9.3 Classifying Hydrocarbons

Chemists group hydrocarbons and other organic compounds into the categories shown in Figure 9.11. The International Union of Pure and Applied Chemistry (IUPAC) has developed a comprehensive set of rules for naming the compounds within each category. Using these rules, you will be able to classify and name all the hydrocarbon compounds that you will encounter in this unit.

The names that are based on the IUPAC rules are called *systematic names*. During your study of organic chemistry, you will also run across many common names for organic compounds. For example, the systematic name for the organic acid CH_3CO_2H is ethanoic acid. You are probably more familiar with its common name: vinegar.

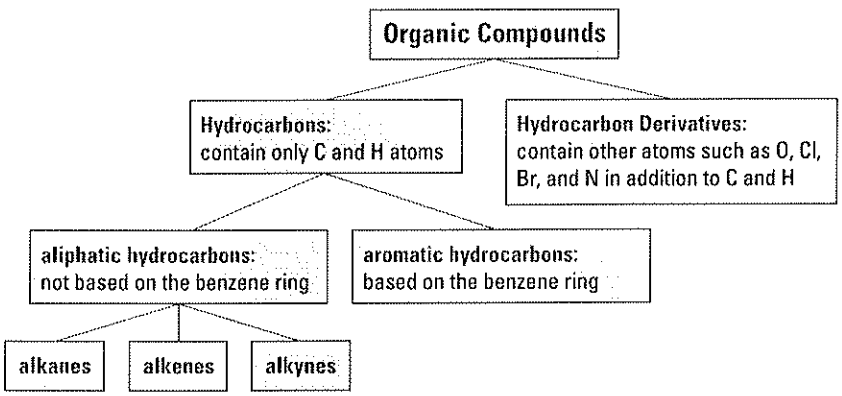


Figure 9.11 This concept map illustrates a system for classifying organic compounds.

Alkanes

Alkanes are hydrocarbon molecules that contain only *single* covalent bonds. They are the simplest hydrocarbons. Methane, CH_4, is the simplest alkane. It is the main component of natural gas. Alkanes are **aliphatic hydrocarbons**: organic compounds in which carbon atoms form chains and non-aromatic rings.

Figure 9.12 on the next page compares the structural formulas of methane and the next three members of the alkane family. Notice three facts about these alkanes:

1. Each carbon atom is bonded to the maximum possible number of atoms (either carbon or hydrogen atoms). As a result, chemists refer to alkanes as **saturated hydrocarbons**.
2. Each molecule differs from the next molecule by the structural unit $–CH_2–$. A series of molecules like this, in which each member increases by the same structural unit, is called a **homologous series**.
3. A mathematical pattern underlies the number of carbon and hydrogen atoms in each alkane. All alkanes have the general formula C_nH_{2n+2}, where n is the number of carbon atoms. For example, propane has 3 carbon atoms. Using the general formula, we find that

$$2n + 2 = 2(3) + 2 = 8$$

Thus propane should have the formula C_3H_8, which it does.

Section Preview/Outcomes

In this section, you will

- **demonstrate** an understanding of the carbon atom by classifying hydrocarbons and by analyzing the bonds that carbon forms in aliphatic hydrocarbons
- **name** alkanes, alkenes, and alkynes, and **draw** structural representations for them
- **describe** some of the physical properties of hydrocarbons
- **predict** the products of reactions of hydrocarbons
- **determine** through experimentation some of the characteristic properties of saturated and unsaturated hydrocarbons
- **communicate** your understanding of the following terms: *alkanes, aliphatic hydrocarbons, saturated hydrocarbons, alkyl group, homologous series, complete combustion, incomplete combustion, alkenes, unsaturated hydrocarbons, cis-trans isomer, addition reaction, Markovnikov's Rule, alkynes, cyclic hydrocarbons, aromatic hydrocarbon, substitution reaction*

Language LINK

The name "aliphatic" comes from the Greek word *aleiphatos*, meaning "fat." Early chemists found these compounds to be less dense than water and insoluble in water, like fats. "Aliphatic" now refers to the classes of hydrocarbons called alkanes, alkenes, and alkynes.

CONCEPT CHECK

Why is methane the simplest of all the millions of hydrocarbons? **Hint:** Recall what you know about chemical bonding and the common valences of elements.

