Chapter

11

Hydrocarbons

In this chapter, you will be able to

- describe the origins and major sources of organic compounds, particularly hydrocarbons;
- describe and explain the characteristics of different structures of hydrocarbons, using Lewis bonding theory;
- describe the process of petroleum refining and the uses society has for the products of this process;
- describe and determine by experimentation some physical and chemical properties of single-, double-, and triple-bonded hydrocarbon compounds;
- name and draw structural formulas for a wide variety of hydrocarbon compounds;
- represent a wide variety of hydrocarbon compounds by using molecular models to show their atom arrangement;
- describe science- and technology-based careers in the petrochemical industry;
- discuss the risks and benefits of society's dependence on petrochemicals, particularly hydrocarbons.

Organic chemicals include most chemicals that compose living material—both plants and animals. All carbohydrates, proteins, and fats (lipids) are organic compounds. Pesticides and antibiotics are organic compounds. DNA, RNA, chromosomes, and genes are composed of organic compounds. Fossil fuels, lubricants, and gasoline are organic. Polyethylene, polypropylene, nylon, and polyester are organic polymers. In this unit you will study hydrocarbons, a class of organic chemicals made up of only carbon and hydrogen atoms.

Hydrocarbons serve a dual purpose in society: They are fuels that may be used to produce electricity, run automobiles, and cook meals; and they are used to produce petrochemicals and thus may be the source of almost anything manufactured, including furniture, processed foods, computers, stereos, plastics, synthetic fabrics, cosmetics, synthetic sweeteners, soaps, solvents, and refrigerants. The list grows longer and longer each year.

This dual purpose of hydrocarbons is integrated into the carbon cycle, as illustrated in **Figure 1**. Knowledge of the chemistry of hydrocarbons will help you make increasingly important decisions about our society and our planet.

Reflect on your Learning

1. Recall the products of incomplete combustion of hydrocarbons. Which one is visible?
2. What are fossil fuels? Name one fuel that is not a fossil fuel.

Throughout this chapter, note any changes in your ideas as you learn new concepts and develop your skills.

Try This Activity

Butane Behaviour

The hydrocarbon butane, $C_4H_{10(g)}$, is used in a wide variety of small personal devices, such as lighters. Butane is a gas at SATP, but liquefies under only moderate pressure, a property that makes it a very convenient fuel.

Butane is flammable. Do not heat the cylinder directly.

Conduct this activity in a fume hood.

Materials: a small (sandwich-size) resealable plastic bag, a butane cylinder (for refilling butane lighters), a 250-mL beaker, eye protection, matches

- Hold the cylinder with the nozzle end down, inside the open plastic bag, and pull the nozzle back so that a small amount (approximately 1–2 mL) of liquid butane sprays into the bag.
- Seal the plastic bag and hold it so that the liquid butane inside is warmed by your hand. Don't overdo this and freeze your skin; boiling butane is very cold.
- Observe the physical properties (volume, temperature, colour) of butane as it changes physical state. Then open the bag upside down

