CHAPTER 21

Hydrocarbons

BIG Idea **Organic compounds called hydrocarbons differ by their types of bonds.**

21.1 Introduction to Hydrocarbons

MAIN Idea Hydrocarbons are carbon-containing organic compounds that provide a source of energy and raw materials.

21.2 Alkanes

MAIN Idea Alkanes are hydrocarbons that contain only single bonds.

21.3 Alkenes and Alkynes

MAIN Idea Alkenes are hydrocarbons that contain at least one double bond, and alkynes are hydrocarbons that contain at least one triple bond.

21.4 Hydrocarbon Isomers

MAIN Idea Some hydrocarbons have the same molecular formula but have different molecular structures.

21.5 Aromatic Hydrocarbons

MAIN Idea Aromatic hydrocarbons are unusually stable compounds with ring structures in which electrons are shared by many atoms.

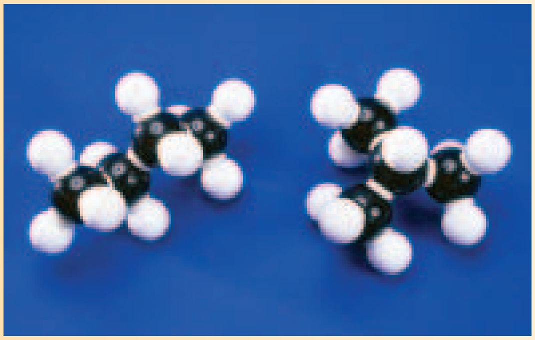
ChemFacts

- The primary source of hydrocarbons is petroleum.
- About 75 million barrels of petroleum are pumped out of the Earth each day.
- Hydrocarbons are used as fuels and are the raw materials for products such as plastics, synthetic fibers, solvents, and industrial chemicals.

LAUNCH Lab

How can you model simple hydrocarbons?

Hydrocarbons are made of hydrogen and carbon atoms. Recall that carbon has four valence electrons and it can form four covalent bonds.



Procedure

1. Read and complete the lab safety form.
2. Use a **molecular model kit** to build a structure with two carbon atoms connected by a single bond.
3. Place hydrogen atoms in all of the unoccupied positions on your model so that each carbon atom has a total of four bonds.
4. Repeat Steps 2–3 for models based on three, four, and five carbon atoms each. Be sure that each carbon atom is attached to a maximum of two other carbon atoms.

Analysis

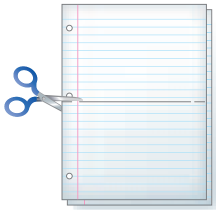
1. **Make** a table listing the number of carbon and hydrogen atoms in each structure.
2. **Describe** the composition of each structure with a molecular formula.
3. **Analyze** the pattern of the carbon-to-hydrogen ratio to develop a generic formula for hydrocarbons with single bonds.

Inquiry How do you think the molecular formula would be affected if the carbon atoms were attached by double and triple bonds?

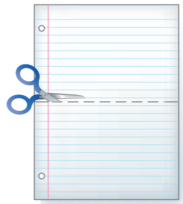
FOLDABLES™ Study Organizer

Hydrocarbon Compounds Make the following Foldable to help you organize information about hydrocarbon compounds.

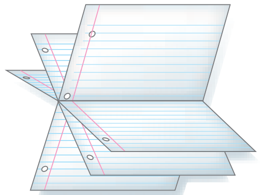
STEP 1 Fold three sheets of notebook paper in half horizontally. Holding two sheets of paper together, make a 3-cm cut at the fold line on each side of the paper.

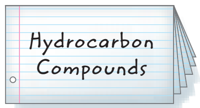


STEP 2 On the third sheet, cut along the fold line leaving a 3 cm portion uncut on each side of the paper.



STEP 3 Slip the first two sheets through the cut in the third sheet to make a 12-page book. Label your book *Hydrocarbon Compounds*.





FOLDABLES **Use this Foldable with Sections 21.2, 21.3, 21.4, and 21.5.** As you read these sections, use your book to record features of each type of hydrocarbon, distinguishing characteristics, and real-world examples.

Chemistry Online

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Section 21.1

Objectives

- **Explain** the terms *organic compound* and *organic chemistry*.
- **Identify** hydrocarbons and the models used to represent them.
- **Distinguish** between saturated and unsaturated hydrocarbons.
- **Describe** where hydrocarbons are obtained and how they are separated.

Review Vocabulary

microorganism: a tiny organism, such as a bacterium or a protozoan, that cannot be seen without a microscope

New Vocabulary

organic compound
hydrocarbon
saturated hydrocarbon
unsaturated hydrocarbon
fractional distillation
cracking

Introduction to Hydrocarbons

MAIN Idea Hydrocarbons are carbon-containing organic compounds that provide a source of energy and raw materials.

Real-World Reading Link If you have ridden in a car or a bus, you have used hydrocarbons. The gasoline and diesel fuel that are used in cars, trucks, and buses are hydrocarbons.

Organic Compounds

Chemists in the early nineteenth century knew that living things, such as the plants and panda shown in **Figure 21.1,** 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. They were able to synthesize many new and useful substances. However, scientists were not able to synthesize organic compounds. Many scientists incorrectly concluded that they were unable to synthesize organic compounds because of vitalism. According to vitalism, organisms possessed a mysterious "vital force," enabling them to assemble carbon compounds.

Disproving vitalism Friedrich Wöhler (1800—1882), a German chemist, was the first scientist to realize that he had produced an organic compound by synthesis in a laboratory. Wöhler's experiment did not immediately disprove vitalism, but it prompted a chain of similar experiments by other European chemists. Eventually, the idea that the synthesis of organic compounds required a vital force was discredited and scientists realized they could synthesize organic compounds.

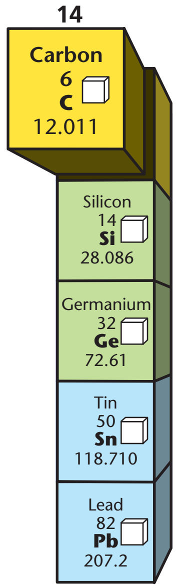
Figure 21.1 Living things contain, are made up of, and produce a variety of organic compounds.
Identify ***two organic compounds that you have studied in a previous science course.***

Organic chemistry 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. Because there are so many organic compounds, an entire branch of chemistry, called organic chemistry, is devoted to their study. Recall that carbon is an element in group 14 of the periodic table, as shown in **Figure 21.2.** With the electron configuration of $1s^22s^22p^2$, carbon nearly always shares its electrons and forms four covalent bonds. In organic compounds, carbon atoms are 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 form chains from two to thousands of carbon atoms in length. Also, because carbon forms four bonds, it forms complex, branched-chain structures, ring structures, and even cagelike structures. With all of these bonding possibilities, chemists have identified millions of different organic compounds and are synthesizing more every day.

Reading Check **Explain** why carbon forms many compounds.

■ **Figure 21.2** Carbon is found in group 14 of the periodic table. It can bond to four other elements and form thousands of different compounds.



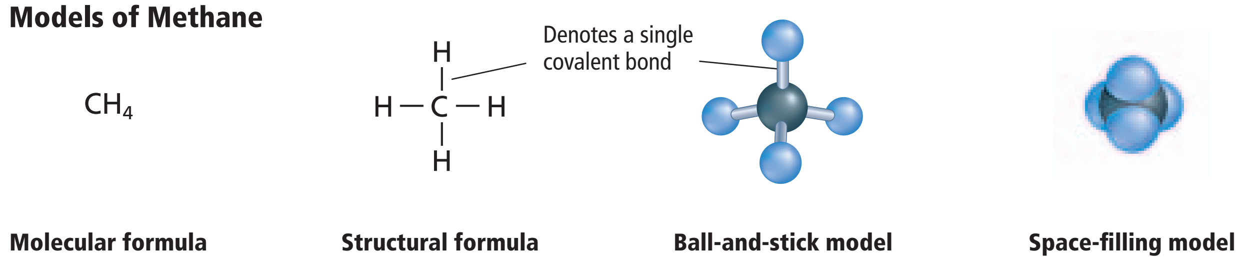
Hydrocarbons

The simplest organic compounds are **hydrocarbons,** which contain only the elements carbon and hydrogen. How many different compounds do you think two elements can form? You might guess that only a few compounds are possible. However, thousands of hydrocarbons are known, each containing only the elements carbon and hydrogen. The simplest hydrocarbon molecule, CH_4, consists of a carbon atom bonded to four hydrogen atoms. This substance, called methane, is an excellent fuel and is the main component of natural gas, as shown in **Figure 21.3.**

Reading Check **Name** two uses of methane or natural gas in your home or community.

■ **Figure 21.3** Methane—a hydrocarbon found in natural gas—is the simplest hydrocarbon.

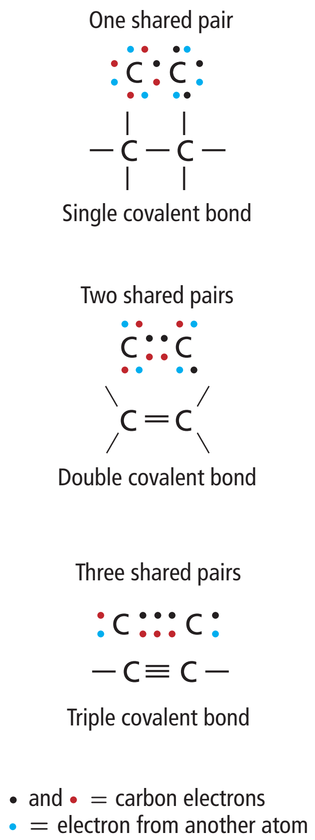
Identify ***In addition to hydrogen, what other elements readily bond with carbon?***



■ **Figure 21.4** Chemists use four different models to represent a methane (CH_4) molecule. Refer to page 968 for a key to atom color conventions.

Models and hydrocarbons Chemists represent organic molecules in a variety of ways. **Figure 21.4** shows four different ways to represent a methane molecule. Covalent bonds are represented by a single straight line, which denotes two shared electrons. Most often, chemists use the type of model that best shows the information they want to highlight. As shown in **Figure 21.4,** 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, three-dimensional geometry. The ball-and-stick model demonstrates the geometry of the molecule clearly, but the space-filling model gives a more realistic picture of what a molecule would look like if you could see it. Keep in mind as you look at the models that the atoms are held closely together by electron-sharing bonds.

■ **Figure 21.5** Carbon can bond to other carbon atoms in double and triple bonds. These Lewis structures and structural formulas show two ways to denote double and triple bonds.



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, as shown in **Figure 21.5.** As you recall from Chapter 8, in a double bond, atoms share two pairs of electrons; in a triple bond, they share three pairs of electrons.

In the nineteenth century, before chemists understood bonding and the structure of organic substances, they 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 small amount of bromine, some would react with more, and some would not react with any amount of bromine. 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.

Present-day chemists can now explain the experimental results obtained 170 years ago. Hydrocarbons that reacted with bromine had double or triple covalent bonds. Those compounds that did not react with bromine had only single covalent bonds. Today, a hydrocarbon having only single bonds is defined as a **saturated hydrocarbon.** A hydrocarbon that has at least one double or triple bond between carbon atoms is an **unsaturated hydrocarbon.** You will learn more about these different types of hydrocarbons later in this chapter.

Reading Check **Explain** the origin of the terms *saturated* and *unsaturated hydrocarbons.*

Refining Hydrocarbons

Today, many hydrocarbons are obtained from a fossil fuel called petroleum. 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 floor. 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 contains small amounts of other hydrocarbons that have from two to five carbon atoms.

