctane

Because there are three methyl groups, there will be three numbers, separated by commas, in front of *trimethyl*.

3-ethyl-**2,4,5-**trimethyloctane

The full name is 3-ethyl-2,4,5-trimethyloctane.

The procedure for naming simple branched-chain alkanes can be summarized as follows.

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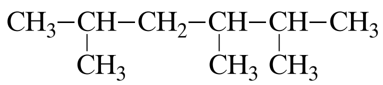
Alkane Nomenclature

1. **Name the parent hydrocarbon.** Find the longest continuous chain of carbon atoms with straight-chain branches. Add the suffix *-ane* to the prefix corresponding to the number of carbon atoms in the chain.
2. **Add the names of the alkyl groups.** Add the names of the alkyl groups in front of the name of the parent hydrocarbon in alphabetical order. When there is more than one branch of the same alkyl group present, attach the appropriate numerical prefix to the name, *di* = 2, *tri* = 3, *tetra* = 4, and so on. Do this after the names have been put in alphabetical order.
3. **Number the carbon atoms in the parent hydrocarbon.** If one or more alkyl groups are present, number the carbon atoms in the continuous chain to give the lowest numbers possible in the name. If there are two equivalent lowest positions with two different alkyl groups, give the lowest number to the alkyl group that comes first in the name. (This will be the alkyl group that is first in alphabetical order, *before* any prefixes are attached.)
4. **Insert position numbers.** Put the position numbers of each alkyl group in front of the name of that alkyl group.
5. **Punctuate the name.** Separate the position numbers from the names with hyphens. If there are more than one number in front of a name, separate the numbers by commas.

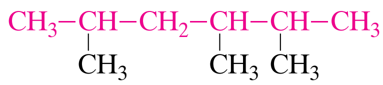
SAMPLE PROBLEM 20-1

Name the following simple branched-chain alkane:



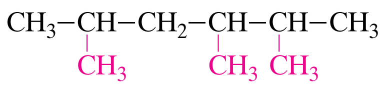
SOLUTION

1. Identify and name the parent hydrocarbon.



Because the longest continuous chain contains six carbon atoms, the parent hydrocarbon is *hexane*.

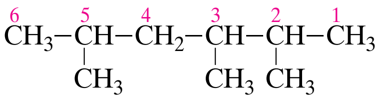
2. Identify and name the alkyl groups attached to the chain.



There is only one type of alkyl group, with one carbon atom. Alkyl groups with one carbon atom are methyl groups. Add the name *methyl* in front of the name of the continuous chain. Add the prefix *tri-* to show that there are three methyl groups present.

trimethylhexane

3. Number the carbon atoms in the continuous chain so that the alkyl groups have the lowest numbers possible.



4. The methyl groups are on the carbon atoms numbered *2*, *3*, and *5*. Put the numbers of the positions of the alkyl groups, separated by commas, in front of the name of the alkyl group. Separate the numbers from the name with a hyphen.

2,3,5-trimethylhexane

The complete name is 2,3,5-trimethylhexane.

SAMPLE PROBLEM 20-2

Draw the condensed structural formula of 3-ethyl-4-methylhexane.

SOLUTION

1. Identify the name of the parent hydrocarbon.

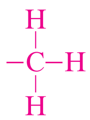
3-ethyl-4-methyl**hexane**

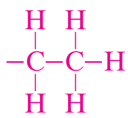
The parent hydrocarbon is hexane, so there are six carbon atoms in the chain. Draw and number the carbon atoms in the chain.

2. Identify the alkyl groups, and determine the number of carbon atoms in the alkyl groups.

3-**ethyl**-4-**methyl**hexane

Methyl groups have one carbon atom and ethyl groups have two carbon atoms.

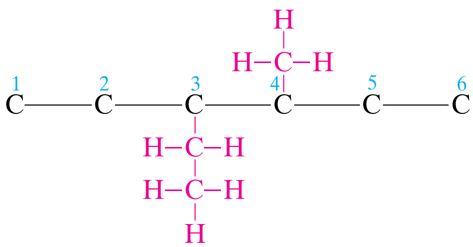




3. Locate the position numbers for the ethyl and methyl groups.

3-ethyl-**4**-methylhexane

Draw the alkyl groups on the parent hydrocarbon in the correct positions.



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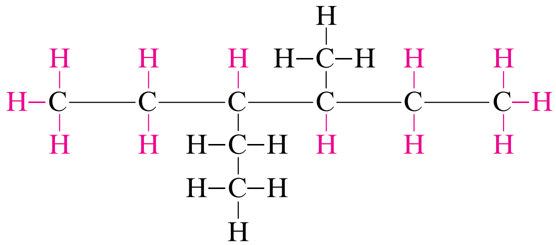
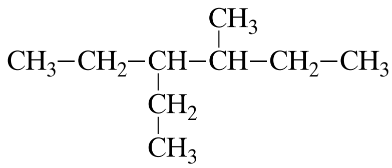
Notice that in this molecule the methyl group and the ethyl group were in equivalent positions from the end of the chain. They are both on third carbons from the end. In such a case, the alkyl group that comes first in the name is given the lower number.

4. Add the correct number of hydrogen atoms so that each carbon atom has four single bonds. This is the complete, uncondensed, structural formula.

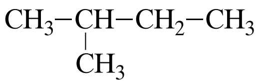


5. To draw the condensed structural formula, show only the bonds between carbon atoms.



PRACTICE

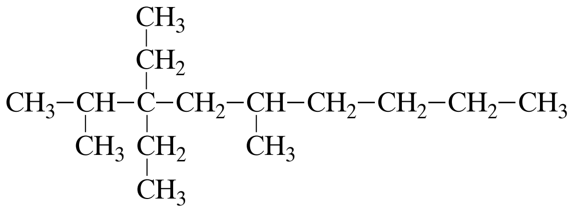
1. Name the following molecule:



Answer
methylbutane

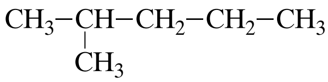
2. Draw the condensed structural formula for 3,3-diethyl-2,5-dimethylnonane.

Answer

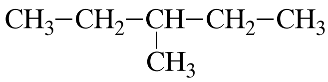


3. Draw the condensed structural formulas for the two structural isomers of methylpentane and name the isomers.

Answer



2-methylpentane



3-methylpentane

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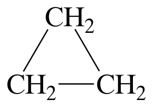
Cycloalkane Nomenclature

When naming simple cycloalkanes, the cycloalkane is the parent hydrocarbon. Cycloalkanes are named by adding the prefix *cyclo-* to the name of the straight-chain alkane with the same number of hydrocarbons.

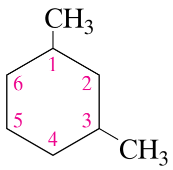
$$CH_3{-}CH_2{-}CH_3$$

propane



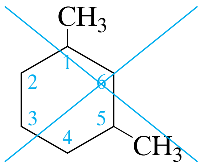
cyclopropane

When there is only one alkyl group attached to the ring, no position number is necessary. When there is more than one alkyl group attached to the ring, the carbon atoms in the ring are numbered to give the lowest numbers possible to the alkyl groups. This means that one of the alkyl groups will always be in position 1.



