Learning Objectives

- Explain the following laws within the Ideal Gas Law:
  - Avogadro's law of gases

Hydrocarbons

Approximately one-third of the compounds produced industrially are organic compounds. All living organisms are composed of organic compounds, as are most foods, medicines, clothing fibers, and plastics. The detection of organic compounds is useful in many fields. In one recently developed application, scientists have devised a new method called “material degradomics” to monitor the degradation of old books and historical documents. As paper ages, it produces a familiar “old book smell” from the release of organic compounds in gaseous form. The composition of the gas depends on the original type of paper used, a book’s binding, and the applied media. By analyzing these organic gases and isolating the individual components, preservationists are better able to determine the condition of an object and those books and documents most in need of immediate protection.

The simplest class of organic compounds is the hydrocarbons, which consist entirely of carbon and hydrogen. Petroleum and natural gas are complex, naturally occurring mixtures of many different hydrocarbons that furnish raw materials for the chemical industry. The four major classes of hydrocarbons are the following: the alkanes, which contain only carbon–hydrogen and carbon–carbon single bonds; the alkenes, which contain at least one carbon–carbon double bond; the alkynes, which contain at least one carbon–carbon triple bond; and the aromatic hydrocarbons, which usually contain rings of six carbon atoms that can be drawn with alternating single and double bonds. Alkanes are also called saturated hydrocarbons, whereas hydrocarbons that contain multiple bonds (alkenes, alkynes, and aromatics) are unsaturated.

Alkanes

The simplest alkane is methane (CH$_4$), a colorless, odorless gas that is the major component of natural gas. In larger alkanes whose carbon atoms are joined in an unbranched chain (straight-chain alkanes), each carbon atom is bonded to at most two other carbon atoms. The structures of two simple alkanes are shown in Figure 3.7.1, and the names and condensed structural formulas for the first 10 straight-chain alkanes are in Table 3.7.1. The names of all alkanes end in -ane, and their boiling points increase as the number of carbon atoms increases.

![Figure 3.7.1: Straight-Chain Alkanes with Two and Three Carbon Atoms](image)
### Table 3.7.1: The First 10 Straight-Chain Alkanes

<table>
<thead>
<tr>
<th>Name</th>
<th>Number of Carbon Atoms</th>
<th>Molecular Formula</th>
<th>Condensed Structural Formula</th>
<th>Boiling Point (°C)</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>methane</td>
<td>1</td>
<td>CH₄</td>
<td>CH₄</td>
<td>−162</td>
<td>natural gas constituent</td>
</tr>
<tr>
<td>ethane</td>
<td>2</td>
<td>C₂H₆</td>
<td>CH₃CH₃</td>
<td>−89</td>
<td>natural gas constituent</td>
</tr>
<tr>
<td>propane</td>
<td>3</td>
<td>C₃H₈</td>
<td>CH₃CH₂CH₃</td>
<td>−42</td>
<td>bottled gas</td>
</tr>
<tr>
<td>butane</td>
<td>4</td>
<td>C₄H₁₀</td>
<td>CH₃CH₂CH₂CH₃ or CH₃(CH₂)₂CH₃</td>
<td>0</td>
<td>lighters, bottled gas</td>
</tr>
<tr>
<td>pentane</td>
<td>5</td>
<td>C₅H₁₂</td>
<td>CH₃(CH₂)₃CH₃</td>
<td>36</td>
<td>solvent, gasoline</td>
</tr>
<tr>
<td>hexane</td>
<td>6</td>
<td>C₆H₁₄</td>
<td>CH₃(CH₂)₄CH₃</td>
<td>69</td>
<td>solvent, gasoline</td>
</tr>
<tr>
<td>heptane</td>
<td>7</td>
<td>C₇H₁₆</td>
<td>CH₃(CH₂)₅CH₃</td>
<td>98</td>
<td>solvent, gasoline</td>
</tr>
<tr>
<td>octane</td>
<td>8</td>
<td>C₈H₁₈</td>
<td>CH₃(CH₂)₆CH₃</td>
<td>126</td>
<td>gasoline</td>
</tr>
<tr>
<td>nonane</td>
<td>9</td>
<td>C₉H₂₀</td>
<td>CH₃(CH₂)₇CH₃</td>
<td>151</td>
<td>gasoline</td>
</tr>
<tr>
<td>decane</td>
<td>10</td>
<td>C₁₀H₂₂</td>
<td>CH₃(CH₂)₈CH₃</td>
<td>174</td>
<td>kerosene</td>
</tr>
</tbody>
</table>