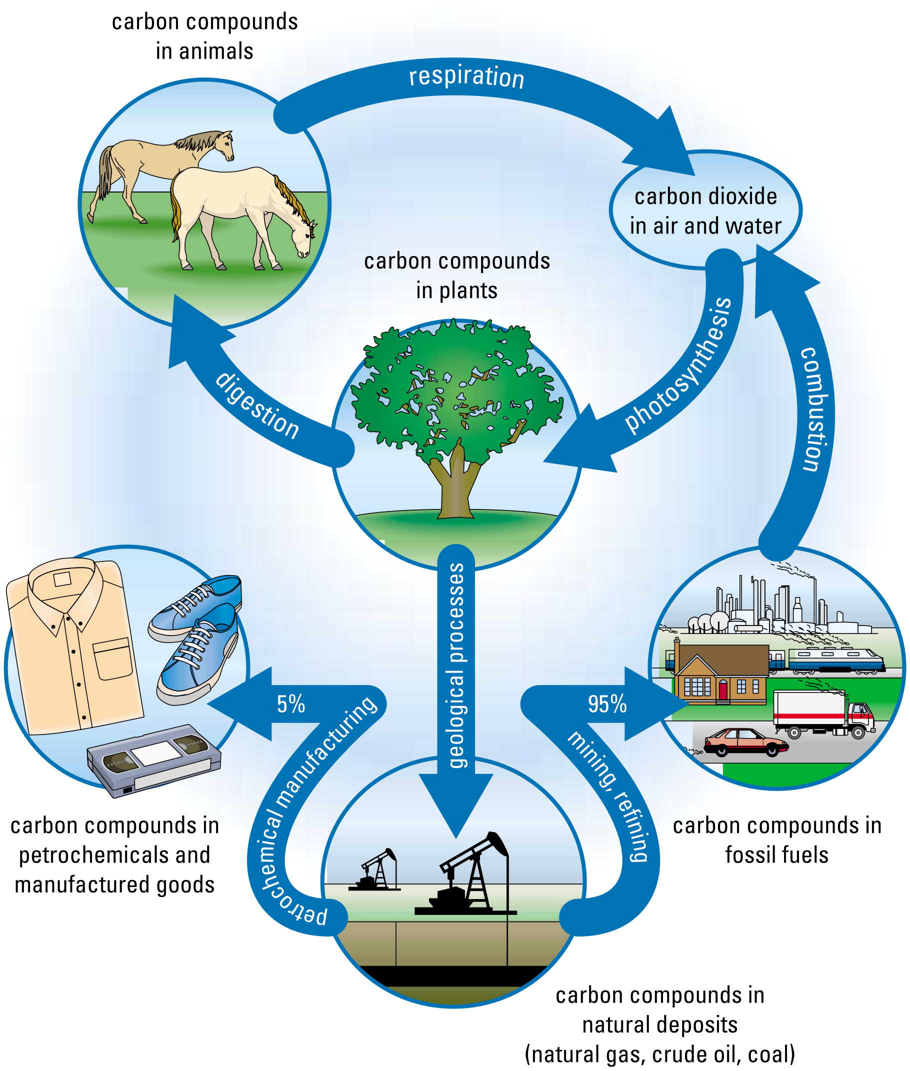


Figure 1
The carbon cycle is an illustration of the interrelationship of all living things with the environment and with the technologies that use fossil fuels.

in a running fume hood (or outdoors, out of an open window) to release the butane from the bag.

- Put on your eye protection and tie back any loose hair. On a level table or bench top in a relatively draft-free area, hold the cylinder with the nozzle end down and spray approximately 1–2 mL of liquid butane into the beaker. Allow the liquid butane to completely vaporize.
- After 5–10 s light a match, and use it to ignite the butane gas in the beaker from the side, being careful not to position your hand directly above the beaker when you light the gas.
- Observe the combustion; when the flame stops, pick up the beaker and feel the bottom. Now wipe the inside top half of the beaker with a clean white tissue, and observe the tissue.

(a) Compare the volumes of the fixed amount of butane in the bag, in its liquid and gaseous forms. How do you know the amount of butane is constant?

(b) Where does the energy come from to boil the butane in the bag? What observation supports your statement?

(c) What does releasing the butane gas from the bag by holding it upside down suggest about the density of butane gas compared to air? Does this explain why butane gas in a beaker will mostly stay in the beaker? What observation tells you this must be true, even though the gas itself is invisible?

(d) Where does the energy come from to boil the butane in the beaker? What observation supports your statement?

(e) What is the dark substance on the tissue after wiping the beaker?