1,3-dimethylcyclohexane

NOT



~~1,5-dimethylcyclohexane~~

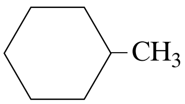
The rules for naming cycloalkanes can be summarized as follows.

Cycloalkane Nomenclature

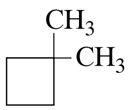
Use the rules for alkane nomenclature on page 639, with the following exceptions.

1. **Name the parent hydrocarbon.** Count the number of carbon atoms in the ring. Add the prefix *cyclo-* to the name of the corresponding straight-chain alkane.
2. **Add the names of the alkyl groups.**
3. **Number the carbon atoms in the parent hydrocarbon.** If there are two or more alkyl groups attached to the ring, number the carbon atoms in the ring. Assign position number one to the alkyl group that comes first in alphabetical order. Then, number in the direction that gives the next lowest number.
4. **Insert position numbers.**
5. **Punctuate the name.**

Two examples of correctly named cycloalkanes are given below.



methylcyclohexane



1,1-dimethylcyclobutane

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TABLE 20-5 Properties of Straight-Chain Alkanes

Molecular formula	IUPAC name	Boiling point (°C)	State at room temperature
CH_4	methane	–164	gas
C_2H_6	ethane	–88.6	
C_3H_8	propane	–42.1	
C_4H_{10}	butane	–0.5	
C_5H_{12}	pentane	36.1	liquid
C_8H_{18}	octane	125.7	
$C_{10}H_{22}$	decane	174.1	
$C_{17}H_{36}$	heptadecane	301.8	solid
$C_{20}H_{42}$	eicosane	343	

Properties and Uses of Alkanes

Properties for some straight-chain alkanes are listed in Table 20-5. The trends in these properties can be explained by examining the structure of alkanes. The carbon-hydrogen bonds of alkanes are nonpolar. The only forces of attraction between nonpolar molecules are weak intermolecular forces, or London dispersion forces. The strength of London dispersion forces increases as the mass of a molecule increases.

Physical States

The physical states at which some alkanes exist at room temperature and atmospheric pressure are found in Table 20-5. Alkanes with the lowest molecular mass, those with one to four carbon atoms, are gases. **Natural gas** *is a fossil fuel composed primarily of alkanes containing one to four carbon atoms*. The existence of these alkanes as gases agrees with the idea that very small molecules have weak London dispersion forces between them and are not held together tightly. Larger alkanes are liquids. Gasoline and kerosene consist mostly of liquid alkanes. Stronger London dispersion forces hold these molecules close enough together to form liquids. Alkanes with a very high molecular mass are solids, corresponding to a greater increase in London dispersion forces. Paraffin wax contains solid alkanes. It can be used in candles, as shown in Figure 20-12.

FIGURE 20-12 Paraffin wax, used in candles, contains solid alkanes. Molecules of paraffin wax contain 26 to 30 carbon atoms.

Boiling Points

The boiling points of alkanes, also shown in Table 20-5, increase with increasing molecular mass. As London dispersion forces increase, more energy, or heat, is required to pull the molecules apart. This property is used in the separation of petroleum, a major source of alkanes. **Petroleum** *is a complex mixture of different hydrocarbons that varies greatly in composition.* The hydrocarbon molecules in petroleum contain from one to more than fifty carbon atoms. This range allows the separation of

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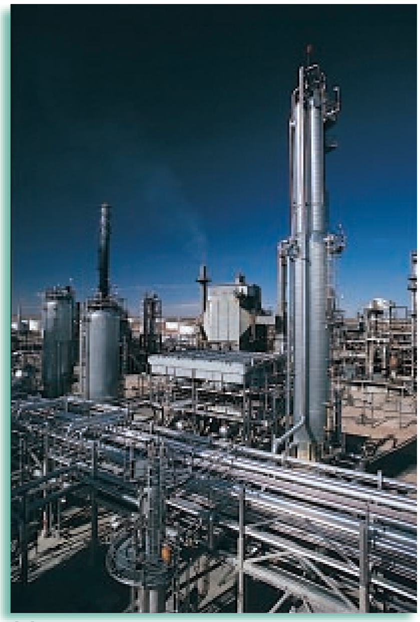
TABLE 20-6 *Petroleum Fractions*

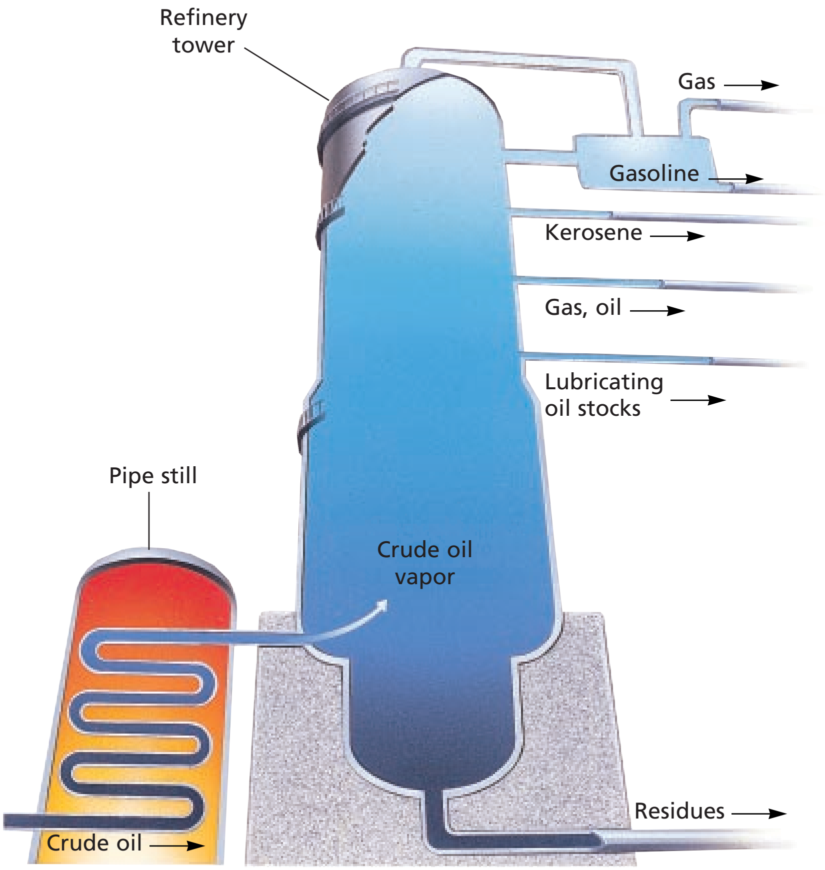
Fraction	Size range of molecules	Boiling-point range (°C)
Gasoline	C_4–C_{12}	up to 200
Kerosene	C_{10}–C_{14}	180–290
Middle distillate, such as heating oil, gas-turbine fuel, diesel	C_{12}–C_{20}	185–345
Wide-cut gas oil, such as lubricating oil, waxes	C_{20}–C_{36}	345–540
Asphalt	above C_{36}	residues

petroleum into different portions with different boiling point ranges, as shown in Table 20-6. In **fractional distillation,** shown in Figure 20-13, *components of a mixture are separated on the basis of boiling point, by condensation of vapor in a fractionating column*. During its fractional distillation, petroleum is heated to about 370°C. Nearly all the components of the petroleum are vaporized at this temperature. As the vapors rise in the fractionating column, or tower, they are gradually cooled.