Fractional distillation Unlike natural gas, 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 or fractions. Separation is carried out in a process called **fractional distillation,** also called fractionation, which involves boiling the petroleum and collecting components or fractions as they condense at different temperatures. Fractional distillation is done in a fractionating tower similar to the one shown in **Figure 21.6.**

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 toward the top. The condensation temperatures (boiling points) generally decrease as molecular mass decreases. Therefore, as the vapors travel up through the column, the hydrocarbons condense and are drawn off, as shown in **Figure 21.6.**

Vocabulary

Science usage v. Common usage

Deposit

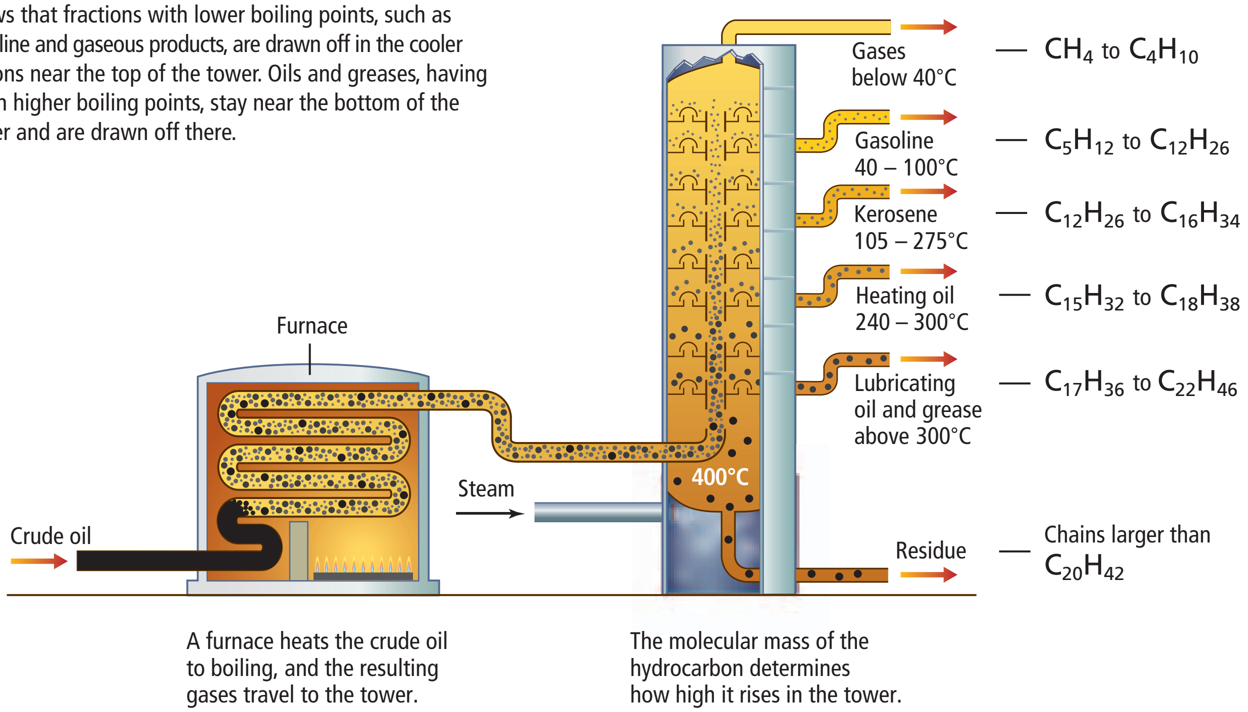
Science usage: a natural collection of oil or ore

There was a rich deposit of copper in the mountain.

Common usage: money placed in a bank account or the act of placing money in a bank account

The store owner placed his deposit in the after-hours slot at the bank.

Figure 21.6 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.



■ **Figure 21.7** Fractional distillation towers separate large quantities of petroleum into usable components. Thousands of products we use in our homes, for transportation, and in industry result from petroleum refining.

Infer ***What types of emissions must be controlled by refineries to protect the environment?***

Figure 21.6 also gives the names of the typical fractions separated from petroleum, along with their boiling points, hydrocarbon size ranges, and common uses. You might recognize some of the fractions because you use them every day. Unfortunately, fractional distillation towers, shown in **Figure 21.7,** do not yield fractions in the same proportions that they are needed. For example, distillation seldom yields the amount of gasoline desired. However, 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 products, including plastic products, films, and synthetic fabrics.

Reading Check **Describe** the process in which large-chain hydrocarbons are broken into more-desirable smaller-chain hydrocarbons.

Rating gasoline None of the petroleum fractions is a pure substance. As shown in **Figure 21.6,** gasoline is not a pure substance, but rather a mixture of hydrocarbons. Most molecules with single covalent bonds in gasoline have 5 to 12 carbon atoms. However, the gasoline pumped into cars today is different from the gasoline used in automobiles in the early 1900s. The gasoline fraction that is distilled from petroleum is modified by adjusting its composition and adding substances 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 will be wasted, fuel efficiency will drop, and the engine will 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.

CAREERS IN CHEMISTRY

Petroleum Technician This science technician uses instruments to measure and record physical and geological information about oil or gas wells. For example, a petroleum technician might test a geological sample to determine its petroleum content and its mineral or element composition. For more information on chemistry careers, visit glencoe.com.

■ **Figure 21.8** Octane ratings are used to give the antiknock rating of fuel. Mid-grade gasoline for cars has an octane rating of about 89. Aviation fuel has an octane rating of about 100. Racing fuel has an octane rating of about 110.

In the late 1920s, an antiknock, or octane rating, system for gasoline was established, resulting in the octane ratings posted on gasoline pumps like those shown in **Figure 21.8.** Mid-grade gasoline today has a rating of about 89, whereas premium gasoline has higher ratings of 91 or higher. 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.

Connection to Earth Science Since ancient times, people have found petroleum seeping from cracks in rocks. Historical records show that petroleum has been used for more than 5000 years. In the nineteenth century, as the United States entered the machine age and its population increased, the demand for petroleum products, namely kerosene for lighting and lubricants for machines, increased. In an attempt to find a reliable petroleum supply, Edwin Drake drilled the first oil well in the United States in Pennsylvania, in 1859. The oil industry flourished for a time, but when Thomas Edison introduced the electric light in 1882, investors feared that the industry was doomed. However, the invention of the automobile in the 1890s revived the industry on a massive scale.

Section 21.1 Assessment

Section Summary

- Organic compounds contain carbon, which is able to form straight chains and branched chains.
- Hydrocarbons are organic substances composed of carbon and hydrogen.
- The major sources of hydrocarbons are petroleum and natural gas.
- Petroleum can be separated into components by the process of fractional distillation.

1. **MAIN Idea** **Identify** three applications of hydrocarbons as a source of energy and raw materials.
2. **Name** an organic compound and explain what an organic chemist studies.
3. **Identify** what each of the four molecular models highlights about a molecule.
4. **Compare and contrast** saturated and unsaturated hydrocarbons.
5. **Describe** the process of fractional distillation.
6. **Infer** Some shortening products are described as "hydrogenated vegetable oil," which are oils that reacted with hydrogen in the presence of a catalyst. Form a hypothesis to explain why hydrogen reacted with the oils.
7. **Interpret Data** Refer to **Figure 21.6.** What property of hydrocarbon molecules correlates to the viscosity of a particular fraction when it is cooled to room temperature?

Section 21.2

Objectives

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

Review Vocabulary

IUPAC (International Union of Pure and Applied Chemistry): an international group that aids communication between chemists by setting rules and standards in areas such as chemical nomenclature, terminology, and standardized methods

New Vocabulary

alkane
homologous series
parent chain
substituent group
cyclic hydrocarbon
cycloalkane

Alkanes

MAIN Idea Alkanes are hydrocarbons that contain only single bonds.

Real-World Reading Link Have you ever used a Bunsen burner or an outdoor gas grill? If so, you have used an alkane. Natural gas and propane are the two most common gases used in these applications, and both are alkanes.

Straight-Chain Alkanes

Methane is the smallest member of a series of hydrocarbons known as alkanes. It is used as a fuel in homes and science labs and is a product of many biological processes. **Alkanes** are hydrocarbons that have only single bonds between atoms. Look in Section 21.1 to review the various models of methane. The models for ethane (C_2H_6), the second member of the alkane series, are shown in **Table 21.1.** Ethane consists of two carbon atoms bonded together with a single bond and six hydrogen atoms sharing the remaining valence electrons of the carbon atoms.

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 and the formula C_4H_{10}. Compare the structures of ethane, propane, and butane in **Table 21.1.**

Propane, also known as LP (liquified propane) gas, is sold as a fuel for cooking and heating. Butane is used as fuel in small lighters and in some torches. It is also used in the manufacture of synthetic rubber.

Table 21.1 Simple Alkanes

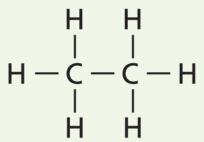
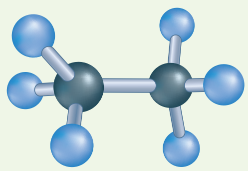
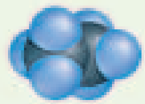
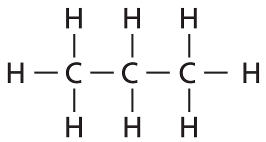
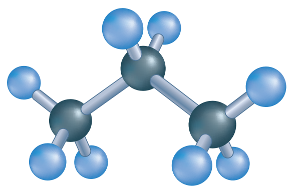
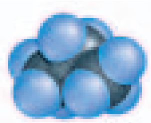
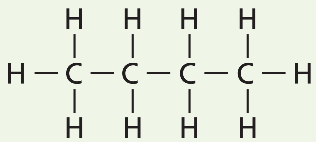
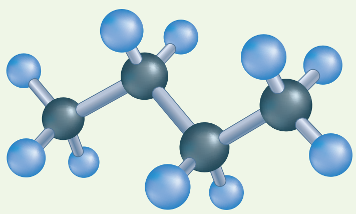
Molecular Formula	Structural Formula	Ball-and-Stick Model	Space-Filling Model
Ethane (C_2H_6)			
Propane (C_3H_8)			
Butane (C_4H_{10})			

Table 21.2 First Ten of the Alkane Series

Name	Molecular Formula	Condensed Structural Formula
Methane	CH_4	CH_4
Ethane	C_2H_6	CH_3CH_3
Propane	C_3H_8	$CH_3CH_2CH_3$
Butane	C_4H_{10}	$CH_3CH_2CH_2CH_3$
Pentane	C_5H_{12}	$CH_3CH_2CH_2CH_2CH_3$
Hexane	C_6H_{14}	$CH_3CH_2CH_2CH_2CH_2CH_3$
Heptane	C_7H_{16}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$
Octane	C_8H_{18}	$CH_3(CH_2)_6CH_3$
Nonane	C_9H_{20}	$CH_3(CH_2)_7CH_3$
Decane	$C_{10}H_{22}$	$CH_3(CH_2)_8CH_3$

Naming straight-chain alkanes By now, you have likely 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 21.2** shows the names and structures of the first ten alkanes. Notice the underlined prefix representing the number of carbon atoms in the molecule.

In **Table 21.2,** you can see that the structural formulas are written in a different way from those in **Table 21.1.** These formulas, called condensed structural formulas, save space by not showing how the hydrogen atoms branch off from the carbon atoms. Condensed formulas can be written in several ways. In **Table 21.2,** the lines between carbon atoms have been eliminated to save space.

In **Table 21.2,** you can see that $–CH_2–$ is a repeating unit in the chain of carbon atoms. Note, for example, that pentane has one more $–CH_2–$ unit than butane. 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 octane, 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 carbon atoms, so its formula is $C_7H_{2(7)+2}$, or C_7H_{16}.

Reading Check **Write** the molecular formula for an alkane that has 13 carbon atoms in its molecular structure.

VOCABULARY
WORD ORIGIN
Homologous
comes from the Greek word *homologos* meaning *agreeing*

Branched-Chain Alkanes

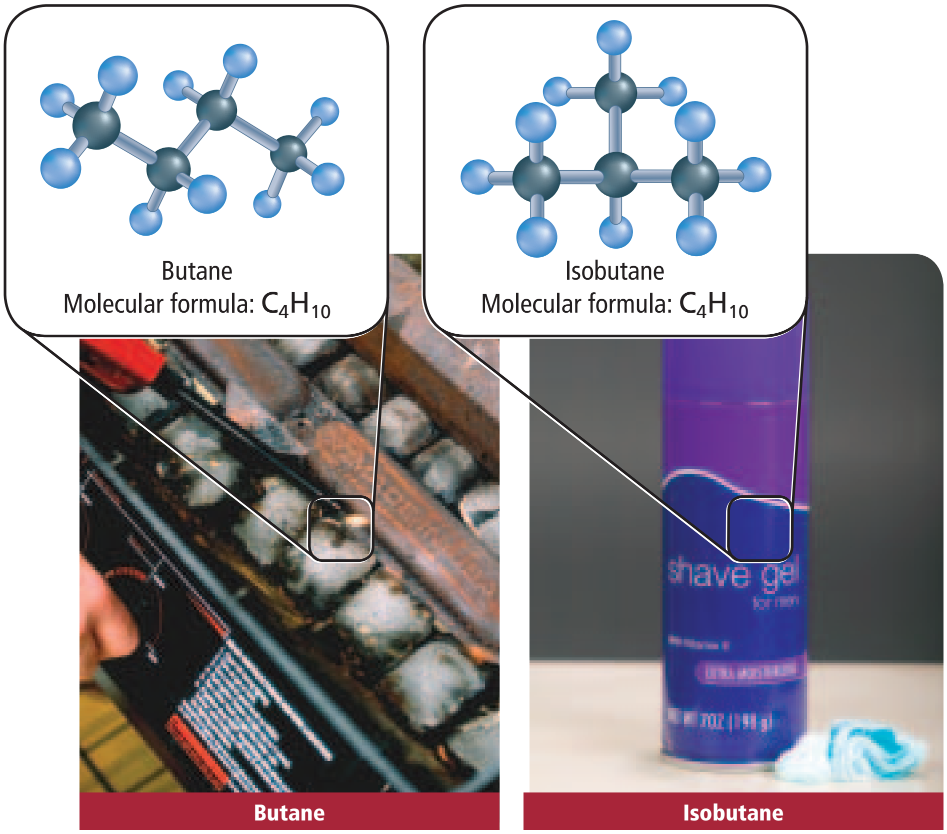
The alkanes discussed so far in this chapter are called straight-chain alkanes because the carbon atoms are bonded to each other in a single line. Now look at the two structures in **Figure 21.9.** If you count the carbon and hydrogen atoms, you will discover that both structures have the same molecular formula, C_4H_{10}. Do the structures in **Figure 21.9** represent the same substance?