11.1 Organic Compounds

In the early 19th century, Swedish chemist Jöns Jakob Berzelius (1779–1848) classified compounds into two primary categories: those obtained from living organisms, which he called organic, and those obtained from mineral sources, which he called inorganic. At that time, most chemists believed that organic chemicals could be synthesized only in living systems. A theory called "vitalism" proposed that the laws of nature were somehow different for living and nonliving systems and that the synthesis of organic compounds necessarily involved a "vital force," present only in living organisms.

This theory was shown to be unacceptable in 1828 by German chemist Friedrich Wöhler (1800–1882). Wöhler performed a revolutionary laboratory experiment in which he used the inorganic compound ammonium cyanate, $NH_4OCN_{(s)}$, to synthesize urea, $H_2NCONH_{2(s)}$, a well-known organic compound that is produced by many living organisms. In the years following Wöhler's experiment, chemists synthesized many other organic compounds. For example, acetic acid (ethanoic acid), $HC_2H_3O_{2(l)}$, a relatively simple molecule, was synthesized in 1845 in Germany by Adolph Kolbe (1818–1884). Sucrose, $C_{12}H_{22}O_{11(s)}$, (**Figure 1**), has a more complex structure and was long thought impossible to create in a laboratory—until 1953, when it was first synthesized by Canadian chemist Raymond Lemieux (1920–2001).

Figure 1
Sucrose (table sugar, $C_{12}H_{22}O_{11(s)}$) occurs naturally in plants and in fairly high concentrations in sugar beets and sugar cane (shown here). No sugar cane is grown in Canada, although it is refined in New Brunswick, Quebec, and Ontario. Sugar beets are grown and refined in Quebec, Manitoba, and Alberta. High-fructose (fruit sugar, $C_6H_{12}O_{6(s)}$) corn syrup is refined in Ontario.

organic compounds: compounds that contain carbon, except $CO_{(g)}$, $CO_{2(g)}$, and ionic compounds with carbon

organic chemistry: the study of organic compounds

Today, **organic compounds** are defined as compounds that contain carbon, and **organic chemistry** is defined as the study of organic compounds. This can seem like a limitless task, since more than nine million such compounds have been identified. We simplify our organization by grouping organic compounds according to their properties and molecular structures, which, we explain, are a result of the structure of the covalent bonds within organic molecules. By common convention, the two oxides of carbon, $CO_{2(g)}$ and $CO_{(g)}$, are not normally considered to be organic compounds. Compounds of carbonate, bicarbonate, cyanide, cyanate, and thiocyanate ions all contain carbon atoms, but these are also not considered to be organic compounds because their properties are explained by ionic bonds.

The simplest way to begin a detailed study of organic compounds is with **hydrocarbons,** those compounds containing only carbon and hydrogen atoms. Based on previous generalizations (Unit 1), hydrocarbons are all nonpolar substances. Therefore, they all have a low solubility in water, and their physical properties—such as states, densities, and melting and boiling points—form clear trends largely explained by London (dispersion) forces. We consider all organic compounds to be derivatives of hydrocarbons for classification purposes; that is, we classify all organic compounds as though they were hydrocarbons that were then changed by atom rearrangement, addition, and substitution into their present chemical structure. Because we use this system, understanding hydrocarbons is essential for the study of any area within the field of organic chemistry.

hydrocarbons: organic compounds that contain only carbon and hydrogen atoms in their molecular structure

Figure 2
The first oil company in North America was created in 1854 by Charles Tripp, and the first oil well was dug in 1859 by James Williams at Oil Springs, Ontario. Williams constructed the first oil refinery in Canada at Hamilton in 1860. A replica of one of the oil wells is found near the Oil Museum of Canada in Oil Springs, Ontario.

