CHAPTER 22

Hydrocarbons

What You'll Learn

- You will compare the structures and properties of alkanes, alkenes, and alkynes.
- You will recognize and compare the properties of structural isomers and stereoisomers.
- You will describe how useful hydrocarbons are obtained from natural sources.

Why It's Important

Fuels, medicines, synthetic textiles, plastics, and dyes are just a few examples of hydrocabon-derived organic chemicals we use every day.

Chemistry Online

Visit the Chemistry Web site at **chemistrymc.com** to find links about hydrocarbons.

Oil pipelines transport petroleum that remains a vital resource for the manufacture of fuels, plastics, solvents, pharmaceuticals, and other important carbon compounds.

DISCOVERY LAB

Viscosity of Motor Oil

The molecules of motor oil have long chains of carbon atoms. Oil's viscosity, a measure of resistance to flow, is related to the oil's weight numbers. How do two weights of oil differ in viscosity?

Materials

wide-mouth jars and lids (3)
lead weights, BB size (9)
screws, nuts, and washers
long forceps
10W-30 and 20W-50 motor oil
stopwatch
paper towels

Safety Precautions

Procedure

1. Add a 50-mm depth of water to the first jar, the same depth of 10W-30 motor oil to the second jar, and an equal depth of 20W-50 oil to the third jar.
2. Drop a lead weight from just above the surface of the liquid in the first jar. Time the weight as it sinks to the bottom. Repeat the process twice with two other small metal objects.
3. Repeat step 2 with the jars of oil.
4. Use forceps to remove the weights. Dry them on paper towels. Save the oil for reuse.

Analysis

What do your results tell you about the relationship between viscosity and the weight numbers of motor oil? Which oil is more likely to be used in heavy machinery that requires a high-viscosity oil?

Section 22.1 Alkanes

Objectives

- **Describe** the structures of alkanes.
- **Name** an alkane by examining its structure.
- **Draw** the structure of an alkane given its name.

Vocabulary

organic compound
hydrocarbon
alkane
homologous series
parent chain
substituent group

The Alaskan pipeline shown in the photo on the opposite page was built to carry crude oil from the oil fields in the frozen north to an ice-free southern Alaskan seaport. Crude oil, also called petroleum, is a complex mixture of carbon compounds produced by heat and pressure acting on the remains of once-living organisms buried deep beneath Earth's surface.

Organic Chemistry

Chemists of the early nineteenth century knew that living things produce an immense variety of carbon compounds. Chemists referred to these compounds as "organic" compounds because they were produced by living organisms.

Once Dalton's atomic theory was accepted in the early nineteenth century, chemists began to understand that compounds, including those made by living organisms, consisted of arrangements of atoms bonded together in certain combinations. With this knowledge, they were able to go to their laboratories and synthesize many new and useful substances—but not the organic compounds made by living things. One of the main reasons for their failure was that chemists, like most other scientists of the time, accepted an idea called *vitalism*. According to vitalism, organisms possess a mysterious

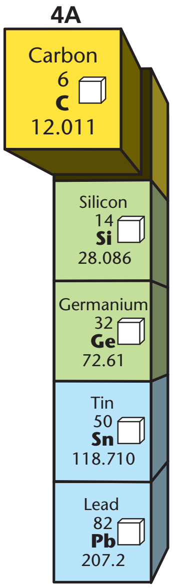


Figure 22-1

Carbon is a nonmetal element located in group 4A of the periodic table. Elements in this group have four valence electrons. Carbon usually shares its four valence electrons to form four covalent bonds.

"vital force" that enables them to assemble carbon compounds, and such compounds could never be produced in the laboratory.

Disproving vitalism Friedrich Wöhler (1800–1882) was a German chemist who questioned the idea of vitalism. While working in Berlin in 1828, he carried out a reaction that he thought would produce the compound ammonium cyanate (NH_4OCN). To his surprise, the product of the reaction turned out to be urea (NH_2CONH_2), a compound that had the same empirical formula as ammonium cyanate. Previously, urea was known only as a waste product found in the urine of humans and other animals. Wöhler wrote to the Swedish chemist Berzelius that he had "made urea without the kidney of an animal, either man or dog."

Although Wöhler's experiment did not immediately disprove vitalism, it started a chain of similar experiments by other European chemists. Eventually, the idea that the synthesis of organic compounds required a vital force was discredited. Today the term **organic compound** is applied to all carbon-containing compounds with the primary exceptions of carbon oxides, carbides, and carbonates, which are considered inorganic. An entire branch of chemistry, called organic chemistry, is devoted to the study of carbon compounds.

Why is an entire field of study focused on compounds containing carbon? To answer this question, recall that carbon is in the group 4A elements of the periodic table, as shown in **Figure 22-1**. With its electron configuration of $1s^2 2s^2 2p^2$, carbon nearly always shares its electrons, forming four covalent bonds. In organic compounds, carbon atoms are found bonded to hydrogen atoms or atoms of other elements that are near carbon in the periodic table—especially nitrogen, oxygen, sulfur, phosphorus, and the halogens.

Most importantly, carbon atoms also bond to other carbon atoms and can form chains from two to thousands of carbon atoms in length. Also, because carbon forms four bonds, it can form complex, branched-chain structures, ring structures, and even cagelike structures. With all of these bonding possibilities, millions of different organic compounds are known, and chemists are synthesizing more every day.

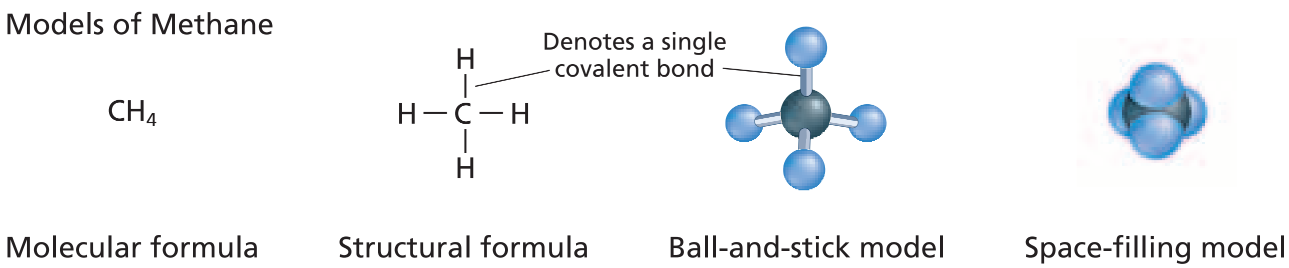
Hydrocarbons

The simplest organic compounds are the **hydrocarbons**, which contain only the elements carbon and hydrogen. How many different compounds do you think it is possible to make from two elements? You might guess one, or maybe a few more, say 10 or 12. Actually, thousands of hydrocarbons are known, each containing only the elements carbon and hydrogen.

As you know, carbon forms four bonds. Hydrogen, having only one valence electron, forms only one covalent bond by sharing this electron with another atom. Therefore, the simplest hydrocarbon molecule consists of a carbon atom bonded to four hydrogen atoms, CH_4. This substance is called methane and is an excellent fuel and the main component of natural gas.

Figure 22-2

Methane (CH_4) consists of one carbon atom bonded to four hydrogen atoms in a tetrahedral arrangement. Here are four ways to represent a methane molecule. Refer to **Table C-1** in Appendix C for a key to atom color convention.



In chemistry, covalent bonds in which two electrons are shared are represented by a single straight line, denoting a single covalent bond. **Figure 22-2** shows four different ways to represent a methane molecule.

A review of models Chemists represent organic molecules in a variety of ways. Most often, they use the type of model that best shows the information they want to highlight. As you see in **Figure 22-2** on the previous page, molecular formulas give no information about the geometry of the molecule. A structural formula shows the general arrangement of atoms in the molecule but not the exact geometry. Space-filling models give a more realistic picture of what a molecule would look like if you could see it, but ball-and-stick models demonstrate the geometry of the molecule more clearly. Keep in mind, however, that the atoms are not at the ends of sticks but are held closely together by electron-sharing bonds.

Straight-Chain Alkanes

Methane is the smallest member of a series of hydrocarbons known as alkanes. **Alkanes** are hydrocarbons that have only single bonds between atoms. The next member of the series consists of two carbon atoms bonded together with a single bond and six hydrogen atoms sharing the remaining valence electrons of the carbon atoms. This molecule is called ethane (C_2H_6) and is shown in **Figure 22-3**.

The third member of the alkane series, propane, has three carbon atoms and eight hydrogen atoms, giving it the molecular formula C_3H_8. The next member, butane, has four carbon atoms in a continuous chain and the formula C_4H_{10}. Compare the structures of ethane, propane, and butane in **Figure 22-3.**

Most propane and butane come from petroleum. Propane, known also as LP (liquified propane) gas, is sold as a fuel for cooking and heating. Another use of propane is illustrated in **Figure 22-4** on page 700. Butane is used as fuel in small lighters and in some torches. It is also used in the manufacture of synthetic rubber and gasoline. Carry out the **CHEMLAB** at the end of the chapter to determine which alkanes are found in your lab's gas supply.

Figure 22-3

Ethane makes up about nine percent of natural gas. Because the bonds around carbon are arranged in a tetrahedral fashion, propane and butane have a zig-zag geometry.

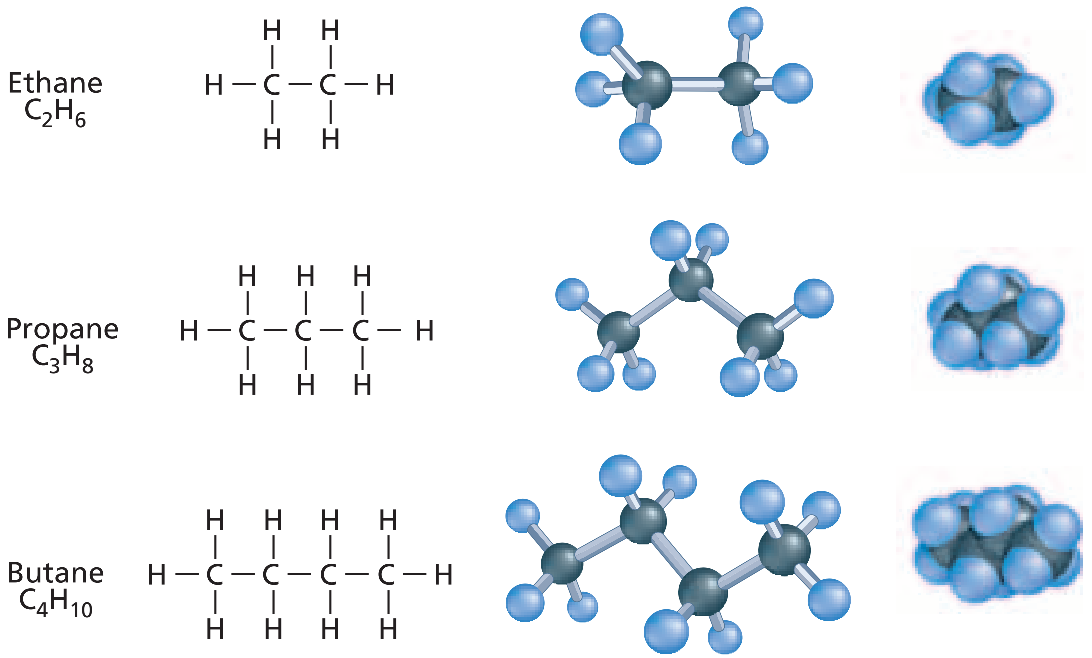


Figure 22-4

This taxi in Bangkok, Thailand is one of many cars, trucks, and buses that have been modified to burn propane. Burning propane benefits the environment because it produces less air pollution than does gasoline.

By now you have noticed that names of alkanes end in *-ane*. Also, alkanes with five or more carbons in a chain have names that use a prefix derived from the Greek or Latin word for the number of carbons in each chain. For example, *pent*ane has five carbons just as a *pent*agon has five sides, and *oct*ane has eight carbons just as an *oct*opus has eight tentacles. Because methane, ethane, propane, and butane were named before alkane structures were known, their names do not have numerical prefixes. **Table 22-1** shows the names and structures of the first ten alkanes. Notice the underlined prefix representing the number of carbon atoms in the molecule.

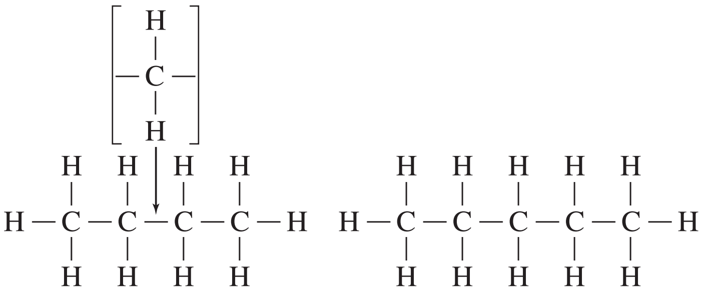
Table 22-1

First Ten of the Alkane Series

Name	Molecular formula	Condensed structural formula	Melting point (°C)	Boiling point (°C)
Methane	CH_4	CH_4	−182	−162
Ethane	C_2H_6	CH_3CH_3	−183	−89
Propane	C_3H_8	$CH_3CH_2CH_3$	−188	−42
Butane	C_4H_{10}	$CH_3CH_2CH_2CH_3$	−138	−0.5
Pentane	C_5H_{12}	$CH_3CH_2CH_2CH_2CH_3$	−130	36
Hexane	C_6H_{14}	$CH_3CH_2CH_2CH_2CH_2CH_3$	−95	69
Heptane	C_7H_{16}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$	−91	98
Octane	C_8H_{18}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	−57	126
Nonane	C_9H_{20}	$CH_3(CH_2)_7CH_3$	−54	151
Decane	$C_{10}H_{22}$	$CH_3(CH_2)_8CH_3$	−29	174

In **Table 22-1**, you can see that the structural formulas are written in a different way from those in **Figure 22-3.** These formulas, called condensed structural formulas, save space by not showing how the hydrogen atoms branch off the carbon atoms. Condensed formulas can be written in several ways. In **Table 22-1**, the lines between carbon atoms have been eliminated to save space.

Looking at the alkane series in **Table 22-1,** you can see that —CH_2— is a repeating unit in the chain of carbon atoms. Note, for example, in the diagram below that pentane has one more —CH_2— unit than butane.



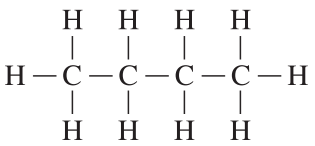
Butane (C_4H_{10}) Pentane (C_5H_{12})

You can further condense structural formulas by writing the —CH_2— unit in parentheses followed by a subscript to show the number of units, as is done with nonane and decane.

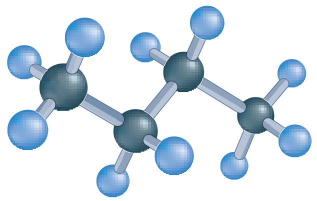
A series of compounds that differ from one another by a repeating unit is called a **homologous series**. A homologous series has a fixed numerical relationship among the numbers of atoms. For alkanes, the relationship between the numbers of carbon and hydrogen atoms can be expressed as C_nH_{2n+2}, where n is equal to the number of carbon atoms in the alkane. Given the number of carbon atoms in an alkane, you can write the molecular formula for any alkane. For example, heptane has seven carbons so its formula is $C_7H_{2(7)+2}$, or C_7H_{16}. What is the molecular formula for a 13-carbon alkane?