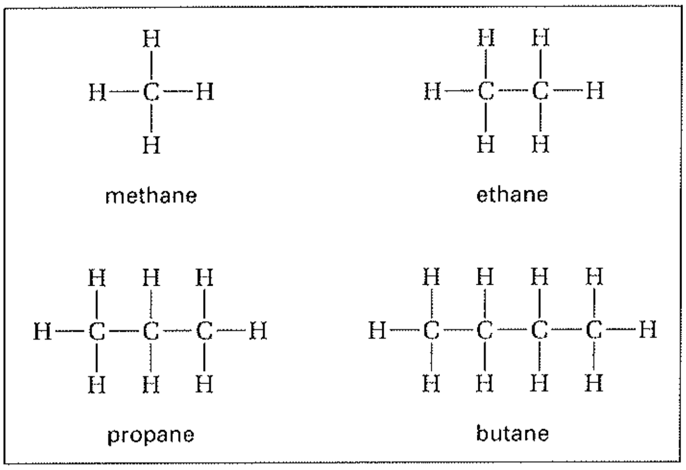
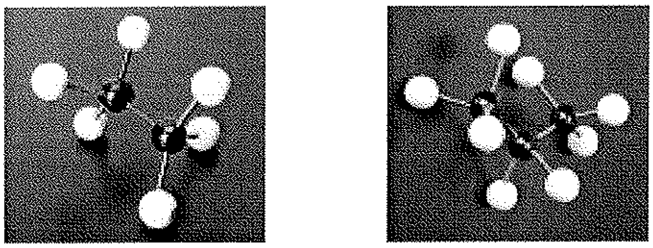


Figure 9.12 Carefully examine these four molecules. They are the first four alkanes. In what ways are they similar? In what ways are they different?

Figure 9.13 illustrates these three important facts about alkanes. Study the two alkanes, then complete the Practice Problems that follow.



$CH_3—CH_3$ + **$-CH_2-$** → CH_3—**CH_2**—CH_3

ethane propane

Figure 9.13 How are these two alkanes similar? How are they different? Use the ideas and terms you have just learned to help you answer these questions.

Practice Problems

1. Heptane has 7 carbon atoms. What is the chemical formula of heptane?
2. Nonane has 9 carbon atoms. What is its chemical formula?
3. An alkane has 4 carbon atoms. How many hydrogen atoms does it have?
4. Candle wax contains an alkane with 52 hydrogen atoms. How many carbon atoms does this alkane have?

Naming Alkanes

The IUPAC system for naming organic compounds is very logical and thorough. The rules for naming alkanes are the basis for naming the other organic compounds that you will study. Therefore it is important that you understand how to name alkanes.

Straight-Chain Alkanes

Recall that carbon can bond to form long, continuous, chain-like structures. Alkanes that bond in this way are called *straight-chain alkanes.* (They are also called *unbranched alkanes.*) Straight-chain alkanes are the simplest alkanes. Table 9.2 lists the names of the first ten straight-chain alkanes.

Table 9.2 The First Ten Straight-Chain Alkanes

Name	Number of carbon atoms	Expanded molecular formula
methane	1	CH_4
ethane	2	CH_3CH_3
propane	3	$CH_3CH_2CH_3$
butane	4	$CH_3(CH_2)_2CH_3$
pentane	5	$CH_3(CH_2)_3CH_3$
hexane	6	$CH_3(CH_2)_4CH_3$
heptane	7	$CH_3(CH_2)_5CH_3$
octane	8	$CH_3(CH_2)_6CH_3$
nonane	9	$CH_3(CH_2)_7CH_3$
decane	10	$CH_3(CH_2)_8CH_3$

The *root* of each name (highlighted in colour) serves an important function. It tells you the number of carbon atoms in the chain. The *suffix* -ane tells you that these compounds are alkane hydrocarbons. Thus the root and the suffix of one of these simple names provide the complete structural story of the compound.

Branched-Chain Alkanes

The names for straight-chain alkanes can, with a few additions, help you recognize and name other organic compounds. You now know that the name of a straight-chain alkane is composed of a root (such as meth-) plus a suffix (-ane). Earlier in the chapter, you saw the isomers of C_6H_{14}. Figure 9.14 shows one of them, called 2-methylpentane.