Sources and Uses

Coal, crude oil, oil sands, heavy oil, and natural gas are the nonrenewable sources of fuels that power our society. All of these substances are formed over millions of years from plant and animal material that, over geologic time periods, is subjected to heat and pressure. The original compounds gradually convert to a very complex mix of organic compounds we generally name according to the physical state of the mixture, for example, sand, oil, and gas. We call all of these compound mixtures "fossil" fuels because of the way they are formed. These fuels are primarily hydrocarbons. Over 95% of our society's hydrocarbon use is for combustion reactions to provide heat and electrical energy (primary uses). Hydrocarbons are also the starting materials in the industrial chemical synthesis of thousands of products such as fuels, plastics, solvents, medicines, and synthetic fibres (secondary uses). Some hydrocarbons are obtained directly by physical separation from petroleum and natural gas, whereas others come from oil and gas refining (**Figure 2**).

Refining is the technology that includes separating complex mixtures into simpler purified components. The refining of coal and natural gas involves physical as well as chemical processes; for example, coal may be crushed and treated with solvents. Components of natural gas are separated either by selectively dissolving them in chosen solvents or by condensation and distillation. Petroleum refining, that is, refining crude oil, is much more complex than coal or gas refining, but many more products are obtained from crude oil.

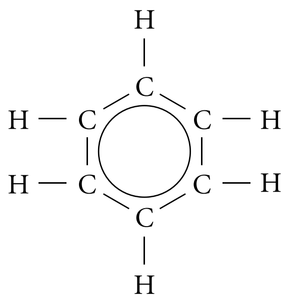
refining: the physical and/or chemical process that converts complex organic mixtures into simpler mixtures or purified substances

Sources of hydrocarbons other than fossil fuels are all living things, and, of course, we believe fossil fuels were living things very long ago. Plant crops and animal decomposition products can be used to produce hydrocarbons and other organic compounds. For example, in old landfill waste disposal sites, methane, $CH_{4(g)}$, is produced underground by bacterial decomposition of organic waste material. Many cities tap into these sites to capture the gas, which can then be burned as fuel in power-generating plants.

Practice

Understanding Concepts

1. Describe the difference between the original and the current definitions of organic compounds.
2. What are the major sources of hydrocarbons used by our society?
3. How do scientists explain how these sources of hydrocarbons were originally formed?
4. List the primary and some secondary uses of hydrocarbons in our society.



benzene

Figure 4
Benzene, $C_6H_{6(l)}$, is the simplest example of an aromatic compound. It is an important component of gasoline. A benzene molecule has some unique carbon–carbon bonds, indicated by the circle in the ring.

aliphatic compound: one that has a structure based on straight or branched chains or rings of carbon atoms; not including aromatic compounds, for example, benzene

Making Connections

5. Considering the percentages of primary and secondary uses of hydrocarbons in our technological society, write a paragraph on the need to conserve this nonrenewable resource.
6. Some politicians from developed countries are calling for a significant international reduction of hydrocarbon combustion. What might this mean for the future development of developing countries on our planet?

Reflecting

7. What other high-school science course heavily involves organic chemistry, and why?

Classification of Hydrocarbons

The molecular structures of hydrocarbons determine how they are classified (**Figure 3**). Organic compounds with molecular structures that are straight or branched chains or rings of carbon-to-carbon bonds are called **aliphatic compounds**. As you can see in **Figure 3**, this subgroup of hydrocarbons is further classified into alkanes, alkenes, and alkynes. The main purpose of this chapter is to study the properties, molecular structure, and naming of these three groups of aliphatic hydrocarbons, including both open-chain and ring compounds. Hydrocarbons are either aliphatic or aromatic; aromatic compounds are organic compounds that contain a benzene-like ring structure (**Figure 4**). For now, the only aromatic compound that you need to know about is benzene, $C_6H_{6(l)}$. You may study aromatic hydrocarbons and the hydrocarbon derivatives in future chemistry courses.