Alkanes with four or more carbon atoms can have more than one arrangement of atoms. The carbon atoms can form a single unbranched chain, or the primary chain of carbon atoms can have one or more shorter chains that form branches. For example, butane (C₄H₁₀) has two possible structures. *Normal* butane (usually called *n*-butane) is CH₃CH₂CH₂CH₃, in which the carbon atoms form a single unbranched chain. In contrast, the condensed structural formula for *isobutane* is (CH₃)₂CHCH₃, in which the primary chain of three carbon atoms has a one-carbon chain branching at the central carbon. Three-dimensional representations of both structures are as follows:
The systematic names for branched hydrocarbons use the lowest possible number to indicate the position of the branch along the longest straight carbon chain in the structure. Thus the systematic name for isobutane is 2-methylpropane, which indicates that a methyl group (a branch consisting of −CH₃) is attached to the second carbon of a propane molecule. Similarly, Section 2.6 "Industrially Important Chemicals" states that one of the major components of gasoline is commonly called isoctane; its structure is as follows:

The compound has a chain of five carbon atoms, so it is a derivative of pentane. There are two methyl group branches at one carbon atom and one methyl group at another. Using the lowest possible numbers for the branches gives 2,2,4-trimethylpentane for the systematic name of this compound.
Alkenes

The simplest alkenes are ethylene, \( \text{C}_2\text{H}_4 \) or \( \text{CH}_2=\text{CH}_2 \), and propylene, \( \text{C}_3\text{H}_6 \) or \( \text{CH}_3\text{CH}=\text{CH}_2 \) (part (a) in Figure 3.7.2). The names of alkenes that have more than three carbon atoms use the same stems as the names of the alkanes (Table 3.7.1 “The First 10 Straight-Chain Alkanes”) but end in \(-\text{ene}\) instead of \(-\text{ane}\).

As with alkanes, more than one structure is possible for alkenes with four or more carbon atoms. For example, an alkene with four carbon atoms has three possible structures. One is \( \text{CH}_2=\text{CHCH}_2\text{CH}_3 \) (1-butene), which has the double bond between the first and second carbon atoms in the chain. The other two structures have the double bond between the second and third carbon atoms and are forms of \( \text{CH}_2\text{CH}=\text{CHCH}_3 \) (2-butene). All four carbon atoms in 2-butene lie in the same plane, so there are two possible structures (part (a) in Figure 3.7.2). If the two methyl groups are on the same side of the double bond, the compound is cis-2-butene (from the Latin \textit{cis}, meaning “on the same side”). If the two methyl groups are on opposite sides of the double bond, the compound is trans-2-butene (from the Latin \textit{trans}, meaning “across”). These are distinctly different molecules: cis-2-butene melts at \(-138.9^\circ\text{C}\), whereas trans-2-butene melts at \(-105.5^\circ\text{C}\).

Figure 3.7.2: Some Simple (a) Alkenes, (b) Alkynes, and (c) Cyclic Hydrocarbons. The positions of the carbon atoms in the chain are indicated by \( \text{C}_1 \) or \( \text{C}_2 \).

Just as a number indicates the positions of branches in an alkane, the number in the name of an alkene specifies the position of the first carbon atom of the double bond. The name is based on the lowest possible number starting from \textit{either end} of the carbon chain, so \( \text{CH}_3\text{CH}_2\text{CH}=\text{CH}_2 \) is called 1-butene, \textit{not} 3-butene. Note that \( \text{CH}_2=\text{CHCH}_2\text{CH}_3 \) and \( \text{CH}_3\text{CH}_2\text{CH}=\text{CH}_2 \) are different ways of writing the \textit{same molecule} (1-butene) in two different orientations.
The name of a compound does **not** depend on its orientation. As illustrated for 1-butene, both condensed structural formulas and molecular models show different orientations of the same molecule. It is important to be able to recognize the same structure no matter what its orientation.

Note

The positions of groups or multiple bonds are always indicated by the lowest number possible.

### Alkynes

The simplest alkyne is **acetylene**, C₂H₂ or HC≡CH (part (b) in [Figure 3.7.2](#)). Because a mixture of acetylene and oxygen burns with a flame that is hot enough (>3000°C) to cut metals such as hardened steel, acetylene is widely used in cutting and welding torches. The names of other alkynes are similar to those of the corresponding alkanes but end in -yne. For example, HC≡CCH₃ is **propyne**, and CH₃C≡CCH₃ is **2-butyne** because the multiple bond begins on the second carbon atom.