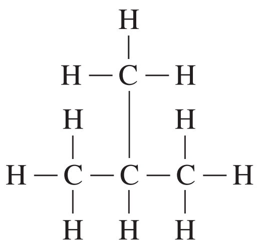
Branched-Chain Alkanes

The alkanes you have studied so far are called straight-chain alkanes because the carbon atoms are bonded to each other in a single line. Now look at the two structures in the following diagram. If you count the carbon and hydrogen atoms, you will discover that both structures have the same molecular formula, C_4H_{10}. Do these structures represent the same substance?

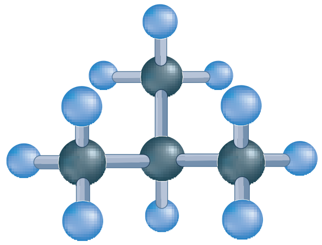


Butane
Molecular formula: C_4H_{10}





Isobutane
Molecular formula: C_4H_{10}



If you think that the structures represent two different substances, you are right. The structure on the left represents butane, and the structure on the right represents a branched-chain alkane, known as isobutane, a substance whose chemical and physical properties are different from those of butane. As you see, carbon atoms can bond to one, two, three, or even four other carbon atoms. This property makes possible a variety of branched-chain alkanes. How do you name isobutane using IUPAC rules?

Naming Branched-Chain Alkanes

You've seen that both a straight-chain and a branched-chain alkane can have the same molecular formula. This fact illustrates a basic principle of organic chemistry: the order and arrangement of atoms in an organic molecule determine its identity. Therefore, the name of an organic compound also must describe the molecular structure of the compound accurately.

For the purpose of naming, branched-chain alkanes are viewed as consisting of a straight chain of carbon atoms with other carbon atoms or groups of carbon atoms branching off the straight chain. The longest continuous chain of carbon atoms is called the **parent chain**. All side branches are called **substituent groups** because they appear to substitute for a hydrogen atom in the straight chain.

Biology CONNECTION

By the middle of the 19th century, inorganic chemistry and physics were regarded as rigorous experimental sciences. However, the biological sciences were held back in part by the prevailing belief in vitalism—the idea that the processes and materials of living things could not be explained by the same laws and theories that applied to physics and chemistry. Vitalism was dealt its final blow in 1897, when Eduard Buchner, a German chemist, showed that extracts of yeast could carry out fermentation of sugar when no living cells were present.

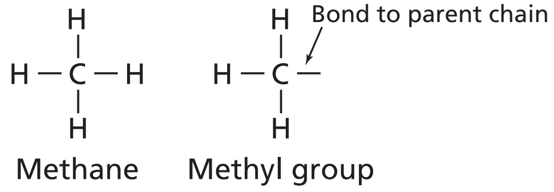
Careers Using Chemistry

Alternative Fuel Technician

Are you interested in improving the quality of the air you breathe and reducing our dependence on petroleum resources? Do you like to work with cars? Then consider a career as an alternative fuels technician.

Alternative fuels are being developed and used today to replace fossil fuels such as oil. As an alternative fuels technician, you may work in research developing new vehicles. Or, you may educate consumers and service and maintain their environmentally friendly vehicles.

Each alkane-based substituent group branching from the parent chain is named for the straight-chain alkane having the same number of carbon atoms as the substituent. The ending *-ane* is replaced with the letters *-yl,* as shown in the following diagram.

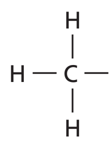
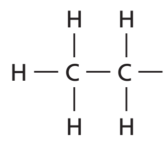
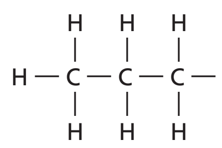
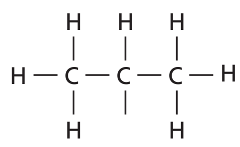
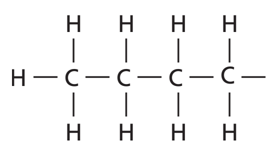


An alkane-based substituent group is called an alkyl group. Several common alkyl groups are shown in **Table 22-2**. What relationship exists between these groups and the alkanes in **Table 22-1**?

The naming process To name organic structures, chemists follow systematic rules approved by the International Union of Pure and Applied Chemistry (IUPAC). Here are the rules for naming branched-chain alkanes.

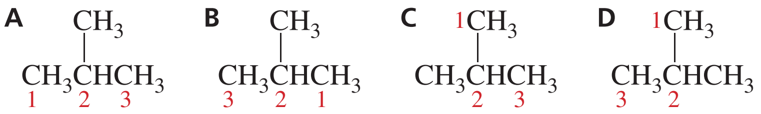
1. *Count the number of carbon atoms in the longest continuous chain.* Use the name of the straight-chain alkane with that number of carbons as the name of the parent chain of the structure.
2. *Number each carbon in the parent chain.* Locate the end carbon closest to a substituent group. Label that carbon position one. This step gives all the substituent groups the lowest position numbers possible.
3. *Name each alkyl group substituent.* The names of these groups are placed before the name of the parent chain.

Table 22-2

Common Alkyl Groups		
Name	**Condensed structural formula**	**Structural formula**
Methyl	CH_3-	
Ethyl	CH_3CH_2-	
Propyl	$CH_3CH_2CH_2-$	
Isopropyl	$CH_3\overset{|}{C}HCH_3$	
Butyl	$CH_3CH_2CH_2CH_2-$	

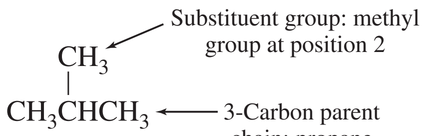
4. *If the same alkyl group occurs more than once as a branch on the parent structure, use a prefix (di-, tri-, tetra-, etc.) before its name to indicate how many times it appears.* Then use the number of the carbon to which each is attached to indicate its position.
5. *Whenever different alkyl groups are attached to the same parent structure, place their names in alphabetical order.* Do not consider the prefixes (*di-*, *tri-*, etc.) when determining alphabetical order.
6. *Write the entire name using hyphens to separate numbers from words and commas to separate numbers.* No space is added between the substituent name and the name of the parent chain.

Now, try to name the branched-chain structure, isobutane.



1. The longest chain in the structures above contains three carbons. This is true if you start on the left (A), right (B), or carbon in the branch (C, D), as you can see in the accompanying diagram. Therefore, the name of the parent chain will be *propane*.
2. No matter where the numbering starts in this molecule, the alkyl group is at position 2. So, the four options are equivalent.
3. The alkyl group here is a methyl group because it has only one carbon.
4. No prefix is needed because only one alkyl group is present.
5. Alphabetical order does not need to be considered because only one group is present.

After applying the rules, you can write the IUPAC name *2-methylpropane* for isobutane. See **Figure 22-5.** Note that the name of the alkyl group is added in front of the name of the parent chain with no space between them. A hyphen separates the number from the word.



2-Methylpropane

Because structural formulas can be written with chains oriented in various ways, you need to be careful in finding the longest continuous carbon chain. The following examples are written as skeletal formulas. A skeletal formula shows only the carbon atoms of an organic molecule in order to emphasize the chain arrangement. Hydrogen atoms are not shown in these skeletal formulas. Study the correct numbering of carbon atoms in the following examples. Note that numbering either carbon chain starting on the left-most carbon would disobey rule 1 on the previous page.

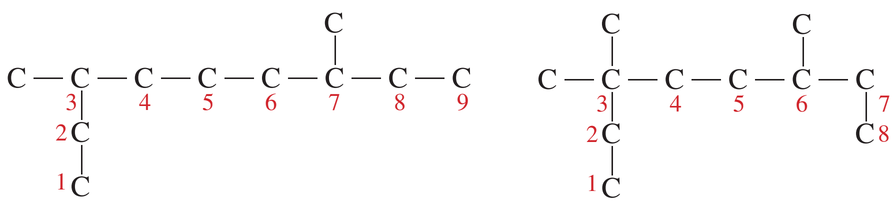
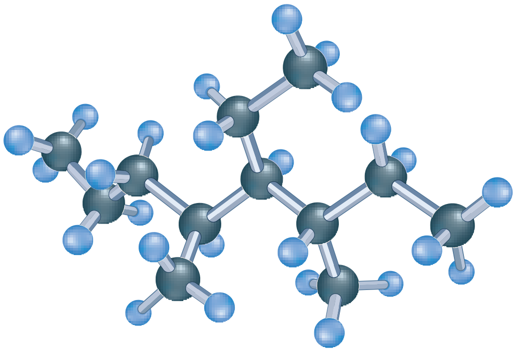


Figure 22-5

Many of today's automobile and truck air conditioners can use hydrocarbon refrigerant mixtures containing 2-methylpropane that are environmentally safe.

Example Problem 22-1 and the Practice Problems that follow it will help you develop skill at naming branched-chain alkanes.

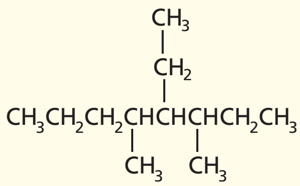


This ball-and-stick model of the molecule in Example Problem 22-1 shows how the molecule looks in three dimensions.

EXAMPLE PROBLEM 22-1

Naming Branched-Chain Alkanes

Name the following alkane.



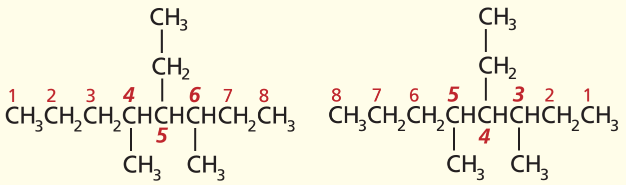
1. Analyze the Problem

You are given a structure. To determine the name of the parent chain and the names and locations of branches, follow the IUPAC rules.

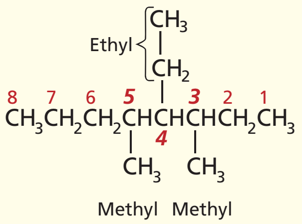
2. Solve for the Unknown

a. Count carefully to find the longest chain. In this case, it is easy. The longest chain has eight carbon atoms, so the parent name is *octane*.

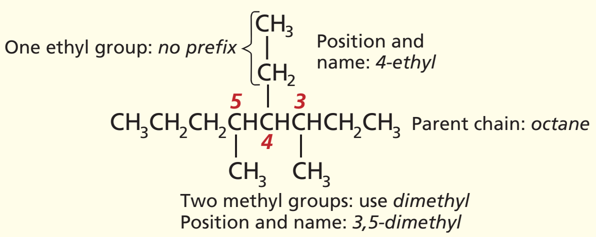
b. Number the chain in both directions. Numbering from the left puts the alkyl groups at positions 4, 5, and 6. Numbering from the right puts alkyl groups at positions 3, 4, and 5. Therefore, 3, 4, and 5 are the lowest position numbers and will be used in the name.



c. Identify and name the alkyl groups branching from the parent chain. There are one-carbon *methyl* groups at positions 3 and 5, and a two-carbon *ethyl* group at position 4.



d. Look for and count the alkyl groups that occur more than once. Determine the prefix to use to show the number of times each group appears. In this example, the prefix *di-* will be added to the name *methyl* because two methyl groups are present. No prefix is needed for the one ethyl group. Then show the position of each group with the appropriate number.



f. Place the names of the alkyl branches in alphabetical order, *ignoring the prefixes*. Alphabetical order puts the name ethyl before dimethyl.

g. Write the name of the structure using hyphens and commas as needed. The name should be written as *4-ethyl-3,5-dimethyloctane*.

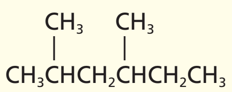
3. Evaluate the Answer

The longest continuous carbon chain has been found and numbered correctly. All branches have been designated with correct prefixes and alkyl-group names. Alphabetical order and punctuation are correct.

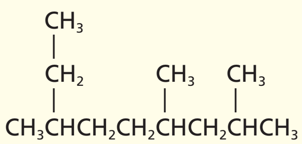
PRACTICE PROBLEMS

1. Use IUPAC rules to name the following structures.

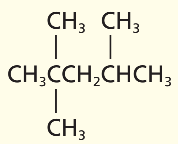
a.



b.



c.



2. Draw the structures of the following branched-chain alkanes.

a. 2,3-dimethyl-5-propyldecane

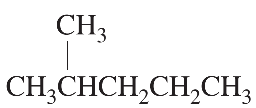
b. 3,4,5-triethyloctane

Practice! For more practice with naming branched-chain alkanes go to **Supplemental Practice Problems** in Appendix A.

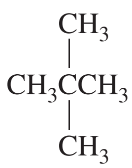
Section 22.1 Assessment

3. Use IUPAC rules to name the following structures.

a.



b.



4. Write a condensed structural formula for each of the following.

a. 3,4-diethylheptane

b. 4-isopropyl-3-methyldecane

5. Name two types of carbon-containing compounds that are considered inorganic rather than organic.

6. Write correct molecular formulas for pentadecane, a 15-carbon alkane, and icosane, a 20-carbon alkane.

7. Why is the name 3-*butylpentane* incorrect? Based on this name, write the structural formula for the compound. What is the correct IUPAC name for 3-butylpentane?

8. **Thinking Critically** Hexane is called a straight-chain alkane. Yet, a molecule of hexane has a zig-zag rather than a linear geometry. Explain this apparent paradox. Explain what characteristic of carbon atoms causes the zig-zag geometry of straight-chain alkanes.

9. **Graphing** Use data from **Table 22-1** to graph boiling point versus the number of carbon atoms in the alkane chain for the first ten alkanes. Use the graph to predict boiling points for straight-chain alkanes with 11 and 12 carbon atoms. For more help, refer to *Drawing and Using Line Graphs* in the **Math Handbook** on pages 903–907 of this textbook.

Section 22.2

Cyclic Alkanes and Alkane Properties

Objectives

- **Name** a cyclic alkane by examining its structure.
- **Draw** the structure of a cyclic alkane given its name.
- **Describe** the properties of alkanes.
- **Distinguish** between saturated and unsaturated hydrocarbons.

Vocabulary

cyclic hydrocarbon
cycloalkane
saturated hydrocarbon
unsaturated hydrocarbon

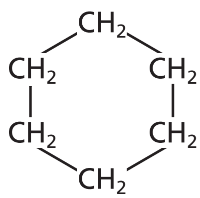
One of the reasons that such a variety of organic compounds exists is that carbon atoms can form ring structures. An organic compound that contains a hydrocarbon ring is called a **cyclic hydrocarbon**.

Cycloalkanes

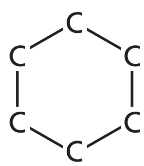
To indicate that a hydrocarbon has a ring structure, the prefix *cyclo-* is used with the hydrocarbon name. Thus cyclic hydrocarbons that contain single bonds only are called **cycloalkanes.** Cycloalkanes can have rings with three, four, five, six, or even more carbon atoms. Cyclopropane, the smallest cycloalkane, is a gas that was used for many years as an anesthetic for surgery. However, it is no longer used because it is highly flammable. The name for the six-carbon cycloalkane is cyclohexane. Obtained from petroleum, cyclohexane is used in paint and varnish removers and for extracting essential oils to make perfume. Note that cyclohexane (C_6H_{12}) has two fewer hydrogen atoms than straight-chain hexane (C_6H_{14}) because a valence electron from each of two carbon atoms is now forming a carbon-carbon bond rather than a carbon-hydrogen bond.