FIGURE 20-13 (a) Fractional distillation takes place in petroleum refinery towers. (b) This is a model of a fractional distillation tower. Because fractions contain hydrocarbons of different masses, they condense and are drawn off at different levels.



(a)



(b)

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Alkanes with higher boiling points have higher condensation temperatures and condense for collection lower in the tower. For example, lubricating oils, which have higher condensation temperatures than gasoline has, are collected lower in the fractionating tower.

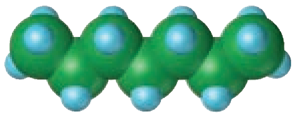
Combustion

Alkanes are less reactive than other hydrocarbons because of the stability of their single covalent bonds. One reaction alkanes do undergo is combustion. Because alkanes make up a large proportion of gaseous and liquid fossil fuels, combustion is their most important reaction. Complete combustion of hydrocarbons produces energy, CO_2, and H_2O. The reaction for the combustion of methane produces 890 kJ/mol.

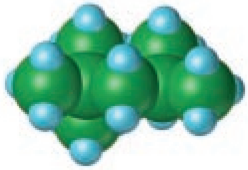
$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

One concern about the combustion of fossil fuels is their possible contribution to the greenhouse effect. CO_2 is one of the atmospheric molecules that absorbs infrared radiation. Increased levels of CO_2 through the combustion of fossil fuels may increase the amount of infrared energy absorbed by the atmosphere to a level that can increase the average temperature of Earth.

Engines can be powered by gasoline combustion. When fuel ignites spontaneously before it is reached by the flame front, there is a decrease in the amount of power gained, and engine knocking results. Straight-chain hydrocarbons are more likely to ignite spontaneously than branched-chain hydrocarbons. This tendency is the basis for the octane rating scale. *The* **octane rating** *of a fuel is a measure of its burning efficiency and its antiknock properties*. The octane rating scale is based on mixtures of 2,2,4-trimethylpentane, a highly branched alkane, and heptane, a straight-chain alkane. The term *octane* comes from the common name of 2,2,4-trimethylpentane, *isooctane*. Pure 2,2,4-trimethylpentane is very resistant to knocking and is assigned an octane number of 100. Pure heptane has an octane number of 0 and burns with a lot of knocking. Increasing the percentage of branched-chain alkanes in gasoline is one way to increase octane rating. The octane rating on gasoline pumps is shown in Figure 20-14.



heptane



2,2,4-trimethylpentane

FIGURE 20-14 The octane rating scale is based on a rating of 100 for 2,2,4-trimethylpentane and 0 for heptane. Compare their molecular shapes.

SECTION REVIEW

1. What is the basic structural characteristic of alkanes?
2. Draw all of the condensed structural formulas that can represent C_5H_{12}.
3. Give the systematic name for each of the compounds whose formulas appear in item 2.
4. Relate the properties of some alkanes to their uses.
5. Draw the condensed structural formulas of 3,4-dimethylhexane and 1-methyl-3-propylcyclopentane.

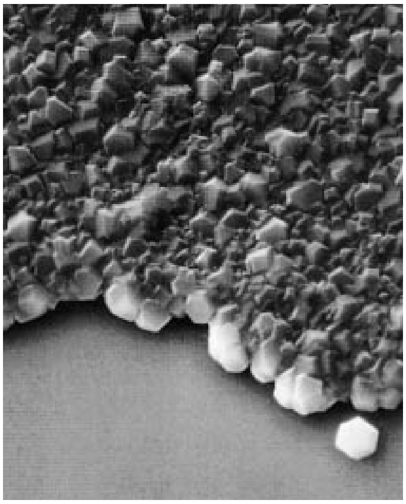
Synthetic Diamonds

Diamonds made to order? Almost. A thin coating of diamond film may not be pretty to look at, but it does offer many useful properties to industry. A number of methods are being developed to produce diamond coatings cheaply and efficiently. If successful, the processes will affect the way tools, containers, computer chips, and a host of other items are manufactured.

James Adair is an associate professor of material science and engineering at the University of Florida. "Natural diamonds are made at very, very high pressures and heat," Adair says. "Basically, it's a naturally occurring process that literally took millennia to form the diamond. We make diamonds in a couple of minutes." The process involves sticking very fine diamond particles on all kinds of different surfaces. Chemical Vapor Deposition is then used to grow more diamond from these diamond "seeds."

In Chemical Vapor Deposition, the objects to be coated—in this case, the diamond seeds—are placed inside a chamber filled with methane and other gases. The gases are subjected to microwave radiation, which breaks them down into hydrogen, carbon, and its mixtures (carbon-hydrogen radicals). Diamond crystals grow when these carbon atoms coat the diamond-seed crystals.

Another method of coating with diamond, invented by metallurgist Pravin Mistry, uses lasers to scan the object to be coated. The energy of the lasers breaks down CO_2 (supplied by a gas delivery system) into carbon and oxygen



This picture, taken with an electron microscope, shows synthetic diamond formed by Chemical Vapor Deposition.

atoms and vaporizes the surface of the object, forming a superheated plasma. The plasma serves as an environment for bonding the carbon atoms into a coating of crystalline diamond.

One of the biggest challenges in making synthetic diamond coatings is making sure that the carbon crystallizes correctly to form diamond and not graphite. Graphite is useful for making lubricants and pencil leads, but it is not as strong and durable as diamond. In the crystalline molecular structure of graphite, the spaces between carbon atoms are relatively far apart. The process must compress the spaces to form a compact octagonal diamond crystal.

Diamond is one of the hardest materials known to man, so diamond coatings would be particularly useful for making machine tools, work surfaces, and other applications where a durable protective covering is needed. Diamond also has the highest thermoconductivity of any material, which means that it transports heat very effectively. You wouldn't want to drink from a diamond coffee cup because the cup would warm up rapidly and you'd burn your lips. But diamond's ability to conduct heat makes it very useful as a coating on silicon computer chips.

"For microelectronics," says Adair, "dealing with the heat generated by the circuit is one of the biggest problems. If the heat builds up too much within a silicon circuit, it can literally melt the silicon. And it's not going to act as a very good computer brain for you. Diamond can pull that heat out of the silicon chip, so the circuit can run a little bit cooler."

If a computer chip is prevented from getting too hot, it can perform faster. And a faster chip can lead to a new breed of computers with enhanced capabilities.

Unsaturated Hydrocarbons

SECTION 20-4

OBJECTIVES

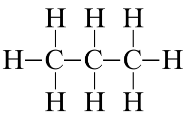
- Distinguish between the structures of alkenes, alkynes, and aromatic hydrocarbons.
- Be able to name and write structural formulas for unsaturated hydrocarbons.
- Explain how structures of unsaturated hydrocarbons relate to their properties and how those properties affect the uses of specific hydrocarbons.