Note

The number of bonds between carbon atoms in a hydrocarbon is indicated in the suffix:

- **alkane**: only carbon–carbon single bonds
- **alkene**: at least one carbon–carbon double bond
- **alkyne**: at least one carbon–carbon triple bond
Cyclic Hydrocarbons

In a cyclic hydrocarbon, the ends of a hydrocarbon chain are connected to form a ring of covalently bonded carbon atoms. Cyclic hydrocarbons are named by attaching the prefix cyclo- to the name of the alkane, the alkene, or the alkyne. The simplest cyclic alkanes are cyclopropane (C₃H₆) a flammable gas that is also a powerful anesthetic, and cyclobutane (C₄H₈) (part (c) in Figure 3.7.2). The most common way to draw the structures of cyclic alkanes is to sketch a polygon with the same number of vertices as there are carbon atoms in the ring; each vertex represents a CH₂ unit. The structures of the cycloalkanes that contain three to six carbon atoms are shown schematically in Figure 3.7.3.

<table>
<thead>
<tr>
<th>Name</th>
<th>Molecular Formula</th>
<th>Structural Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>cyclopropane</td>
<td>C₃H₆</td>
<td><img src="structure.png" alt="Structure" /></td>
</tr>
<tr>
<td>cyclobutane</td>
<td>C₄H₈</td>
<td><img src="structure.png" alt="Structure" /></td>
</tr>
<tr>
<td>cyclopentane</td>
<td>C₅H₁₀</td>
<td><img src="structure.png" alt="Structure" /></td>
</tr>
<tr>
<td>cyclohexane</td>
<td>C₆H₁₂</td>
<td><img src="structure.png" alt="Structure" /></td>
</tr>
</tbody>
</table>

Figure 3.7.3: The Simple Cycloalkanes

Aromatic Hydrocarbons

Alkanes, alkenes, alkynes, and cyclic hydrocarbons are generally called aliphatic hydrocarbons. The name comes from the Greek aleiphar, meaning “oil,” because the first examples were extracted from animal fats. In contrast, the first examples of aromatic hydrocarbons, also called arenes, were obtained by the distillation and degradation of highly scented (thus aromatic) resins from tropical trees.

The simplest aromatic hydrocarbon is benzene (C₆H₆), which was first obtained from a coal distillate. The word aromatic now refers to benzene and structurally similar compounds. As shown in part (a) in Figure 3.7.4, it is possible to draw the structure of benzene in two different but equivalent ways, depending on which carbon atoms are connected by double bonds or single bonds. Toluene is similar to benzene, except that one hydrogen atom is replaced by a –CH₃ group; it has the formula C₇H₈ (part (b) in Figure 3.7.4). The chemical behavior of aromatic compounds differs from the behavior of aliphatic compounds. Benzene and toluene are found in gasoline, and benzene is the starting material for preparing substances as diverse as aspirin and nylon.
**Figure 3.7.4: Two Aromatic Hydrocarbons: (a) Benzene and (b) Toluene**

Figure 3.7.5 illustrates two of the molecular structures possible for hydrocarbons that have six carbon atoms. As shown, compounds with the same molecular formula can have very different structures.

**Figure 3.7.5: Two Hydrocarbons with the Molecular Formula C₆H₁₂**

Example 3.7.1

Write the condensed structural formula for each hydrocarbon.

a. n-heptane
b. 2-pentene
c. 2-butyne
d. cyclooctene

**Given:** name of hydrocarbon
**Asked for:** condensed structural formula

**Strategy:**

A. Use the prefix to determine the number of carbon atoms in the molecule and whether it is cyclic. From the suffix, determine whether multiple bonds are present.

B. Identify the position of any multiple bonds from the number(s) in the name and then write the condensed structural formula.