If you think that the structures represent two different substances, you are correct. 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. Carbon atoms can bond to one, two, three, or even four other carbon atoms. This property makes possible a variety of branched-chain alkanes.

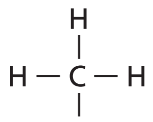
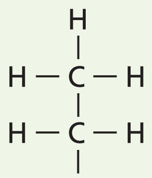
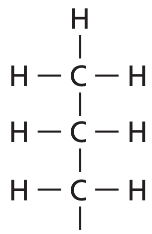
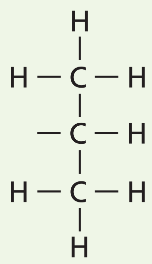
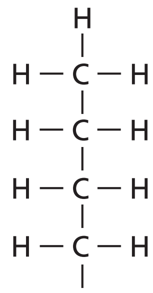
Recall that butane is used in lighters and in torches. Isobutane is used as both an environmentally-safe refrigerant and a propellant in products such as shaving gel, as shown in **Figure 21.9.** In addition to these applications, both butane and isobutane are used as raw materials for many chemical processes.

Reading Check **Describe** the difference in the molecular structures of butane and isobutane.

Alkyl groups You have 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 must also accurately describe the molecular structure of the compound.



■ **Figure 21.9** Butane is a fuel used in lighters. Isobutane is used as a propellant in products such as shaving gel.

Table 21.3	Common Alkyl Groups				
Name	Methyl	Ethyl	Propyl	Isopropyl	Butyl
Condensed structural formula	$CH_3—$	$CH_3CH_2—$	$CH_3CH_2CH_2—$	$CH_3\underset{\vert}{C}HCH_3$	$CH_3CH_2CH_2CH_2—$
Structural formula					

When naming branched-chain alkanes, 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. Each alkane-based substituent group branching from the parent chain is named for the straight-chain alkane that has the same number of carbon atoms as the substituent. The ending *-ane* is replaced with the letters *-yl*. An alkane-based substituent group is called an alkyl group. Several alkyl groups are shown in **Table 21.3.**

Naming branched-chain alkanes To name organic structures, chemists use the following systematic rules approved by the International Union of Pure and Applied Chemistry (IUPAC).

Step 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.

Step 2. *Number each carbon in the parent chain.* Locate the end carbon closest to a substituent group. Label that carbon *Position 1*. This step gives all the substituent groups the lowest position numbers possible.

Step 3. *Name each alkyl group substituent.* Place the name of the group before the name of the parent chain.

Step 4. *If the same alkyl group occurs more than once as a branch on the parent structure, use a prefix* (di-, tri-, tetra-, *and so on*) *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.

Step 5. *When different alkyl groups are attached to the same parent structure, place their names in alphabetical order.* Do not consider the prefixes (*di-*, *tri-*, and so on) when determining alphabetical order.

Step 6. *Write the entire name, using hyphens to separate numbers from words and commas to separate numbers.* Do not add a space between the substituent name and the name of the parent chain.

VOCABULARY

ACADEMIC VOCABULARY

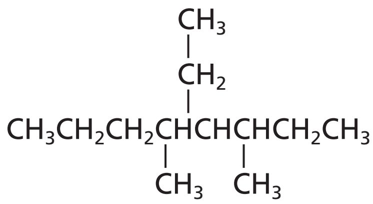
Substitute

a person or thing that takes the place of another

A substitute teacher taught chemistry class yesterday.

EXAMPLE Problem 21.1

Naming Branched-Chain Alkanes
Name the alkane shown.



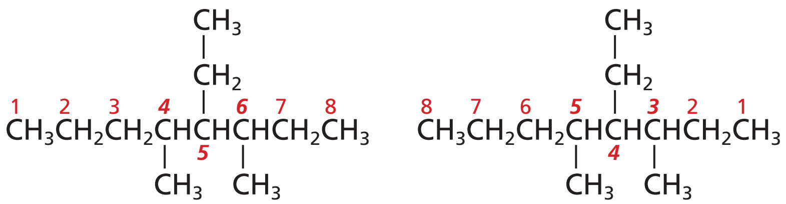
1 Analyze the Problem

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

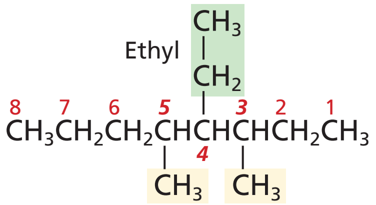
2 Solve for the Unknown

Step 1. *Count the number of carbon atoms in the longest continuous chain.* Because structural formulas can be written with chains oriented in various ways, you need to be careful in finding the longest continuous carbon chain. In this case, it is easy. The longest chain has eight carbon atoms, so the parent name is *octane*.

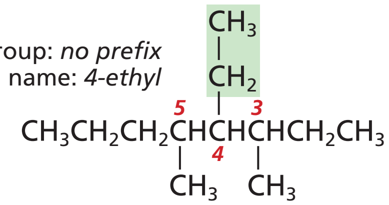
Step 2. *Number each carbon in the parent chain.* Number the chain in both directions, as shown below. Numbering from the left puts the alkyl groups at Positions 4, 5, and 6. Numbering from the right puts alkyl groups at Positions 3, 4, and 5. Because 3, 4, and 5 are the lowest position numbers, they will be used in the name.



Step 3. *Name each alkyl group substituent.* 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.



Step 4. *If the same alkyl group occurs more than once as a branch on the parent structure, use a prefix* (di-, tri-, tetra-, *and so on) before its name to indicate how many times it appears.* 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.



Chemistry Online
Personal Tutor For help naming hydrocarbons, visit glencoe.com.

Step 5. *Whenever different alkyl groups are attached to the same parent structure, place their names in alphabetical order.* Place the names of the alkyl branches in alphabetical order, ignoring the prefixes. Alphabetical order puts the name <u>e</u>thyl before di<u>m</u>ethyl.

Step 6. *Write the entire name, using hyphens to separate numbers from words and commas to separate numbers.* 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

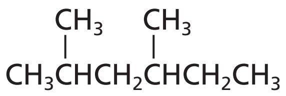
The longest continuous carbon chain has been found and numbered correctly. All branches have been designated with correct prefixes and alkyl-group names. Alphabetical order and punctuation are correct.

PRACTICE Problems

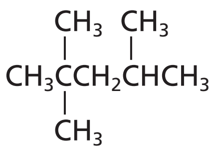
Extra Practice Page 991 and glencoe.com

8. Use the IUPAC rules to name the following structures.

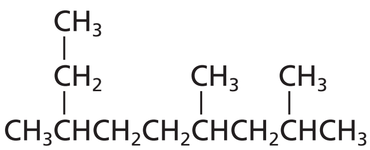
a.



b.



c.



9. Challenge Draw the structures of the following branched-chain alkanes.

a. 2,3-dimethyl-5-propyldecane

b. 3,4,5-triethyloctane

Cycloalkanes

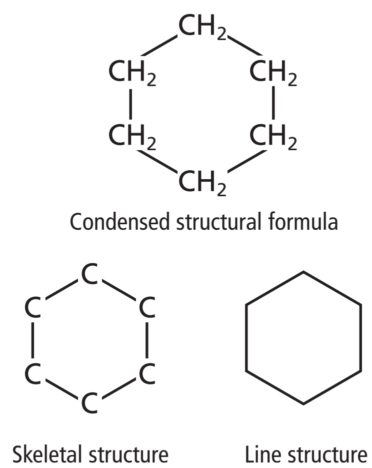
One of the reasons that such a variety of organic compounds exists is that carbon atoms can form ring structures. An organic compound that contains a hydrocarbon ring is called a **cyclic hydrocarbon.** To indicate that a hydrocarbon has a ring structure, the prefix *cyclo-* is used with the hydrocarbon name. Thus, cyclic hydrocarbons that contain only single bonds are called **cycloalkanes.**

Cycloalkanes can have rings with three, four, five, six, or even more carbon atoms. The name for the six-carbon cycloalkane is *cyclohexane.* Cyclohexane, which is obtained from petroleum, 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.

Reading Check Evaluate If the prefix *cyclo-* is present in the name of an alkane, what do you know about the alkane?

As shown in **Figure 21.10,** 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. Hydrogens are also not shown in skeletal structures.

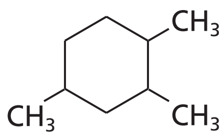
Figure 21.10 Cyclohexane can be represented in several ways.



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 illustrates the naming process for cycloalkanes.

EXAMPLE Problem 21.2

Naming Cycloalkanes
Name the cycloalkane shown.



1 Analyze the Problem

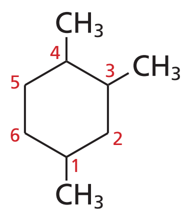
You are given a structure. To determine the parent cyclic structure and the location of branches, follow the IUPAC rules.

2 Solve for the Unknown

Step 1. 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*.

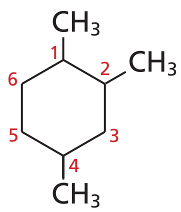
Step 2. Number the ring, starting from one of the CH_3— branches. Find the numbering that gives the lowest possible set of numbers for the branches. Here are two ways of numbering the ring.

A



1,3,4

B



1,2,4

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 Positions 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.

Step 3. Name the substituents. All three are the same—carbon methyl groups.

Step 4. Add the prefix to show the number of groups present. Three methyl groups are present, so you add the prefix *tri-* to the name *methyl* to make *trimethyl*.

Step 5. Alphabetical order can be ignored because only one type of group is present.

Step 6. Put the name together using the name of the parent cycloalkane. Use commas between separate numbers, and hyphens between numbers and words. Write the name as *1,2,4-trimethylcyclohexane*.

3 Evaluate the Answer

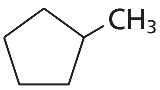
The parent-ring structure is numbered to give the branches the lowest possible set of numbers. The prefix *tri-* indicates that three methyl groups are present. No alphabetization is necessary because all branches are methyl groups.

PRACTICE Problems

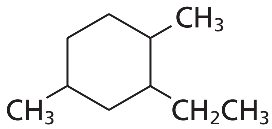
Extra Practice Page 991 and glencoe.com

10. Use IUPAC rules to name the following structures.

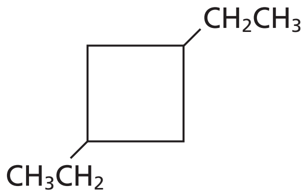
a.



b.



c.



11. Challenge 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, 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 between two carbon atoms. A bond between two identical atoms, such as carbon, can never be polar. Because all of the bonds in alkanes are nonpolar, alkane molecules are nonpolar, which makes them good solvents for other nonpolar substances, as shown in **Figure 21.11.**

Figure 21.11 Many solvents—used as thinners for paints, coatings, waxes, photocopier toners, adhesives, and printer press inks—contain alkanes and cycloalkanes.

Table 21.4	**Comparing Physical Properties**	
Substance and formula	Water (H_2O)	Methane (CH_4)
Molecular mass	18 amu	16 amu
State at room temperature	liquid	gas
Boiling point	100°C	−162°C
Melting point	0°C	−182°C

FOLDABLES Incorporate information from this section into your Foldable.

Physical properties of alkanes How do the properties of a polar and nonpolar compound compare? Refer to **Table 21.4,** and 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.

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.

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 electric 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 can also be attributed to the relatively strong C–C and C–H bonds.

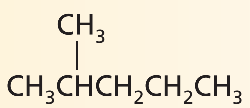
Section 21.2 Assessment

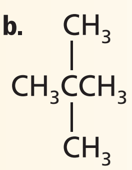
Section Summary

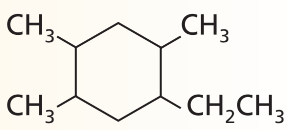
- Alkanes contain only single bonds between carbon atoms.
- Alkanes and other organic compounds are best represented by structural formulas and can be named using systematic rules determined by the International Union of Pure and Applied Chemistry (IUPAC).
- Alkanes that contain hydrocarbon rings are called cyclic alkanes.

12. MAIN Idea **Describe** the main structural characteristics of alkane molecules.

13. Name the following structures using IUPAC rules.

a.


b.


c.


14. Describe the general properties of alkanes.

15. Draw the molecular structure for each of the following.

a. 3, 4-diethylheptane

b. 4-isopropyl-3-methyldecane

c. 1-ethyl-4-methylcyclohexane

d. 1,2-dimethylcyclopropane

16. Interpret Chemical Structures 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?

Section 21.3

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.

Review Vocabulary

hormone: chemical produced in one part of an organism and transported to another part, where it causes a physiological change

New Vocabulary

alkene
alkyne

Alkenes and Alkynes

MAIN Idea Alkenes are hydrocarbons that contain at least one double bond, and alkynes are hydrocarbons that contain at least one triple bond.