Hydrocarbons that do not contain the maximum amount of hydrogen are referred to as unsaturated. **Unsaturated hydrocarbons** *are hydrocarbons in which not all carbon atoms have four single covalent bonds.*

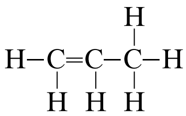
Alkenes

Alkenes *are hydrocarbons that contain double covalent bonds.* Some examples of alkenes are given in Table 20-7. Notice that because alkenes have a double bond, the simplest alkene, ethene, has two carbon atoms.

Carbon atoms linked by double bonds cannot bind as many atoms as those that are linked by only single bonds. An alkene with one double bond has two fewer hydrogen atoms than the corresponding alkane.



C_3H_8



C_3H_6

Thus, the general formula for noncyclic alkenes with one double bond is C_nH_{2n}.

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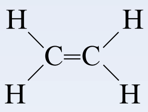
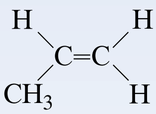
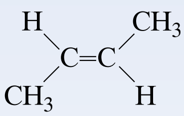
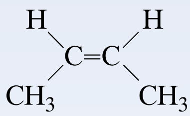
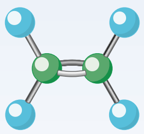
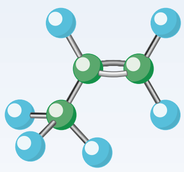
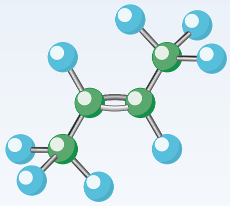
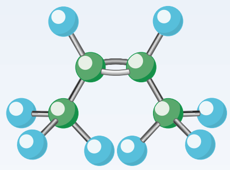
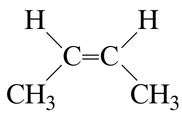
TABLE 20-7 *Structures of Alkenes*

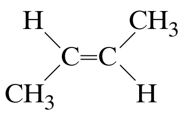
	ethene	propene	*trans*-2-butene	*cis*-2-butene
Structural formula				
Ball-and-stick model				

Back

Because alkenes have a double bond, they can have geometric isomers, as shown in the examples below.



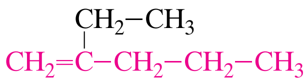
cis-2-butene



trans-2-butene

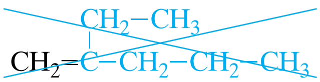
Systematic Names of Alkenes

The rules for naming a simple alkene are similar to those for naming an alkane. The parent hydrocarbon is the longest continuous chain of carbon atoms *that contains the double bond*. If there is only one double bond, the suffix *-ene* is added to the carbon-chain prefix. Here, the longest chain that contains the double bond has five carbon atoms and one double bond, so the parent hydrocarbon is pentene.



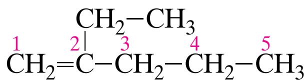
pentene

NOT



~~hexane~~

The carbon atoms in the chain are numbered so that the first carbon atom in the double bond has the lowest number. The number indicating the position of the double bond is placed before the name of the hydrocarbon chain and separated by a hyphen.



1-pentene

The position number and name of the alkyl group are placed in front of the double-bond position number. This alkyl group has two carbon atoms, an ethyl group. It is on the second carbon atom of the parent hydrocarbon.

2-ethyl-1-pentene

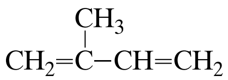
The molecule is 2-ethyl-1-pentene.

If there is more than one double bond, the suffix is modified to indicate the number of double bonds: 2 = *-adiene*, 3 = *-atriene*, and so on.

$$CH_2{=}CH{-}CH_2{-}CH{=}CH_2$$

1,4-pentadiene

If numbering from both ends gives equivalent positions for the double bonds in an alkene with two double bonds, then the chain is numbered from the end nearest the first alkyl group.



2-methyl-1,3-butadiene

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The procedure for naming alkenes can be summarized as follows.

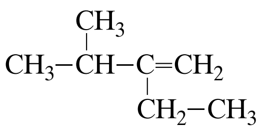
Alkene Nomenclature

Use the rules for alkane nomenclature on page 639, with the following exceptions.

1. **Name the parent hydrocarbon.** Locate the longest continuous chain that *contains the double bond(s)*. If there is only one double bond, add the suffix *-ene* to the prefix corresponding to the number of carbon atoms in this chain. If there is more than one double bond, modify the suffix to indicate the number of double bonds. For example, 2 = *-adiene,* 3 = *-atriene,* and so on.
2. **Add the names of the alkyl groups.**
3. **Number the carbon atoms in the parent hydrocarbon.** Number the carbon atoms in the chain so that the first carbon atom in the double bond nearest the end of the chain has the lowest number. If numbering from both ends gives equivalent positions for two double bonds, then number from the end nearest the first alkyl group.
4. **Insert position numbers.** Place double-bond position numbers immediately before the name of the parent hydrocarbon alkene. Place alkyl group position numbers immediately before the name of the corresponding alkyl group.
5. **Punctuate the name.**

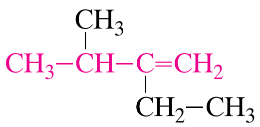
SAMPLE PROBLEM 20-3

Name the following alkene.



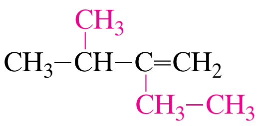
SOLUTION

1. Identify and name the parent hydrocarbon.



The parent hydrocarbon has four carbon atoms and one double bond, so it is named *butene*.

2. Identify and name the alkyl groups.



The alkyl groups are *ethyl* and *methyl*.
Place their names in front of the name of the parent hydrocarbon in alphabetical order.

ethyl methyl butene

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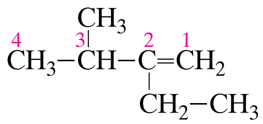
3. Number the carbon chain to give the double bond the lowest position.



4. Place the position number of the double bond in front of butene. Place the position numbers of the alkyl groups in front of each alkyl group. Separate the numbers from the name with hyphens.

The first carbon in the double bond is in position *1*.
The ethyl group is on carbon *2*.
The methyl group is on carbon *3*.

2-ethyl-**3**-methyl-**1**-butene

The full name is 2-ethyl-3-methyl-1-butene.

PRACTICE

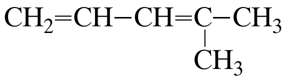
1. Name the following alkene:

$CH_3{-}CH_2{-}CH_2{-}CH{=}CH{-}CH_3$

Answer
2-hexene

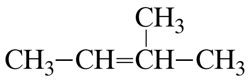
2. Draw the condensed structural formula for 4-methyl-1,3-pentadiene.

Answer

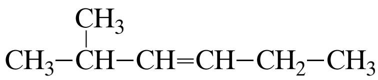


3. Name the following alkenes:

a.

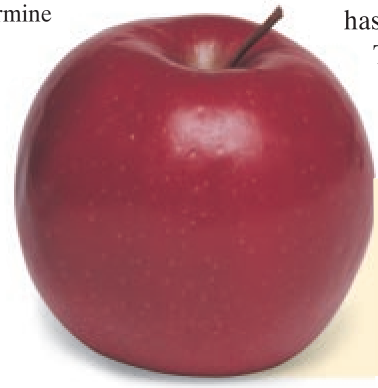


b.



