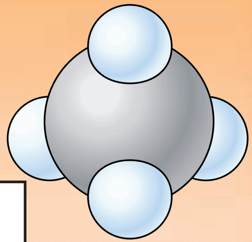
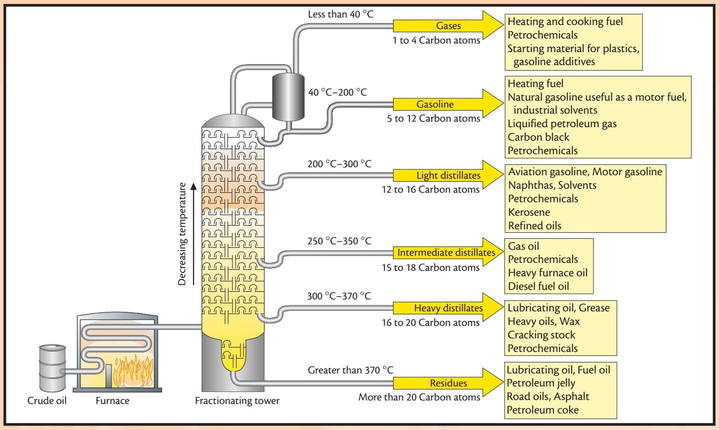
UNIT 3

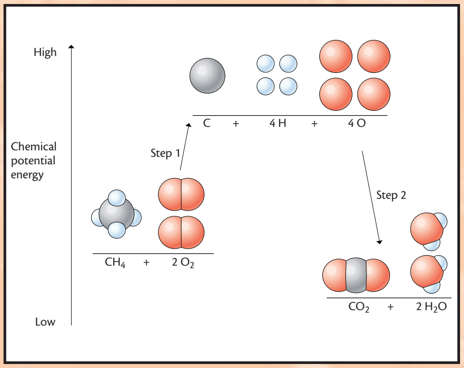
WHAT are the chemical and physical properties of hydrocarbons?





SECTION A **Petroleum—What Is It?**
(page 176)

WHY do hydrocarbons make such good fuels?



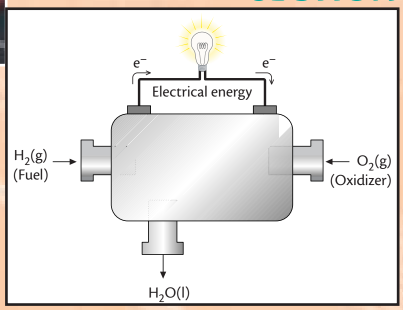
SECTION B **Petroleum as an Energy Source**
(page 195)

PETROLEUM: BREAKING AND MAKING BONDS

WHY are carbon-based molecules so versatile as chemical building blocks?

SECTION C **Petroleum as a Building Source**
(page 216)

WHAT properties are important in considering substitutes for petroleum?



SECTION D **Energy Alternatives to Petroleum**
(page 234)

There is increased interest in alternative-energy transportation. Why? What are advantages and disadvantages to petroleum alternatives? How can the global supply of petroleum best be used? Turn the page to learn more about this energy-rich resource.

THE NEW ARL-600 TV COMMERCIAL—WORKING SCRIPT

Text/Script	Image/Sound
Clean . . .	(Video of driver and three passengers riding in the vehicle.)
Comfortable . . . ***Convenient . . .***	(The words "clean," "comfortable," "convenient" appear, in turn, as the announcer speaks them. "Clean" appears at the top of the screen; "Comfortable" appears in the middle; "Convenient" appears at the bottom. The "C" moves from the top to the bottom as the words appear.)
Those three words describe the new breakthrough personal vehicle, the ARL-600.	(Show the ARL-600 driving along a road as announcer reads line.)
Clean . . .	("Clean" appears on the screen and moves from left to right.)
Unlike petroleum-fueled vehicles, the ARL-600 is emission-free—no air pollutants, smoke, or smog. Why? Because the ARL-600 is directly powered by electricity, thanks to its new, high-capacity electric storage batteries. You drive guilt-free, knowing you're helping, not hurting, the environment.	(Show the ARL-600 accelerating [after sitting at a stoplight] next to gasoline-burning vehicles to show the difference in emissions.)
Comfortable . . .	("Comfortable" appears on the screen and moves from the top left corner to the bottom right corner.)
You and three others can easily ride in the ARL-600. And—thanks to electrical power—the ride is so quiet that driving the ARL-600 seems more like a walk in the park.	(Show four people riding in the ARL-600, then change the perspective to that of the driver with the window rolled down. The driver can hear birds chirping and children playing as she drives past a park.)
Convenient . . .	("Convenient" appears on the screen and moves from top center to bottom center.)

Imagine an end to stops at busy gas stations. How? You simply recharge your ARL-600's batteries when you return home, and you're ready for another day of gasoline-free driving.	(The ARL-600 passes a gas station, pulls up to a house, and the driver "plugs in" the vehicle.)
When fully charged, your electric-powered ARL-600 will take you wherever you want to go within a 90-mile range—school, work, or even soccer practice.	(Images of the ARL-600 in a variety of settings—shopping center, office parking lot, school, recreation area.)
One place you *won't* need to visit, however, is the auto-repair shop. Fewer moving parts mean less time and money spent on engine repairs.	(The ARL-600 drives past an auto-repair shop.)
And using your petroleum-free ARL-600 is easy on the pocketbook—as little as two cents per mile to operate. Compare that to more than five cents per mile for gasoline-burning vehicles.	(Image of a piggy bank being shaken with coins [mostly pennies] falling out onto the table.)
Help conserve petroleum resources! Visit your ARL-600 dealer for a test drive today.	(Side view of an ARL-600 at a dealer showroom with several people examining it. The "ARL-600" logo then appears below the vehicle.)

You live in a world of new products, devices, and materials. Whether presented on a billboard, displayed on television, featured in a magazine, or announced on the radio, every advertisement attempts to sell its product by informing the audience about specific features. The product may be "faster," "lighter," "easier to use," "newer," or "great-tasting"—to sample just a few of many common product claims. The advertisement for the ARL-600 is no exception; it highlights several energy- and fuel-related features of a new and (so it is claimed) "petroleum-free" vehicle.

In this unit, you will gain the knowledge and perspective you need to analyze the merits of the claims made about the ARL-600. For example, you will learn what petroleum is, what chemical and physical properties make it so useful, and how it is used. Then you can evaluate whether the ARL-600 is actually "petroleum-free" or not.

But you will learn more about petroleum than its use as a fuel. Many products you use every day are made from petroleum—an outstanding example is plastics. What is it that allows petroleum to be useful as both a fuel to burn and a building block from which to make many new substances? How long will known world reserves of petroleum last? What alternatives to petroleum are there?

As you learn about this valuable resource, consider the energy and fuel claims made in the ARL-600 advertisement. You will soon be invited to analyze those claims. Later in the unit you will have the opportunity to produce a design for a new-vehicle advertisement based on the knowledge you have gained.

SECTION A

PETROLEUM—WHAT IS IT?