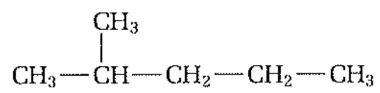


Figure 9.14 2-methylpentane

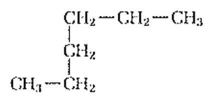
Notice four important facts about 2-methylpentane:

1. Its structure is different from the structure of a straight-chain alkane. Like many hydrocarbons, this isomer of C_6H_{14} has a branch-like structure. Alkanes such as 2-methylpentane are called *branched-chain alkanes.* (The branch is sometimes called a *side-chain.*)
2. The name of this alkane has a *prefix* (2-methyl-) as well as a root and a suffix. Many of the hydrocarbons you will name from now on have a prefix.
3. This alkane has a single CH_3 unit that branches off from the main (parent) chain of the compound.

CHEM FACT

When is an isomer not an isomer? When it is *exactly* the same compound! The hydrocarbon C_6H_{14} has only five isomers. Examine these two representations for one of them, hexane.

$CH_3-CH_2-CH_2-CH_2-CH_2-CH_3$



You might think that these are different isomers, but they are actually the same. The structure on the bottom is just a bent version of the structure on the top. Think about a length of chain. You can lay it out straight, or you can bend it. The chain is still a chain in either case. It just looks different. Naming a compound helps you recognize the difference between a true isomer and a structure that just looks like an isomer.

CONCEPT CHECK

The root and the suffix of an alkane name do not tell you directly about the number of hydrogen atoms in the compound. If you did not know the molecular formula of heptane, for example, how would you still know that heptane contains 16 hydrogen atoms?

Naming Alkanes

The names of branched-chain alkanes (and most other organic compounds) have the same general format, as shown below. This format will become clearer as you learn and practise the rules for naming hydrocarbons.

prefix + root + suffix

The Root: How Long is the Main Chain?

The root of a compound's name indicates the number of carbon atoms in the main (parent) chain or ring. Table 9.2 on the previous page lists the roots for hydrocarbon chains that are up to ten carbons long.

The Suffix: What Family Does the Compound Belong To?

The suffix indicates the type of organic compound. As you progress through this unit, you will learn the suffixes for different chemical families. You have already learned that the suffix -ane indicates an alkane.

The Prefix: What is Attached to the Main Chain?

The prefix indicates the name and location of each branch or other type of group on the main carbon chain. Many organic compounds have hydrocarbon branches, called alkyl groups, attached to the main chain. An **alkyl group** is obtained by removing one hydrogen atom from an alkane. To name an alkyl group, start with the name of the corresponding alkane, and then change the -ane suffix to -yl. For example, the methyl group, $—CH_3$, is the alkyl group that is derived from methane, CH_4. Table 9.3 gives the names of the most common alkyl groups.

Table 9.3 Common Alkyl Groups

methyl	ethyl	propyl	isopropyl
$—CH_3$	$—CH_2CH_3$	$—CH_2CH_2CH_3$	CH_3 $—CH$ CH_3
butyl	**sec-butyl**	**iso-butyl**	**tert-butyl**
$—CH_2CH_2CH_2CH_3$	CH_3 $—CH$ CH_2CH_3	CH_3 $—CH_2—CH$ CH_3	CH_3 $—C—CH_3$ CH_3

The steps on the next page illustrate the process of naming alkanes. The same steps, with a few variations, also apply for many other organic compounds. Figure 9.15 illustrates these rules.

Rules for Naming Alkanes

Step 1 Find the root: Identify the longest continuous chain or ring in the hydrocarbon. Count the number of carbon atoms in the main chain to obtain the root.

- Remember that the main chain can be bent; it does not have to look like a straight line.
- If more than one chain could be the main chain (because they are the same length), choose the chain that has the most branches attached.

Step 2 Find the suffix: If the compound is an alkane, use the suffix *-ane*. Later in this unit, you will learn the suffixes for other chemical families.

Step 3 Give position numbers: Identify any branches that are present. Then give a consecutive number to every carbon atom in the main chain. Number the main chain starting from the end that gives the lowest number to the first location at which branching occurs. See Figure 9.15, part (b).