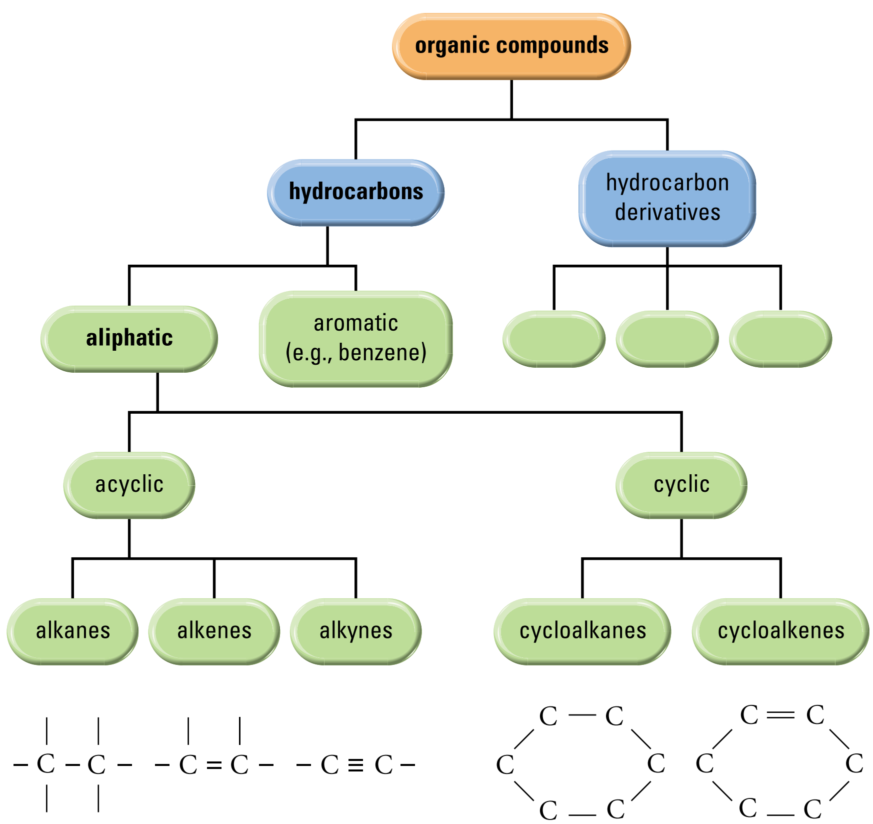


Figure 3
This classification system helps scientists organize their knowledge of organic compounds. You start your study of organic compounds with simple alkanes.

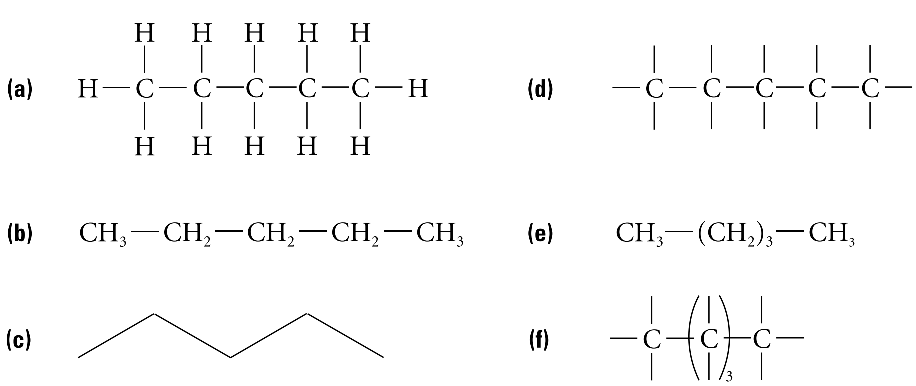
Simple Alkanes

Aliphatic hydrocarbons with molecules containing only single carbon-to-carbon bonds with an open-chain (noncyclic) structure are called **alkanes**. The classification system in **Figure 3** shows where the study of alkanes fits into the big picture of organic compounds. The simplest member of the alkane series is methane, $CH_{4(g)}$, which is the main constituent of natural gas used for home heating. Other simple alkanes containing up to 10 carbon atoms in a continuous chain are listed in **Table 1**. Each molecular formula in the series has one more CH_2 group than the one before it. Such a series of compounds, where each differs from the one before it by the same increment (CH_2 in this case), is called a homologous series. Comparing the formulas, you can see that the general formula for these alkanes is always C_nH_{2n+2}; that is, they are a series of CH_2 units plus two terminal hydrogen atoms.