Introduction CD-ROM WWW.

The word "petroleum" is probably quite familiar to you. But do you know what petroleum is or what it is made of? Can you explain what properties make it useful for both burning and building? In this section you will explore the characteristics of some key compounds found in petroleum. Specifically, you will focus on their structure, bonding, and properties.

A.1 WHAT *IS* PETROLEUM?

The word "petroleum" comes from the Latin words petr- ("rock") and oleum ("oil").

Petroleum is a vitally important world resource. As pumped from underground, petroleum is known as crude oil, or "black gold." This liquid varies from colorless to greenish-brown to black, and may be as thin as water or as thick as soft tar. Crude oil cannot be used in its natural state. Instead, it is shipped by pipeline, ocean tanker, train, or barge to oil refineries, where it is separated into simpler mixtures. Some of these mixtures are ready for use, whereas others require further refinement. Refined petroleum is chiefly a mixture of various **hydrocarbons**—molecular compounds that contain atoms of the elements hydrogen and carbon only. Can you see how this class of compounds got its name?

Nearly 50% of the total energy needs of the United States are met by burning petroleum. Thus most petroleum is consumed as a fuel. Converted to gasoline, petroleum powers millions of automobiles in the United States, each traveling an average of 11 000 miles annually. Other petroleum-based fuels provide heat to homes and businesses, deliver energy to generate electricity, and propel diesel engines and jet aircraft.

But petroleum's importance goes beyond its use as just a fuel. Its other major use is as a raw material from which a stunning array of familiar and useful products are manufactured—from CDs, sports equipment, clothing, automobile parts, and carpeting to prescription drugs and artificial limbs. Based on your experiences with petroleum fuels and products, what percent of petroleum would you estimate is used for burning? For building? Can you identify other uses of petroleum? The answers in the next paragraph may surprise you.

What did you predict for the percent of petroleum used for burning? Fifty percent? Sixty percent? Astonishingly, 84% of petroleum is burned outright as fuel. Only about 7% is used for producing substances such as medications and plastics. The remaining 9% is used as lubricants, road-paving materials, and an assortment of miscellaneous products. For every gallon of petroleum that is used to produce useful products, more than five gallons are burned to release energy.

What happens to molecules in petroleum when they are burned or used in manufacturing? As in all chemical reactions, the atoms become rearranged to form new molecules. When hydrocarbons burn, they react with oxygen gas in the air to form carbon dioxide (CO_2) gas and water vapor.

These gases disperse in the air. The hydrocarbon fuel is used up; it will take millions of years for natural processes to replace it. Thus petroleum is a nonrenewable resource—much like the minerals you studied in Unit 2.

Like other resources, petroleum is not uniformly distributed around the world. Approximately 57% of the world's known crude oil reserves are located in just five Middle Eastern nations: Iran, Iraq, Kuwait, Saudi Arabia, and the United Arab Emirates. By contrast, the petroleum reserves of North America amount to only about 7% of the world's known supply. The distribution of crude oil reserves does not necessarily correspond to population or use of petroleum. For example, Asia, the Far East, and Oceania account for 60% of the world's population, but this region has only about 4% of the world's petroleum reserves. Figure 1 shows these global distributions.

You have just learned what petroleum is, what it is used for, and where it is found. Petroleum is actually a complex mixture of hydrocarbons that must be refined or separated into simpler mixtures in order to be useful. In the following activity, you will find out about this basic separation process as you investigate a simple mixture of two liquids.

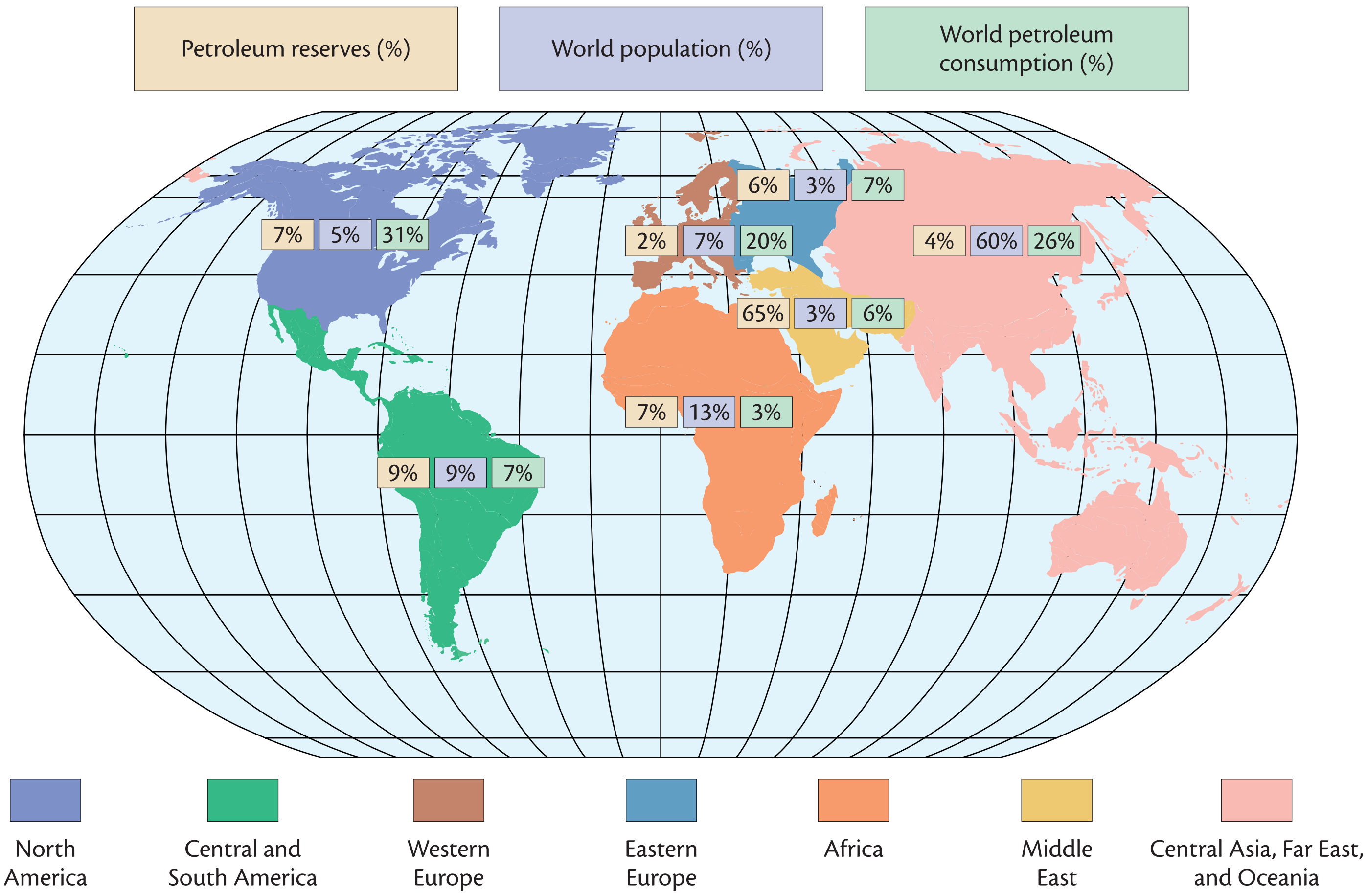


Figure 1 *Distribution of world's petroleum reserves, population, and consumption of petroleum.*

A.2 SEPARATION BY DISTILLATION

Laboratory Activity

Introduction

You know that substances can often be separated by taking advantage of their different physical properties. One physical property commonly used to separate two liquids is density. But density will work only if the two substances are insoluble in each other, which is not the case with petroleum. Another physical property chemists often use is the boiling point of a substance. The separation of liquid substances according to their differing boiling points is called **distillation**.