Real-World Reading Link Plants produce ethene as a natural ripening hormone. For efficiency in harvesting and transporting produce to market, fruits and vegetables are often picked while unripe and are exposed to ethene so they will ripen at the same time.

Alkenes

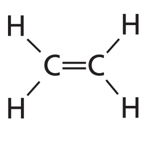
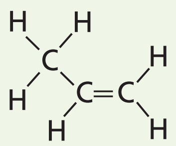
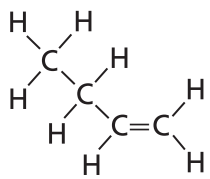
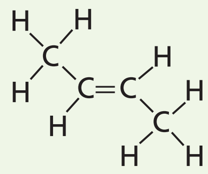
Recall that alkanes are saturated hydrocarbons because they contain only single covalent bonds between carbon atoms, and that unsaturated hydrocarbons have at least one double or triple bond between carbon atoms. Unsaturated hydrocarbons that contain one or more double covalent bonds between carbon atoms 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).

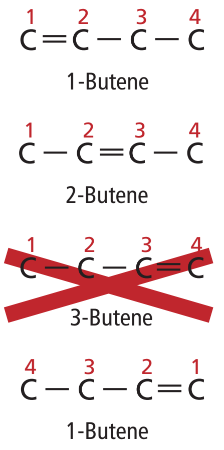
Alkenes with only one double bond constitute a homologous series. Recall from Section 21.2 that a homologous series has a fixed numerical relationship among the numbers of atoms. If you study the molecular formulas for the substances shown in **Table 21.5,** you will see that each has twice as many hydrogen 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?

Concepts In Motion

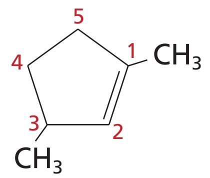
Interactive Table Explore alkenes at glencoe.com.

Table 21.5 Examples of Alkenes

Name	Ethene	Propene	1-Butene	2-Butene
Molecular formula	C_2H_4	C_3H_6	C_4H_8	C_4H_8
Structural formula				
Condensed structural formula	$CH_2{=}CH_2$	$CH_3CH{=}CH_2$	$CH_3CH_2CH{=}CH_2$	$CH_3CH{=}CHCH_3$



a. Straight-chain alkenes



b. Cyclic alkenes

■ **Figure 21.12** When naming either branched or straight-chain alkenes, they must be numbered using IUPAC rules.

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, more 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, as shown in the examples in **Figure 21.12a.** This is done 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, use only that number in the name.

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.

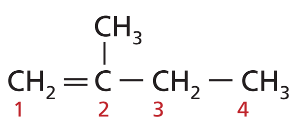
Cyclic alkenes are named in much the same way as cyclic alkanes; however, carbon number 1 must be one of the carbons connected by the double bond. In **Figure 21.12b,** note the numbering in the compound. The name of this compound is 1,3-dimethylcyclopentene.

Reading Check **Infer** why it is necessary to identify where the double bond is located in the name of an alkene.

Naming branched-chain alkenes When naming branched-chain alkenes, follow the IUPAC rules for naming branched-chain alkanes, but with two exceptions. First, in alkenes, the parent chain is always the longest chain that contains the double bond, whether or not it is the longest chain of carbon atoms. 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 in **Figure 21.13a,** but only the one with the double bond is used as a basis for naming. This branched-chain alkene is 2-methylbutene.

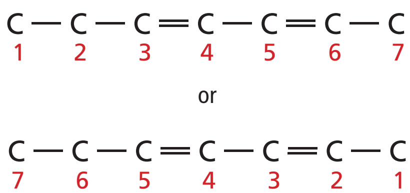
Some unsaturated hydrocarbons contain more than one double (or triple) bond. The number of double bonds in such molecules is shown by using a prefix (*di-*, *tri-*, *tetra-*, and so on) before the suffix *-ene*. The positions of the bonds are numbered in a way that gives the lowest set of numbers. Which numbering system would you use in the example in **Figure 21.13b?** Because the molecule has a seven-carbon chain, you would use the prefix *hepta-*. Because it has two double bonds, you would use the prefix *di-* before *-ene*, giving the name *heptadiene*. Adding the numbers 2 and 4 to designate the positions of the double bonds gives the name *2,4-heptadiene*.

■ **Figure 21.13** The positions of the double bonds in alkenes are numbered in a way that gives the lowest set of numbers. This is true of both branched and straight-chain alkenes.



2-methylbutene

a. Single double bond

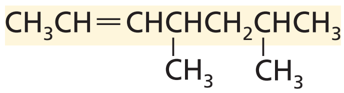


2,4-heptadiene

b. Two double bonds

EXAMPLE Problem 21.3

Naming Branched-Chain Alkenes
Name the alkene shown.

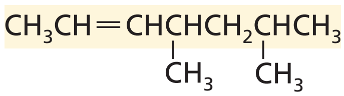


1 Analyze the Problem

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.

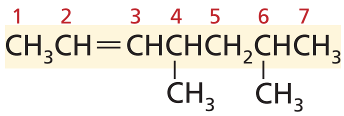
2 Solve for the Unknown

Step 1. 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.



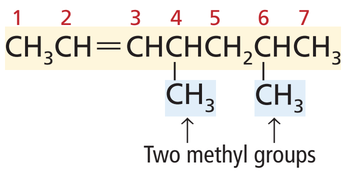
***Heptene* parent chain**

Step 2. Number the chain to give the lowest number to the double bond.



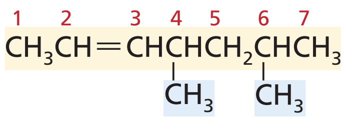
***2-Heptene* parent chain**

Step 3. Name each substituent.



***2-Heptene* parent chain**

Step 4. 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.



***2-Heptene* parent chain**
Two methyl groups at Positions 4 and 6
Prefix is 4,6-*dimethyl*

Step 5. The names of substituents do not have to be alphabetized because they are the same. Apply the complete prefix to the name of the parent alkene chain. Use commas between numbers, and hyphens between numbers and words. Write the name 4,6-*dimethyl*-2-*heptene*.

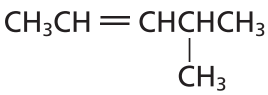
3 Evaluate the Answer

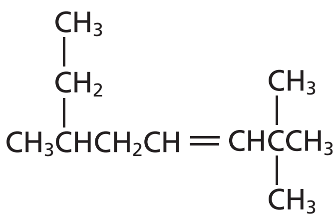
The longest carbon chain includes the double bond, and the position of the double bond has the lowest possible number. Correct prefixes and alkyl-group names designate the branches.

PRACTICE Problems

Extra Practice Page 991 and glencoe.com

17. Use the IUPAC rules to name the following structures.

a. 

b. 

18. Challenge Draw the structure of 1,3-pentadiene.

■ **Figure 21.14** The use of ethene to ripen produce allows growers to harvest fruits and vegetables before they ripen. **Explain** *why this is a benefit to growers.*

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 is a hormone produced naturally by plants. It causes fruit to ripen and plays a part in causing leaves to fall from deciduous trees in preparation for winter. The fruits shown in **Figure 21.14** and other produce sold in grocery stores ripen artificially when they are exposed to ethene. Ethene is also the starting material for the synthesis of the plastic polyethylene, which is used to manufacture many products, including plastic bags, rope, and milk jugs. Other alkenes are responsible for the scents of lemons, limes, and pine trees.

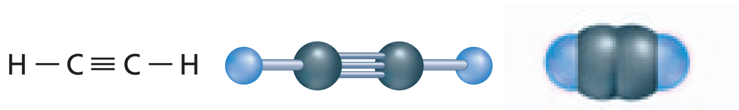
Alkynes

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 **Figure 21.15.**

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 21.6.** Alkynes with one triple covalent bond form a homologous series with the general formula C_nH_{2n-2}.

Reading Check **Infer,** by looking at the bonds in ethyne, why it is highly reactive with oxygen.

■ **Figure 21.15** These three molecular models represent ethyne.

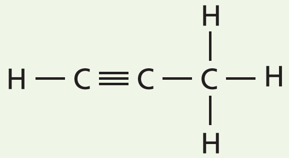
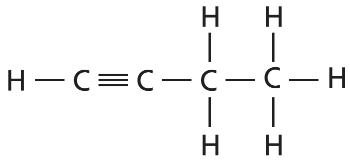
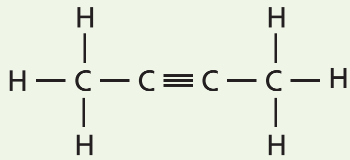


Models of ethyne (acetylene)

Concepts In Motion

Interactive Table Explore the gas laws at glencoe.com.

Table 21.6 Examples of Alkynes

Name	Molecular Formula	Structural Formula	Condensed Structural Formula
Ethyne	C_2H_2	$H-C\equiv C-H$	$CH\equiv CH$
Propyne	C_3H_4		$CH\equiv CCH_3$
1-Butyne	C_4H_6		$CH\equiv CCH_2CH_3$
2-Butyne	C_4H_6		$CH_3C\equiv CCH_3$

MiniLab

Synthesize and Observe Ethyne

Why is ethyne used in welding torches?

Procedure

1. Read and complete the lab safety form.
2. Use a **rubber band** to attach a **wood splint** to one end of a **ruler** that is about 40 cm long, so that about 10 cm of the splint extends beyond the ruler.
3. Place 120 mL **water** in a **150-mL beaker,** and add 5 mL **dishwashing detergent.** Mix thoroughly.
4. Use **forceps** to pick up a pea-sized lump of **calcium carbide** (CaC_2). Do not touch the CaC_2 with your fingers. **WARNING:** ***CaC_2 is corrosive; 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.
5. 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.
6. Use a **stirring rod** to dislodge a few large bubbles of ethyne. Do they float or sink in air?
7. 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. **Infer** What can you infer about the density of ethyne compared to the density of air?
2. **Predict** The reaction of calcium carbide with water yields two products. One is ethyne gas (C_2H_2). What is the other product? Write a balanced chemical equation for the reaction.

■ **Figure 21.16** Ethyne, or acetylene, reacts with oxygen in the chemical reaction $2C_2H_2 + 5O_2 \longrightarrow 4CO_2 + 2H_2O$, which produces enough heat to weld metals.

FOLDABLES Incorporate information from this section into your Foldable.

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

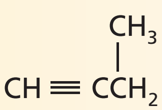
Ethyne—known commonly as acetylene—is a by-product of oil refining and is also made in large quantities by the reaction of calcium carbide (CaC_2) with water. When supplied with enough oxygen, ethyne burns with an intensely hot flame that can reach temperatures as high as 3000°C. Acetylene torches are commonly used in welding, as shown in **Figure 21.16.** Because the triple bond makes alkynes reactive, simple alkynes like ethyne are used as starting materials in the manufacture of plastics and other organic chemicals used in industry.

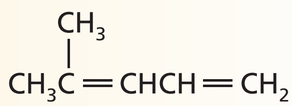
Section 21.3 Assessment

Section Summary

- 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 alkanes.

19. **MAIN Idea** **Describe** how the molecular structures of alkenes and alkynes differ from the structure of alkanes.
20. **Identify** how the chemical properties of alkenes and alkynes differ from those of alkanes.
21. **Name** the structures shown using IUPAC rules.

    a. 

    b. 
22. **Draw** the molecular structure of 4-methyl-1,3-pentadiene and 2,3-dimethyl-2-butene.
23. **Infer** how the boiling and freezing points of alkynes compare with those of alkanes with the same number of carbon atoms. Explain your reasoning, then research data to see it if supports your idea.
24. **Predict** What geometric arrangement would you expect from the bonds surrounding the carbon atom in alkanes, alkenes, and alkynes? *(Hint: VSEPR theory can be used to predict the shape.)*

Chemistry Online Self-Check Quiz glencoe.com

Section 21.4

Objectives

- **Distinguish** between the two main categories of isomers—structural isomers and stereoisomers.
- **Differentiate** between geometric isomers with *cis-* and *trans-* prefixes.
- **Describe** the structural variation in molecules that results in optical isomers.

Review Vocabulary

electromagnetic radiation: transverse waves that carry energy through empty space

New Vocabulary

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

Hydrocarbon Isomers

MAIN Idea Some hydrocarbons have the same molecular formula but have different molecular structures.

Real-World Reading Link Have you ever met a pair of identical twins? Identical twins have the same genetic makeup, yet they are two separate individuals with different personalities. Isomers are similar to twins—they have the same molecular formula, but different molecular structures and properties.

Structural Isomers

Examine the models of three alkanes in **Figure 21.17** to determine how they are similar and how they are different. All three have 5 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 and three different compounds—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}.