As you can see in **Figure 22-6**, cyclic hydrocarbons such as cyclohexane are represented by condensed, skeletal, and line structures. Line structures show only the carbon-carbon bonds with carbon atoms understood to be at each vertex of the structure. Hydrogen atoms are assumed to occupy the remaining bonding positions unless substituents are present.

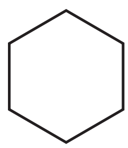
Naming substituted cycloalkanes Like other alkanes, cycloalkanes can have substituent groups. Substituted cycloalkanes are named by following the same IUPAC rules used for straight-chain alkanes, but with a few modifications. With cycloalkanes, there is no need to find the longest chain because the ring is always considered to be the parent chain. Because a cyclic structure has no ends, numbering is started on the carbon that is bonded to the substituent group. When there are two or more substituents, the carbons are numbered around the ring in a way that gives the lowest possible set of numbers for the substituents. If only one group is attached to the ring, no number is necessary. The following Example Problem will show you how a cycloalkane is named.



Condensed structural formula



Skeletal structure



Line structure

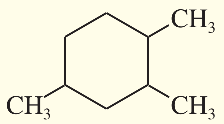
Figure 22-6

Cyclohexane can be represented in several ways. Chemists most often draw line structures for cyclic hydrocarbons because the molecules have distinct shapes that are easily identifiable.

EXAMPLE PROBLEM 22-2

Naming Cycloalkanes

Name the cycloalkane shown.



1. Analyze the Problem

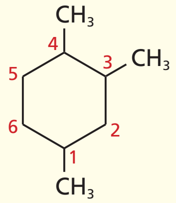
You are given a structure. To determine the parent cyclic structure and the location of branches, follow the IUPAC rules.

2. Solve for the Unknown

a. Count the carbons in the ring and use the name of the parent cyclic hydrocarbon. In this case, the ring has six carbons, so the parent name is *cyclohexane*.

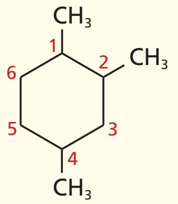
b. Number the ring, starting from one of the CH_3- branches. Find the numbering that gives the lowest possible set of numbers for the branches. Here are two ways of numbering the ring.

A



1,3,4-Trimethylcyclohexane

B



1,2,4-Trimethylcyclohexane

Numbering from the carbon atom at the bottom of the ring puts the CH_3- groups at positions 1, 3, and 4 in structure A. Numbering from the carbon at the top of the ring gives the position numbers 1, 2, and 4. All other numbering schemes place the CH_3- groups at higher position numbers. Thus, 1, 2, and 4 are the lowest possible position numbers and will be used in the name.

c. Name the substituents. All three are the same—one-carbon methyl groups.

d. Add the prefix to show the number of groups present. Three methyl groups are present, so the prefix *tri-* will be added to the name *methyl* to make *trimethyl.*

e. Alphabetical order can be ignored because only one type of group is present.

g. Put the name together using the name of the parent cycloalkane. Use commas to separate numbers and hyphens between numbers and words. Write the name as *1,2,4-trimethylcyclohexane*.

3. Evaluate the Answer

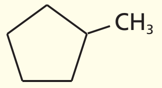
The parent ring structure is numbered to give the branches the lowest possible set of numbers. The prefix *tri-* indicates that three methyl groups are present. No alphabetization is necessary because all branches are methyl groups.

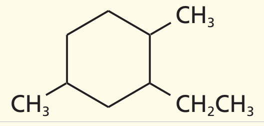
Stains and varnishes used to refinish wood often use cyclohexane as a solvent.

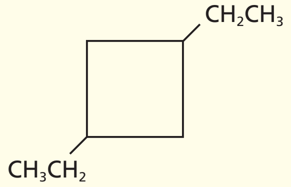
For more practice with naming cycloalkanes go to **Supplemental Practice Problems** in Appendix A.

PRACTICE PROBLEMS

10. Use IUPAC rules to name the following structures.

a.


b.


c.


11. Draw the structures of the following cycloalkanes.

a. 1-ethyl-3-propylcyclopentane

b. 1,2,2,4-tetramethylcyclohexane

Properties of Alkanes

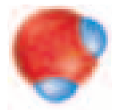
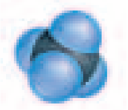
You have learned that the structure of a molecule affects its properties. For example, ammonia (NH_3) can accept a proton from an acid to become an ammonium ion (NH_4^+) because the nitrogen atom has an unshared pair of electrons. As another example, the O—H bonds in a water molecule are polar, and because the H—O—H molecule has a bent geometry, the molecule itself is polar. Thus water molecules are attracted to each other and can form hydrogen bonds with each other. As a result, the boiling and melting points of water are much higher than those of other substances having similar molecular mass and size.

What properties would you predict for alkanes? All of the bonds in these hydrocarbons are between either a carbon atom and a hydrogen atom or two carbon atoms. Are these bonds polar? Remember, a bond between two atoms is polar only if the atoms differ by at least 0.5 in their Pauling electronegativity values. Carbon's electronegativity value is 2.55, and hydrogen's is 2.20, so a C—H bond has a difference of only 0.35. Thus, it is not polar. A bond between two identical atoms such as carbon can never be polar because the difference in their electronegativity values is zero. Because all of the bonds in alkanes are nonpolar, alkane molecules are nonpolar.

Physical properties of alkanes What types of physical properties do nonpolar compounds have? A comparison of two molecular substances—one

Table 22-3

Comparing Physical Properties of Water and Methane

Substance and formula	Water (H_2O)	Methane (CH_4)
Model		
Molecular mass	18 amu	16 amu
State at room temperature	liquid	gas
Boiling point	100°C	−162°C
Melting point	0°C	−182°C

CONTENTS



Figure 22-7

Alkane hydrocarbons are often used as fuels to provide heat and, sometimes, light. The smudge pots shown on the left produce heat that helps prevent cold-weather damage to citrus crops. The gas lantern gives off light, and the gas-log fireplace provides both heat and light.

polar and the other nonpolar—will help you answer this question. **Table 22-3** compares the properties of water and methane.

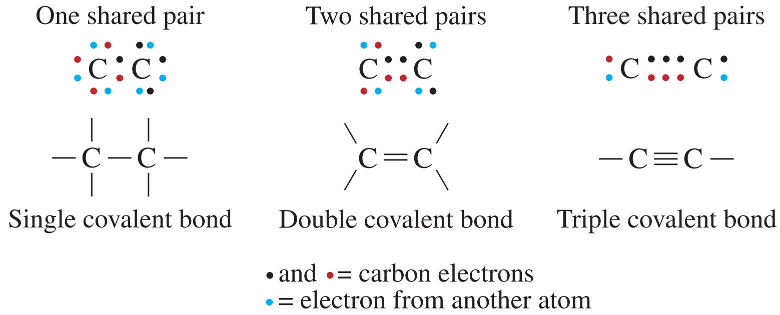
Note that the molecular mass of methane (16 amu) is close to the molecular mass of water (18 amu). Also, water and methane molecules are similar in size. However, when you compare the melting and boiling points of methane to those of water, you can see evidence that the molecules differ in some significant way. These temperatures differ greatly because methane molecules have little intermolecular attraction compared to water molecules. This difference in attraction can be explained by the fact that methane molecules are nonpolar and do not form hydrogen bonds with each other, whereas water molecules are polar and freely form hydrogen bonds. What straight-chain alkane in **Table 22-1** has a boiling point nearest that of water?

The difference in polarity and hydrogen bonding also explains the immiscibility of alkanes and other hydrocarbons with water. If you try to dissolve alkanes, such as lubricating oils, in water, the two liquids separate almost immediately into two phases. This separation happens because the attractive forces between alkane molecules are stronger than the attractive forces between the alkane and water molecules. Therefore, alkanes are more soluble in solvents composed of nonpolar molecules like themselves than in water, a polar solvent. This is another example of the rule of thumb that "like dissolves like."

Chemical properties of alkanes The main chemical property of alkanes is their low reactivity. Recall that many chemical reactions occur when a reactant with a full electrical charge, such as an ion, or with a partial charge, such as a polar molecule, is attracted to another reactant with the opposite charge. Molecules such as alkanes, in which atoms are connected by nonpolar bonds, have no charge. As a result, they have little attraction for ions or polar molecules. The low reactivity of alkanes also can be attributed to the relatively strong C—C and C—H bonds. The low reactivity of alkanes limits their uses. As you can see from **Figure 22-7,** alkanes are commonly used as fuels because they readily undergo combustion in oxygen.

Multiple Carbon-Carbon Bonds

Carbon atoms can bond to each other not only by single covalent bonds but also by double and triple covalent bonds. In a double bond, atoms share two pairs of electrons; in a triple bond, they share three pairs of electrons. The following diagram shows Lewis structures and structural formulas for single, double, and triple covalent bonds.



Try at Home LAB

See page 962 in Appendix E for **Comparing Water and a Hydrocarbon**

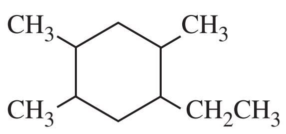
In the nineteenth century, before they understood bonding and the structure of organic substances, chemists experimented with hydrocarbons obtained from heating animal fats and plant oils. They classified these hydrocarbons according to a chemical test in which they mixed each hydrocarbon with bromine and then measured how much reacted with the hydrocarbon. Some hydrocarbons would react with a little bromine, some would react with more, and some would not react at all. Chemists called the hydrocarbons that reacted with bromine unsaturated hydrocarbons in the same sense that an unsaturated aqueous solution can dissolve more solute. Hydrocarbons that did not react with bromine were said to be saturated.

Modern chemists can explain the results of the chemists of 170 years ago. Hydrocarbons that reacted with bromine had double or triple covalent bonds. Those that took up no bromine had only single covalent bonds. Today, a **saturated hydrocarbon** is defined as a hydrocarbon having only single bonds—in other words, an alkane. An **unsaturated hydrocarbon** is a hydrocarbon that has at least one double or triple bond between carbon atoms. You will learn more about unsaturated hydrocarbons in Section 22.3.

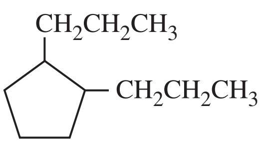
Section 22.2 Assessment

12. Use IUPAC rules to name the following structures.

a.



b.



13. Write a condensed structural formula for each of the following.

a. 1-ethyl-4-methylcyclohexane

b. 1,2-dimethylcyclopropane

14. Describe the main structural characteristics of alkane molecules. Give two examples of how these characteristics determine the physical properties of alkanes.

15. What structural characteristic distinguishes saturated from unsaturated hydrocarbons?

16. Thinking Critically Some shortening is described as "hydrogenated vegetable oil." This means that the oils reacted with hydrogen in the presence of a catalyst. Make a hypothesis to explain why hydrogen reacted with the oils.

17. Modeling Construct ball-and-stick molecular models of the following cyclic alkanes.

a. isopropylcyclobutane

b. 1,2,4-trimethylcyclopentane

Section 22.3 Alkenes and Alkynes

You now know that alkanes are saturated hydrocarbons because they contain only single covalent bonds between carbon atoms, and that unsaturated hydrocarbons have at least one double or triple bond between carbon atoms.

Objectives

- **Compare** the properties of alkenes and alkynes with those of alkanes.
- **Describe** the molecular structures of alkenes and alkynes.
- **Name** an alkene or alkyne by examining its structure.
- **Draw** the structure of an alkene or alkyne by analyzing its name.

Vocabulary

alkene
alkyne

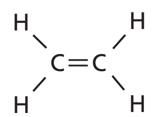
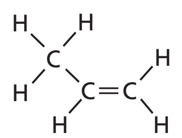
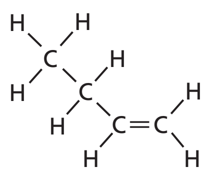
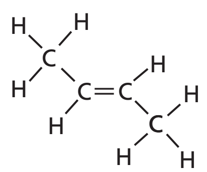
Alkenes

Unsaturated hydrocarbons that contain one or more double covalent bonds between carbon atoms in a chain are called **alkenes**. Because an alkene must have a double bond between carbon atoms, there is no 1-carbon alkene. The simplest alkene has two carbon atoms double-bonded to each other. The remaining four electrons—two from each carbon atom—are shared with four hydrogen atoms to give the molecule ethene (C_2H_4).

Alkenes with only one double bond constitute a homologous series. If you study the molecular formulas for the substances shown in **Table 22-4**, you will see that each has twice as many hydrogen atoms as carbon atoms. The general formula for the series is C_nH_{2n}. Each alkene has two fewer hydrogen atoms than the corresponding alkane because two electrons now form the second covalent bond and are no longer available for bonding to hydrogen atoms. What are the molecular formulas for 6-carbon and 9-carbon alkenes?

Table 22-4

Examples of Alkenes

Name	Molecular formula	Structural formula	Condensed structural formula	Melting point (°C)	Boiling point (°C)
Ethene	C_2H_4		$CH_2{=}CH_2$	−169	−104
Propene	C_3H_6		$CH_3CH{=}CH_2$	−185	−48
1-Butene	C_4H_8		$CH_2{=}CHCH_2CH_3$	−185	−6
2-Butene	C_4H_8		$CH_3CH{=}CHCH_3$	−106	0.8

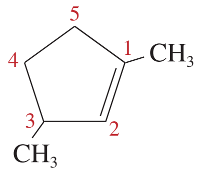
Naming alkenes Alkenes are named in much the same way as alkanes. Their names are formed by changing the *-ane* ending of the corresponding alkane to *-ene*. An alkane with two carbons is named eth*ane*, and an alkene with two carbons is named eth*ene*. Likewise, a three-carbon alkene is named propene. Ethene and propene have older, common names *ethylene* and *propylene*, respectively.

To name alkenes with four or more carbons in the chain, it is necessary to specify the location of the double bond. You do this by numbering the carbons in the parent chain starting at the end of the chain that will give the first carbon in the double bond the lowest number. Then you use only that number in the name.

1 2 3 4	1 2 3 4	1 2 3 4	4 3 2 1
C=C−C−C	C−C=C−C	~~C−C−C=C~~	C−C−C=C
1-Butene	2-Butene	~~3-Butene~~	1-Butene

Note that the third structure is not "3-butene" because it is identical to the first structure, 1-butene. It is important to recognize that 1-butene and 2-butene are two different substances, each with its own properties.

Cyclic alkenes are named in much the same way as cyclic alkanes; however, carbon number 1 must be one of the carbons connected by the double bond. Note the numbering in the compound shown below, 1,3-dimethylcyclopentene.