As a liquid mixture is heated, the substance with the lower boiling point will vaporize first and leave the distillation flask; it will then be converted back to a liquid as it passes through a condenser—all before the second substance begins to boil. Each condensed liquid substance, called a **distillate**, can thus be collected separately.

As you might expect, heating the liquid mixture raises its temperature. However, once the first substance begins to boil and vaporize from the mixture, the temperature of the liquid remains steady until that component is completely distilled from the mixture. Continued heating will then cause the temperature to rise once again, this time until the second component begins to boil and distill.

In this activity, you will use distillation to separate a mixture of two liquids. Then you will identify the two substances in the mixture by comparing the observed distillation temperatures with the boiling points of several possible compounds listed in Figure 2.

The boiling points listed in Figure 2 are based on normal sea-level atmospheric pressure.

Figure 2 *Properties of substances that may be in the distillation mixture.*

Properties of Possible Components of Distillation Mixture

Substance	Formula	Boiling Pt. (°C)	Appearance with I_2
2-Propanol (rubbing alcohol)	C_3H_7OH	82.4	Bright yellow
Acetone	C_3H_6O	56.5	Yellow to brown
Water	H_2O	100	Colorless to light yellow
Cyclohexane	C_6H_{12}	80.7	Magenta

Before you begin, read the Procedure to familiarize yourself with the intended observations and measurements.

Procedure

1. Construct suitable data tables to record your observations and measurements.
2. Assemble an apparatus similar to that shown in Figure 3. Label two beakers Distillate 1 and Distillate 2.
3. Using a clean, dry graduated cylinder, measure a 50-mL sample of the distillation mixture. Pour it into the flask and add a boiling chip.

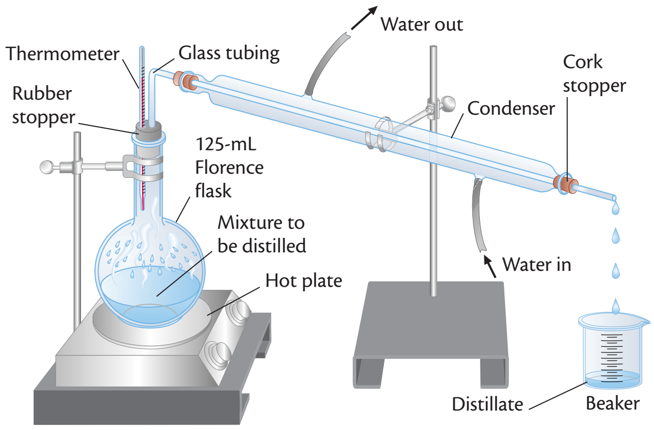


Figure 3 *Distillation of a simple mixture.*

4. Record your observations of the starting mixture.
5. Connect the flask to a condenser as indicated in Figure 3. Ensure that the hoses are attached to the condenser and water supply as shown. Position the Distillate 1 beaker at the outlet of the condenser so it will catch the distillate.
6. Ensure that all connections are tight and will not leak.
7. Turn on the water to the condenser and then turn on the hot plate to start gently heating the flask.
8. Record the temperature at which the first drop of distillate enters the beaker. Then continue to record the temperature every 30 seconds. Continue to heat the flask and collect distillate until the temperature begins to rise again. At this point, replace the Distillate 1 beaker with the Distillate 2 beaker.
9. Continue heating and recording the temperature every 30 seconds until the second substance just begins to distill. Record the temperature at which the first drop of second distillate enters the beaker. Collect 1 to 2 mL of the second distillate. **CAUTION:** *Do not allow all of the liquid to boil from the flask.*
10. Turn off the heat and allow the apparatus to cool. While the apparatus is cooling, test the relative solubility of solid iodine (I_2) in Distillate 1 and Distillate 2 by adding a small amount of iodine to each beaker and stirring. Record your observations.
11. Disassemble and clean the distillation apparatus and dispose of your distillates as directed by your teacher.
12. Wash your hands thoroughly before leaving the laboratory.

Questions

1. Plot your data on a graph of time (x axis) vs. temperature (y axis). Be sure to include all features of a correctly drawn graph. See page 66.
2. a. Using your graph, identify the temperature at which the first substance distilled and the temperature at which the second substance distilled.
   b. Because the liquid temperature does not change appreciably during distillation of a particular component, those portions of

the graph line should appear flat (horizontal). How well do these plateaus match the temperatures at which the first drops of each distillate were collected?

3. Using data in Figure 2 on page 178, identify each distillate sample.
4. Compile your data with the data of those students who distilled the same mixture.
   a. Find the mean and the mode for each distillate temperature.
   b. All laboratory teams did not obtain the same distillation temperatures. Why?
5. In which distillate was iodine more soluble? Explain.
6. What laboratory tests could you perform to decide whether the liquid left behind in the flask is a mixture or a pure substance?
7. Of the substances listed in Figure 2, which two would be most difficult to separate by distillation? Why?
8. a. What would a graph of time vs. temperature look like for the distillation of a mixture of all four substances listed in Figure 2?
   b. Sketch the graph and describe its features.

The statistical mode is the most frequently reported value in a set of data.

A.3 PETROLEUM REFINING

Unlike the simple laboratory mixture you investigated in the preceding activity, crude oil is a mixture of many compounds. Separating such a complex mixture requires the application of distillation techniques to large-scale oil refining. The refining process does not separate each compound contained in crude oil. Rather, it produces several distinctive mixtures called **fractions**. This process is known as **fractional distillation**. Compounds in each fraction have a particular range of boiling points and specific uses. Figure 4 illustrates the fractional distillation (fractionation) of crude oil.

First, the crude oil is heated to about 400 °C in a furnace. It is then pumped into the base of a distilling column (fractionating tower), which is usually more than 30 m (100 ft) tall. Many of the component substances of the heated crude oil vaporize. The temperature of the column is highest at the bottom and decreases toward the top. Trays are arranged at appropriate heights inside the column to collect the various fractions.