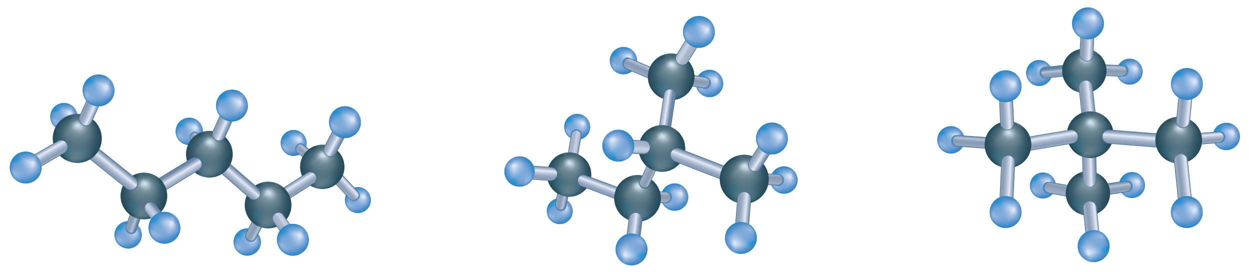
There are two main classes of isomers. **Figure 21.17** shows compounds that are examples of structural isomers. **Structural isomers** have the same chemical formula, but their atoms are bonded in different arrangements. Structural isomers have different chemical and physical properties despite having 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, there are nine alkanes with the molecular formula C_7H_{16}. There are more than 300,000 structural isomers with the formula $C_{20}H_{42}$.

■ **Figure 21.17** These compounds with the same molecular formula, C_5H_{12}, are structural isomers. Note how their boiling points differ.

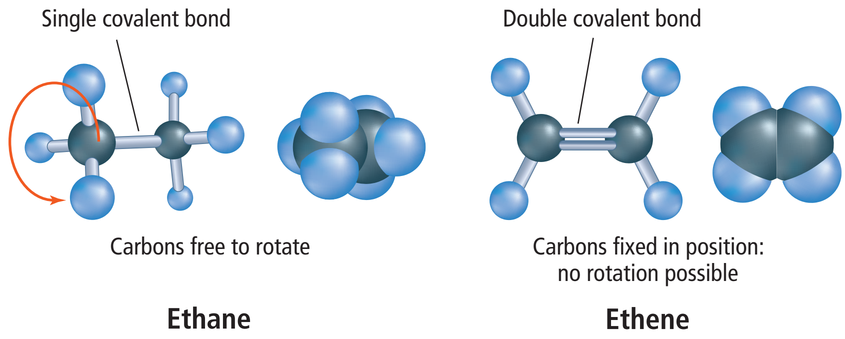
Concepts In Motion

Interactive Figure To see an animation of the isomers of pentane, visit glencoe.com.



Pentane bp = 36°C | **2-Methylbutane** bp = 28°C | **2,2-Dimethylpropane** bp = 9°C

■ **Figure 21.18** The single-bonded carbons in ethane are free to rotate around the bond. The double-bonded carbons in ethene resist being rotated.
Explain ***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

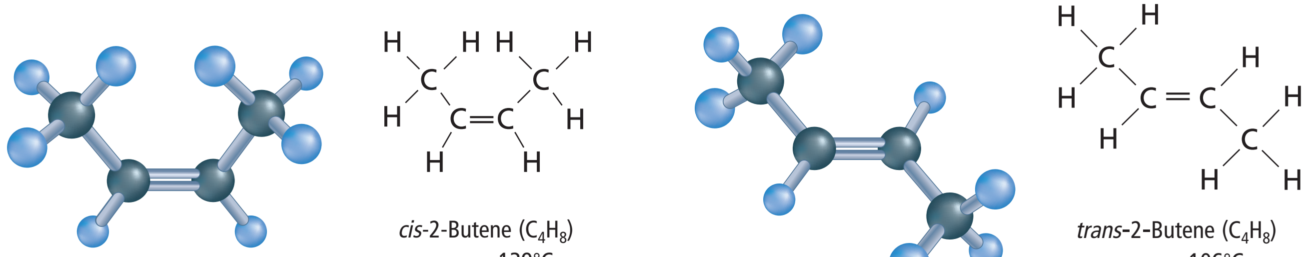
The second class of isomers involves a more subtle difference in bonding. **Stereoisomers** are isomers in which all atoms are bonded in the same order but are arranged differently in space. There are two types of stereoisomers. One type occurs in alkenes, which contain double bonds. Two carbon atoms 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 21.18.**

Compare the two possible structures of 2-butene shown in **Figure 21.19.** 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 carbon atoms 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 very different effects.

Reading Check **Explain** how structural and geometric isomers differ.

■ **Figure 21.19** 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 are fixed in one of these two arrangements.



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

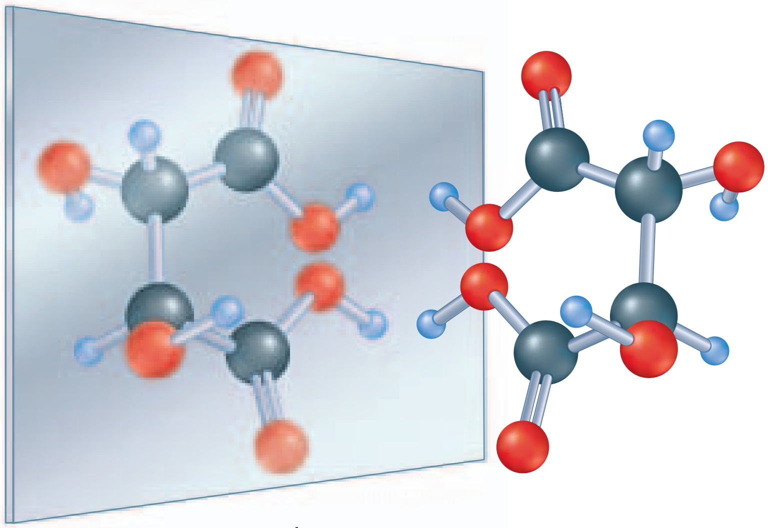
trans-2-Butene (C_4H_8)
mp = −106°C
bp = 0.8°C

■ **Figure 21.20** Molecules of D-tartaric acid and L-tartaric acid resemble each other in the same way that your right hand and left hand resemble each other. The reflection of your right hand looks the same as your left hand.

Chirality

Connection to Biology 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 21.20,** 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 they could not use the right-handed form.

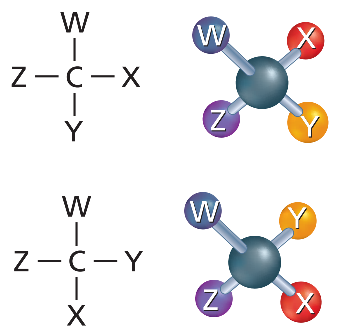
Pasteur concluded that the two crystalline forms of tartaric acid exist because the tartaric acid molecules themselves exist in two arrangements, as shown in **Figure 21.21.** The property in which a molecule exists in a right- and left-handed form is called **chirality.** Many of the substances found in living organisms, such as the amino acids that make up proteins, have this property.



■ **Figure 21.21** These models represent the two forms of tartaric acid that Pasteur studied. If the model of D-tartaric acid is reflected in a mirror, its image is a model of L-tartaric acid.

Real-World Chemistry
Trans fats

Isomers in the diet Fats with *trans* isomers are called *trans* fats. Many pre-packaged foods are made with *trans* fats because they have a longer shelf life. Evidence suggests that *trans* fat increases the unhealthy form of cholesterol and decreases the healthy form, which increases the chance of heart disease.



■ **Figure 21.22** These models represent two different molecules. Groups X and Y have switched places.

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 can always 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 in **Figure 22.22.** Note that the structures differ in that groups X and Y have 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. Therefore, the molecules are different even though they look very much alike.

Isomers that result from different arrangements of four different groups around 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 also be important. For example, only one isomer of some drugs is effective and the other isomer can be harmful.

FOLDABLES Incorporate information from this section into your Foldable.

DATA ANALYSIS LAB

Based on Real Data*

Interpret Data

What are the rates of oxidation of dichloroethene isomers? *Pseudomonas butanovora* is a bacterium that uses some alkanes, alcohols, and organic acids as sources of carbon and energy. This bacteria was tested as an agent to rid groundwater of dichloroethene (DCE) contaminants. The chemical reactions are oxidation reactions using butane monooxygenase as a catalyst and various reducing agents as electron acceptors.

Data and Observations

The table shows the rate of oxidation of each compound in butane-grown *P. butanovora.*

Rates of Oxidation

	Initial Rate of Oxidation (nmol min^{-1} mg protein^{-1})	
Reducing Agent	**1,2-cis DCE**	**1,2-trans DCE**
Buffer	0.9 (1.0)	1.6 (1.0)
Butyrate	6.8 (7.6)	2.0 (1.3)
Propionate	5.9 (6.6)	0.4 (0.3)
Acetate	8.5 (9.4)	3.8 (2.8)
Formate	1.4 (1.6)	1.2 (0.7)
Lactate	11 (12.2)	4.5 (2.8)

Values in parentheses represent the increase (*n*-fold) above the buffer rate.

Think Critically

1. **Compare** Which reducing agent was most useful in oxidizing each isomer?
2. **Conclude** Which isomer oxidized the slowest?

Data obtained from: Doughty, D.M. et al. 2005. Effects of dichloroethene isomers on the induction and activity of butane monooxygenase in the alkane-oxidizing Bacterium *"Pseudomonas butanovora." Applied Environmental Microbiology.* October: 6054–6059.

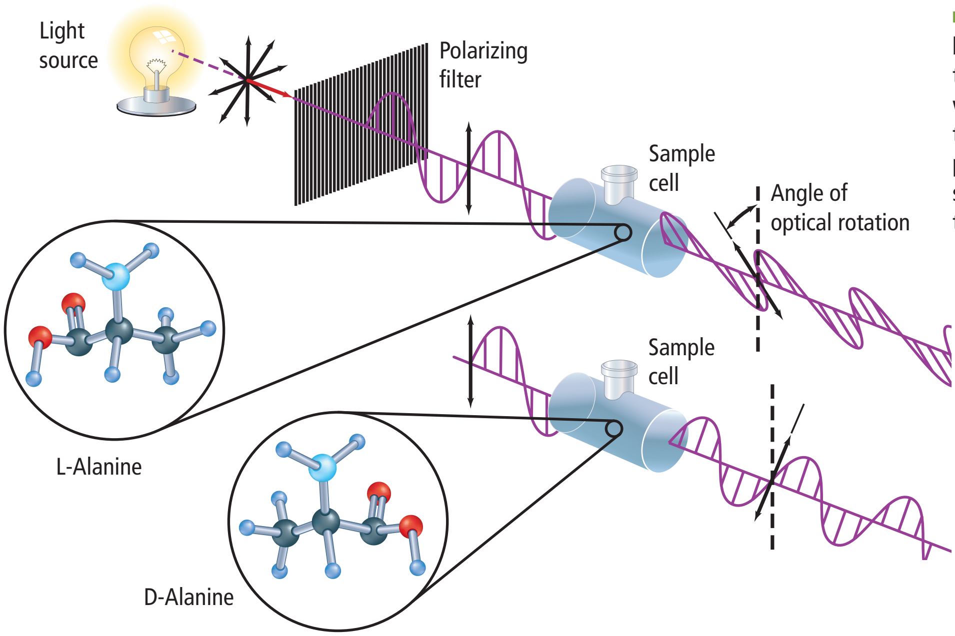


Figure 21.23 Polarized light can be produced by passing ordinary light through a filter that transmits light waves that lie in only one plane. Here, the filtered light waves are in a vertical plane before they pass through the sample cells. The two isomers rotate the light in different directions.

Optical rotation Mirror-image isomers are called optical isomers because they affect light passing through them. Normally, the light waves in a beam from the Sun or a lightbulb move in all possible planes. 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.

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 (counter-clockwise) by an L-isomer, producing an effect called **optical rotation.** This effect is shown in **Figure 21.23.**

One optical isomer that you might have used is L-menthol. This natural isomer has a strong, minty flavor, and a cooling odor and taste. The mirror-image isomer, D-menthol, does not have the same cooling effect as L-menthol.

Section 21.4 Assessment

Section Summary

- 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.
- Stereoisomers have all atoms bonded in the same order but arranged differently in space.

25. MAIN Idea **Draw** all of the structural isomers possible for the alkane with the molecular formula C_6H_{14}. Show only the carbon chains.
26. **Explain** the difference between structural isomers and stereoisomers.
27. **Draw** the structures of *cis*-3-hexene and *trans*-3-hexene.
28. **Infer** why living organisms can make use of one only chiral form of a substance.
29. **Evaluate** 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.
30. **Formulate 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 21.5

Objectives

- **Compare and contrast** the properties of aromatic and aliphatic hydrocarbons.
- **Explain** what a carcinogen is, and list some examples.

Review Vocabulary

hybrid orbitals: equivalent atomic orbitals that form during bonding by the rearrangement of valence electrons

New Vocabulary

aromatic compound
aliphatic compound

Aromatic Hydrocarbons

MAIN Idea Aromatic hydrocarbons are unusually stable compounds with ring structures in which electrons are shared by many atoms.

Real-World Reading Link What do bright, colorful fabrics and essential oils for perfumes have in common? They both contain aromatic hydrocarbons.

The Structure of Benzene

Natural dyes, like those found in the fabrics in **Figure 21.25,** and essential oils for perfumes contain six-carbon ring structures. Compounds with these structures have been used for centuries. 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, certain hydrocarbon ring structures remained a mystery.