Step 4 Find the prefix: Name each branch as an alkyl group. Give each branch a position number. The number indicates which carbon in the main chain the branch is bonded to. See Figure 9.15, part (c).

- If more than one branch is present, write the names of the branches in alphabetical order. Determine the alphabetical order by using the first letter of the prefix (e.g., methyl or ethyl), not the multiplying prefix (e.g., di-, tri-, tetra-, etc.).
- If there are two or more of the same type of branch, use multiplying prefixes such as di- (meaning 2), tri- (meaning 3), and tetra- (meaning 4) to indicate how many of each type of branch are present.
- Use hyphens to separate words from numbers. Use commas to separate numbers.
- When possible, put numbers in ascending order. For example, you would write 2,2,5-trimethylpentane instead of 5,2,2-trimethylpentane.

Step 5 Put the name together: prefix + root + suffix

The following Sample Problem gives two examples of naming alkanes. Complete the Practice Problems that follow to apply what you have learned.

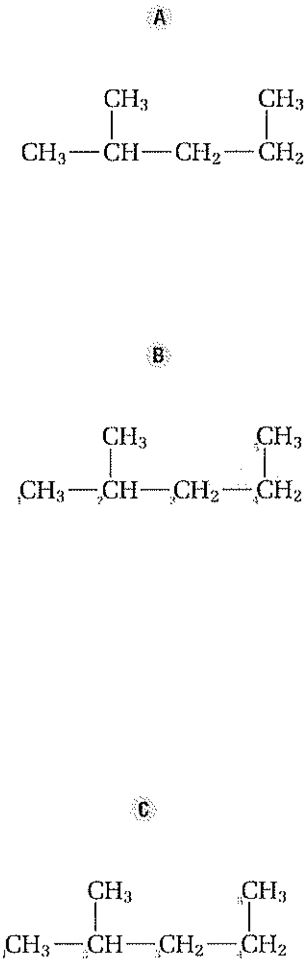
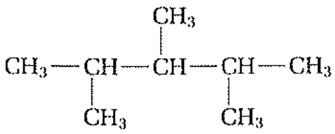


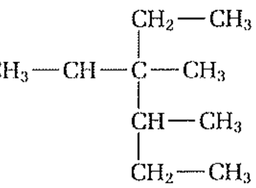
Figure 9.15 (A) There are five carbons in the longest chain, as highlighted. The root of the name is *-pent-*. (B) There is only one branch. Since the branch is closer to the left end of the molecule, number the carbon at the left end "1." Then number the other main chain carbons consecutively. (C) The branch is a methyl group. The branch is bonded to the number 2 carbon in the main chain, so it has the position number 2. The prefix is *2-methyl*. The full name is 2-methylpentane.

Sample Problem
Naming Alkanes

Problem

Name the following alkanes.

(a) 

(b) 

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Solution

(a) Step 1 **Find the root:** The longest chain has 5 carbon atoms, so the root is -pent-.

Step 2 **Find the suffix:** The suffix is -ane.

Step 3 **Give position numbers:** It doesn't matter which end you start numbering at, the result will be the same.

Step 4 **Find the prefix:** Three methyl groups are attached to the main chain at positions 2, 3, and 4. The prefix is 2,3,4-trimethyl-.

Step 5 The full name is 2,3,4-trimethylpentane.

(b) Steps 1 and 2 **Find the root and suffix:** There are 6 carbon atoms in the main chain. (Note that the main chain is bent at two places.) The root is -hex-. The suffix is -ane.

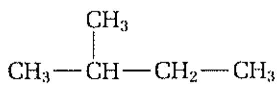
Step 3 **Give position numbers:** Number from the left so there are two branches at position 3 and one branch at position 4.

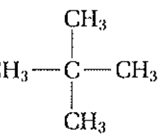
Step 4 **Find the prefix:** There is an ethyl group and a methyl group at position 3, and another methyl group at position 4. The prefix is 3-ethyl-3,4-dimethyl-.

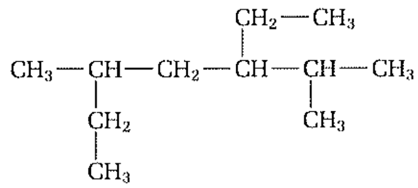
Step 5 The full name is 3-ethyl-3,4-dimethylhexane.