During distillation, the vaporized molecules move upward in the distilling column. The smaller, lighter molecules have low boiling points and either condense high in the column or are drawn off the top of the tower as gases. Fractions with higher boiling points contain larger molecules, which are more difficult to separate from one another and thus require more thermal energy to vaporize. These molecules condense in trays lower in the column. Substances with the highest boiling points never vaporize. These thick, or viscous, liquids—called bottoms—drain from the column's base. Each arrow in Figure 4 indicates the name of a particular fraction and its boiling-point range.

Although the names given to various fractions and their boiling ranges may vary somewhat, crude oil refining always has the same general features.

As you learn more about the characteristics of the fractions obtained from petroleum, think about how their products find uses in both traditional and electric vehicles.

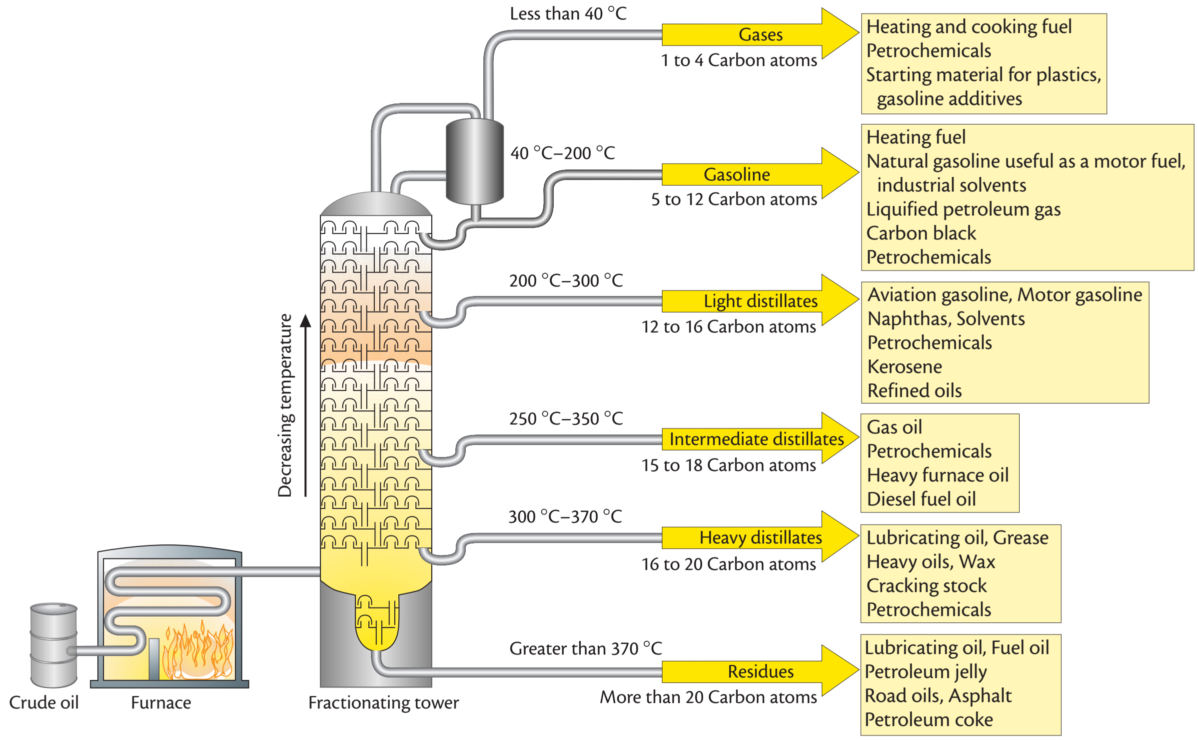


Figure 4 *A fractioning tower.*

A.4 A LOOK AT PETROLEUM'S MOLECULES

Petroleum's gaseous fraction contains compounds with low boiling points (less than 40 °C). These small hydrocarbon molecules, which contain from one to four carbon atoms, have low boiling points because they are only slightly attracted to each other or to other molecules in petroleum. Forces of attraction between molecules are called **intermolecular forces**. As a result of weak intermolecular forces, these small hydrocarbon molecules readily separate from each other and rise through the distillation column as gases.

Just as "interstate highway" means a road that runs between states, intermolecular forces means forces between molecules.

Petroleum's liquid fractions—including gasoline, kerosene, and heavier oils—consist of molecules having from five to about twenty carbon atoms. Molecules with even more carbon atoms are found in the greasy solid fraction that does not vaporize. These thick, "sticky" compounds have the strongest intermolecular forces among all substances found in petroleum. It is not surprising that they are solids at room temperature.

Now complete the following activity to learn more about physical properties of hydrocarbons.

HYDROCARBON BOILING POINTS

Building Skills 1

Chemists often gather and analyze data about the physical and chemical properties of substances. These data can be organized in many ways, but the most useful techniques uncover trends or patterns among the data.

The development of the Periodic Table is an example of this approach. To refresh your memory about the Periodic Table, refer back to Section 2A.

Figure 5 *The boiling points of selected hydrocarbons.*

Hydrocarbon Boiling Points	
Hydrocarbon	**Boiling Point (°C)**
Butane	−0.5
Decane	174.0
Ethane	−88.6
Heptane	98.4
Hexane	68.7
Methane	−161.7
Nonane	150.8
Octane	125.7
Pentane	36.1
Propane	−42.1

In a manner similar to the one you used earlier to predict a property of an unknown element, you can examine patterns among the boiling points of some hydrocarbons in order to make valuable predictions. Use the data found in Figure 5 to answer the following questions.

1. a. In what pattern or order are Figure 5 data organized?
   b. Is this a useful way to present the information? Explain.
2. You are searching for a trend or pattern among these boiling points.
   a. Propose a more useful way to arrange these data.
   b. Reorganize the data table based on your idea.

Use your reorganized data table to answer these questions:

3. Which substance(s) are gases (have already boiled) at room temperature (22 °C)?
4. Which substance(s) boil between 22 °C (room temperature) and 37 °C (body temperature)?
5. What can you infer about intermolecular forces among decane molecules compared to those in butane?

A.5 CHEMICAL BONDING

Chemical Bonding CD-ROM WWW.

Hydrocarbons and their derivatives are the focus of the branch of chemistry known as **organic chemistry**. These substances are called organic compounds because early chemists thought that living systems—plants or animals—were needed to produce them. However, chemists have known for more than 150 years how to make many organic compounds without any assistance from living systems. In fact, starting materials other than petroleum can be used to produce organic compounds. You will learn about some of these starting materials in Section C.

The carbon chain forms a framework to which a wide variety of other atoms can be attached.

In hydrocarbon molecules, carbon atoms are joined to form a backbone called a **carbon chain**. Hydrogen atoms are attached to the carbon backbone. Carbon's versatility in forming bonds helps to explain the abundance of different hydrocarbon compounds, as you will soon learn. Hydrocarbons can be regarded as "parents" of an even larger number of compounds that contain atoms of other elements attached to a carbon chain.