The simplest example of this class of hydrocarbon is benzene, which the English physicist Michael Faraday (1791–1867) first isolated in 1825 from the gases given off when either whale oil or coal was heated. 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.

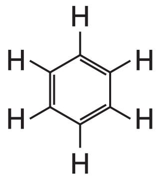
$$CH_2{=}C{=}CH{-}CH{=}C{=}CH_2$$

Although this structure has a molecular formula of C_6H_6, such a hydrocarbon would be unstable and extremely reactive because of its many double bonds. However, benzene was fairly unreactive, and it did not react 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.

Figure 21.24 Dyes used to produce brightly-colored fabrics have been used for centuries.

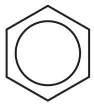
Explain *What do many natural dyes and essential oils for perfumes have in common?*

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 did 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, benzene's unreactivity could not be explained 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 21.25** 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 it is important to 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.



Aromatic Compounds

Organic compounds that contain benzene rings as part of their structures 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. What are some examples of animal fats that might contain aliphatic compounds?

Reading Check **Infer** why the terms *aromatic compound* and *aliphatic compound* continue to be used by chemists today.

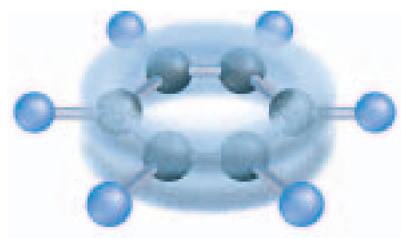


Figure 21.25 Benzene's bonding electrons spread evenly in a double-donut shape around the ring instead of remaining near individual atoms.

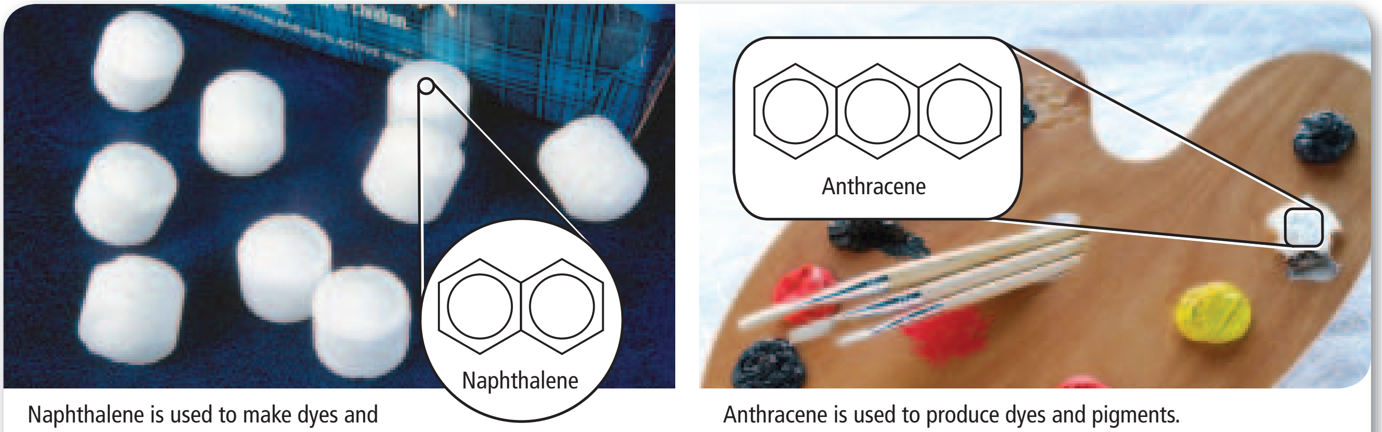
Concepts In Motion

Interactive Figure To see an animation of sigma- and pi-bonding in benzene, visit glencoe.com.

VOCABULARY
SCIENCE USAGE V. COMMON USAGE

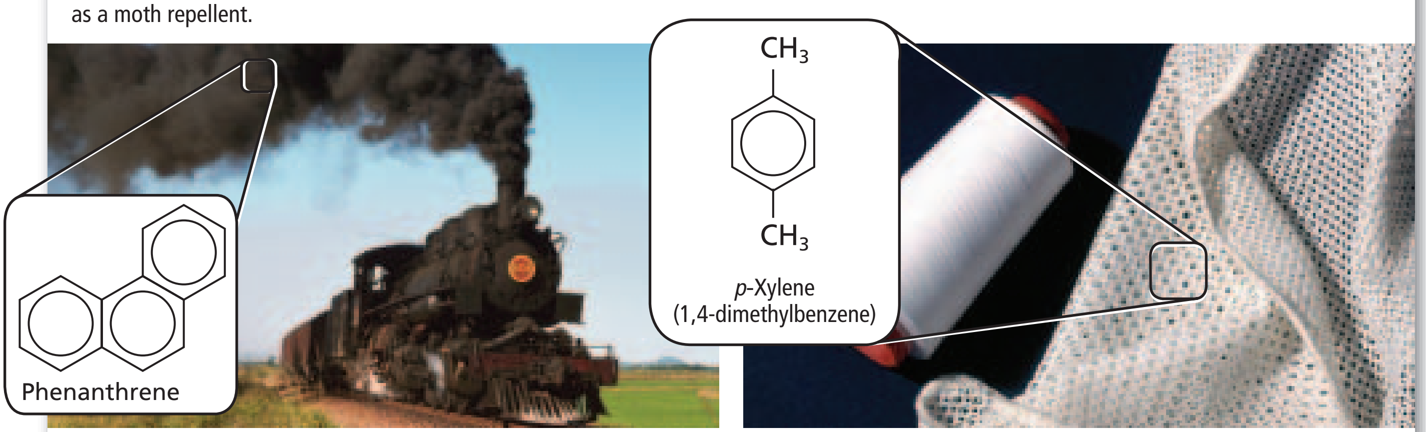
Aromatic
Science usage: an organic compound with increased chemical stability due to the delocalization of electrons
Benzene is an aromatic compound.

Common usage: having a strong odor or smell
The perfume was very aromatic.



Naphthalene is used to make dyes and as a moth repellent.

Anthracene is used to produce dyes and pigments.



Phenanthrene is present in the atmosphere due to the incomplete combustion of hydrocarbons.

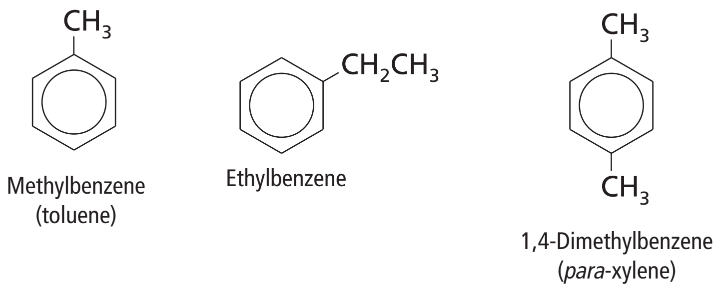
Xylene is used to make polyester fibers and fabrics.

Figure 21.26 Aromatic hydrocarbons are found in the environment due to the incomplete combustion of hydrocarbons and are used to make a variety of products.

Structures of some aromatic compounds are shown in **Figure 21.26.** 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 are shared by the carbon atoms that make up the ring systems.

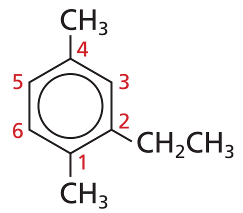
Naming substituted aromatic compounds Like other hydrocarbons, aromatic compounds can have different groups attached to their carbon atoms. For example, methylbenzene, also known as toluene, consists of a methyl group attached to a benzene ring in place of one hydrogen atom. Whenever you see something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

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



Just as with substituted cycloalkanes, substituted benzene rings are numbered in a way that gives the lowest-possible numbers for the substituents, as shown in **Figure 21.27.** Numbering the ring as shown gives the numbers 1, 2, and 4 for the substituent positions. Because *ethyl* comes before *methyl* in the alphabet, it is written first in the name: 2-ethyl-1,4-dimethylbenzene.

Reading Check **Explain** what the circle means inside the six-ring structure in **Figure 21.27.**

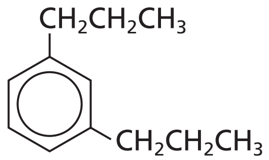


2-Ethyl-1,4-dimethylbenzene

Figure 21.27 Substituted benzene rings are named in the same way as cyclic alkanes.

EXAMPLE Problem 21.4

Naming Aromatic Compounds Name the aromatic compound shown.

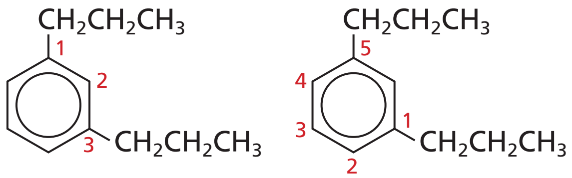


1 Analyze the Problem

You are given an aromatic compound. Follow the rules to name the aromatic compound.

2 Solve for the Unknown

Step 1. Number the carbon atoms to give the lowest numbers possible.



As you can see, the numbers 1 and 3 are lower than the numbers 1 and 5. So the numbers used to name the hydrocarbon should be 1 and 3.

Step 2. Determine the name of the substituents. If the same substituent appears more than once, add the prefix to show the number of groups present.

Step 3. Put the name together. Alphabetize the substituent names, and use commas between numbers and hyphens between numbers and words. Write the name as 1,3-dipropylbenzene.

3 Evaluate the Answer

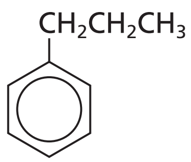
The benzene ring is numbered to give the branches the lowest possible set of numbers. The names of the substituent groups are correctly identified.

PRACTICE Problems

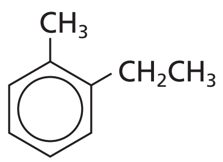
Extra Practice Page 991 and glencoe.com

31. Name the following structures.

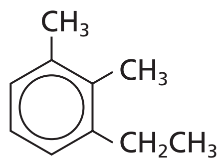
a.



b.

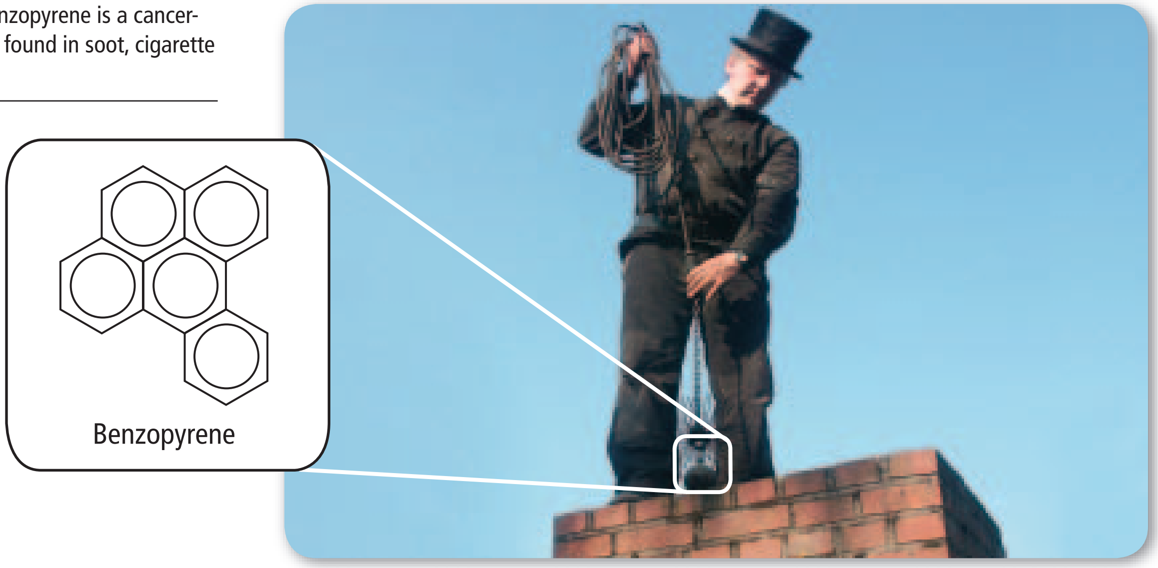


c.



32. Challenge Draw the structure of 1,4-dimethylbenzene.

Figure 21.28 Benzopyrene is a cancer-causing chemical that is found in soot, cigarette smoke, and car exhaust.



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 can 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. Scientists discovered that the cause of the cancer was the aromatic compound benzopyrene, shown in **Figure 21.28.** 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.

FOLDABLES Incorporate information from this section into your Foldable.

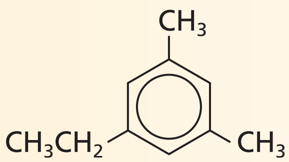
Section 21.5 Assessment

Section Summary

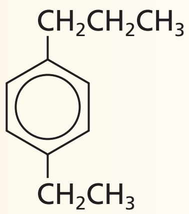
- Aromatic hydrocarbons contain benzene rings as part of their molecular structures.
- The electrons in aromatic hydrocarbons are shared evenly over the entire benzene ring.