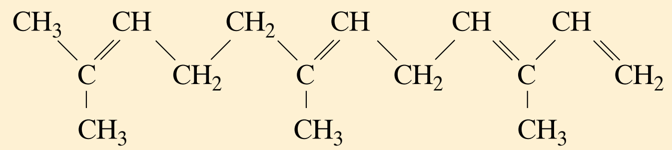
Answer
a. 2-methyl-2-butene
b. 2-methyl-3-hexene

FIGURE 20-15 α-farnesene is a solid alkene found in the natural wax covering of apples. Can you determine the IUPAC name for this large alkene?



Properties and Uses of Alkenes

Alkenes are nonpolar and show trends in properties similar to those of alkanes in boiling points and physical states. For example, α-farnesene has 15 carbon atoms and 4 double bonds, as shown in Figure 20-15. This large alkene is a solid at room temperature and atmospheric pressure. It is found in the natural wax covering of apples. Ethene, the smallest alkene, is a gas.



α-farnesene

Ethene is the hydrocarbon commercially produced in the greatest quantity in the United States. It is used in the synthesis of many plastics and commercially important alcohols. Ethene is also an important plant hormone. Induction of flowering and fruit ripening, as shown in Figure 20-16, are effects of ethene hormone action that can be manipulated by commercial growers.

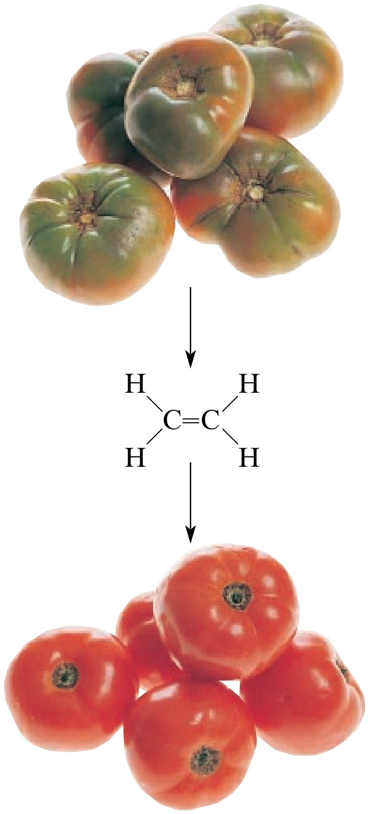


FIGURE 20-16 Ethene is a plant hormone that triggers fruit ripening. Its small size allows it to travel as a gas.

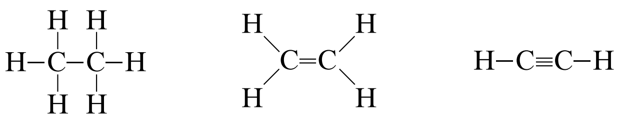
Alkynes

Hydrocarbons with triple covalent bonds are **alkynes.** Like the double bond of alkenes, the triple bond of alkynes requires that the simplest alkyne has two carbon atoms.

$$H-C\equiv C-H$$

ethyne

The general formula for the alkynes is C_nH_{2n-2}. Alkynes have four fewer hydrogen atoms than the corresponding alkanes and two fewer than the corresponding alkenes.



C_2H_6 C_2H_4 C_2H_2

Systematic Naming of Alkynes

Alkyne nomenclature is almost the same as alkene nomenclature. The only difference is that the *-ene* suffix of the corresponding alkene is replaced with *-yne*. A complete list of rules follows.

Alkyne nomenclature

Use the rules for alkane nomenclature on page 639, with the following exceptions.

1. **Name the parent hydrocarbon.** Locate the longest continuous chain that *contains the triple bond(s)*. If there is only one triple bond, add the suffix *-yne* to the prefix corresponding to the number of carbon atoms in the chain. If there is more than one triple bond, modify the suffix to indicate the number of triple bonds. For example, 2 = *-adiyne,* 3 = *-atriyne,* and so on.
2. **Add the names of the alkyl groups.**
3. **Number the carbon atoms in the parent hydrocarbon.** Number the carbon atoms in the chain so that the first carbon atom in the triple bond nearest the end of the chain has the lowest number. If numbering from both ends gives the same positions for two triple bonds, then number from the end nearest the first alkyl group.

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FIGURE 20-17 Ethyne is the fuel used in oxyacetylene torches. Oxyacetylene torches can reach temperatures of over 3000°C.

4. **Insert position numbers.** Place the position numbers of the triple bonds immediately before the name of the parent hydrocarbon alkyne. Place alkyl group position numbers immediately before the name of the corresponding alkyl group.
5. **Punctuate the name.**

Two examples of correctly named alkynes are given below.

$$CH_3{-}CH_2{-}CH_2{-}C{\equiv}CH$$

1-pentyne

$$CH{\equiv}C{-}\underset{\displaystyle CH_3}{\underset{|}{CH}}{-}CH_3$$

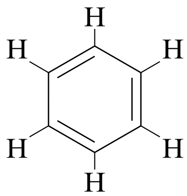
3-methyl-1-butyne

Properties and Uses of Alkynes

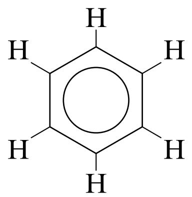
Alkynes are nonpolar and exhibit the same trends in boiling points and physical state as other hydrocarbons. The smallest alkyne, ethyne, is a gas. The combustion of ethyne when it is mixed with pure oxygen produces the intense heat of welding torches, as shown in Figure 20-17. The common name of ethyne is *acetylene,* and these welding torches are commonly called oxyacetylene torches.

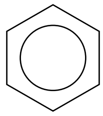
Aromatic Hydrocarbons

Aromatic hydrocarbons *are hydrocarbons with six-membered carbon rings and delocalized electrons.* **Benzene** *is the primary aromatic hydrocarbon*. The molecular formula of benzene is C_6H_6. One possible structural formula is a six-carbon atom ring with three double bonds.

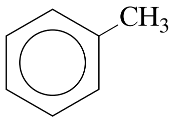


However, benzene does not behave chemically like an alkene. All of the carbon–carbon bonds in the molecule are the same. Like graphite, benzene contains resonance hybrid bonds. The structure of the benzene ring allows the delocalized electrons to be spread over the ring. The entire molecule lies in the same plane, as shown in Figure 20-18. The following structural formulas are often used to show this spreading of electrons. In the condensed form, the hydrogen atom at each corner is understood.





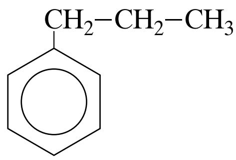
Aromatic hydrocarbons can be thought of as derivatives of benzene. The simplest have one benzene ring, as shown in the following example.



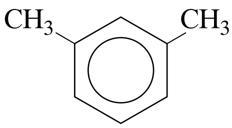
methylbenzene

Systematic Names of Aromatic Hydrocarbons

The simplest aromatic hydrocarbons are named as alkyl-substituted benzenes. The names of the alkyl groups are added in front of the word *benzene* according to the rules for other hydrocarbons. As with cycloalkanes, the carbon atoms in the ring do not need to be numbered if there is only one alkyl group. If there is more than one alkyl group, the carbons are numbered in order to give all of the alkyl groups the lowest possible numbers. Following are some examples.



propylbenzene



1,3-dimethylbenzene

The rules for naming simple aromatic hydrocarbons can be summarized as follows.