Electron Shells

How are atoms of carbon or other elements held to each other in compounds? The answer is closely related to the arrangement of electrons in atoms. You already know that atoms are made up of neutrons, protons, and electrons. Neutrons and protons are located in the small, dense, central region of the atom called the nucleus. Electrons occupy different **energy levels** in the space surrounding the nucleus. Similar energy levels are grouped into shells, each of which can hold only a certain maximum number of electrons. For example, the first shell surrounding the nucleus of an atom has a capacity of two electrons. The second shell can hold a maximum of eight electrons.

Consider an atom of helium (He), the first member of the noble-gas family. A helium atom has two protons (and two neutrons) in its nucleus and two electrons occupying the first, or innermost, shell. Because two is the maximum this shell can hold, the shell is completely filled.

The next noble gas, neon (Ne), has an atomic number of 10. This means that each neutral neon atom contains ten protons and ten electrons. Two electrons occupy (and fill) the first shell. The remaining eight electrons fill the second shell. In neon, each shell has reached its electron capacity.

Both helium and neon are chemically unreactive—their atoms do not combine with each other or with atoms of other elements to form compounds. By contrast, sodium (Na) atoms—with an atomic number of 11 and one more electron than neon atoms—are extremely reactive. Chemists explain sodium's reactivity as due to its tendency to lose that additional electron. Fluorine (F) atoms each have nine electrons—one less than neon atoms—and are also extremely reactive. Their reactivity is due to their tendency to gain an additional electron.

Noble-gas elements are essentially unreactive because their separate atoms already have filled electron shells. All but helium have eight electrons in their outer shells; helium needs only two to reach its first-shell maximum. A useful key to understanding the chemical behavior of many elements is to recognize that atoms with filled electron shells are particularly stable—that is, they are chemically unreactive. How does this guideline help to explain both the stability of noble-gas elements and the reactivity of elements such as sodium and fluorine?

When sodium metal reacts, sodium ions (Na^+) form. The +1 electrical charge indicates that each sodium atom has lost one electron. Each Na^+ ion contains eleven positively charged protons but only ten negatively charged electrons—thus the net +1 charge. With ten electrons, Na^+ possesses filled electron shells (two electrons in the first shell and eight in the second), just like a neon atom. Unlike sodium atoms, Na^+ ions are highly stable. In fact, the world's entire natural supply of sodium is found as Na^+ ions.

Fluorine atoms react to form fluoride ions (F^-). The −1 electrical charge indicates that each electrically neutral fluorine atom has gained one electron. Each fluoride ion contains nine protons and ten electrons—a net −1 charge. The ten electrons in an F^- ion constitute the same electron population found in a neon atom. Once again, an element has reacted to attain the special stability associated with filled electron shells.

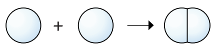
By losing an electron, each sodium atom has been oxidized. If you need to review this concept from Unit 2, see page 193.

By gaining an electron, each fluorine atom has been reduced. See Unit 2, page 193, for a review of this concept.

Covalent Bonds

As you have just learned, electrons are either lost or gained in the formation of ionic substances. In molecular (non-ionic) substances, atoms achieve filled electron shells by sharing electrons rather than by losing or gaining electrons. Many molecular substances are composed of atoms of nonmetals that do not readily lose electrons. As you will see, the sharing of electrons between two nonmetallic atoms allows both atoms to complete their outer shells.

A hydrogen molecule (H_2) provides a simple example of electron sharing. Each hydrogen atom contains only one electron, so one more electron is needed to fill the first shell. Two hydrogen atoms can accomplish this if they each share their single electron. If an electron is represented by a dot (·), then the formation of a hydrogen molecule can be depicted this way:

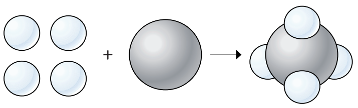


$$H\cdot + \cdot H \longrightarrow H{:}H$$

The number of outer-shell electrons for any Group A element is equal to its group number in the Periodic Table. Thus Group 6 A elements each have six outer-shell electrons. The number of electrons in this section is also equal to the last digit in the 1–18 system.

The chemical bond formed between two atoms that share a pair of electrons is called a **single covalent bond**. Through such sharing, both atoms achieve the stability associated with complete electron shells. A carbon atom, atomic number 6, has six electrons—two in the first shell and four in the second shell. Only the electrons in the outer shell participate in chemical reactions. To fill the second shell to its capacity of eight, four more electrons are needed. These electrons can be obtained through covalent bonding.

Consider the simplest hydrocarbon molecule, methane (CH_4). In this molecule, each hydrogen atom shares its single electron with the carbon atom. Similarly, the carbon atom shares one of its four outer-shell electrons with each hydrogen atom. This arrangement is represented below.



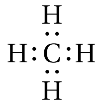
$$4\,H\cdot \;+\; \cdot\dot{\underset{\cdot}{C}}\cdot \longrightarrow H{:}\overset{\displaystyle H}{\underset{\displaystyle H}{\ddot{\underset{..}{C}}}}{:}H$$

Electron-dot formulas are also referred to as Lewis structures. G.N. Lewis is given credit for laying the foundation of our current understanding of bond formation.

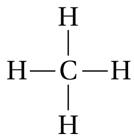
Here, as in the formula for a hydrogen molecule, dots surrounding each element's symbol represent the outer-shell electrons for that atom. Structures such as these are called **electron-dot formulas**. The two electrons in each covalent bond "belong" to both bonded atoms. Dots placed between the symbols of two atoms represent electrons that are shared by those atoms.

When determining the number of electrons associated with each atom, each shared electron in a covalent bond is "counted" twice, once for each element. For example, count the dots surrounding each atom in methane. You should notice that each hydrogen atom has a filled outer electron shell—two electrons in its first shell. The carbon atom also has a filled outer electron shell—eight electrons. Each hydrogen atom is associated with one pair of electrons; the carbon atom has four pairs of electrons, or eight electrons.

For convenience, each pair of electrons in a covalent bond can be represented by a line drawn between the symbols of each atom. This yields another common representation of a covalently bonded substance called a **structural formula**.



Electron-dot formula of methane, CH_4



Structural formula of methane, CH_4

Although you can draw two-dimensional pictures of molecules on flat paper, assembling three-dimensional models gives a more accurate representation. Such an atomic model helps to predict a molecule's physical and chemical properties. The following activity provides an opportunity for you to assemble such models.

A.6 MODELING ALKANES

Laboratory Activity

Introduction

In this activity you will assemble models of several simple hydrocarbons. Your goal is to associate the three-dimensional shapes of these molecules with the names, formulas, and pictures used to represent them on paper.

Two types of molecular models are shown in Figure 6. Most likely, you will use ball-and-stick models. Each ball represents an atom, and each stick represents a single covalent bond (a shared electron pair) connecting two atoms. But of course molecules are not composed of ball-like atoms located at the ends of sticklike bonds. Experimental evidence shows that atoms are in contact with each other, much like what you see in space-filling models. However, ball-and-stick models are still useful because they can clearly represent the structure and geometry of molecules.