Naming branched-chain alkenes When naming branched-chain alkenes, follow the IUPAC rules for naming branched-chain alkanes—with two differences. First, in alkenes the parent chain is always the longest chain that contains the double bond, whether it is the longest chain of carbon atoms or not. Second, the position of the double bond, not the branches, determines how the chain is numbered. Note that there are two 4-carbon chains in the molecule shown below, but only the one with the double bond is used as a basis for naming. This branched-chain alkene is 2-methylbutene.

$$\underset{1}{CH_2}=\underset{2}{\overset{\overset{\displaystyle CH_3}{|}}{C}}-\underset{3}{CH_2}-\underset{4}{CH_3}$$

Some unsaturated hydrocarbons contain more than one double (or triple) bond. The number of double bonds in such molecules is shown by using a prefix (*di*-, *tri*-, *tetra*-, etc.) before the suffix *-ene*. The positions of the bonds are numbered in a way that gives the lowest set of numbers. Which numbering system would you use in the following example?

$$\underset{1}{C}-\underset{2}{C}-\underset{3}{C}=\underset{4}{C}-\underset{5}{C}=\underset{6}{C}-\underset{7}{C} \quad \text{or} \quad \underset{7}{C}-\underset{6}{C}-\underset{5}{C}=\underset{4}{C}-\underset{3}{C}=\underset{2}{C}-\underset{1}{C}$$

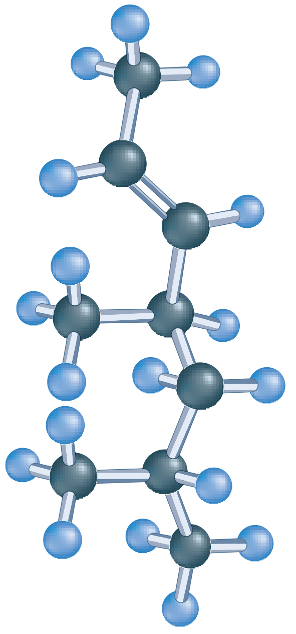
Because the molecule has a seven-carbon chain, you use the prefix *hepta*-. Because it has two double bonds, you use the prefix *di*- before *-ene,* giving the name *heptadiene*. Adding the numbers 2 and 4 to designate the positions of the double bonds, you arrive at the name *2,4-heptadiene*.

EXAMPLE PROBLEM 22-3

Naming Branched-Chain Alkenes

Name the alkene shown.

```
CH3CH=CHCHCH2CHCH3
        |     |
        CH3   CH3
```



This is a ball-and-stick model of the structure in Example Problem 22-3.

1. Analyze the Problem

You are given a branched-chain alkene that contains one double bond and two alkyl groups. Follow the IUPAC rules to name the organic compound.

2. Solve for the Unknown

a. The longest continuous carbon chain that includes the double bond contains seven carbons. The 7-carbon alkane is heptane, but the name is changed to hept*ene* because a double bond is present.

```
CH3CH=CHCHCH2CHCH3      Heptene parent chain
        |     |
        CH3   CH3
```

b. Number the chain to give the lowest number to the double bond.

```
1   2    3  4  5   6  7
CH3CH=CHCHCH2CHCH3      2-Heptene parent chain
        |     |
        CH3   CH3
```

c. Name each substituent.

```
1   2    3  4  5   6  7
CH3CH=CHCHCH2CHCH3      2-Heptene parent chain
        |     |
        CH3   CH3
        ↑     ↑
   Two methyl groups
```

d. Determine how many of each substituent is present, and assign the correct prefix to represent that number. Then, include the position numbers to get the complete prefix.

```
1   2    3  4  5   6  7
CH3CH=CHCHCH2CHCH3      2-Heptene parent chain
        |     |
        CH3   CH3       Two methyl groups at positions 4 and 6
                        Prefix is 4,6-dimethyl
```

e. The names of substituents do not have to be alphabetized because they are the same.

f. Apply the complete prefix to the name of the parent alkene chain. Use commas to separate numbers and hyphens between numbers and words. Write the name *4,6-dimethyl-2-heptene*.

3. Evaluate the Answer

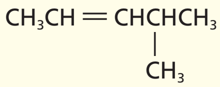
The longest carbon chain includes the double bond, and the position of the double bond has the lowest possible number. Correct prefixes and alkyl-group names designate the branches.

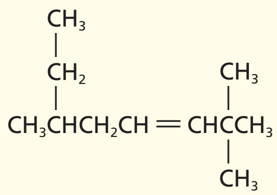
CONTENTS

For more practice with naming alkenes go to **Supplemental Practice Problems** in Appendix A.

PRACTICE PROBLEMS

18. Use IUPAC rules to name the following structures.

a. 

b. 

19. Draw the structure of 1,3-pentadiene.

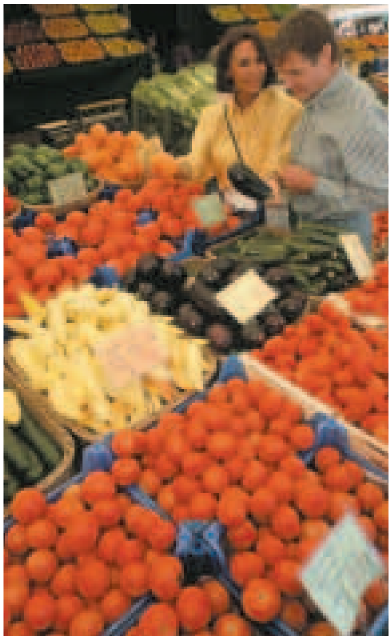


Figure 22-8

In large-scale operations, tomatoes are harvested when they are mostly green. The fruit is ripened by exposing it to ethene gas during shipment to markets.

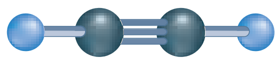
Properties and uses of alkenes Like alkanes, alkenes are nonpolar and therefore have low solubility in water as well as relatively low melting and boiling points. However, alkenes are more reactive than alkanes because the second covalent bond increases the electron density between two carbon atoms, providing a good site for chemical reactivity. Reactants that attract electrons can pull the electrons away from the double bond.

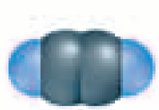
Several alkenes occur naturally in living organisms. For example, ethene (ethylene) is produced naturally by plants as a hormone. It causes fruit to ripen, and plays a part in causing leaves to fall from deciduous trees in preparation for winter. The tomatoes shown in **Figure 22-8** and other grocery store fruit can be ripened artificially by introducing ethene. Ethene also is the starting material for the synthesis of the plastic polyethylene, which is used to manufacture many products, including plastic bags and milk jugs. Natural rubber is another polymerized alkene. Other alkenes are responsible for the scents of lemons, limes, and pine trees.

Alkynes

Unsaturated hydrocarbons that contain one or more triple bonds between carbon atoms in a chain are called **alkynes**. Triple bonds involve the sharing of three pairs of electrons. The simplest and most commonly used alkyne is ethyne (C_2H_2), which is widely known by its common name *acetylene*. Study the models of ethyne in the following diagram.

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

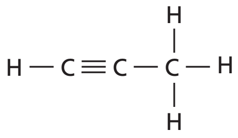
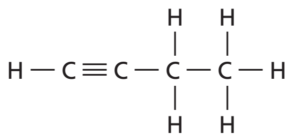
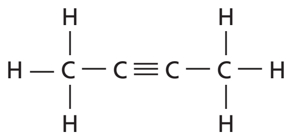




Models of ethyne (acetylene)

Naming alkynes Straight-chain alkynes and branched-chain alkynes are named in the same way as alkenes. The only difference is that the name of the parent chain ends in *-yne* rather than *-ene*. Study the examples in **Table 22-5**. Alkynes with one triple covalent bond form a homologous series with the general formula C_nH_{2n-2}. What are the molecular formulas for 5-carbon and 8-carbon alkynes?

Table 22-5

Examples of Alkynes					
Name	**Molecular formula**	**Structural formula**	**Condensed structural formula**	**Melting point (°C)**	**Boiling point (°C)**
Ethyne	C_2H_2	H—C≡C—H	CH≡CH	−81	Sublimes at −85°C
Propyne	C_3H_4		$CH_3C{\equiv}CH$	−103	−23
1-Butyne	C_4H_6		$CH{\equiv}CCH_2CH_3$	−126	8
2-Butyne	C_4H_6		$CH_3C{\equiv}CCH_3$	−32	27

The reactivities of alkynes make them useful starting materials in many synthesis reactions. In the **miniLAB** below, you will generate ethyne and investigate some of its properties.

miniLAB

Synthesis and Reactivity of Ethyne

Observing and Inferring Ethyne, often called *acetylene*, is used as a fuel in welding torches. In this lab, you will generate ethyne from the reaction of calcium carbide with water.

Materials 150-mL beaker, stirring rod, liquid dishwashing detergent, calcium carbide, forceps, wood splints, matches, ruler about 40 cm long, rubber band, phenolphthalein solution

Procedure 

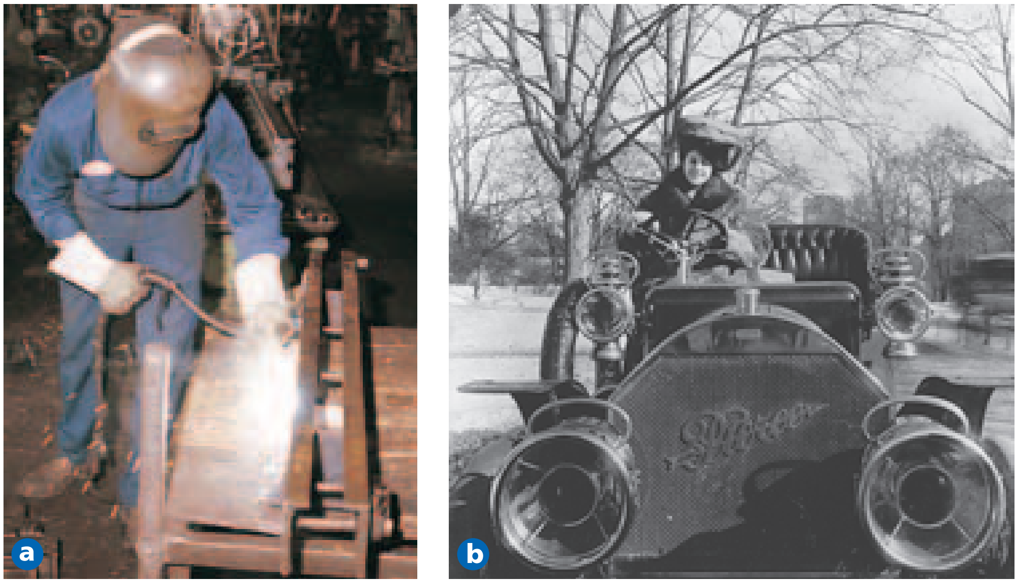
1. Use a rubber band to attach a wood splint to one end of the ruler so that about 10 cm of the splint extends beyond the stick.
2. Place 120 mL water in the beaker and add 5 mL dishwashing detergent. Mix thoroughly.
3. Use forceps to pick up a pea-sized lump of calcium carbide (CaC_2). Do not touch the CaC_2 with your fingers. **CAUTION:** *If CaC_2 dust touches your skin, wash it away immediately with a lot of water.* Place the lump of CaC_2 in the beaker of detergent solution.
4. Use a match to light the splint while holding the ruler at the opposite end. Immediately bring the burning splint to the bubbles that have formed from the reaction in the beaker. Extinguish the splint after observing the reaction.
5. Use the stirring rod to dislodge a few large bubbles of ethyne and determine whether they float upward or sink in air.
6. Rinse the beaker thoroughly, then add 25 mL distilled water and a drop of phenolphthalein solution. Use forceps to place a small piece of CaC_2 in the solution. Observe the results.

Analysis

1. Describe your observations in steps 3 and 4. Could ethyne be used as a fuel?
2. Based on your observations in step 5, what can you infer about the density of ethyne compared to the density of air?
3. The reaction of calcium carbide with water yields two products. One is ethyne gas (C_2H_2). From your observation in step 6, suggest what the other product is, and write a balanced chemical equation for the reaction.

Figure 22-9

a An alkyne you may already be familiar with is ethyne, commonly called acetylene, used to produce an extremely hot flame needed for welding metals. **b** Early automobiles burned acetylene in their headlamps to light the road ahead. Drivers had to get out to light the headlights with a match.



Properties of alkynes Alkynes have physical and chemical properties similar to those of the alkenes. Many of the reactions alkenes undergo, alkynes undergo as well. However, alkynes generally are more reactive than alkenes because the triple bond of alkynes has even greater electron density than the double bond of alkenes. This cluster of electrons is effective at inducing dipoles in nearby molecules, causing them to become unevenly charged and thus reactive.

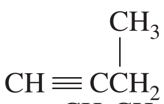
Ethyne is a by-product of oil refining and also is made in industrial quantities by the reaction of calcium carbide, CaC_2, with water. You learned about the production of ethyne by this method when you did the **miniLAB** on the previous page. When supplied with enough oxygen, ethyne burns with an intensely hot flame that can reach temperatures as high as 3000°C. Acetylene torches are commonly used in welding, as you see in **Figure 22-9**. Because the triple bond makes alkynes reactive, ethyne is used as a starting material in the manufacture of plastics and other organic chemicals used in industry.

Section 22.3 Assessment

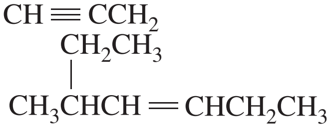
20. In what major way do the chemical properties of alkenes and alkynes differ from those of alkanes? What is responsible for this difference?

21. Name the structures shown using IUPAC rules.

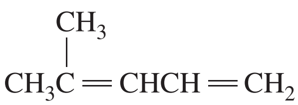
a.



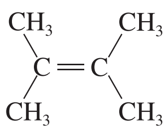
b.



c.



d.

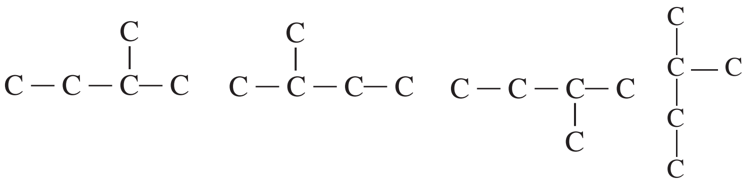


22. **Thinking Critically** Speculate on how the boiling and freezing points of alkynes compare with those of alkanes with the same number of carbon atoms. Explain your reasoning, then look up data to see if it supports your idea.

23. **Making Predictions** A carbon atom in an alkane is bonded to four other atoms. In an alkene, a carbon in a double bond is bonded to three other atoms, and in an alkyne, a carbon in a triple bond is bonded to two other atoms. What geometric arrangement would you predict for the bonds surrounding the carbon atom in each of these cases? (Hint: VSEPR theory can be used to predict shape.)

Section 22.4 Isomers

Study the structural formulas in the following diagram. How many different organic compounds are represented by these structures?



If you said that all of these structures represent the same compound, you are correct. The diagram simply shows four ways of drawing a structural formula for 2-methylbutane. As you can see, the structural formula for a given hydrocarbon can be written in several ways. Before you continue reading, make sure that you understand why these structural formulas are all alike. You'll soon learn, however, that three distinctly different alkanes have the molecular formula C_5H_{12}.

Objectives

- **Distinguish** between the two main categories of isomers, structural isomers and stereoisomers.
- **Differentiate** between *cis*- and *trans*- geometric isomers.
- **Recognize** different structural isomers given a structural formula.
- **Describe** the structural variation in molecules that results in optical isomers.

Vocabulary

isomer
structural isomer
stereoisomer
geometric isomer
chirality
asymmetric carbon
optical isomer
polarized light
optical rotation

Structural Isomers

Now, examine the models of three alkanes in **Figure 22-10** to determine how they are similar and how they differ.