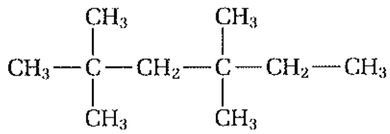
Practice Problems

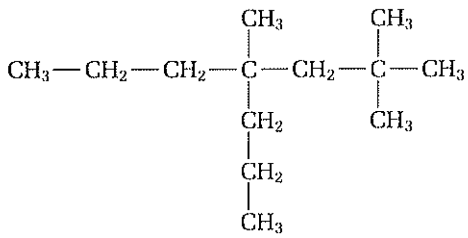
5. Name each compound.

(a) 

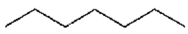
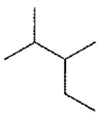
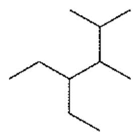
(b) 

(c) 

(d) 

(e) 

6. Identify any errors in the name of each hydrocarbon.
   (a) 2,2,3-dimethylbutane
   (b) 2,4-diethyloctane
   (c) 3-methyl-4,5-diethyl-nonane

7. Name each compound.
   (a) 
   (b) 
   (c) 

Drawing Alkanes

As you learned earlier in this chapter, three kinds of diagrams can be used to represent the structure of a hydrocarbon. The easiest kind is probably the condensed structural diagram. When you are asked to draw a condensed structural diagram for an alkane, such as 2,3-dimethylhexane, you can follow several simple rules. These rules are listed below. After you have studied the rules, use the Practice Problems to practise your alkane-drawing skills.

Rules for Drawing Condensed Structural Diagrams

Step 1 Identify the root and the suffix of the name. In 2,3-dimethylhexane, for example, the root and suffix are -hexane. The -*hex*- tells you that there are six carbons in the main chain. The -*ane* tells you that the compound is an alkane. Therefore this compound has single carbon-carbon bonds only.

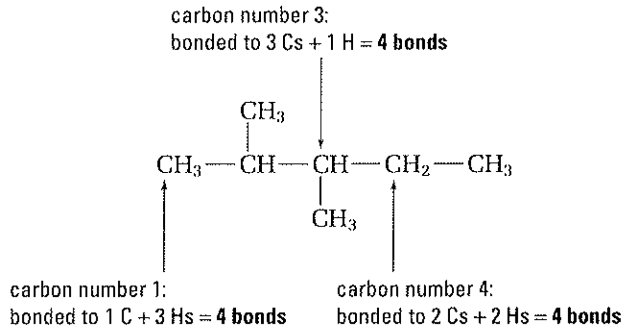
Step 2 Draw the main chain first. Draw it straight, to avoid mistakes caused by a fancy shape. Do not include any hydrogen atoms. You will need to add branches before you finalize the number of hydrogen atoms on each carbon. Leave space beside each carbon on the main chain to write the number of hydrogen atoms later.

C —C —C —C —C —C

Step 3 Choose one end of your carbon chain to be carbon number 1. Then locate the carbon atoms to which the branches must be added. Add the appropriate number and size of branches, according to the prefix in the name of the compound. In this example, *2,3-dimethyl* tells you that there is one methyl (single carbon-containing) branch on the second carbon of the main chain, and another methyl branch on the third carbon of the main chain. It does not matter whether you place both branches above the main chain, both below, or one above and one below. The compound will still be the same.

```
      CH3
      |
C  —C  —C  —C  —C  —C
           |
           CH3
```

Step 4 Finish drawing your diagram by adding the appropriate number of hydrogen atoms beside each carbon. Remember that each carbon has a valence of four. So if a carbon atom has one other carbon atom bonded to it, you need to add three hydrogen atoms. If a carbon atom has two other carbon atoms bonded to it, you need to add two hydrogen atoms, and so on.



Sample Problem

Drawing an Alkane

Problem

Draw a condensed structural diagram for 3-ethyl-2-methylheptane.