The empirical formulas for the alkanes, such as the ones listed in **Table 1**, can be determined by combustion analysis and mass spectrometry. Empirically determined chemical formulas are useful for communicating the numbers of atoms present in a molecule. For simple molecules, the structure is often evident. As the number of atoms in a molecule increases, the molecular formula must be expanded in order to communicate the structure. One simple alternative is to cluster groups of atoms, for example, writing $CH_3CH_2CH_2CH_2CH_3$ to represent the way in which the atoms bond in C_5H_{12} molecules.

The *expanded* molecular formula, $CH_3CH_2CH_2CH_2CH_3$, is one alternative to the usual molecular formula for pentane, $C_5H_{12(l)}$. Chemists have created other ways to communicate the structures of these compounds. People are very visual beings and often find models to be an effective way of understanding how we believe something exists and operates. In chemistry, ball-and-stick models and space-filling models help us visualize the structures and shapes of molecules. Ball-and-stick models, like the pentane model in **Figure 5**, are more effective in showing types of covalent bonds and the angles between the bonds, but not as good at showing molecular shape and atomic size. Space-filling models (**Figure 6**) do this well.

Structural diagrams are another way to communicate molecular structure, but less completely than 3-D models. A complete structural diagram, as in **Figure 7(a)**, shows all atoms and bonds; a condensed structural diagram, as in **Figure 7(b)**, omits showing the C—H bonds but shows the carbon–carbon bonds. A line structural diagram, as in **Figure 7(c)**, is an efficient way to represent long chains of carbon atoms; the ends of each line segment represent carbon atoms, and hydrogen atoms are not shown. Since information is left out of any diagram, it must be replaced by your knowledge. For example, in a line structural diagram, wherever you see fewer than four lines at an intersection, it is assumed that H atoms are bonded there to make four bonds to each carbon.



alkane: a hydrocarbon with only single bonds between carbon atoms

Table 1: The Alkane Family of Organic Compounds

IUPAC name	Molecular formula
methane	$CH_{4(g)}$
ethane	$C_2H_{6(g)}$
propane	$C_3H_{8(g)}$
butane	$C_4H_{10(g)}$
pentane	$C_5H_{12(l)}$
hexane	$C_6H_{14(l)}$
heptane	$C_7H_{16(l)}$
octane	$C_8H_{18(l)}$
nonane	$C_9H_{20(l)}$
decane	$C_{10}H_{22(l)}$
–ane	C_nH_{2n+2}

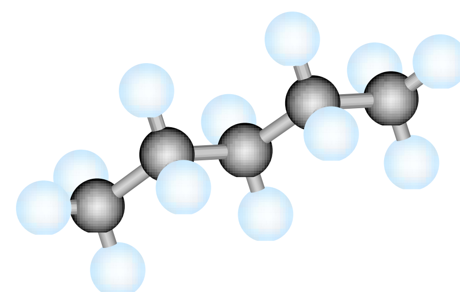


Figure 5
A ball-and-stick model of pentane, $C_5H_{12(l)}$, helps us visualize this theoretical structure.

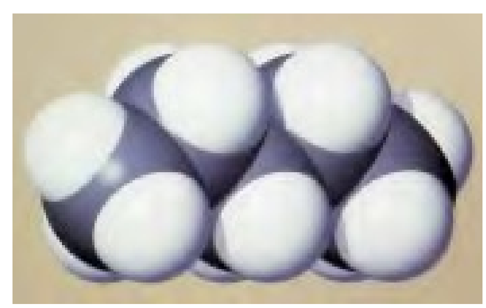


Figure 6
This is a space-filling model, also of pentane, $C_5H_{12(l)}$, used to show the shape of the molecule and the relative size of the atoms.