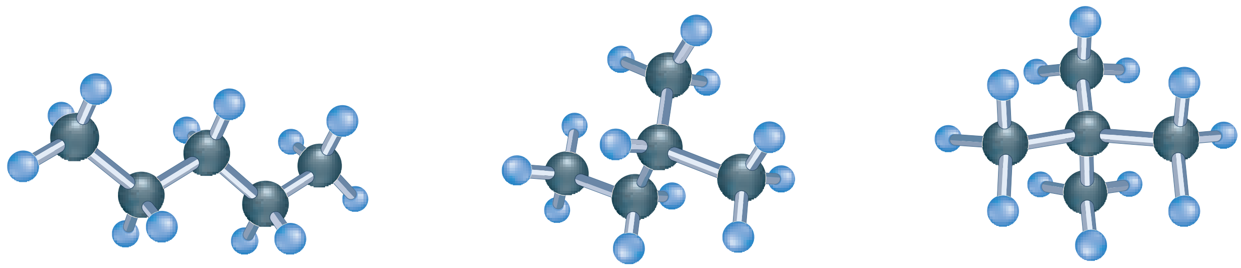
All three have five carbon atoms and 12 hydrogen atoms, so they have the molecular formula C_5H_{12}. However, as you can see, these models represent three different arrangements of atoms, pentane, 2-methylbutane, and 2,2-dimethylpropane. These three compounds are isomers. **Isomers** are two or more compounds that have the same molecular formula but different molecular structures. Note that cyclopentane and pentane are not isomers because cyclopentane's molecular formula is C_5H_{10}.

There are two main classes of isomers. **Figure 22-10** shows compounds that are examples of structural isomers. The atoms of **structural isomers** are bonded in different orders. The members of a group of structural isomers have different chemical and physical properties despite having the same formula. This observation supports one of the main principles of chemistry: The structure of a substance determines its properties. How does the trend in boiling points of C_5H_{12} isomers relate to their molecular structures?

As the number of carbons in a hydrocarbon increases, the number of possible structural isomers increases. For example, nine alkanes having the molecular formula C_7H_{16} exist. $C_{20}H_{42}$ has 316 319 structural isomers.

Figure 22-10

There are three different compounds that have the molecular formula C_5H_{12}. They are structural isomers. Note how their boiling points differ. Draw structural formulas for these three isomers.



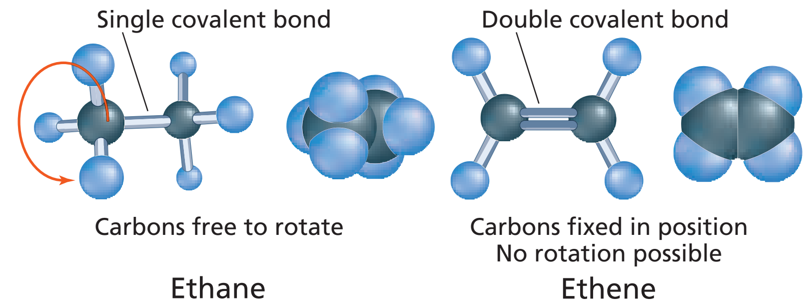
Pentane
bp = 36°C

2-Methylbutane
bp = 28°C

2,2-Dimethylpropane
bp = 9°C

Figure 22-11

The single-bonded carbons in ethane are free to rotate about the bond. The double-bonded carbons in ethene resist being rotated. How do you think this difference in ability to rotate would affect atoms or groups of atoms bonded to single-bonded and double-bonded carbon atoms?



Stereoisomers

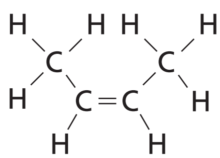
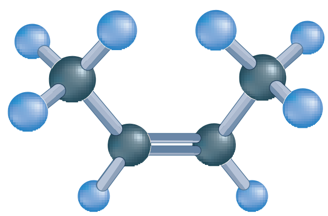
The second class of isomers involves a more subtle difference in bonding. **Stereoisomers** are isomers in which all atoms are bonded in the same order but are arranged differently in space. There are two types of stereoisomers. One type occurs in alkenes, which contain double bonds. Two carbon atoms with a single bond between them can rotate freely in relationship to each other. However, when a second covalent bond is present, the carbons can no longer rotate; they are locked in place, as shown in **Figure 22-11**.

To understand the consequences of this inability to rotate, compare the two possible structures of 2-butene shown in **Figure 22-12**. The arrangement in which the two methyl groups are on the same side of the molecule is indicated by the prefix *cis*-. The arrangement in which the two methyl groups are on opposite sides of the molecule is indicated by the prefix *trans*-. These terms derive from Latin: *cis* means *on the same side*, and *trans* means *across from*. Because the double-bonded carbons cannot rotate, the *cis*- form cannot easily change into the *trans*- form.

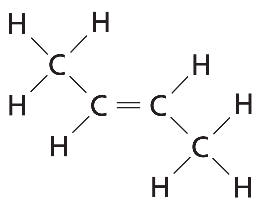
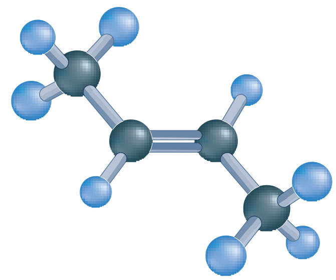
Isomers resulting from different arrangements of groups around a double bond are called **geometric isomers**. Note how the difference in geometry affects the isomers' physical properties such as melting point and boiling point. Geometric isomers differ in some chemical properties as well. If the compound is biologically active, such as a drug, the *cis*- and *trans*- isomers usually have greatly different effects. You may have read about the possible health concerns associated with *trans*- fatty acids in the diet. The *cis*- forms of the same acids seem not to be as harmful.

Figure 22-12

These isomers of 2-butene differ in the arrangement in space of the two methyl groups at the ends. The double-bonded carbon atoms cannot rotate with respect to each other, so the methyl groups must be in one of these two arrangements.

cis-2-Butene (C_4H_8)
mp = −139°C
bp = 3.7°C

trans-2-Butene (C_4H_8)
mp = −106°C
bp = 0.8°C

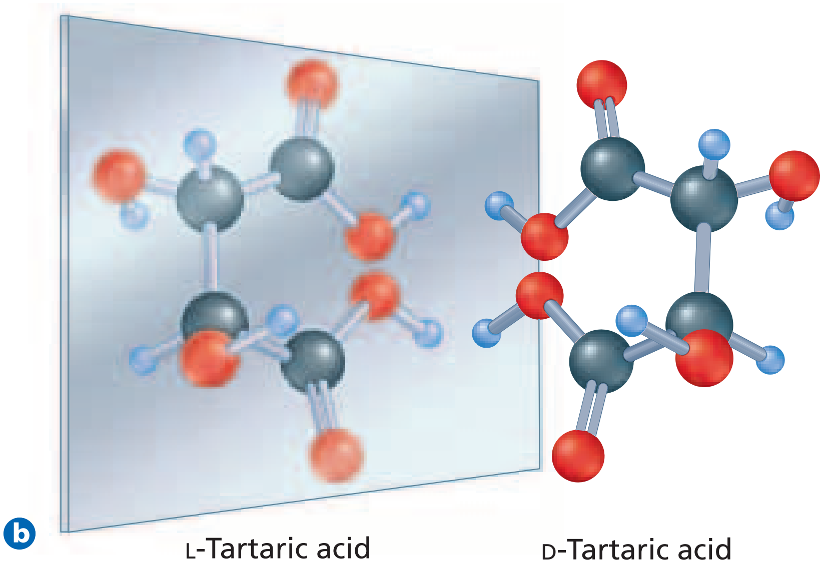
Chirality

In 1848, the young French chemist Louis Pasteur (1822–1895) reported his discovery that crystals of the organic compound tartaric acid, which is a by-product of the fermentation of grape juice to make wine, existed in two shapes that were not the same, but were mirror images of each other. Because a person's hands are like mirror images, as shown in **Figure 22-13a**, the crystals were called the right-handed and left-handed forms. The two forms of tartaric acid had the same chemical properties, melting point, density, and solubility in water, but only the left-handed form was produced by fermentation. In addition, bacteria were able to multiply when they were fed the left-handed form as a nutrient, but could not use the right-handed form.

Pasteur concluded that the two crystalline forms of tartaric acid exist because the tartaric acid molecules themselves exist in two arrangements, as shown in **Figure 22-13b**. Today, these two forms are called D-tartaric acid and L-tartaric acid. The letters D and L stand for the Latin prefixes *dextro-*, which means *to the right*, and *levo-*, which means *to the left*. Since Pasteur's time, chemists have discovered thousands of compounds that exist in right and left forms. This property is called **chirality**, a word derived from the Latin prefix *chiro-* for hand. Many of the substances found in living organisms, such as the amino acids that make up proteins, have this property. In general, living organisms make use of only one chiral form of a substance because only this form fits the active site of an enzyme.

Optical Isomers

In the 1860s, chemists realized that chirality occurs whenever a compound contains an asymmetric carbon. An **asymmetric carbon** is a carbon atom that has four different atoms or groups of atoms attached to it. The four groups always can be arranged in two different ways. Suppose that groups W, X, Y, and Z are attached to the same carbon atom in the two arrangements shown on the next page. Note that the structures differ in that groups X and Y have



L-Tartaric acid D-Tartaric acid

Figure 22-13

a Molecules of D-tartaric acid and L-tartaric acid are related to each other in the same way that your right hand and left hand are related. A mirror image of your right hand appears the same as your left hand. **b** These models represent the two forms of tartaric acid that Pasteur studied. If the model of D-tartaric acid (right) is reflected in a mirror, its image is a model of L-tartaric acid.

been exchanged. You cannot rotate the two arrangements in any way that will make them identical to each other.

Now suppose that you build models of these two structures. Is there any way you could turn one structure so that it looks the same as the other? (Whether letters appear forward or backward does not matter.) You would discover that there is no way to accomplish the task without removing X and Y from the carbon atom and switching their positions. So, the molecules are different even though they look very much alike.

Isomers that result from different arrangements of four different groups about the same carbon atom represent another class of stereoisomers called **optical isomers**. Optical isomers have the same physical and chemical properties except in chemical reactions where chirality is important, such as enzyme-catalyzed reactions in biological systems. Human cells, for example, incorporate only L-amino acids into proteins. Only the L-form of ascorbic acid is active as Vitamin C. The chirality of a drug molecule can greatly affect its activity. For example, only the L-form of the drug methyldopa is effective in reducing high blood pressure.

Now try your hand at distinguishing among types of isomers in the **problem-solving LAB.**

Optical rotation Mirror-image isomers are called optical isomers because they affect light passing through them. Recall that light is a form of electromagnetic radiation—transverse waves that can travel through empty space. Normally, the light waves in a beam from the sun or a lightbulb move in all possible planes, as shown in **Figure 22-14**. However, light can be filtered or reflected in such a way that the resulting waves all lie in the same plane. This type of light is called **polarized light**.

problem-solving LAB

Identifying Structural, Geometric, and Optical Isomers

Interpreting Scientific Illustrations

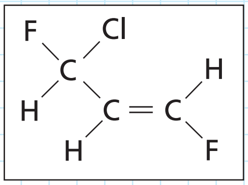
Identifying isomers requires skill in visualizing a molecule in three dimensions. Building models of molecules helps clarify their geometry.

Analysis

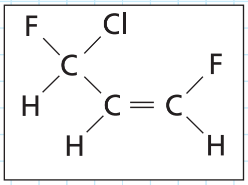
Structure 1 represents an organic molecule. **Structures 2, 3, and 4** represent three different isomers of the first molecule. Study each of these three structures to determine how they are related to **Structure 1**.

Thinking Critically

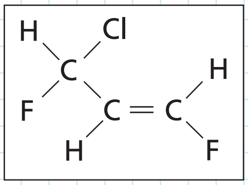
Write a sentence for each isomer describing how it differs from **Structure 1.** Which kind of isomer does each structure represent?



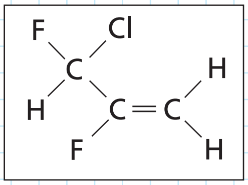
Structure 1



Structure 2

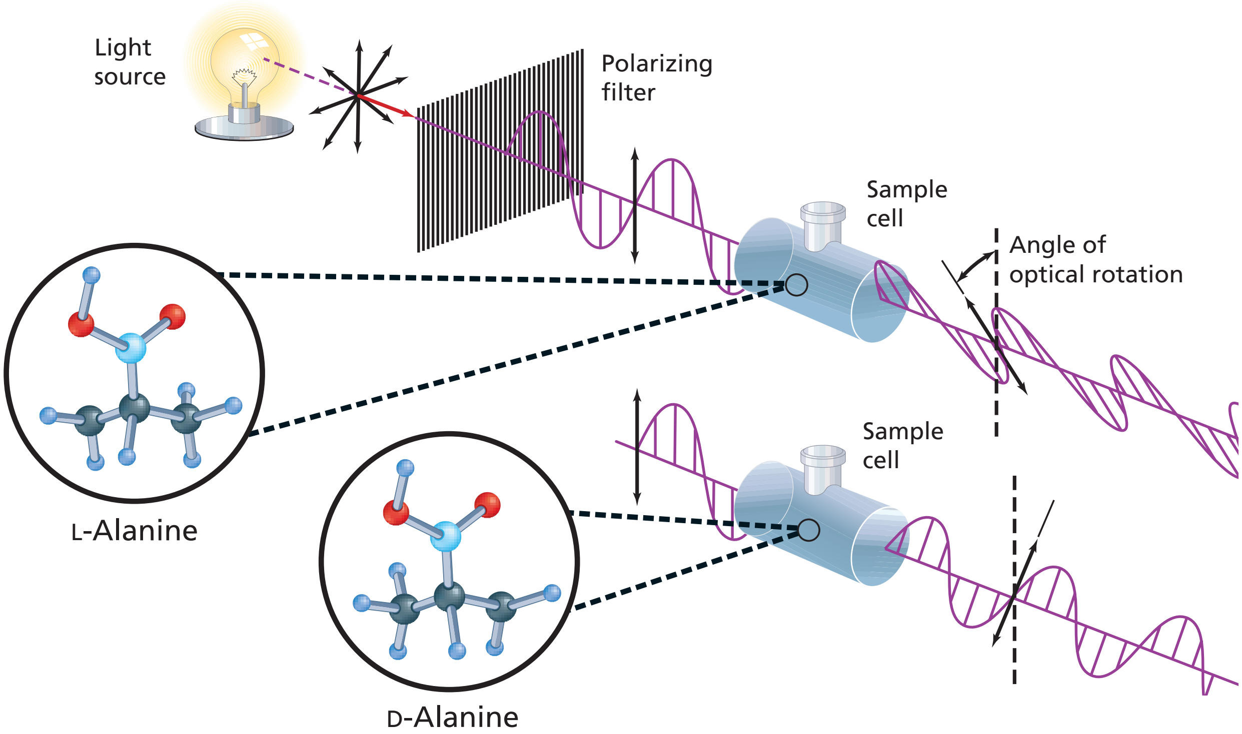


Structure 3



Structure 4

CONTENTS



When polarized light passes through a solution containing an optical isomer, the plane of polarization is rotated to the right (clockwise, when looking toward the light source) by a D-isomer or to the left (counterclockwise) by an L-isomer. Rotation to the left is illustrated in the upper part of **Figure 22-14**. This effect is called **optical rotation**. What do you think happens to polarized light when it passes through a 50:50 mixture of the D-form and L-form of a chiral substance?

Figure 22-14

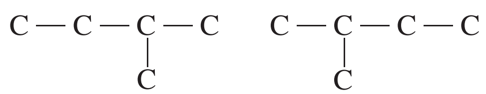
Polarized light can be produced by passing ordinary light through a filter that transmits light waves that lie in only one plane. Here, the filtered light waves are in a vertical plane before they pass through the sample cells.