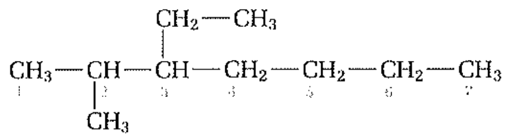
Solution

Step 1 The root and suffix are -heptane. The -hept tells you that there are 7 carbons in the main chain. The -ane tells you that this compound is an alkane, with only single carbon-carbon bonds.

Step 2 Draw 7 carbon atoms in a row, leaving spaces for hydrogen atoms.

Step 3 The ethyl group is attached to carbon 3, and the methyl group to carbon 2.

Step 4 Add hydrogen atoms so each carbon atom forms 4 bonds.



Practice Problems

8. Draw a condensed structural diagram for each hydrocarbon.

(a) propane
(b) 4-ethyl-3-methylheptane
(c) 3-methyloctane

9. Use each *incorrect* name to draw the corresponding hydrocarbon. Examine your drawing, and rename the hydrocarbon correctly.

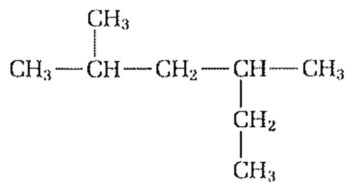
(a) 3-propyl-butane
(b) 1,3-dimethyl-hexane
(c) 4-methylpentane

10. Draw a line structural diagram for each alkane.

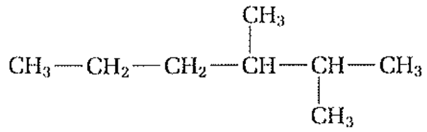
(a) 3-ethyl-3,4-dimethyloctane
(b) 2,3,4-trimethylhexane
(c) 5-ethyl-3,3-dimethylheptane
(d) 6-isobutyl-4-ethyl-5-methyldecane

11. One way to assess how well you have learned a new skill is to identify mistakes. Examine the following compounds and their names. Identify any mistakes, and correct the names.

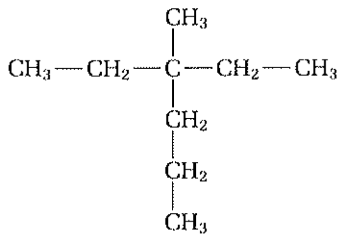
(a) 4-ethyl-2-methylpentane



(b) 4,5-methylhexane



(c) 3-methyl-3-ethylpentane



Physical Properties of Alkanes

Alkanes (and all other aliphatic compounds) have an important physical property. They are non-polar. Therefore, alkanes are soluble in benzene and other non-polar solvents. They are not soluble in water and other polar solvents. The intermolecular forces between non-polar molecules are fairly weak. As a result, hydrocarbons such as alkanes have relatively low boiling points. As the number of atoms in the hydrocarbon molecule increases, the boiling point increases. Because of this, alkanes exist in a range of states under standard conditions.

Table 9.4 compares the sizes (number of carbon atoms per molecule) and boiling points of alkanes. Notice how the state changes as the size increases.

Table 9.4 Comparing the Sizes and Boiling Points of Alkanes

Size (number of carbon atoms per molecule)	Boiling point range (°C)	Examples of products
1 to 5	below 30	gases: used for fuels to cook and heat homes
5 to 16	30 to 275	liquids: used for automotive, diesel, and jet engine fuels; also used as raw materials for the petrochemical industry
16 to 22	over 250	heavy liquids: used for oil furnaces and lubricating oils; also used as raw materials to break down more complex hydrocarbons into smaller molecules
over 18	over 400	semi-solids: used for lubricating greases and paraffin waxes to make candles, waxed paper, and cosmetics
over 26	over 500	solid residues: used for asphalts and tars in the paving and roofing industries

CHEM FACT

You have learned how the non-polar nature of alkanes affects their boiling point. This non-polarity also affects another physical property: the solubility of alkanes in water. For example, the solubility of pentane in water is only 5.0×10^{-3} mol/L at 25°C. Hydrocarbon compounds, such as those found in crude oil, do not dissolve in water. Instead they float on the surface. This physical property helps clean-up crews minimize the devastating effects of an oil spill.

CONCEPT CHECK

Many industries rely on alkane hydrocarbons. The states of these hydrocarbons can affect how they are stored at industrial sites. For example, methane is a gas under standard conditions. In what state would you expect a large quantity of methane to be stored? What safety precautions would be necessary?