**Solution:**

a. A The prefix hept- tells us that this hydrocarbon has seven carbon atoms, and n- indicates that the carbon atoms form a straight chain. The suffix -ane tells that it is an alkane, with no carbon–carbon double or triple bonds. B The condensed structural formula is \( \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 \), which can also be written as \( \text{CH}_3(\text{CH}_2)_5\text{CH}_3 \).

b. A The prefix pent- tells us that this hydrocarbon has five carbon atoms, and the suffix -ene indicates that it is an alkene, with a carbon–carbon double bond. B The 2- tells us that the double bond begins on the second carbon of the five-carbon atom chain. The condensed structural formula of the compound is therefore \( \text{CH}_3\text{CH}=\text{CHCH}_2\text{CH}_3 \).

c. A The prefix but- tells us that the compound has a chain of four carbon atoms, and the suffix -yne indicates that it has a carbon–carbon triple bond. B The 2- tells us that the triple bond begins on the second carbon of the four-carbon atom chain. So the condensed structural formula for the compound is \( \text{CH}_3\text{C}≡\text{CCH}_3 \).
d. The prefix cyclo- tells us that this hydrocarbon has a ring structure, and oct- indicates that it contains eight carbon atoms, which we can draw as

The suffix -ene tells us that the compound contains a carbon–carbon double bond, but where in the ring do we place the double bond? Because all eight carbon atoms are identical, it doesn’t matter. We can draw the structure of cyclooctene as

Exercise 3.7.1

Write the condensed structural formula for each hydrocarbon.

a. n-octane
b. 2-hexene
c. 1-heptyne
d. cyclopentane

Answer:

a. CH₃(CH₂)₆CH₃
b. CH₃CH=CHCH₂CH₂CH₃
c. HC≡C(CH₂)₄CH₃
The general name for a group of atoms derived from an alkane is an **alkyl group**. The name of an alkyl group is derived from the name of the alkane by adding the suffix -yl. Thus the –CH₃ fragment is a *methyl* group, the –CH₂CH₃ fragment is an *ethyl* group, and so forth, where the dash represents a single bond to some other atom or group. Similarly, groups of atoms derived from aromatic hydrocarbons are *aryl groups*, which sometimes have unexpected names. For example, the –C₆H₅ fragment is derived from benzene, but it is called a *phenyl* group. In general formulas and structures, alkyl and aryl groups are often abbreviated as R.

**Structures of alkyl and aryl groups.** The methyl group is an example of an alkyl group, and the phenyl group is an example of an aryl group.

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**Alcohols**

Replacing one or more hydrogen atoms of a hydrocarbon with an –OH group gives an alcohol, represented as ROH. The simplest alcohol (CH₃OH) is called either *methanol* (its systematic name) or *methyl alcohol* (its common name). Methanol is the antifreeze in automobile windshield washer fluids, and it is also used as an efficient fuel for racing cars, most notably in the Indianapolis 500. Ethanol (or ethyl alcohol, CH₃CH₂OH) is familiar as the alcohol in fermented or distilled beverages, such as beer, wine, and whiskey; it is also used as a gasoline additive (Section 2.6 "Industrially Important Chemicals"). The simplest alcohol derived from an aromatic hydrocarbon is C₆H₅OH, *phenol* (shortened from phenyl alcohol), a potent disinfectant used in some sore throat medications and mouthwashes.
Ethanol, which is easy to obtain from fermentation processes, has successfully been used as an alternative fuel for several decades. Although it is a “green” fuel when derived from plants, it is an imperfect substitute for fossil fuels because it is less efficient than gasoline. Moreover, because ethanol absorbs water from the atmosphere, it can corrode an engine’s seals. Thus other types of processes are being developed that use bacteria to create more complex alcohols, such as octanol, that are more energy efficient and that have a lower tendency to absorb water. As scientists attempt to reduce mankind’s dependence on fossil fuels, the development of these so-called biofuels is a particularly active area of research.

**Summary**

The simplest organic compounds are the **hydrocarbons**, which contain *only* carbon and hydrogen. **Alkanes** contain only carbon–hydrogen and carbon–carbon single bonds, **alkenes** contain at least one carbon–carbon double bond, and **alkynes** contain one or more carbon–carbon triple bonds. Hydrocarbons can also be **cyclic**, with the ends of the chain connected to form a ring. Collectively, alkanes, alkenes, and alkynes are called **aliphatic hydrocarbons**. **Aromatic hydrocarbons**, or **arenes**, are another important class of hydrocarbons that contain rings of carbon atoms related to the structure of benzene (C\(_6\)H\(_6\)). A derivative of an alkane or an arene from which one hydrogen atom has been removed is called an **alkyl group** or an **aryl group**, respectively. **Alcohols** are another common class of organic compound, which contain an –OH group covalently bonded to either an alkyl group or an aryl group (often abbreviated R).