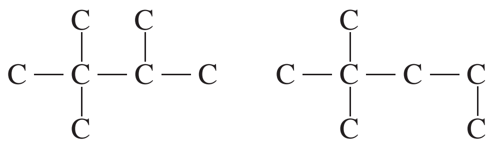
Section 22.4 Assessment

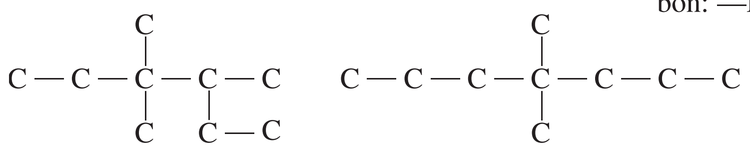
24. Explain the difference between structural isomers and stereoisomers.

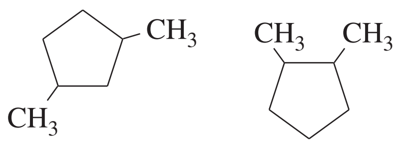
25. Draw all of the structural isomers possible for the alkane with a molecular formula of C_6H_{14}. Show only the carbon chains.

26. Decide whether the carbon chains shown in each of the following pairs represent the same compound or pairs of isomers.

a. 

b. 

c. 

d. 

27. Draw the structures of *cis*-3-hexene and *trans*-3-hexene.

28. Thinking Critically A certain reaction yields 80% *trans*-2-pentene and 20% *cis*-2-pentene. Draw the structures of these two geometric isomers, and develop a hypothesis to explain why the isomers form in the proportions cited.

29. Formulating Models Starting with a single carbon atom, draw two different optical isomers by attaching the following atoms or groups to the carbon: —H, $—CH_3$, $—CH_2CH_3$, $—CH_2CH_2CH_3$

Section 22.5

Aromatic Hydrocarbons and Petroleum

Objectives

- **Compare** and **contrast** the properties of aromatic and aliphatic hydrocarbons.
- **Explain** what a carcinogen is and list some examples.
- **Describe** the processes used to separate petroleum into fractions and to balance each fraction's output with market demands.
- **Identify** the fractions into which petroleum can be separated.

Vocabulary

aromatic compound
aliphatic compound
fractional distillation
cracking

By the middle of the nineteenth century, chemists had a basic understanding of the structures of hydrocarbons with single, double, and triple covalent bonds. However, a fourth class of hydrocarbon compounds remained a mystery. The simplest example of this class of hydrocarbon is benzene, which the English physicist Michael Faraday (1791–1867) had first isolated in 1825 from the gases given off when either whale oil or coal was heated.

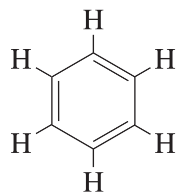
The Structure of Benzene

Although chemists had determined that benzene's molecular formula was C_6H_6, it was hard for them to determine what sort of hydrocarbon structure would give such a formula. After all, the formula of the saturated hydrocarbon with six carbon atoms, hexane, was C_6H_{14}. Because the benzene molecule had so few hydrogen atoms, chemists reasoned that it must be unsaturated; that is, it must have several double or triple bonds, or a combination of both. They proposed many different structures, including this one suggested in 1860.

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

Although this structure has a molecular formula of C_6H_6, such a hydrocarbon should be unstable and extremely reactive because of its many double bonds. However, benzene was fairly unreactive and, when it did react, it was not in the ways that alkenes and alkynes usually react. For that reason, chemists reasoned that structures such as the one shown above must be incorrect.

Kekulé's dream In 1865, the German chemist Friedrich August Kekulé (1829–1896) proposed a different kind of structure for benzene—a hexagon of carbon atoms with alternating single and double bonds. How does the molecular formula of this structure compare with that of benzene?



Kekulé claimed that benzene's structure came to him in a dream while he dozed in front of a fireplace in Ghent, Belgium. He said that he had dreamed of the Ouroboros, an ancient Egyptian emblem of a snake devouring its own tail, and that had made him think of a ring-shaped structure. The flat, hexagonal structure Kekulé proposed explained some of the properties of benzene, but it still could not explain benzene's lack of reactivity.

A modern model of benzene Since the time of Kekulé's proposal, research has confirmed that benzene's molecular structure is indeed hexagonal. However, an explanation of benzene's unreactivity had to wait until the 1930s when Linus Pauling proposed the theory of hybrid orbitals. When applied to benzene, this theory predicts that the pairs of electrons that form the second bond of each of benzene's double bonds are not localized between only two specific carbon atoms as they are in alkenes. Instead, the electron pairs are delocalized, which means they are shared among all six carbons in the ring. **Figure 22-15** shows that this delocalization makes the benzene molecule chemically stable because electrons shared by six carbon nuclei are harder to pull away than electrons held by only two nuclei. The six hydrogen atoms are usually not shown, but you should remember that they are there. In this representation, the circle in the middle of the hexagon symbolizes the cloud formed by the three pairs of electrons.

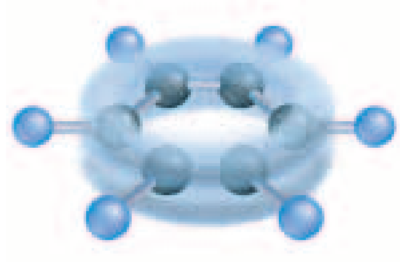
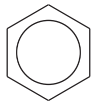


Figure 22-15

Benzene's bonding electrons spread evenly in a double-donut shape around the ring instead of remaining near individual atoms.



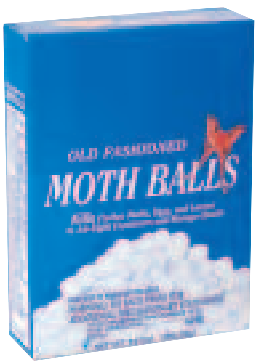
Aromatic Compounds

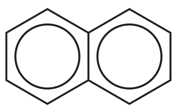
Organic compounds that contain benzene rings as part of their structure are called **aromatic compounds**. The term *aromatic* was originally used because many of the benzene-related compounds known in the nineteenth century were found in pleasant-smelling oils that came from spices, fruits, and other plant parts. Hydrocarbons such as the alkanes, alkenes, and alkynes are called **aliphatic compounds** to distinguish them from aromatic compounds. The term *aliphatic* comes from the Greek word for fat, which is *aleiphatos*. Early chemists obtained aliphatic compounds by heating animal fats.

Structures of some aromatic compounds are shown in **Figure 22-16**. Note that naphthalene has a structure that looks like two benzene rings arranged side by side. Naphthalene is an example of a *fused ring system*, in which an organic compound has two or more cyclic structures with a common side. As in benzene, electrons in naphthalene are shared around all ten carbon atoms making up the double ring. Anthracene is another example of a fused ring system; it appears to be formed from three benzene rings.

Figure 22-16

Shown here are a few of the many aromatic organic compounds that have practical uses. The common names of these compounds are used more frequently than their formal names.

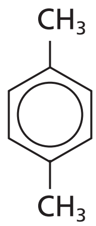




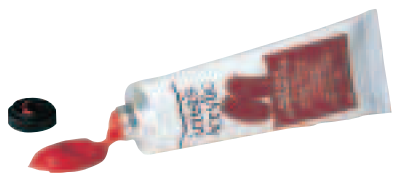
Naphthalene

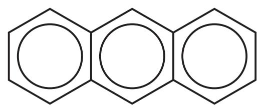
a **Naphthalene** is used in chemical manufacturing and in some kinds of moth repellent.

b ***p*-Xylene** is a starting material for the manufacture of polyester fabrics.



p-Xylene
(1,4-dimethylbenzene)





Anthracene

c **Anthracene** is important in the manufacture of richly colored dyes and pigments.

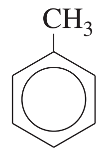
ChemistryOnline

Topic: PAHs
To learn more about polyatomic aromatic hydrocarbons (PAH), visit the Chemistry Web site at **chemistrymc.com**

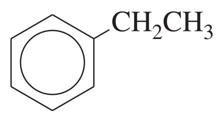
Activity: Research the current concerns about PAHs. Explain the main concern about these substances. Write an informative news article on the risks, benefits, and safe handling of PAHs.

Substituted aromatic compounds Like other hydrocarbons, aromatic compounds may have different groups attached to their carbon atoms. For example, methylbenzene, also known as toluene, consists of a methyl group attached to a benzene ring in place of one hydrogen atom. Whenever you see something attached to an aromatic ring system, remember that the hydrogen atom is no longer there.

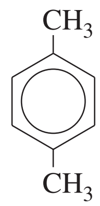
Substituted benzene compounds are named in the same way cyclic alkanes are. For example, ethylbenzene has a 2-carbon ethyl group attached, and 1,4-dimethylbenzene, also known as *para*-xylene, has methyl groups attached at positions 1 and 4.



Methylbenzene
(toluene)

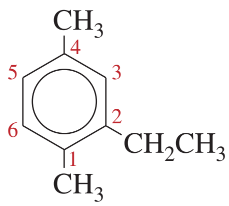


Ethylbenzene



1,4-Dimethylbenzene
(*para*-xylene)

Just as with substituted cycloalkanes, substituted benzene rings are numbered in a way that gives the lowest possible numbers for the substituents. In the following structure, numbering the ring as shown gives the numbers 1, 2, and 4 for the substituent positions. Because *ethyl* is lower in the alphabet than *methyl*, it is written first in the name 2-ethyl-1,4-dimethylbenzene.



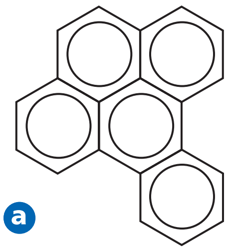
2-Ethyl-1,4-dimethylbenzene

Carcinogens Many aromatic compounds, particularly benzene, toluene, and xylene, were once commonly used as industrial and laboratory solvents. However, tests have shown that the use of such compounds should be limited because they may affect the health of people who are exposed to them regularly. Health risks linked to aromatic compounds include respiratory ailments, liver problems, and damage to the nervous system. Beyond these hazards, some aromatic compounds are carcinogens, which are substances that can cause cancer.

The first known carcinogen was an aromatic substance discovered around the turn of the twentieth century in chimney soot. Chimney sweeps in Great Britain were known to have abnormally high rates of cancer of the scrotum, and the cause was found to be the aromatic compound benzopyrene, shown in **Figure 22-17a**. This compound is a by-product of the burning of complex mixtures of organic substances, such as wood and coal. Some aromatic compounds found in gasoline are also known to be carcinogenic, as you can tell from warning labels on gasoline pumps, **Figure 22-17b**.

Figure 22-17

a This is the structure of benzopyrene, produced when coal is burned for heat. It caused cancer in British chimney sweeps. **b** Signs like this one warn consumers of the carcinogens in gasoline.



a

Benzopyrene

b

Natural Sources of Hydrocarbons

Today, benzene and other aromatic and aliphatic hydrocarbons are obtained from fossil fuels, which formed over millions of years from the remains of living things. The main source of these compounds is petroleum, a complex mixture of alkanes, some aromatic hydrocarbons, and organic compounds containing sulfur or nitrogen atoms.

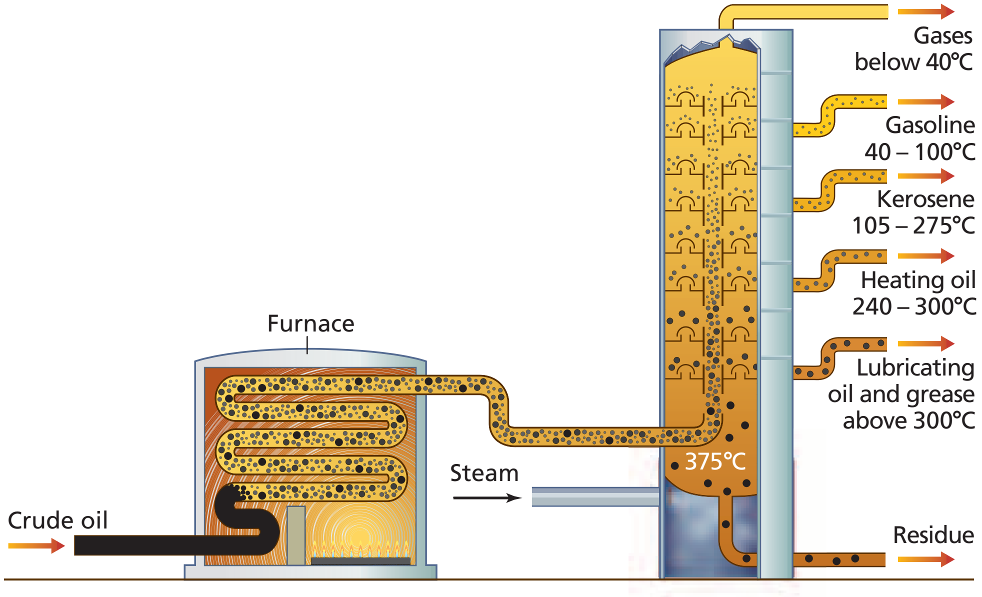
Petroleum formed from the remains of microorganisms that lived in Earth's oceans millions of years ago. Over time, the remains formed thick layers of mudlike deposits on the ocean bottom. Heat from Earth's interior and the tremendous pressure of overlying sediments transformed this mud into oil-rich shale and natural gas. In certain kinds of geological formations, the petroleum ran out of the shale and collected in pools deep in Earth's crust. Natural gas, which formed at the same time and in the same way as petroleum, is usually found with petroleum deposits. Natural gas is composed primarily of methane, but it also has small amounts of alkanes having two to five carbon atoms.

Fractional distillation Petroleum is a complex mixture containing more than a thousand different compounds. For this reason, raw petroleum, sometimes called crude oil, has little practical use. Petroleum is much more useful to humans when it is separated into simpler components, called fractions. Separation is carried out by boiling the petroleum and collecting the fractions as they condense at different temperatures. This process is called **fractional distillation** or sometimes just *fractionation*. Fractional distillation of petroleum is done in a fractionating tower similar to the one shown in **Figure 22-18**.

The temperature inside the fractionating tower is controlled so that it remains near 400°C at the bottom where the petroleum is boiling and gradually decreases moving toward the top. The condensation temperatures (boiling points) of alkanes generally decrease as molecular mass decreases. Therefore, as the vapors travel up through the column, hydrocarbons with more carbon atoms condense closer to the bottom of the tower and are drawn off. Hydrocarbons with fewer carbon atoms remain in the vapor phase until they reach regions of cooler temperatures farther up the column. By tapping

Figure 22-18

This diagram of a fractionating tower shows that fractions with lower boiling points, such as gasoline and gaseous products, are drawn off in the cooler regions near the top of the tower. Oils and greases, having much higher boiling points, stay near the bottom of the tower and are drawn off there.



Earth Science CONNECTION

Throughout human history, people have collected petroleum to burn in lamps to provide light. They found petroleum seeping from cracks in rocks in certain locations. In fact, the word petroleum literally means "rock oil" and is derived from the Latin words for rock (*petra*) and oil (*oleum*). In the 19th century, as the U.S. entered the machine age and its population increased, the demand for petroleum to produce kerosene for lighting and as a machine lubricant also increased. Because there was no reliable petroleum supply, Edwin Drake drilled the first oil well in the United States near Titusville, Pennsylvania in 1859. The oil industry flourished for a time, but when Edison introduced the electric light in 1882, investors feared that the industry was doomed. However, the invention of the automobile in the 1890s soon revived the industry on a massive scale.