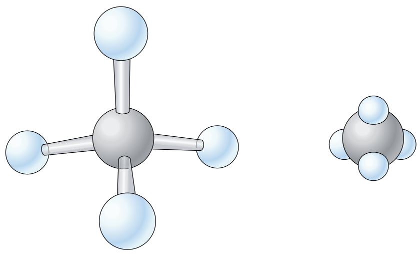


Figure 6 *Three-dimensional CH_4 models: ball-and-stick (left); space-filling (right).*

Look again at the electron-dot structure and structural formula for methane (CH_4) above. Methane, the simplest hydrocarbon, is the first member of a series of hydrocarbons known as **alkanes**. You will explore alkanes in this activity. Each carbon atom in an alkane forms single covalent bonds with four other atoms. Because each carbon atom is bonded to the maximum number of other atoms (four), alkanes are considered **saturated hydrocarbons**.

Procedure

1. Assemble a model of methane (CH_4). Compare your model to the electron-dot and structural formulas on page 185. Note that the angles defined by bonds between atoms are not 90°, as you might think by looking at the structural formula. If you were to build a close-fitting box to surround a CH_4 molecule, the box would be shaped like a triangular pyramid, or a pyramid with a triangle as a base. A **tetrahedron** is the name given to this three-dimensional shape.

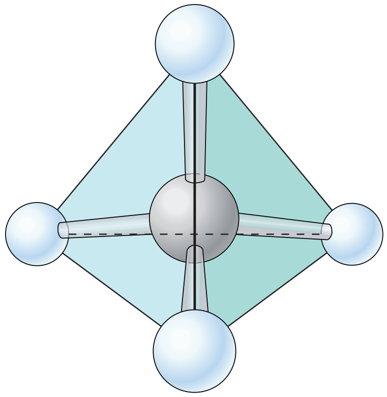


Figure 7 *The tetrahedral shape of a methane molecule.*

Why would the shape of a methane molecule be tetrahedral? Assume that the four pairs of electrons in the bonds surrounding the carbon atom—all with negative charges—repel one another. That is, the electron pairs stay as far away from one another as possible, arranging themselves so that they point to the corners of a tetrahedron. The angle formed by each C—H bond is 109.5°, a value that has been verified with several experimental methods. The angles are not 90°, as they would be if methane were flat. Verify this shape for yourself by arranging the atoms in your model.

2. Compare your three-dimensional model of methane to the representation of a tetrahedral molecule in Figure 7.
   a. How does the two-dimensional drawing (Figure 7) incorporate features that aid in visualizing the three-dimensional structure?
   b. Are there features of the two-dimensional figure that are difficult to translate into a three-dimensional structure? Explain.
   c. Translate your three-dimensional model into a two-dimensional drawing. Your drawing should convey the tetrahedral structure of methane.
3. Assemble models of a two-carbon and a three-carbon alkane molecule. Recall that each carbon atom in an alkane is bonded to four other atoms.
   a. How many hydrogen atoms are present in the two-carbon alkane?
   b. How many hydrogen atoms are present in the three-carbon alkane?
   c. Draw a ball-and-stick model, similar to the one in Figure 6 on page 185, of the three-carbon alkane.
4. a. Draw electron-dot and structural formulas for the two- and three-carbon alkanes.
   b. The molecular formulas of the first two alkanes are CH_4 and C_2H_6. What is the molecular formula of the third?

Examine your three-carbon alkane model and the structural formula you drew for it. Note that the middle carbon atom is attached to two hydrogen atoms, but the carbon atom at each end is attached to three hydrogen atoms. This molecule can be represented as $CH_3—CH_2—CH_3$, or $CH_3CH_2CH_3$. Formulas such as these provide convenient information about how atoms are arranged in molecules. For many purposes, such "condensed" formulas are more useful than molecular formulas such as C_3H_8.

Consider the formulas of the first few alkanes: CH_4, C_2H_6, and C_3H_8. Given the pattern represented by that series, try to predict the formula of the four-carbon alkane. If you answered C_4H_{10}, you are correct! The general molecular formula of all alkane molecules can be written as C_nH_{2n+2}, where

n is the number of carbon atoms in the molecule. So even without assembling a model, you can predict the formula of a five-carbon alkane: If $n = 5$, then $2n + 2 = 12$, and the formula is C_5H_{12}.

n can be any positive integer.

5. Using the general alkane formula, predict molecular formulas for the rest of the first ten alkanes. After doing this, compare your molecular formulas with the formulas given in Figure 8 to check your predictions.

The names of the first ten alkanes are also given in Figure 8. As you can see, each name is composed of a prefix, followed by *-ane* (designating an alk*ane*). The prefix indicates the number of carbon atoms in the backbone carbon chain. To a chemist, *meth-* means one carbon atom, *eth-* means two, *prop-* means three, and *but-* means four. For alkanes with five to ten carbon atoms, the prefix is derived from Greek—*pent-* for five, *hex-* for six, and so on.

6. Write structural formulas for butane and pentane.
7. a. Name the alkanes with these condensed formulas:
   (i) $CH_3CH_2CH_2CH_2CH_2CH_2CH_3$
   (ii) $CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$
   b. Write molecular formulas for the two alkanes in Question 7a.
8. a. Write the formula of an alkane containing 25 carbon atoms.
   b. Did you write the molecular formula or the condensed formula of this compound? Why?
9. Name the alkane having a molar mass of
   a. 30 g/mol.
   b. 58 g/mol.
   c. 114 g/mol.

Some Members of the Alkane Series

Name	Number of Carbons	Alkane Molecular Formulas: Short Version	Long Version
Methane	1	CH_4	CH_4
Ethane	2	C_2H_6	CH_3CH_3
Propane	3	C_3H_8	$CH_3CH_2CH_3$
Butane	4	C_4H_{10}	$CH_3CH_2CH_2CH_3$
Pentane	5	C_5H_{12}	$CH_3CH_2CH_2CH_2CH_3$
Hexane	6	C_6H_{14}	$CH_3CH_2CH_2CH_2CH_2CH_3$
Heptane	7	C_7H_{16}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$
Octane	8	C_8H_{18}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$
Nonane	9	C_9H_{20}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$
Decane	10	$C_{10}H_{22}$	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$

CD-ROM WWW. **Modeling Alkanes**

Figure 8 *The first ten alkanes.*

TRENDS IN ALKANE BOILING POINTS

Building Skills 2

In the laboratory activity involving distillation, you used a technique that separates liquid mixtures according to boiling points of substances. You also know that the fractions of petroleum are separated based on their boiling points. Why do the fractions with the highest boiling points contain the largest molecules? Why are the smallest molecules found in the fractions with the lowest boiling points? In this activity, you will explore this trend in alkane boiling points.

Using data for the alkanes found in Figure 5 (page 182) and Figure 8 (page 187), prepare a graph of boiling points. The x axis scale should range from 1 to 13 carbon atoms (even though you will initially plot data for 1 to 10 carbon atoms). The y axis scale should extend from −200 °C to +250 °C.

1. Plot the data points. Draw a best-fit line through your data points according to these guidelines:
   - The line should follow the trend of your data points.
   - The data points should be equally distributed above and below the line.
   - The line should not extend past your data points.