Simple Aromatic Hydrocarbon Nomenclature

Use the rules for alkane nomenclature on page 639, with the following exceptions.

1. **Name the parent hydrocarbon.** The parent hydrocarbon is the benzene ring, *benzene*.
2. **Add the names of the alkyl groups.**

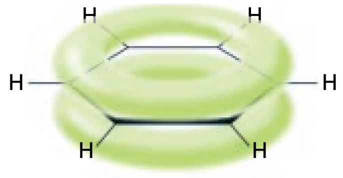


FIGURE 20-18 Electron orbitals in benzene overlap to form continuous orbitals that allow the delocalized electrons to spread uniformly over the entire ring.

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3. **Number the carbon atoms in the parent hydrocarbon.** If there are two or more alkyl groups attached to the benzene ring, number the carbon atoms in the ring. Assign position number one to the alkyl group that comes first in alphabetical order. Then number in the direction that gives the rest of the alkyl groups the lowest numbers possible.
4. **Insert position numbers.**
5. **Punctuate the name.**

SAMPLE PROBLEM 20-4

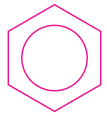
Draw the condensed structural formula for 1,2-dimethylbenzene.

SOLUTION

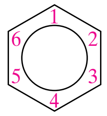
1. Identify the parent hydrocarbon in the name.

1,2-dimethyl**benzene**

2. Draw the benzene ring.



3. Number the carbon atoms in the benzene ring.



4. Identify any alkyl groups.

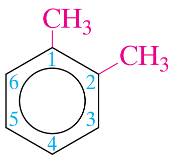
1,2-di**methyl**benzene

There are only methyl groups in this molecule. The prefix *di-* is attached to the word *methyl,* so there are two methyl groups.

5. Locate the position numbers for the methyl groups.

1,2-dimethylbenzene

6. Attach the methyl groups to the carbon atoms numbered *1* and *2*.



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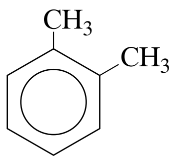
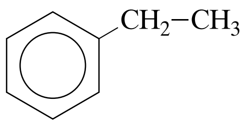
7. The complete structural formula for 1,2-dimethylbenzene is as follows.



PRACTICE

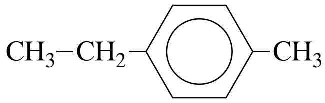
1. Name the following compound:



Answer
ethylbenzene

2. Draw the condensed structural formula for 1-ethyl-4-methylbenzene.

Answer



Properties and Uses of Aromatic Hydrocarbons

Benzene rings are chemically very stable, a property that can be explained by the concept of delocalized electrons. Therefore, aromatic hydrocarbons are less reactive than alkenes and alkynes are. In the past, benzene was used as a nonpolar solvent because of this stability. However, benzene is both a poison and a carcinogen. Like other hydrocarbons, benzene is nonpolar and has limited solubility in water. It appears that oxidation of the benzene ring, in an attempt to solubilize it for elimination from the body, produces toxic molecules. This has led to the replacement of benzene as a solvent with methylbenzene, which is less toxic. Another aromatic hydrocarbon, 3,4-benzpyrene, is found in coal tar, tar from cigarette smoke, and soot in heavily polluted urban areas. Studies have shown this compound can cause cancer.

SECTION REVIEW

1. List the basic structural features that characterize each of the following:
a. alkenes
b. alkynes
c. aromatic hydrocarbons

2. Draw three condensed structural formulas that can represent C_4H_8.

3. Give the systematic name for each compound in your answer to item 2.

4. Give examples of a property or use of three unsaturated hydrocarbons.

5. Draw the condensed structural formula for each of the following:
a. 1,3-butadiene
b. 2-pentyne
c. 1,2-diethylbenzene

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CHAPTER 20 REVIEW

CHAPTER SUMMARY

20-1

- Carbon is important because all living matter contains carbon.
- Hybridized orbitals allow carbon atoms to form single, double, and triple covalent bonds.
- Carbon occurs in several solid allotropic forms, such as diamond, graphite, and fullerenes, all of which have different structures and properties.

Vocabulary

delocalized electrons (627) diamond (626) fullerenes (626) graphite (626)

20-2

- All organic compounds contain carbon, but not all carbon-containing compounds are classified as organic.
- The number of possible organic compounds is virtually unlimited because of the bonding properties of carbon. The unique catenation ability of carbon allows it to link together to form long chains and rings. The ability of carbon to bind other elements and to allow different arrangements of atoms adds to the diversity of carbon compounds.
- Isomers are compounds with the same molecular formula but different structures. Structural formulas are needed to show the bonding order and arrangement of atoms in an organic molecule to distinguish between isomers.
- Structural isomers are isomers in which the atoms are bonded together in different orders. Geometric isomers are isomers in which the order of atom bonding is the same but the atoms are arranged differently in space.

Vocabulary

catenation (630) hydrocarbons (630) organic compounds (629) structural isomers (631)
geometric isomers (632) isomers (630) structural formula (630)

20-3

- In saturated hydrocarbons, each carbon atom has four single covalent bonds. Alkanes are saturated hydrocarbons.
- Organic compounds are named according to a systematic method developed by IUPAC.
- Alkanes contain only single bonds. Because alkanes consist of saturated single covalent bonds, these compounds are not very reactive. One important reaction they do undergo is combustion.
- Trends in physical states, boiling points, and combustion properties correspond to trends in alkane size and amount of branching.

Vocabulary

alkanes (634) fractional distillation (644) natural gas (643) petroleum (643)
alkyl groups (637) homologous series (634) octane rating (645) saturated hydrocarbons (634)
cycloalkanes (635)

20-4

- Carbon atoms in unsaturated hydrocarbons do not all have four single covalent bonds. Alkenes, alkynes, and aromatic hydrocarbons are unsaturated hydrocarbons.
- Alkenes contain carbon-carbon double bonds and can have geometric isomers. The smallest alkene, ethene, is an important industrial and agricultural chemical.
- Alkynes contain carbon-carbon triple bonds.
- Benzene and derivatives of benzene are aromatic hydrocarbons. The concept of delocalized electrons helps explain the stability of the benzene ring.