Figure 7
These structural diagrams all represent the same pentane molecule, C_5H_{12}.

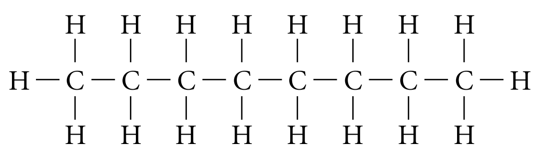
Other variations of structural diagrams, such as **Figure 7(d)**, **(e)**, and **(f)** page 509, are also used by some people.

Structural diagrams, in general, do not communicate the shape of the molecule. Knowledge of the three-dimensional structure of the molecule is sacrificed to make the communication simpler. When knowledge of the three-dimensional character of a molecule is required, a structural diagram is replaced by a more sophisticated diagram.

Sample Problem 1

Octane is a component of gasoline. Draw a complete structural diagram and a condensed structural diagram for octane.

Solution



$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$

Practice

Understanding Concepts

8. Why do scientists create classification systems?
9. Using your own words, define the class of organic compounds called hydrocarbons.
10. Name the two major classes of hydrocarbons as created by scientists.
11. Are hydrocarbon molecules polar or nonpolar? What does this suggest about the type of intermolecular forces present between hydrocarbon molecules?
12. Draw a Lewis diagram for a carbon atom and a hydrogen atom, and indicate how many covalent bonds each of these atoms can form.
13. Draw a Lewis diagram and a complete structural diagram for methane, the main component of natural gas.
14. Crude oil is a complex mixture of hydrocarbons that includes most of the simple alkanes. Draw complete structural diagrams for the straight-chain alkanes, from ethane through decane. Label each diagram.
15. What is the molecular formula for an alkane containing 30 carbon atoms?
16. What is the common feature in the names of the simple alkanes in **Table 1**? Where do you think this common feature came from?

Section 11.1 Questions

Understanding Concepts

1. Classify each of the following compounds as inorganic or organic:
   (a) $CaCO_{3(s)}$
   (b) $C_6H_{6(l)}$
   (c) $CO_{2(g)}$
   (d) $C_4H_{10(g)}$
   (e) $CH_3(CH_2)_6CH_{3(l)}$
2. What is believed to be the origin of most hydrocarbons on Earth?
3. Identify the sources of most organic compounds.
4. List three common fuels that are hydrocarbon compounds.
5. Draw a complete structural diagram to explain each of the following empirical formulas:
   (a) $C_3H_{8(g)}$
   (b) $C_5H_{12(l)}$
   (c) $C_7H_{16(l)}$
6. Name the following hydrocarbons, which are found in a sample of crude oil:
   (a) $C_2H_{6(g)}$
   (b) $C_4H_{10(g)}$
   (c) $C_6H_{14(l)}$
   (d) $C_9H_{20(l)}$
7. Can the hydrocarbon $C_{45}H_{92(s)}$ be classified as an alkane? Justify your answer.

Applying Inquiry Skills

8. Complete the Analysis section of the following lab report.

   Question

   What is the chemical formula, molecular structure, and name of an unknown gas?

   Experimental Design

   A sample of a gas is analyzed with a combustion analyzer and a mass spectrometer.

   Evidence

   percent by mass of carbon = 81.68%

   percent by mass of hydrogen = 18.32%

   molar mass by analysis = 44.01 g/mol

   Analysis

   (a) Determine the empirical molecular formula of the hydrocarbon, name it, and draw a structural diagram.

Making Connections

9. Are fossil fuels a finite source of hydrocarbons? Provide your reasoning.

Reflecting

10. What will we use for an energy source and raw material for making plastics, fabric, detergents, and so on if sources of fossil fuels are depleted?