33. **MAIN Idea** **Explain** benzene's structure and how it makes the molecule unusually stable.
34. **Explain** how aromatic hydrocarbons differ from aliphatic hydrocarbons.
35. **Describe** the properties of benzene that made chemists think it was not an alkene with several double bonds.
36. **Name** the following structures.

a.



b.



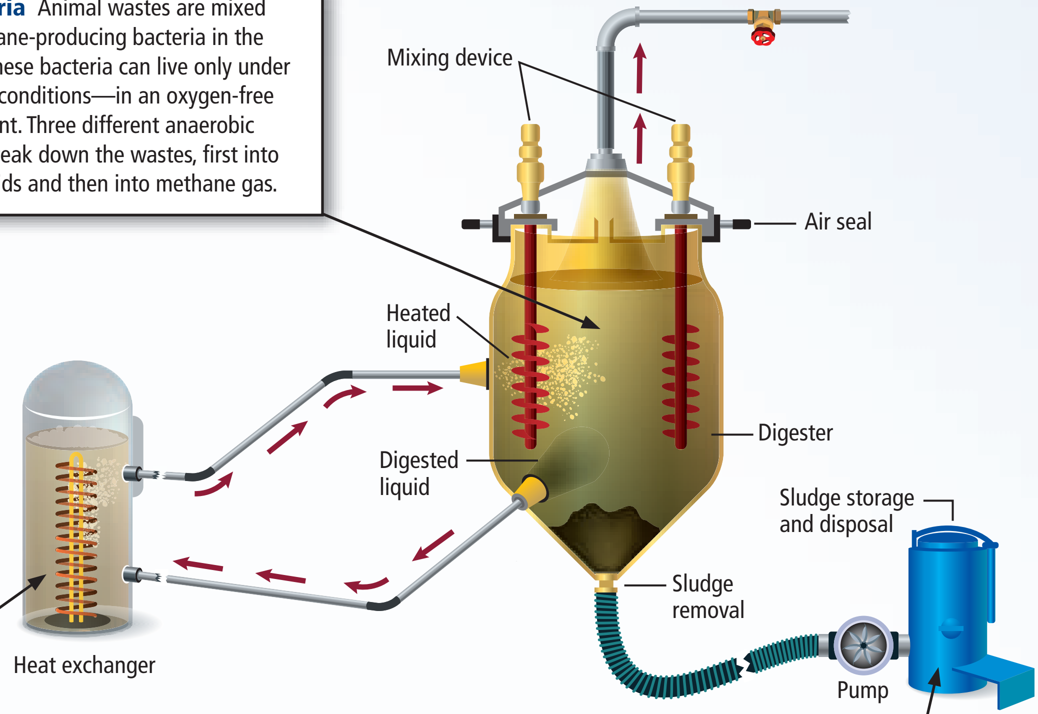
37. **Explain** why the connection between benzopyrene and cancer was significant.

Chemistry Online Self-Check Quiz glencoe.com

How It Works

Pooch to Power: How a Methane Digester Works

Officials in San Francisco are hoping the city's pet owners will contribute their animals' wastes to a pilot project that will convert organic matter into usable energy. A methane digester converts the wastes into biogas—a mixture of methane and carbon dioxide. Burning the methane provides energy for the city.



1 Bacteria Animal wastes are mixed with methane-producing bacteria in the digester. These bacteria can live only under anaerobic conditions—in an oxygen-free environment. Three different anaerobic bacteria break down the wastes, first into organic acids and then into methane gas.

2 Temperature As with any chemical reaction, temperature affects methane production. Like the bacteria in our own bodies, the bacteria in the digester are most efficient between 35°C and 37°C. An external heat exchanger, combined with insulation around the digester chamber, help to keep the temperature constant and within the optimal range.

3 Sludge The bacteria cannot convert 100% of the animal wastes into methane. The remaining indigestible material, called sludge or effluent, is rich in plant nutrients and can be used as a soil conditioner.

4 Gas Methane gas is collected, compressed, and either used immediately or stored. The methane can be used to heat homes or to generate electricity.

WRITING in Chemistry

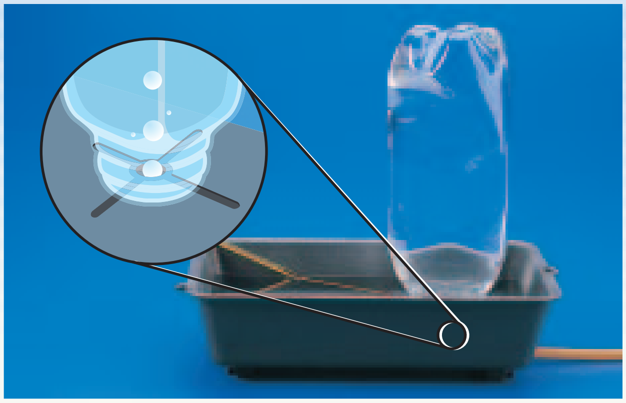
Compare Research and create a pamphlet comparing the advantages of biogas production to other forms of waste disposal for agribusinesses, such as dairies and beef, pork, and poultry producers. Visit glencoe.com for more information about methane digesters.

CHEMLAB

FORENSICS: ANALYZE HYDROCARBON BURNER GASES

Background: **A valve needs to be replaced in the science lab. The custodian says the gas used in the lab is propane, and the chemistry teacher says it is natural gas (methane). Use scientific methods to settle this dispute.**

Question: *What type of alkane gas is used in the science laboratory?*



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

Procedure

1. Read and complete the lab safety form.
2. 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 small amount of gas into the tank to flush the air out of the tubing.
3. Measure the mass of the dry plastic bottle and cap. Record the mass, barometric pressure, and air temperature.
4. 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 the air has risen to the top. Add more water, and recap the bottle.
5. 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 under water. Hold the mouth of the bottle directly over the inlet opening of the trough.
6. Slowly open the gas valve, and allow gas to enter the inverted bottle until all of the water has been displaced. Close the gas valve immediately. Record the temperature of the water.
7. While the bottle is still inverted, screw on the cap. Remove the bottle from the water, and dry the outside of the bottle.
8. Measure and record the mass of the bottle containing the burner gas.
9. Place the bottle in a fume hood, turn on the exhaust fan, 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.
10. **Cleanup and Disposal** Clean your workspace as directed.

Analyze and Conclude

1. **Solve** The density of air at 1 atm and 20°C is 1.205 g/L. Use the volume of the bottle 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.
2. **Calculate** the mass of the empty bottle. Calculate the mass of the collected gas. 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. Use the mass of gas and the number of moles to calculate the molar mass of the gas.
3. **Conclude** How does your experimental molar mass compare with the molar masses of methane, ethane, and propane? Infer which gases are in the burner gas in your lab.
4. **Error Analysis** Suggest possible sources of error in the experiment.

INQUIRY EXTENSION

Design an Experiment to test how one variable, such as temperature or atmospheric pressure, affects your results.

CHAPTER 21

Study Guide

BIG Idea Organic compounds called hydrocarbons differ by their types of bonds.

Section 21.1 Introduction to Hydrocarbons

MAIN Idea Hydrocarbons are carbon-containing organic compounds that provide a source of energy and raw materials.

Vocabulary

- cracking (p. 748)
- fractional distillation (p. 747)
- hydrocarbon (p. 745)
- organic compound (p. 745)
- saturated hydrocarbon (p. 746)
- unsaturated hydrocarbon (p. 746)

Key Concepts

- Organic compounds contain the element carbon, which is able to form straight chains and branched chains.
- Hydrocarbons are organic substances composed of carbon and hydrogen.
- The major sources of hydrocarbons are petroleum and natural gas.
- Petroleum can be separated into components by the process of fractional distillation.

Section 21.2 Alkanes

MAIN Idea Alkanes are hydrocarbons that contain only single bonds.

Vocabulary

- alkane (p. 750)
- cyclic hydrocarbon (p. 755)
- cycloalkane (p. 755)
- homologous series (p. 751)
- parent chain (p. 753)
- substituent group (p. 753)

Key Concepts

- 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).
- Alkanes that contain hydrocarbon rings are called cyclic alkanes.

Section 21.3 Alkenes and Alkynes

MAIN Idea Alkenes are hydrocarbons that contain at least one double bond, and alkynes are hydrocarbons that contain at least one triple bond.

Vocabulary

- alkene (p. 759)
- alkyne (p. 762)

Key Concepts

- 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 alkanes.

Section 21.4 Hydrocarbon Isomers

MAIN Idea Some hydrocarbons have the same molecular formula but have different molecular structures.

Vocabulary

- asymmetric carbon (p. 768)
- chirality (p. 767)
- geometric isomer (p. 766)
- isomer (p. 765)
- optical isomer (p. 768)
- optical rotation (p. 769)
- stereoisomer (p. 766)
- structural isomer (p. 765)

Key Concepts

- 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.
- Stereoisomers have all atoms bonded in the same order but arranged differently in space.

Section 21.5 Aromatic Hydrocarbons

MAIN Idea Aromatic hydrocarbons are unusually stable compounds with ring structures in which electrons are shared by many atoms.

Vocabulary

- aliphatic compound (p. 771)
- aromatic compound (p. 771)

Key Concepts

- Aromatic hydrocarbons contain benzene rings as part of their molecular structures.
- The electrons in aromatic hydrocarbons are shared evenly over the entire benzene ring.

CHAPTER 21 Assessment

Section 21.1

Mastering Concepts

38. Organic Chemistry Why did Wohler's discovery lead to the development of the field of organic chemistry?

39. What is the main characteristic of an organic compound?

40. What characteristic of carbon accounts for the large variety of organic compounds?

41. Name two natural sources of hydrocarbons.

42. Explain what physical property of petroleum compounds is used to separate them during fractional distillation.

43. Explain the difference between saturated hydrocarbons and unsaturated hydrocarbons.

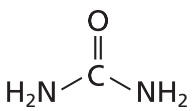
Mastering Problems

44. Distillation Rank the compounds listed in **Table 21.7** in the order in which they will be distilled out of a mixture. Rank the compounds in order of first to distill to last to distill.

Table 21.7 Alkane Boiling Points

Compound	Boiling Point (°C)
hexane	68.7
methane	−161.7
octane	125.7
butane	−0.5
propane	−42.1

45. How many electrons are shared between two carbon at oms in each of the following carbon-carbon bonds?
a. single bond
b. double bond
c. triple bond



■ **Figure 21.29**

46. Figure 21.29 shows two models of urea, a molecule that Friedrich Wöhler first synthesized in 1828.
a. Identify the types of models shown.
b. Is urea an organic or an inorganic compound? Explain your answer.

47. Molecules are modeled using molecular formulas, structural formulas, ball-and-stick models, and space-filling models. What are the advantages and disadvantages of each model?

Section 21.2

Mastering Concepts

48. Describe the characteristics of a homologous series of hydrocarbons.

49. Fuels Name three alkanes used as fuels and describe an additional application for each.

50. Draw the structural formula of each of the following.
a. ethane
b. hexane
c. propane
d. heptane

51. Write the condensed structural formulas for the alkanes in the previous question.

52. Write the name and draw the structure of the alkyl group that corresponds to each of the following alkanes.
a. methane
b. butane
c. octane

53. How does the structure of a cycloalkane differ from that of a straight-chain or branched-chain alkane?

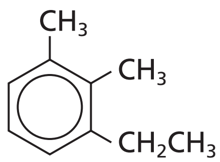
54. Freezing and Boiling Points Use water and methane to explain how intermolecular attractions generally effect the boiling and freezing points of a substance.

Mastering Problems

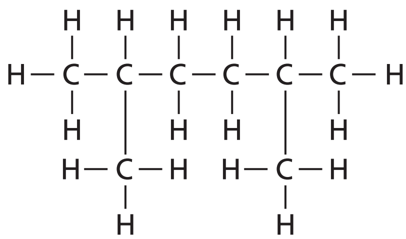
55. Name the compound represented by each of the following structural formulas.

a. $CH_3CH_2CH_2CH_2CH_3$

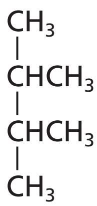
b.



c.



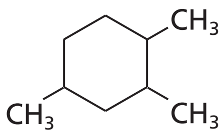
d.

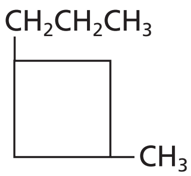


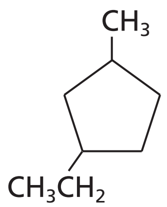
56. Draw full structural formulas for the following compounds.
a. heptane
b. 2-methylhexane
c. 2,3-dimethylpentane
d. 2,2-dimethylpropane

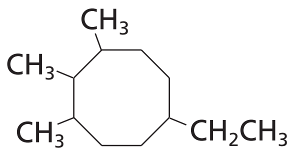
57. Draw condensed structural formulas for the following compounds. Use line structures for rings.
a. 1,2-dimethylcyclopropane
b. 1,1-diethyl-2-methylcyclopentane

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

a. 

c. 

b. 

d. 