Vocabulary

alkenes (647) aromatic hydrocarbons (652) benzene (652) unsaturated hydrocarbons (647)
alkynes (651)

REVIEWING CONCEPTS

1. What is the orientation of the four covalent bonds and the *sp*^{3} orbitals of a carbon atom? (20-1)

2. Name and describe the structures of three allotropic forms of carbon. (20-1)

3. What properties of diamond determine most of its industrial uses? (20-1)

4. Why does graphite conduct electricity while diamond does not? (20-1)

5. Explain why the structure of graphite makes it useful as a lubricant. (20-1)

6. Describe the structure of buckminsterfullerene. (20-1)

7. a. What is catenation?
b. How does catenation contribute to the diversity of organic compounds? (20-2)

8. What are hydrocarbons, and what is their importance? (20-2)

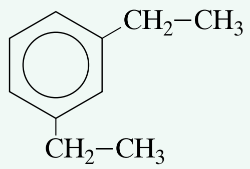
9. a. What information about a compound is provided by a structural formula?
b. How are structural formulas used in organic chemistry? (20-2)

10. Can molecules with the molecular formulas C_4H_{10} and $C_4H_{10}O$ be structural isomers of one another? Why or why not? (20-2)

11. Can molecules with only single bonds (and no rings) have geometric isomers? Why or why not? (20-2)

12. a. What do the terms *saturated* and *unsaturated* mean when applied to hydrocarbons?
b. What other meanings do these terms have in chemistry?
c. Classify alkenes, alkanes, alkynes, and aromatic hydrocarbons as either saturated or unsaturated. (20-3 and 20-4)

13. Classify each of the following as an alkane, alkene, alkyne, or aromatic hydrocarbon.

a. 

b. $CH_3{-}CH{=}CH_2$

c.
$$\begin{array}{l}\qquad\qquad\; CH_3 \\ \qquad\qquad\;\; | \\ CH{\equiv}C{-}CH{-}CH_2{-}CH_3\end{array}$$

d.
$$\begin{array}{l}CH_3{-}CH{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_3 \\ \qquad\quad\; | \\ \qquad\quad CH_3\end{array}$$

(20-3 and 20-4)

14. Give the general formula for the members of the following:
a. alkane series
b. alkene series
c. alkyne series (20-3 and 20-4)

15. Give the molecular formula for each type of hydrocarbon if it contains seven carbon atoms.
a. an alkane
b. an alkene
c. an alkyne (20-3 and 20-4)

16. a. What is a homologous series?
b. By what method are straight-chain hydrocarbons named?
c. Name the straight-chain alkane with the molecular formula $C_{10}H_{22}$. (20-3)

17. What are cycloalkanes? (20-3)

18. a. What trend occurs in the boiling points of alkanes?
b. How would you explain this trend?
c. How is the trend in alkane boiling points used in petroleum fractional distillation? (20-3)

19. How does the structure of alkanes affect the octane rating of gasoline? (20-3)

20. Write a balanced equation for the complete combustion of each of the following:
a. methane
b. ethyne (20-3 and 20-4)

21. Which types of isomers are possible for alkanes (with no rings), alkenes, and alkynes? Why? (20-3 and 20-4)

22. Give examples of ethene's commercial uses. (20-4)

23. a. Alkyne nomenclature is very similar to the nomenclature of what other group of hydrocarbons?
b. How do these nomenclatures differ? (20-4)

24. Give one use for ethyne. (20-4)

25. a. What are delocalized electrons?
b. What is their effect on the reactivity of aromatic hydrocarbons? (20-4)

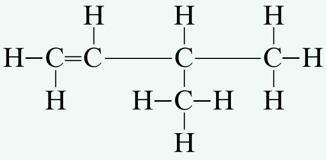
26. What is the name of the parent hydrocarbon of simple aromatic hydrocarbons? (20-4)

27. Describe a possible cause of benzene toxicity. (20-4)

PROBLEMS

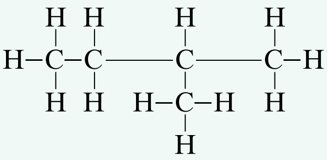
Structural Formulas

28. Draw the condensed structural formula for the following:



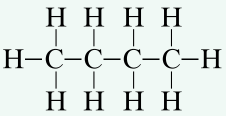
29. Identify each of the following pairs of formulas as representing the same or different molecules:

a. C_5H_{12} AND

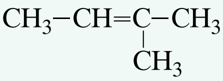


b. $CH_3{-}CH_2{-}CH_3$

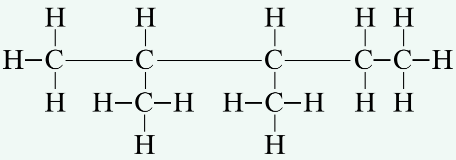
AND



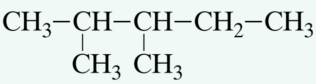
c. C_6H_{10} AND



d.



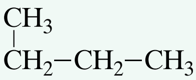
AND



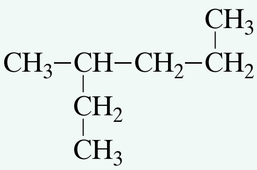
Isomers

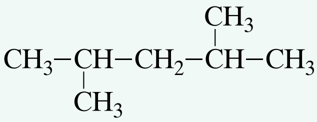
30. Identify whether each pair represents the same molecule or structural isomers.

a. $CH_3{-}CH_2{-}CH_2{-}CH_3$

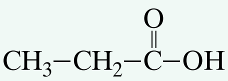


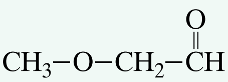
b.





c.





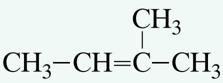
31. Draw structural formulas for the five isomers of C_6H_{14}.

32. Draw the geometric isomers of the following molecule. Label each isomer as *cis* or *trans.*

$CH_3{-}CH{=}CH{-}CH_2{-}CH_3$

33. a. Which of the following can have geometric isomers?

$CH_3{-}CH{=}CH{-}Cl$



$CH_3{-}CH_2{-}CH{=}CH{-}CH_2{-}CH_3$

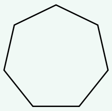
b. Draw the geometric isomers for those that can have geometric isomers.
c. Label each geometric isomer as *cis* or *trans.*

Alkane Nomenclature

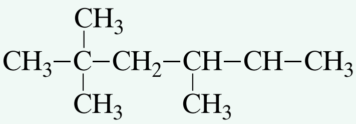
34. Name the following molecules. (Hint: See Sample Problem 20-1.)

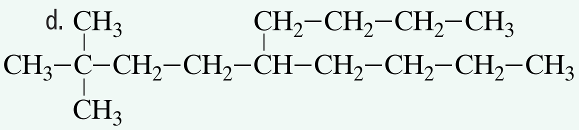
a. $CH_3{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_3$

b.



c.

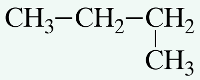


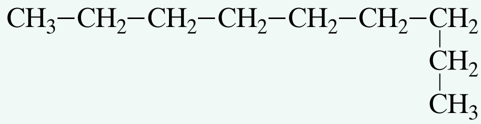
d. 

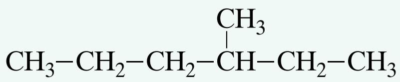
35. Give the complete, uncondensed, structural formula for each of the following alkanes. (Hint: See Sample Problem 20-2.)
a. decane
b. 3,3-dimethylpentane

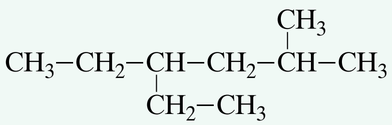
36. Give the condensed structural formula for each of the following alkanes:
a. 1,1-dimethylcyclopropane
b. 2,2,4,4-tetramethylpentane

37. For each of the following, determine whether the alkane is named correctly. If it is not, give the correct name.

a. 
1-methylpropane

b. 
nonane

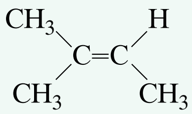
c. 
4-methylhexane

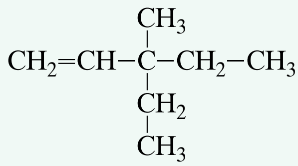
d. 
4-ethyl-2-methylhexane

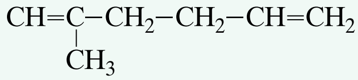
Alkene Nomenclature

38. Name the following alkenes. (Hint: See Sample Problem 20-3.)

a. $CH_2{=}CH{-}CH_2{-}CH_2{-}CH_3$

b. 

c. 

d. 