   Figure 9 shows an example of a best-fit line.

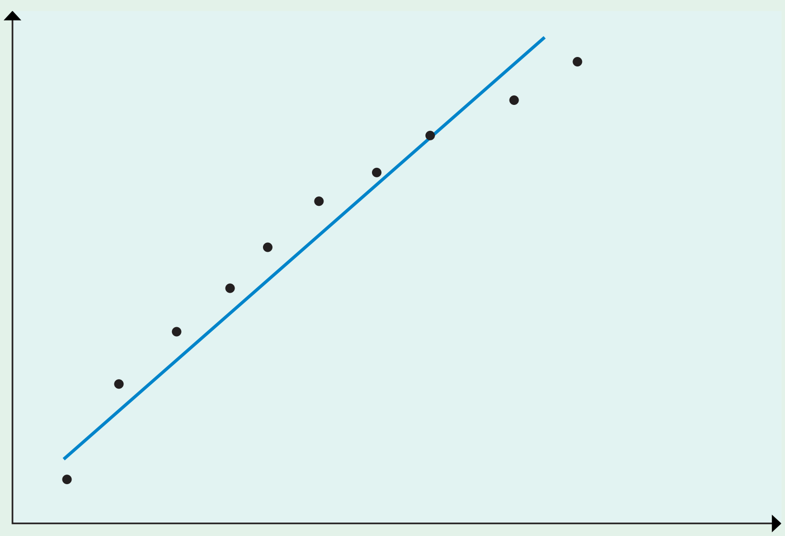


Figure 9 *An example of a best-fit line drawn through several data points.*

2. Estimate the average change in boiling point (in °C) when one carbon atom and two hydrogen atoms ($—CH_2—$) are added to a particular alkane chain.
3. The pattern of boiling points among the first ten alkanes allows you to predict boiling points for other alkanes.

a. Using your graph, estimate the boiling points of undecane ($C_{11}H_{24}$), dodecane ($C_{12}H_{26}$), and tridecane ($C_{13}H_{28}$). To do this, extend the trend of your graph line by drawing a dashed line from the graph line you drew for the first ten alkanes. This procedure is called **extrapolation**. Then read your predicted boiling points for C_{11}, C_{12}, and C_{13} alkanes on the *y* axis.

b. Compare your predicted boiling points to actual values provided by your teacher.

4. You learned that a substance's boiling point depends in part on its intermolecular forces, or attractions among its molecules. For the alkanes you have studied, what is the relationship between these attractions and the number of carbon atoms in each molecule?

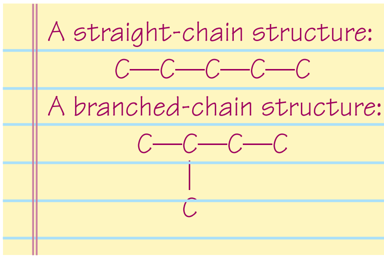
CD-ROM WWW. **Intermolecular Forces and Boiling Point**

A.7 ALKANES REVISITED

Laboratory Activity

Introduction

The alkane molecules you have considered so far are **straight-chain alkanes**—each carbon atom is linked to only one or two other carbon atoms. In alkanes with four or more carbon atoms, many other arrangements of carbon atoms are possible. Alkanes in which one or more carbon atoms are linked to three or four other carbon atoms are called **branched-chain alkanes**. An alkane with four or more carbon atoms can have either a straight-chain or a branched-chain structure. In this activity you will use ball-and-stick molecular models to investigate such variations in alkane structures—variations that can lead to different properties.



Procedure

1. Assemble a ball-and-stick model of a molecule with the formula C_4H_{10}. Compare your model with those built by others. How many different arrangements of atoms in the C_4H_{10} molecule can be constructed?

Molecules that have identical molecular formulas but different arrangements of atoms are called **isomers**. By comparing models, convince yourself that there are only two isomers of C_4H_{10}. The formation of isomers helps to explain the very large number of compounds that contain carbon chains or rings.

2. a. Draw an electron-dot formula for each C_4H_{10} isomer.
b. Write a structural formula for each C_4H_{10} isomer.

3. As you might expect, alkanes containing larger numbers of carbon atoms also have larger numbers of isomers. In fact, the number of different isomers increases rapidly as the number of carbon atoms increases. For example, chemists have identified three pentane (C_5H_{12}) isomers. Their structural formulas are shown in Figure 10. Try building these and other models. Are other pentane isomers possible?

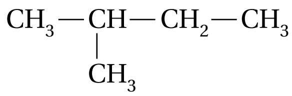
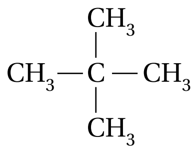
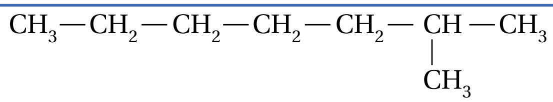
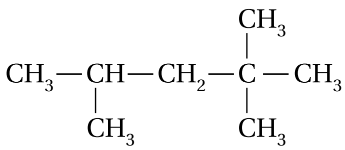
Alkane Isomers		
Alkane	**Structural Formula**	**Boiling Point (°C)**
C_5H_{12} isomers	$CH_3—CH_2—CH_2—CH_2—CH_3$	36.1
		27.8
		9.5
Some C_8H_{18} isomers	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$	125.6
		117.7
		99.2

Figure 10 *Some pentane and octane isomers.*

4. Now consider possible isomers of C_6H_{14}.

a. Working with a partner, draw structural formulas for as many different C_6H_{14} isomers as possible. Compare your structures with those drawn by other groups.

b. How many different C_6H_{14} isomers were found by your class?

5. Build models of one or more C_6H_{14} isomers, as assigned by your teacher.

a. Compare the three-dimensional models built by your class with corresponding structures drawn on paper.

b. Based on your examination of the three-dimensional models, how many different C_6H_{14} isomers are possible?

Because each isomer is a different substance, it has its own characteristic properties. In the next activity, you will examine boiling-point data for some alkane isomers.

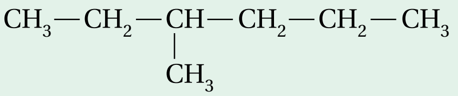
BOILING POINTS OF ALKANE ISOMERS

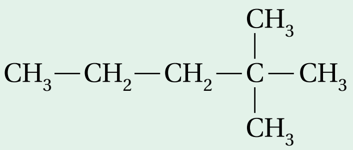
Building Skills 3

You have already observed that boiling points of straight-chain alkanes are related to the number of carbon atoms in their molecules. Increased intermolecular forces are associated with the greater molecule-to-molecule contact possible for larger alkanes. Now consider the boiling points of some isomers.

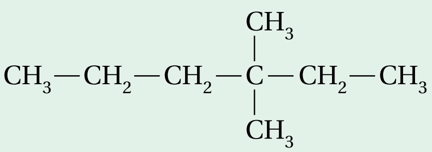
1. Boiling points for two sets of isomers are listed in Figure 10 (page 190). Within a given set, how does the boiling point change as the extent of carbon-chain branching increases? Assign each of the following boiling points to the appropriate C_7H_{16} isomer: 98.4 °C, 92.0 °C, 79.2 °C.