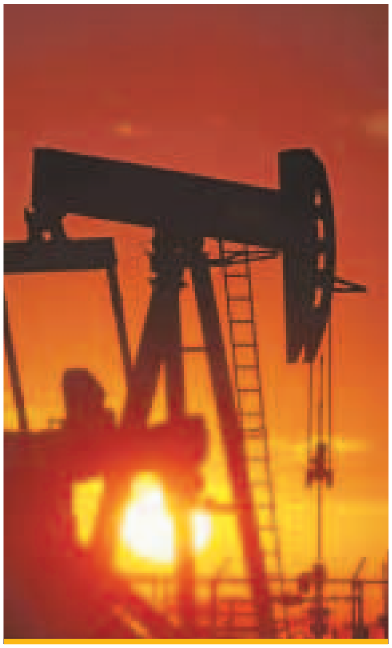


Table 22-6

Petroleum Components Separated by Fractional Distillation

Fraction	Sizes of hydrocarbons	Boiling range (°C)	Common uses
Gases	CH_4 to C_4H_{10}	Below 40	Fuel gas, raw material for plastics manufacture
Gasoline	C_5H_{12} to $C_{12}H_{26}$	40–100	Fuel, solvents
Kerosene	$C_{12}H_{26}$ to $C_{16}H_{34}$	105–275	Home heating, jet fuel, diesel fuel
Heating oil	$C_{15}H_{32}$ to $C_{18}H_{38}$	240–300	Industrial heating
Lubricating oil	$C_{17}H_{36}$ and up	Above 300	Lubricants
Residue	$C_{20}H_{42}$ and up	Above 350	Tar, asphalt, paraffin

into the column at various heights, plant operators can collect the kinds of hydrocarbons they want.

Each group of components removed from the fractionating tower is called a fraction. **Table 22-6** is a list of the names given to the typical fractions separated from petroleum along with their boiling points, hydrocarbon size ranges, and common uses. Unfortunately, fractional distillation of petroleum does not yield these fractions in the same proportions that they are needed. For example, distillation seldom yields enough gasoline, yet it yields more of the heavier oils than the market demands.

Many years ago, petroleum chemists and engineers developed a process to help match the supply with the demand. This process in which heavier fractions are converted to gasoline by breaking their large molecules into smaller molecules is called **cracking**. Cracking is done in the absence of oxygen and in the presence of a catalyst. In addition to breaking heavier hydrocarbons into molecules of the size range needed for gasoline, cracking also produces starting materials for the synthesis of many different organic products.

Rating Gasolines

None of the petroleum fractions are pure substances. As you can see in **Table 22-6**, gasoline is not a pure substance but rather a mixture of hydrocarbons. Most alkane molecules in gasoline have 5 to 12 carbon atoms. However, the gasoline you put into your car today is different from the gasoline your great-grandparents put in their Model T in 1920. The gasoline fraction that is distilled from petroleum is modified by adjusting its composition and adding substances in order to improve its performance in today's automobile engines and to reduce pollution from car exhaust.

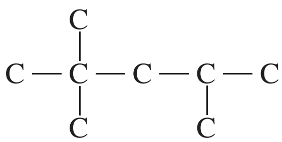
It is critical that the gasoline-air mixture in the cylinder of an automobile engine ignite at exactly the right instant and burn evenly. If it ignites too early or too late, much energy is wasted, fuel efficiency drops, and engines wear out prematurely. Most straight-chain hydrocarbons burn unevenly and tend to ignite from heat and pressure before the piston is in the proper position and the spark plug fires. This early ignition causes a rattling or pinging noise called *knocking*. Branched-chain alkanes, as well as alkenes and cyclic alkanes burn more evenly than alkanes with straight chains. Even burning helps prevent engine knocking.

Figure 22-19

Gas stations provide a range of choices in octane ratings. Many cars manufactured today require mid-grade gasoline. However, cars with high-compression engines may need fuel with a higher octane rating.

Octane ratings In the late 1920s, an octane rating system for gasoline was established, resulting in the octane ratings posted on gasoline pumps like those shown in **Figure 22-19**. Mid-grade gasoline today has a rating of about 89, whereas premium gasolines have higher ratings of up to about 97. Several factors determine which octane rating a car needs, including how much the piston compresses the air-fuel mixture and the altitude at which the car is driven.

What do these ratings mean? You may be surprised to learn that they have almost nothing to do with the 8-carbon, straight-chain alkane called octane. They were first established by assigning a rating of zero to heptane, which was known to cause severe knocking, and a rating of 100 to 2,2,4-trimethylpentane, the compound that had the best anti-knock properties when tests were first performed. The compound 2,2,4-trimethylpentane was commonly called isooctane and erroneously called "octane" by technicians who tested gasoline.



2,2,4-Trimethylpentane (isooctane, erroneously called "octane")

A gasoline with a rating of 90 performs about the same as a mixture of 90% isooctane and 10% heptane. Today, compounds can be added to gasoline to produce octane ratings greater than 100.

Section 22.5 Assessment

30. What properties of benzene made chemists think it was not an alkene with several double bonds?

31. What feature accounts for the difference between aromatic and aliphatic hydrocarbons? Why should people avoid contact with aromatic hydrocarbons?

32. Explain how the physical properties of hydrocarbons make fractional distillation possible.

33. What is the purpose of cracking hydrocarbons?

34. **Thinking Critically** In addition to adjusting octane rating, refiners also vary the volatility of gasoline, mainly by adding (or not adding) butane, C_4H_{10}. Where and when do you think refiners produce gasoline of higher volatility?

35. **Interpreting Data** Look at the data in **Table 22-6**. What property of hydrocarbon molecules seems to correlate to the viscosity of a particular fraction when it is cooled to room temperature?

CHEMLAB 22

Analyzing Hydrocarbon Burner Gases

The fuel that makes a Bunsen burner work is a mixture of alkane hydrocarbons. One type of fuel is natural gas, whose primary component is methane (CH_4). The other type is called LP gas and consists primarily of propane (C_3H_8). In this experiment, you will use the ideal gas equation to help identify the main component of your classroom fuel supply.

Problem

What type of alkane gas is used in the burner fuel supplied to your laboratory?

Objectives

- **Measure** a volume of gas by water displacement.
- **Measure** the temperature, pressure, and mass at which the volume of the gas was measured.
- **Calculate** the molar mass of the burner gas using the ideal gas equation.

Materials

barometer
thermometer
1-L or 2-L plastic soda bottle with cap
burner tubing
pneumatic trough
100-mL graduated cylinder
balance (0.01g)
paper towels

Safety Precautions

- **Always wear safety goggles and an apron in the lab.**
- **Be certain that there are no open flames in the lab.**

Pre-Lab

1. Read the entire **CHEMLAB**.
2. Prepare all written materials that you will take into the laboratory. Include safety precautions, procedure notes, and a data table.
3. Use the formulas of methane, ethane, and propane to calculate the compounds' molar masses.
4. Given *R* and gas pressure, volume, and temperature, show how you will rearrange the ideal gas equation to solve for moles of gas.
5. Suppose that your burner gas contains a small amount of ethane (C_2H_6). How will the presence of this compound affect your calculated molar mass if the burner gas is predominantly:
   a. methane
   b. propane
6. Prepare your data table.

Mass and Volume Data	
Mass of bottle + air (g)	
Mass of air (g)	
Mass of "empty" bottle (g)	
Mass of bottle + collected burner gas (g)	
Mass of collected burner gas (g)	
Barometric pressure (atm)	
Temperature (°C)	
Temperature (K)	
Volume of gas collected (L)	

Procedure

1. Connect the burner tubing from the gas supply to the inlet of the pneumatic trough. Fill the trough with tap water. Open the gas valve slightly and let a little gas bubble through the tank in order to flush all of the air out of the tubing.

2. Measure the mass of the dry plastic soda bottle and cap. Record the mass in the data table (bottle + air). Record both the barometric pressure and the air temperature.
3. Fill the bottle to overflowing with tap water and screw on the cap. If some air bubbles remain, tap the bottle gently on the desktop until all air has risen to the top. Take off the cap, add more water, and recap the bottle.
4. Place the thermometer in the trough. Invert the capped bottle into the pneumatic trough and remove the cap while keeping the mouth of the bottle underwater. Hold the mouth of the bottle directly over the inlet opening of the trough.
5. Slowly open the gas valve and bubble gas into the inverted bottle until all of the water has been displaced. Close the gas valve immediately. Record the temperature of the water.
6. While the bottle is still inverted, screw on the cap. Remove the bottle from the water. Thoroughly dry the outside of the bottle.
7. Measure the mass of the bottle containing the burner gas and record the mass in the data table (bottle + burner gas).
8. Place the bottle in a fume hood and remove the cap. Compress the bottle several times to expel most of the gas. Refill the bottle to overflowing with water and determine the volume of the bottle by pouring the water into a graduated cylinder. Record the volume of the bottle.

Cleanup and Disposal

1. Be certain that all gas valves are closed firmly and dump water out of pneumatic troughs.
2. Clean up water spills and dispose of materials as directed by your teacher.
3. Return all lab equipment to its proper place.

Analyze and Conclude

1. **Acquiring Information** Use the volume of the bottle and look up the density of air to compute the mass of the air the bottle contains. Use gas laws to compute the density of air at the temperature and pressure of your laboratory. The density of air at 1 atm and 20°C is 1.205 g/L.
2. **Using Numbers** Calculate the mass of the empty bottle by subtracting the mass of air from the mass of the bottle and air combined.
3. **Using Numbers** Determine the mass of the collected gas by subtracting the mass of the empty bottle from the mass of the bottle and gas.
4. **Interpreting Data** Use the volume of gas, water temperature, and barometric pressure along with the ideal gas law to calculate the number of moles of gas collected.
5. **Using Numbers** Use the mass of gas and the number of moles to calculate the molar mass of the gas.
6. **Drawing a Conclusion** How does your experimental molar mass compare with the molar masses of methane, ethane, and propane? Suggest which of these gases are in the burner gas in your laboratory.
7. **Error Analysis** If your experimental molar mass does not agree with that of any one of the three possible gases, suggest possible sources of error in the experiment. What factor other than error could produce such a result?

Real-World Chemistry

1. Substances called *odorants* are mixed with natural gas before it is distributed to homes, businesses, and institutions. Why must an odorant be used, and what substances are used as odorants?
2. At 1 atm and 20°C, the densities of methane and propane are 0.65 g/L and 1.83 g/L, respectively. Would either gas tend to settle in a low area such as the basement of a home? Explain.

CONTENTS

Everyday Chemistry

Unlimited Alternative Energy

Fossil fuels are the primary source of energy to run our cars, heat our homes, and produce electricity. Decaying plants and animals millions of years ago produced coal, oil, and natural gas. These sources of energy are finite and need to be conserved.

The Costs of Fossil Fuels

Each time we pay an electricity bill or purchase gasoline, we pay for fossil fuels. The labor to mine coal or drill for oil, the labor and materials to build and operate power plants, and the transportation of coal and oil to these plants are just part of the costs of using fossil fuels. There also are indirect costs such as health problems caused by pollution, environmental problems such as acid rain, and the protection of foreign sources of oil. There is an alternative source of energy readily available for use in your everyday life—solar energy.

What is solar energy?

The sun has always been an energy source. Plants use sunlight to make food through a process called photosynthesis. Animals use energy from the Sun by eating plants. Throughout history, humans have used the heat from sunlight directly to cook food and heat water and homes. When you hang laundry outside to dry, you use solar energy to do work. Plants grow in greenhouses during winter months due to warmth from the Sun. Although the Sun radiates prodigious amounts of energy each day, it will continue to dispense solar energy for approximately five billion years.

By the late 1800s, the use of solar water heaters was common in sunny parts of the United States. When large deposits of oil and natural gas were discovered, these systems were replaced with heaters using cheaper fossil fuels.

Passive Solar Energy

Many different active solar techniques can be used to convert sunlight into useful forms of energy. Add-on devices such as photovoltaic cells that convert sunlight into electricity and rooftop solar panels that use sunlight to heat water use mechanical means to distribute solar energy. "Low-technology" passive solar techniques provide clean, inexpensive energy. Passive solar techniques make use of the building's components and design.

Each time you open the curtains to let in the Sun's rays for warmth or light, you are using passive solar energy. Every building can meet some of its heating requirements with passive solar energy. The use of triple-pane windows, heavily insulated walls and ceilings, and materials with high heat capacity such as adobe walls and clay tile floors increase energy storage.

Passive solar techniques also can be used to reduce use of electricity for air conditioning. Vegetation planted for shade, light colors that reflect sunlight, and careful attention to placement of windows for good airflow will keep a home cooler in summer.

The use of sunlight to replace electric lighting in a building is called daylighting. Daylighting can be useful in the home, and large office buildings that demand large amounts of lighting during the day benefit from large windows, skylights, and atria.

Testing Your Knowledge

1. **Acquiring Information** Investigate and describe how a solar furnace works. Is it an active or passive use of solar energy? Explain your answer.
2. **Hypothesizing** Geothermal energy, wind energy, and solar energy are forms of alternative energy. Which form might be feasible in your state? Explain.

CHAPTER 22 STUDY GUIDE

Summary

22.1 Alkanes

- Organic compounds contain the element carbon, which is able to bond with other carbon atoms to form straight chains and branched chains.
- Hydrocarbons are organic substances composed of only the elements carbon and hydrogen.
- Alkanes contain only single bonds between carbon atoms.
- Alkanes and other organic compounds are best represented by structural formulas and can be named using systematic rules determined by the International Union of Pure and Applied Chemistry (IUPAC).

22.2 Cyclic Alkanes and Alkane Propeties

- Alkanes that contain hydrocarbon rings are called cyclic alkanes.
- Alkanes are nonpolar compounds that have low reactivity and lower melting and boiling points than polar molecules of similar size and mass.

22.3 Alkenes and Alkynes

- Alkenes and alkynes are hydrocarbons that contain at least one double or triple bond, respectively.
- Alkenes and alkynes are nonpolar compounds with greater reactivity than alkanes but with other properties similar to those of the alkanes.
- Alkenes and alkynes, whether straight-chain, branched-chain, or cyclic, can be named using the systematic rules determined by IUPAC.

22.4 Isomers

- Isomers are two or more compounds with the same molecular formula but different molecular structures.
- Structural isomers differ in the order in which atoms are bonded to each other. A straight-chain hydrocarbon and a branched-chain hydrocarbon with the same molecular formula are structural isomers.
- Stereoisomers have all atoms bonded in the same order but arranged differently in space.
- Geometric isomers, a category of stereoisomers, result from different arrangements of groups about carbon atoms that are double bonded to each other.
- Optical isomers, another class of stereoisomers, result from the two possible arrangements of four different atoms or groups of atoms bonded to the same carbon atom. The two isomers are chiral because they are mirror images of each other.

22.5 Aromatic Hydrocarbons and Petroleum

- Aromatic hydrocarbons contain benzene rings as part of their molecular structures. Nonaromatic hydrocarbons are called aliphatic hydrocarbons.
- Aromatic hydrocarbons tend to be less reactive than alkenes or alkynes because they have no double bonds. Instead, electrons are shared evenly over the entire benzene ring.
- Some aromatic compounds, such as naphthalene, contain two or more benzene rings fused together.
- Some aromatic compounds are carcinogenic, which means they can cause cancer.
- The major sources of hydrocarbons are petroleum and natural gas.
- Petroleum can be separated into components of different boiling ranges by the process of fractional distillation.