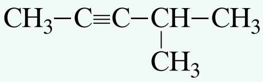
39. Draw the condensed structural formula for each of the following alkenes:
a. 2-methyl-2-hexene
b. 3-ethyl-2,2-dimethyl-3-heptene

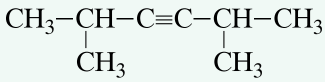
40. Draw structural formulas for geometric isomers of each of the following:
a. $CH_3{-}CH_2{-}CH_2{-}CH{=}CH{-}CH_3$
b. 3-methyl-2-pentene

Alkyne Nomenclature

41. Name the following alkynes:

a. $CH{\equiv}C{-}CH_3$

b. 

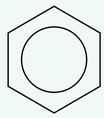
c. 

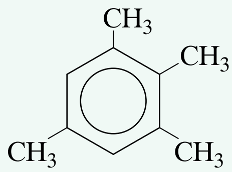
d. $CH{\equiv}C{-}CH_2{-}CH_2{-}CH_2{-}C{\equiv}CH$

42. Draw the condensed structural formula for each of the following alkynes:
a. 1-decyne
b. 6,6-dimethyl-3-heptyne

Aromatic Hydrocarbon Nomenclature

43. Name the following aromatic hydrocarbons. (Hint: See Sample Problem 20-4.)

a. 

b. 

44. Draw the condensed structural formula for each of the following molecules:
a. 1,3,5-trimethylbenzene
b. 1,3-dimethylbenzene

Calculations with Carbon Compounds

45. The jewelers' mass unit for diamond is the carat. By definition, 1 carat equals exactly 200 mg. What is the volume of a 1.00 carat diamond? The density of diamond is 3.51 g/cm^3.

46. For 100.0 g of butadiene, C_4H_6, calculate the following:
a. number of moles
b. number of molecules

47. An alkene has the molecular formula $C_{12}H_{24}$. Determine its percent composition.

48. Assuming that the volumes of carbon dioxide and of propane are measured under the same experimental conditions, what volume of carbon dioxide is produced by the complete combustion of 15.0 L of propane?

49. Assume a gasoline is isooctane, which has a density of 0.692 g/mL. What is the mass in kilograms of 12.0 gal of the gasoline (1 gal = 3.78 L)?

MIXED REVIEW

50. a. Draw the complete, uncondensed structural formula for 4-methyloctane.
b. Convert it into the condensed structural formula.
c. Determine the molecular formula for the molecule from both the structure you drew and the general molecular formula for alkanes. Compare the two. Are they the same?

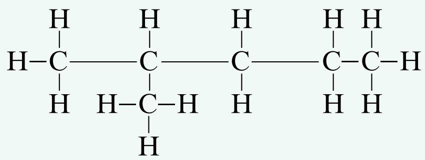
51. Draw and name two different condensed structural formulas for molecules of each of the following types of hydrocarbons containing eight carbon atoms:
a. alkane
b. alkene
c. alkyne
d. aromatic hydrocarbon

52. Draw the condensed structural formulas for 4,4-dimethyl-2-pentyne and 2,2-dimethyl-4-propyloctane.

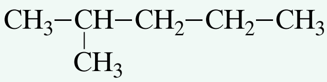
53. Draw the three structural isomers for an alkyne containing five carbon atoms and one triple bond. Name the molecules you draw.

54. Which of the following molecules have geometric isomers? Draw all possible geometric isomers. Label the molecules you draw as either *cis* or *trans*.
a. butane
b. 2-pentene
c. 2-hexyne
d. 2-methyl-1-butene

55. Identify the following pairs as the same compound, isomers, or different compounds that are not isomers:

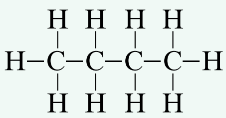
a. 

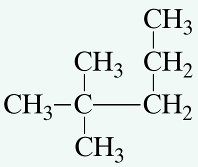
AND



b. C_4H_8

AND



c. 

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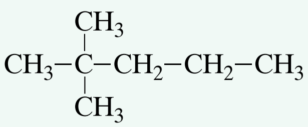
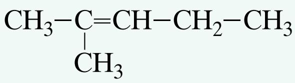


d. 

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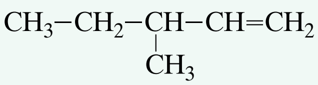

CRITICAL THINKING

56. Inferring Conclusions Why are organic compounds with covalent bonds usually less stable when heated than inorganic compounds with ionic bonds?

57. Inferring Relationships The element that appears in the greatest number of compounds is hydrogen. The element found in the second greatest number of compounds is carbon. Why are there more hydrogen compounds than carbon compounds?

58. Relating Ideas As the number of carbon atoms in an alkane molecule increases, does the percentage of hydrogen increase, decrease, or remain the same?

HANDBOOK SEARCH

59. The top 10 chemicals produced in the United States are listed in Table 7B of the *Elements Handbook*. Review this material, and answer the following:
   a. Which of the top ten compounds are organic?
   b. Write structural formulas for the compounds you listed in item (a).
   c. To what homologous series do each of these compounds belong?

60. The reaction of methane with oxygen produces two different oxides of carbon. Review this material in the *Elements Handbook*, and answer the following:
   a. What conditions determine whether the product of the methane reaction is CO_2 or CO?
   b. If a home heating system is fueled by natural gas, what difference does it make if the combustion produces CO_2 or CO?

61. Silicon is similar to carbon in forming long-chain compounds. Review the material on silicon in the *Elements Handbook* and answer the following:
   a. How does a long-chain silicon compound differ in composition from a long-chain carbon compound?
   b. The simplest alkane is methane. Methyl groups are found in all alkanes. What is a common subunit of a silicate? What is the geometry of that subunit?

62. Mercury in the environment poses a hazard to living things. Review the section on mercury poisoning in the *Elements Handbook*.
   a. Draw a structure formula for the organic mercury compound described in that section.
   b. What is the IUPAC name for this compound?

RESEARCH & WRITING

63. *Chemical and Engineering News* publishes a list once a year of the top 50 chemicals. Find out which chemicals on the current year's list are hydrocarbons, and report your findings to the class.

64. Consult reference materials at the library, and read about products made from hydrocarbons. Keep a list of the number of petroleum-related products you use in a single day.

ALTERNATIVE ASSESSMENT

65. Performance Models are often used to visualize the three-dimensional shape of molecules. Using gumdrops as atoms and toothpicks to bond them together, construct models of different hydrocarbons. Use large gumdrops for carbon and smaller gumdrops for hydrogen. Refer to Figures 20-1 and 20-2 for guidelines on the three-dimensional shapes of hydrocarbons.

66. Performance Using your gumdrop models, demonstrate why alkenes can have geometric isomers, while alkanes cannot.