Section 21.3

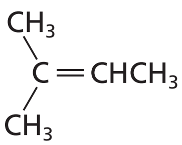
Mastering Concepts

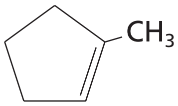
59. Explain how alkenes differ from alkanes. How do alkynes differ from both alkenes and alkanes?

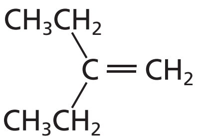
60. The name of a hydrocarbon is based on the name of the parent chain. Explain how the determination of the parent chain when naming alkenes differs from the same determination when naming alkanes.

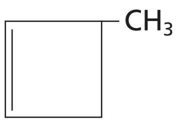
Mastering Problems

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

a. 

c. 

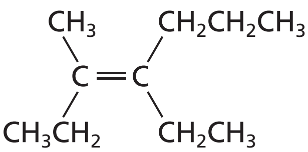
b. 

d. 

62. 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

63. Name the compound represented by the following condensed structural formula.



Section 21.4

Mastering Problems

64. How are two isomers alike, and how are they different?

65. Describe the difference between *cis*- and *trans*- isomers in terms of geometrical arrangement.

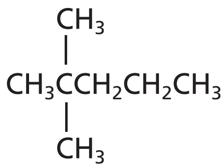
66. What are the characteristics of a chiral substance?

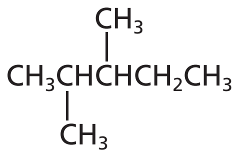
67. **Light** How does polarized light differ from ordinary light, such as light from the Sun?

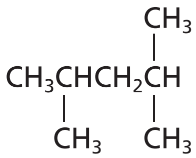
68. How do optical isomers affect polarized light?

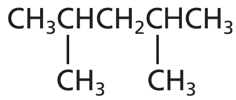
Mastering Problems

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

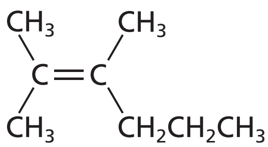
a. 

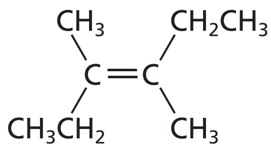
c. 

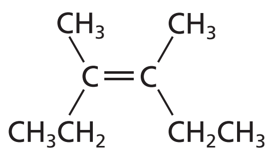
b. 

d. 

70. 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. 

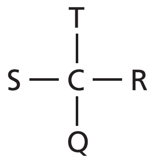
71. Draw condensed structural formulas for four different structural isomers with the molecular formula C_4H_8.

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

$$CH_3CH=CHCH_2CH_3$$

73. 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.



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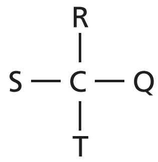
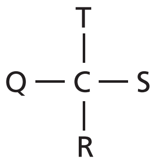
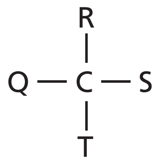


b.



d.



Section 21.5

Mastering Concepts

74. What structural characteristic do all aromatic hydrocarbons share?

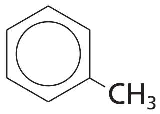
75. What are carcinogens?

Mastering Problems

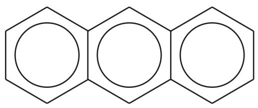
76. Draw the structural formula of 1,2-dimethylbenzene.

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

a.



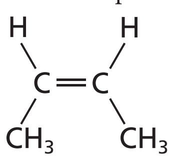
b.



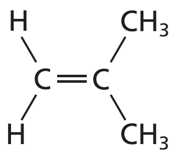
Mixed Review

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

a.



b.



79. 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?

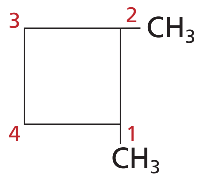
80. The general formula for alkanes is C_nH_{2n+2}. Determine the general formula for cycloalkanes.

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

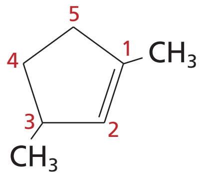
82. Is cyclopentane an isomer of pentane? Explain your answer.

83. Determine whether each of the following structures shows the correct numbering. If the numbering is incorrect, redraw the structure with the correct numbering.

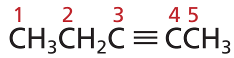
a.



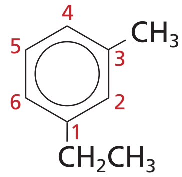
c.



b.



d.



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

85. Which would you expect to have more similar physical properties, a pair of structural isomers or a pair of stereoisomers? Explain your reasoning.

86. Explain why numbers are needed in the IUPAC names of many unbranched alkenes and alkynes but not in the names of unbranched alkanes.

87. A compound with two double bonds is called a diene. The name of the structure shown is 1,4-pentadiene. Apply your knowledge of IUPAC nomenclature to draw the structure of 1,3-penadiene.

$$H_2C=CH-CH_2-CH=CH_2$$

Think Critically

88. 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

89. Infer 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.

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

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

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92. Explain Use **Table 21.8** to construct a statement explaining the relationship between numbers of carbon atoms and boiling points of the members of the alkane series shown.

93. Graph the information given in **Table 21.8.** Predict what the boiling and melting points of the 11- and 12-carbon alkanes will be. Look up the actual values and compare your predictions to the those numbers.

Table 21.8 Data for Selected Alkanes

Name	Melting Point (°C)	Boiling Point (°C)
CH_4	−182	−162
C_2H_6	−183	−89
C_3H_8	−188	−42
C_4H_{10}	−138	−0.5
C_5H_{12}	−130	36
C_6H_{14}	−95	69
C_7H_{16}	−91	98
C_8H_{18}	−57	126
C_9H_{20}	−54	151
$C_{10}H_{22}$	−29	174

Challenge Problem

94. Chiral Carbons Many organic compounds have more than one chiral carbon. For each chiral carbon in a compound, a pair of stereoisomers can exist. The total number of possible isomers for the compound is equal to 2^n, where n is the number of chiral carbons. Draw each structure, and determine how many stereoisomers are possible for each compound named below.
a. 3,5-dimethylnonane
b. 3,7-dimethyl-5-ethyldecane

Cumulative Review

95. What element has the following ground-state electron configuration: $[Ar]4s^2 3d^6$? *(Chapter 5)*

96. What is the charge of an ion formed from the following families? *(Chapter 7)*
a. alkali metals
b. alkaline earth metals
c. halogens

97. Write the chemical equations for the complete combustion of ethane, ethene, and ethyne into carbon dioxide and water. *(Chapter 9)*

Additional Assessment

WRITING in Chemistry

98. Gasoline For many years, a principal antiknock ingredient in gasoline was the compound tetraethyllead. 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.

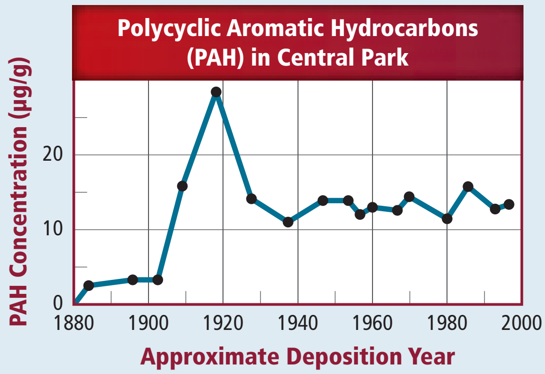
99. Perfume The musk used in perfumes and colognes contains many chemical compounds, including large cycloalkanes. Research and write a short report about the sources used for natural and synthetic musk compounds in these consumer products.

DBQ Document-Based Questions

Polycyclic Aromatic Hydrocarbons *PAH compounds are naturally occurring, but human activities can increase the concentrations in the environment. Soil samples were collected to study PAH compounds. The core sections were dated using radionuclides to determine when each section was deposited.*

Figure 21.30 *shows the concentration of polycyclic aromatic hydrocarbons (PAH) detected in Central Park in New York City.*

Data obtained from: Yan, B. et al, 2005. *Environmental Science Technology* 39 (18): 7012–7019.



■ **Figure 21.30**

100. Compare the average PAH concentrations before 1905 and after 1925.

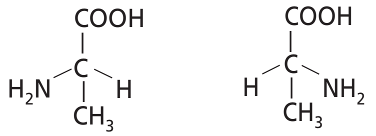
101. PAH compounds are produced in small amounts by some plants and animals, but most come from human activities, such as burning fossil fuels. Infer why the PAH levels were relatively low in the late 1800s and early 1900s.

Cumulative

Standardized Test Practice

Multiple Choice

1. 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. Which term best describes L-Alanine and D-Alanine with respect to one another?

A. structural isomers
B. geometric isomers
C. optical isomers
D. stereoisotopes

2. Which does NOT affect reaction rate?

A. catalysts
B. surface area of reactants
C. concentration of reactants
D. reactivity of products

3. What is the molality of a solution containing 0.25 g of dichlorobenzene ($C_6H_4Cl_2$) dissolved in 10.0 g of cyclohexane (C_6H_{12})?

A. 0.17 mol/kg
B. 0.014 mol/kg
C. 0.025 mol/kg
D. 0.00017 mol/kg

Use the table below to answer Questions 4 to 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}

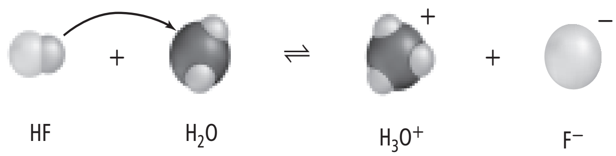
6. It can be predicted from the table that nonane will have a melting point that is

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. At a pressure of 1.00 atm and a temperature of 20°C, 1.72 g CO_2 will dissolve in 1 L of water. How much CO_2 will dissolve if the pressure is raised to 1.35 atm and the temperature stays the same?

A. 2.32 g/L
B. 1.27 g/L
C. 0.785 g/L
D. 0.431 g/L

Use the diagram below to answer Question 8.



8. In the forward reaction, which substance is the Brønsted-Lowry acid?

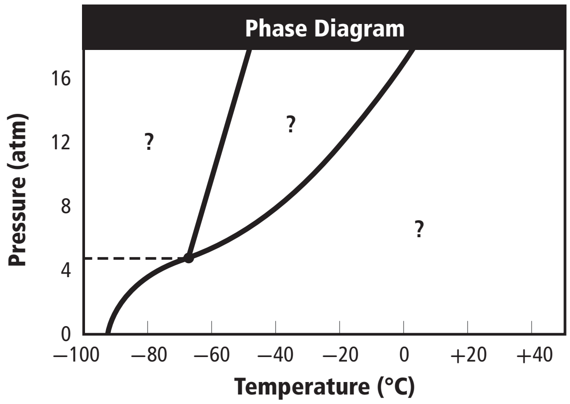
A. HF
B. H_2O
C. H_3O^+
D. F^-

9. Which does NOT describe what happens as a liquid boils?

A. The temperature of the system rises.
B. Energy is absorbed by the system.
C. The vapor pressure of the liquid is equal to atmospheric pressure.
D. The liquid is entering the gas phase.

Short Answer

Use the diagram below to answer Questions 10 to 12.



10. What state of matter is located at a temperature of −80°C and a pressure of 10 atm?

11. What are the temperature and pressure when the substance is at its triple point?

12. Describe the changes in molecular arrangement that occur when the pressure is increased from 8 atm to 16 atm, while the temperature is held constant at 0°C.

Extended Response

Use the data table below to answer Questions 13 and 14.

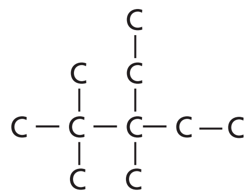
Experimental Data for the Reaction between A and B

[A] Initial	[B] Initial	Initial rate (mol/L•s)
0.10 M	0.10 M	7.93
0.30 M	0.10 M	23.79
0.30 M	0.20 M	95.16

13. Find the values of m and n for the rate law expression $rate = k[A]^m[B]^n$.

14. Determine the value of k for this reaction.

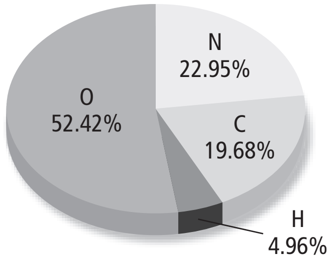
SAT Subject Test: Chemistry



15. 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
E. 2,2-dimethy, 3-diethyl, 3-methylpropane

Use the graph below to answer Questions 16 and 17.



16. What is the formula for this compound?

A. $C_5H_{20}N_4O_2$
B. $C_8H_2N_9O_{11}$
C. $C_{1.6}H_5N_{1.6}O_{3.3}$
D. CH_3NO_2
E. $C_2H_5N_2O_5$

17. How many grams of nitrogen would be present in 475 g of this compound?

A. 33.93 g
B. 52.78 g
C. 67.86 g
D. 109.0 g
E. 110.5 g

NEED EXTRA HELP?																		
If You Missed Question . . .	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Review Section . . .	21.4	16.1	14.2	21.3	21.3	21.3	14.1	18.1	12.4	12.4	12.4	12.4	16.3	16.3	21.2	21.2	10.4	3.4