Vocabulary

- aliphatic compound (p. 723)
- alkane (p. 699)
- alkene (p. 711)
- alkyne (p. 714)
- aromatic compound (p. 723)
- asymmetric carbon (p. 719)
- chirality (p. 719)
- cracking (p. 726)
- cyclic hydrocarbon (p. 706)
- cycloalkane (p. 706)
- fractional distillation (p. 725)
- geometric isomer (p. 718)
- homologous series (p. 701)
- hydrocarbon (p. 698)
- isomer (p. 717)
- optical isomer (p. 720)
- optical rotation (p. 721)
- organic compound (p. 698)
- parent chain (p. 701)
- polarized light (p. 720)
- saturated hydrocarbon (p. 710)
- stereoisomer (p. 718)
- structural isomer (p. 717)
- substituent group (p. 701)
- unsaturated hydrocarbon (p. 710)

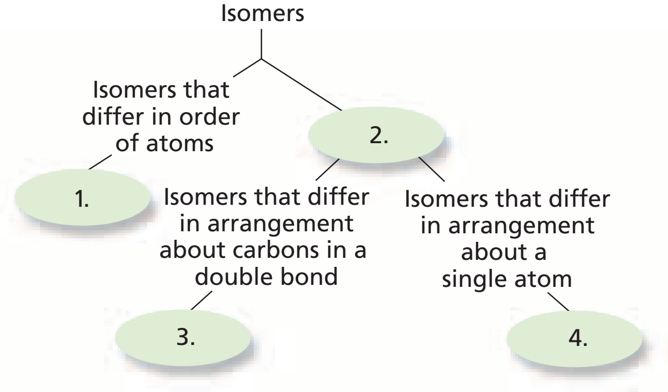
chemistrymc.com/vocabulary_puzzlemaker

CHAPTER 22 ASSESSMENT

Go to the Chemistry Web site at **chemistrymc.com** *for additional Chapter 22 Assessment.*

Concept Mapping

36. Complete the following concept map that shows how the following isomer types are related: stereoisomers, structural isomers, optical isomers, all isomers, geometric isomers.



Mastering Concepts

37. Why did Wohler's discovery lead to the development of the field of organic chemistry? (22.1)

38. What is the main characteristic of an organic compound? (22.1)

39. What characteristic of carbon accounts for the huge variety of organic compounds? (22.1)

40. Describe the characteristics of a homologous series of hydrocarbons. (22.1)

41. Draw the structural formula of each of the following. (22.1)

a. ethane **b.** butane **c.** hexane

42. Write the condensed structural formulas for the alkanes in the previous question. (22.1)

43. Write the name and draw the structure of the alkyl group that corresponds to each of the following alkanes. (22.1)

a. methane **b.** butane **c.** octane

44. How does the structure of a cycloalkane differ from that of a straight-chain or branched-chain alkane? (22.2)

45. Explain the difference between saturated hydrocarbons and unsaturated hydrocarbons. (22.2)

46. Explain how intermolecular attractions generally affect substances' boiling and freezing points.

47. Explain how alkenes differ from alkanes. How do alkynes differ from both alkenes and alkanes? (22.3)

48. The names of hydrocarbons are based on the name of the parent chain. Explain how the determination of the parent chain when naming alkenes differs from the same determination when naming alkanes. (22.3)

49. Name the most common alkyne. How is this substance used? (22.3)

50. How are two isomers alike and how are they different? (22.4)

51. Describe the difference between *cis*- and *trans*- isomers in terms of geometrical arrangement. (22.4)

52. What characteristics does a chiral substance have? (22.4)

53. How does polarized light differ from ordinary light, such as light from the Sun? (22.4)

54. How do optical isomers affect polarized light? (22.4)

55. What structural characteristic do all aromatic hydrocarbons share? (22.5)

56. Draw the structural formula of 1,2-dimethylbenzene. (22.5)

57. What are carcinogens? (22.5)

58. What does fractional distillation of petroleum accomplish? (22.5)

59. What physical property determines the height at which hydrocarbons condense in a fractionation tower? (22.5)

60. What is the cracking process and why is it necessary in petroleum processing? (22.5)

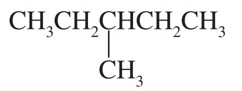
Mastering Problems

Alkanes (22.1)

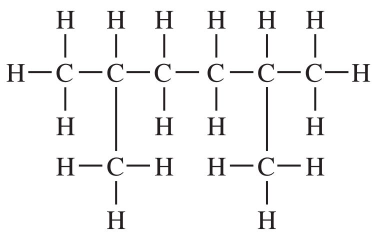
61. Name the compound represented by each of the following structural formulas.

a. $CH_3CH_2CH_2CH_2CH_3$

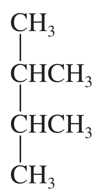
b.



c.



d.



CONTENTS

62. Draw full structural formulas for the following compounds.

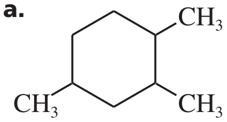
a. heptane
b. 2-methylhexane
c. 2,3-dimethylpentane
d. 2,2-dimethylpropane

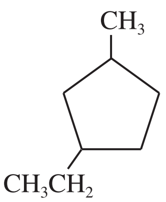
Cyclic Alkanes and Alkane Properties (22.2)

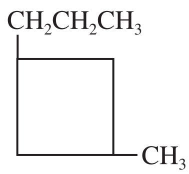
63. Draw condensed structural formulas for the following compounds. Use line structures for rings.

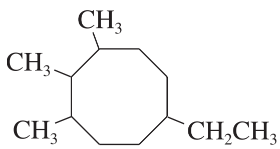
a. 1,2-dimethylcyclopropane
b. 1,1-diethyl-2-methylcyclopentane

64. Name the compound represented by each of the following structural formulas.

a.


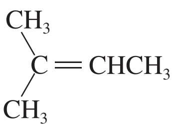
b.


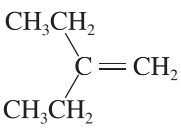
c.


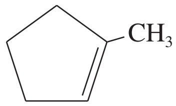
d.


Alkenes and Alkynes (22.3)

65. Name the compound represented by each of the following condensed structural formulas.

a.


b.


c.


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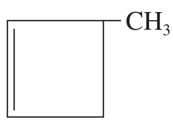
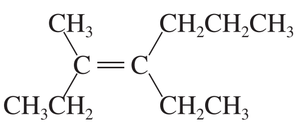
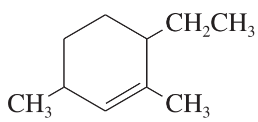


66. Draw condensed structural formulas for the following compounds. Use line structures for rings.

a. 1,4-diethylcyclohexene
b. 2,4-dimethyl-1-octene
c. 2,2-dimethyl-3-hexyne

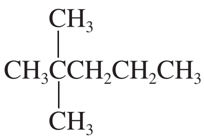
67. Name the compound represented by each of the following condensed structural formulas.

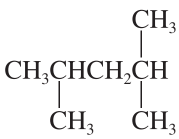
a.


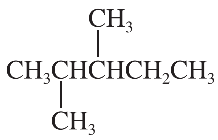
b.


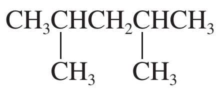
Isomers (22.4)

68. Identify the pair of structural isomers in the following group of condensed structural formulas.

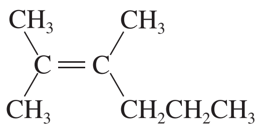
a.


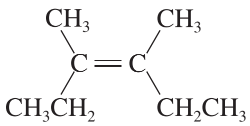
b.


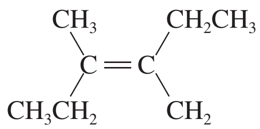
c.


d.


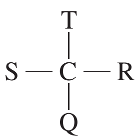
69. Identify the pair of geometric isomers among the following structures. Explain your selections. Explain how the third structure is related to the other two.

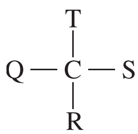
a.


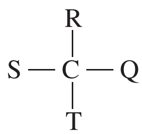
b.


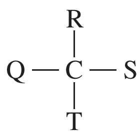
c.


70. Three of the following structures are exactly alike, but the fourth represents an optical isomer of the other three. Identify the optical isomer and explain how you made your choice.

a.


b.


c.


d.


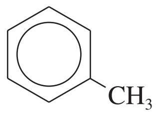
71. Draw condensed structural formulas for four different structural isomers with the molecular formula C_4H_8.

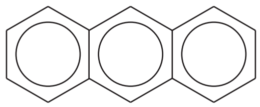
72. Draw and label the *cis*- and *trans*- isomers of the molecule represented by the following condensed formula.

$CH_3CH{=}CHCH_2CH_3$

Aromatic Hydrocarbons and Petroleum (22.5)

73. Name the compound represented by each of the following structural formulas.

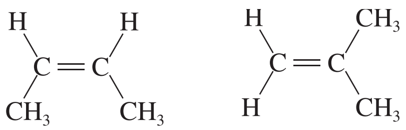
a. 

b. 

Mixed Review

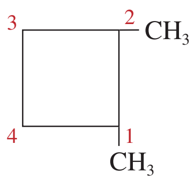
Sharpen your problem-solving skills by answering the following.

74. Do the following structural formulas represent the same molecule? Explain your answer.

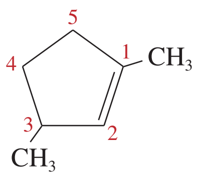


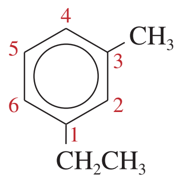
75. How many hydrogen atoms are in an alkane molecule with nine carbon atoms? How many are in an alkene with nine carbon atoms and one double bond?

76. Determine whether or not each of the following structures represents the correct numbering. If the numbering is incorrect, redraw the structure with the correct numbering.

a. 

b. 1 2 3 4 5
$CH_3CH_2C \equiv CCH_3$

c. 

d. 

77. Why do chemists use structural formulas for organic compounds rather than molecular formulas such as C_5H_{12}?

78. The general formula for alkanes is C_nH_{2n+2}. Determine the general formula for cycloalkanes.

79. Why are unsaturated hydrocarbons more useful than saturated hydrocarbons as starting materials in chemical manufacturing?

80. Is cyclopentane an isomer of pentane? Explain your answer.

Thinking Critically

81. Thinking Critically Determine which two of the following names cannot be correct and draw the structures of the molecules.

a. 2-ethyl-2-butene
b. 1,4-dimethylcyclohexene
c. 1,5-dimethylbenzene

82. Drawing a Conclusion The sugar glucose is sometimes called *dextrose* because a solution of glucose is known to be dextrorotatory. Analyze the word *dextrorotatory*, and suggest what the word means.

83. Interpreting Scientific Illustrations Draw Kekulé's structure of benzene and explain why it does not truly represent the actual structure.

84. Recognizing Cause and Effect Explain why alkanes such as hexane and cyclohexane are effective at dissolving grease, whereas water is not.

85. Hypothesizing Do you think that, on average, structural isomers or stereoisomers will have a larger difference in their physical properties? Explain your reasoning. Research this question by comparing physical properties of pairs of isomers as given in the *CRC Handbook of Chemistry and Physics* or *The Merck Index* to see if your hypothesis is correct.

Writing in Chemistry

86. For many years, a principal antiknock ingredient in gasoline was the compound tetraethyllead. Do research to learn about the structure of this compound, the history of its development and use, and why its use was discontinued in the United States. Find out if it is still used as a gasoline additive elsewhere in the world.

Cumulative Review

Refresh your understanding of previous chapters by answering the following.

87. What element has the following ground-state electron configuration: $[Ar]4s^23d^6$? (Chapter 5)

88. What is the charge of an ion formed from the following families? (Chapter 7)

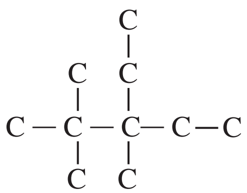
a. alkali metals
b. alkaline earth metals
c. halogens

89. Write the chemical equations for the complete combustion of ethane, ethene, and ethyne into carbon dioxide and water. (Chapter 10)

STANDARDIZED TEST PRACTICE
CHAPTER 22

Use these questions and test-taking tip to prepare for your standardized test.

1. What is the condensed structural formula of heptane?
   - **a.** $(CH_3)_2(CH_2)_5$
   - **b.** $CH_3(CH_2)_6$
   - **c.** $CH_3(CH_2)_5CH_3$
   - **d.** $CH_3CH_3(CH_2)_5$

2. 

   What is the name of the compound whose skeletal formula is shown above?
   - **a.** 2,2,3-trimethyl-3-ethylpentane
   - **b.** 3-ethyl-3,4,4-trimethylpentane
   - **c.** 2-butyl-2-ethylbutane
   - **d.** 3-ethyl-2,2,3-trimethylpentane

3. All of the following are structural isomers of $CH_2{=}CHCH_2CH{=}CHCH_3$ EXCEPT ____.
   - **a.** $CH_2{=}CHCH_2CH_2CH{=}CH_2$
   - **b.** $CH_3CH{=}CHCH_2CH{=}CH_2$
   - **c.** $CH_3CH{=}CHCH{=}CHCH_3$
   - **d.** $CH_2{=}C{=}CHCH_2CH_2CH_3$

Interpreting Tables Use the table to answer questions 4–6.

Data for Various Hydrocarbons

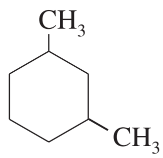
Name	Number of C atoms	Number of H atoms	Melting point (°C)	Boiling point (°C)
Heptane	7	16	–90.6	98.5
1-Heptene	7	14	–119.7	93.6
1-Heptyne	7	12	–81	99.7
Octane	8	18	–56.8	125.6
1-Octene	8	16	–101.7	121.2
1-Octyne	8	14	–79.3	126.3

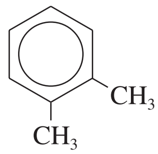
4. Based on the information in the table, what type of hydrocarbon becomes a gas at the lowest temperature?
   - **a.** alkane
   - **b.** alkene
   - **c.** alkyne
   - **d.** aromatic

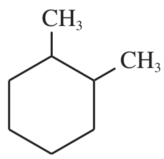
5. If n is the number of carbon atoms in the hydrocarbon, what is the general formula for an alkyne with one triple bond?
   - **a.** C_nH_{n+2}
   - **b.** C_nH_{2n+2}
   - **c.** C_nH_{2n}
   - **d.** C_nH_{2n-2}

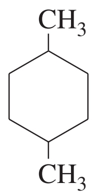
6. It can be predicted from the table that nonane will have a melting point that is
   - **a.** greater than that of octane.
   - **b.** less than that of heptane.
   - **c.** greater than that of decane.
   - **d.** less than that of hexane.

7. Which compound below is 1,2-dimethylcyclohexane?

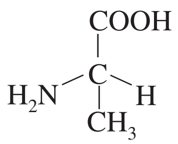
   a. 

   c. 

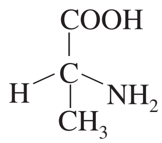
   b. 

   d. 

8. Alanine, like all amino acids, exists in two forms:

   L-Alanine

   D-Alanine

   Almost all of the amino acids found in living organisms are in the L-form. What are L-Alanine and D-Alanine?
   - **a.** structural isomers
   - **b.** geometric isomers
   - **c.** optical isomers
   - **d.** stereoisotopes

TEST-TAKING TIP

Beat the Clock . . . And Then Go Back As you take a practice test, pace yourself to finish each section just a few minutes early so you can go back and check over your work. You'll sometimes find a mistake or two. Don't worry. To err is human. To catch it before you hand it in is better.