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

b. 

c. 

3. Here is the structural formula of a C_8H_{18} isomer:



a. Compare it to each C_8H_{18} isomer listed in Figure 10. Predict whether it has a higher or lower boiling point than each of the other C_8H_{18} isomers.

b. Would the C_8H_{18} isomer shown here have a higher or lower boiling point than each of the three C_5H_{12} isomers shown in Figure 10?

4. How do you explain the boiling point trends that you observed in this activity?

Chemists and chemical engineers use information about molecular structures and boiling points to separate the complex mixture known as petroleum into a variety of useful substances, many of which you are quite familiar with. In Section B, you will learn how bonding helps to explain the use of petroleum as a fuel.

CD-ROM WWW. **Questions and Answers**

SECTION SUMMARY

Reviewing the Concepts

- **Petroleum (crude oil), a nonrenewable resource that must be refined prior to use, consists of a complex mixture of hydrocarbon molecules.**

1. What is a hydrocarbon?
2. What does it mean to refine a natural resource?
3. What is meant by saying that oil is "crude"?
4. What is the likelihood of discovering a pure form of petroleum that can be used directly as it is pumped from the ground? Explain your answer.

- **Petroleum is a source of fuels that provide thermal energy. It is also a source of raw materials for the manufacture of many familiar and useful products. On average, the United States uses about 18 million barrels of petroleum daily.**

5. About 16% of the petroleum used in the United States is used for "molecule building," producing nonfuel products that have a significant impact on everyday life. The remaining 84% of the petroleum is burned as fuel.

   a. What is the average number of barrels of petroleum used daily in the United States for building (nonfuel) purposes?
   b. How many barrels of petroleum are burned as fuel daily in the United States?
   c. List four household items made from petroleum.
   d. What materials could be substituted for each of these four items if petroleum were not available to make them?

6. Name several fuels obtained from crude petroleum.
7. List several products that might not be widely and easily available if petroleum supplies were to dwindle.

- **Liquid substances can often be separated according to their differing boiling points in a process called distillation.**

8. Rank the following hydrocarbons from their lowest boiling point to their highest: hexane (C_6H_{14}), methane (CH_4), pentane (C_5H_{12}), and octane (C_8H_{18}). Explain your rankings.
9. Sketch the basic setup for a laboratory distillation. Label the key parts.
10. Simple distillation is never sufficient to completely separate two liquids. Explain.
11. Explain why thermal energy is added at one point and removed at another point in the process of distillation.

- **Fractional distillation of crude oil produces several distinctive and usable mixtures called fractions. Each fraction contains molecules of similar sizes and boiling points.**

12. How does a fractional distillation differ from a simple distillation?
13. Petroleum fractions include light, intermediate, and heavy distillates and residues. List three useful products derived from each of these fractions.
14. Where in a distillation tower—top, middle, or bottom—would you expect the fraction with the highest boiling point range to be removed? Why?
15. After fractional distillation, each fraction is still a mixture. What must be done to further separate the components of each fraction?

- **Hydrocarbon molecules, whose atoms are joined by covalent bonds, can be represented by electron-dot, structural, or molecular formulas.**

16. What does each dot in an electron-dot diagram represent?
17. Each carbon atom has six electrons. Why does the electron-dot representation of carbon only show four dots?
18. Define the term "covalent bond."
19. Draw an electron-dot diagram for a branched six-carbon hydrocarbon.
20. a. What additional information does a structural formula convey that a molecular formula does not?
    b. In what ways is a structural formula an inadequate representation of a real molecule?

- **Alkanes, saturated hydrocarbons with single covalent bonds, have the general formula C_nH_{2n+2}.**

21. Use the general molecular formula to write the molecular formula for an alkane containing
    a. 6 carbons. b. 10 carbons.
    c. 16 carbons. d. 25 carbons.
22. Alkanes are said to be saturated hydrocarbons. What does "saturated" mean?
23. What does *-ane* imply about the bonding arrangement in compounds such as hexane, butane, methane, and octane?

- **Isomers are molecules with identical molecular formulas but different arrangements of atoms. Each isomer is a separate substance with its own characteristic properties.**

24. Draw structural formulas for at least three isomers of C_9H_{20}.
25. What is the shortest-chain alkane that can demonstrate isomerism?
26. a. Draw two hexane isomers—one straight chain and one branched chain.
    b. Which of the two would have the lower boiling point? Explain your choice.

Connecting the Concepts

27. Why is petroleum considered a nonrenewable resource?
28. In a fractionating tower, petroleum is generally heated to 400 °C. What would happen if it were heated to only 300 °C?
29. The molar masses of methane (16 g/mol) and water (18 g/mol) are similar. At room temperature, methane is a gas and water is a liquid. Explain this difference.
30. The traditional unit of volume for petroleum is one barrel, which contains 42 gallons. Assume that those 42 gallons provide 21 gallons of gasoline. How many barrels of petroleum does it take to operate an automobile for a year, assuming the auto travels 10 000 miles and goes 27 miles on a gallon of gas?
31. Which mixture would be easier to separate by distillation—a mixture of pentane and octane or a mixture of pentane and a branched-chain octane isomer? Explain the reasoning behind your choice.

Extending the Concepts

32. Is it likely that the composition of crude oil in Texas is the same as that of crude oil in Kuwait? Explain your answer.

33. Gasoline's composition, as blended by oil companies, varies in different parts of the nation.

a. Does the composition relate to the time of year?
b. If so, what factors help to determine the composition of gasoline in various seasons?

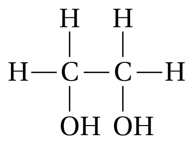
34. What kind of petroleum trade relationship would be expected between North America and the Middle East? If other world regions become more industrialized and global petroleum supplies decrease, how might the North America–Middle East trade relationship change?

35. The hydrocarbon boiling points listed in Figure 5 (page 182) were measured under normal atmospheric conditions. How would those boiling points change if atmospheric pressure were increased? (*Hint:* Although butane is stored as a liquid in a butane lighter, it escapes through the lighter nozzle as a gas.)

36. The two isomers of butane have different physical properties, as illustrated by their different boiling points. They also have different chemical properties. Explain how isomerism may contribute to differences in chemical behavior.

37. What properties of petroleum make it an effective lubricant?

38. When 1,2-ethanediol (ethylene glycol, also known as permanent antifreeze) is dissolved in water in an automobile's radiator, it helps keep the water from freezing. The permanent antifreeze-water solution has a lower freezing point than does pure water. Similarly, when an ionic substance such as table salt (NaCl) is dissolved in water, the solution freezes at a lower temperature than does pure water. Why is NaCl a highly undesirable additive for car radiators, whereas ethylene glycol is a suitable additive? (*Hint:* Compare the structure and chemical properties of these two substances.)



1,2-Ethanediol
(Ethylene glycol)