Chapter 4

Carbon and the Molecular Diversity of Life
What makes carbon the basis for all biological molecules?

Carbon can form four bonds. Carbon can bond to other carbons, resulting in carbon skeletons. Carbon also commonly bonds to hydrogen, oxygen, and nitrogen.

Properties of a carbon-containing molecule depend on its carbon skeleton and chemical groups.

Carbon skeleton

Chemical groups

Dopamine, the molecule shown here, promotes mother-infant bonding.
CONCEPT 4.1: Organic chemistry is key to the origin of life

- **Organic chemistry** is the study of compounds that contain carbon, regardless of origin.

- Organic compounds range from simple molecules to colossal ones.
Organic Molecules and the Origin of Life on Earth

- Stanley Miller’s classic experiment demonstrated the abiotic synthesis of organic compounds.
- Experiments support the idea that abiotic synthesis of organic compounds, perhaps near volcanoes, could have been a stage in the origin of life.
• The overall percentages of the major elements of life—C, H, O, N, S, and P—are quite uniform from one organism to another.

• Because carbon can form four bonds, these building blocks can be used to make an inexhaustible variety of organic molecules.

• The great diversity of organisms on the planet is due to the versatility of carbon.
CONCEPT 4.2: Carbon atoms can form diverse molecules by bonding to four other atoms

- Electron configuration is the key to an atom’s chemical characteristics

- Electron configuration determines the kinds and number of bonds an atom will form with other atoms
The Formation of Bonds with Carbon

• With four valence electrons, carbon can form four covalent bonds with a variety of atoms

• This enables carbon to form large, complex molecules

• In molecules with multiple carbons, each carbon bonded to four other atoms has a tetrahedral shape

• However, when two carbon atoms are joined by a double bond, the atoms joined to the carbons are in the same plane as the carbons
<table>
<thead>
<tr>
<th>Molecule and Molecular Shape</th>
<th>Molecular Formula</th>
<th>Structural Formula</th>
<th>Ball-and-Stick Model (molecular shape in pink)</th>
<th>Space-Filling Model</th>
</tr>
</thead>
</table>
| (a) Methane                  | CH₄               | \[
\begin{align*}
\text{H} & \quad \text{H} \\
\text{C} & \quad \text{H} \\
\text{H} & 
\end{align*}
\] | ![Ball-and-Stick Model](image1) | ![Space-Filling Model](image2) |
| (b) Ethane                   | C₂H₆             | \[
\begin{align*}
\text{H} & \quad \text{H} \\
\text{H} & \quad \text{H} \\
\text{C} & \quad \text{C} \\
\text{H} & \quad \text{H} \\
\text{H} & 
\end{align*}
\] | ![Ball-and-Stick Model](image3) | ![Space-Filling Model](image4) |
| (c) Ethene (ethylene)        | C₂H₄             | \[
\begin{align*}
\text{H} & \quad \text{C} & \quad \text{H} \\
\text{H} & \quad \text{H} & \quad \text{H} \\
\text{C} & \quad \text{C} & \quad \text{H} \\
\text{H} & \quad \text{H} & 
\end{align*}
\] | ![Ball-and-Stick Model](image5) | ![Space-Filling Model](image6) |
Valence and Covalent Bonds

- The number of unpaired electrons in the valence shell of an atom is generally equal to its **valence**, the number of covalent bonds it can form.

- The electron configuration of carbon gives it covalent compatibility with many different elements.

- The most frequent bonding partners of carbon are hydrogen, oxygen, and nitrogen.

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Oxygen</th>
<th>Nitrogen</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewis dot structure</td>
<td>H⁻</td>
<td>O⁻</td>
<td>N⁻</td>
<td>C⁻</td>
</tr>
<tr>
<td>showing existing</td>
<td></td>
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<tr>
<td>valence electrons</td>
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<tr>
<td>Electron distribution</td>
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<tr>
<td>diagram with red</td>
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<td>circles showing</td>
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<tr>
<td>electrons needed to</td>
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<td>fill the valence</td>
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<tr>
<td>shell</td>
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<td></td>
</tr>
<tr>
<td>Number of electrons</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>needed to fill the</td>
<td></td>
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<tr>
<td>valence shell</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valence: Number of</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>bonds the element</td>
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<tr>
<td>can form</td>
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</tr>
</tbody>
</table>
Molecular Diversity Arising from Variation in Carbon Skeletons

- Carbon atoms can partner with atoms other than hydrogen, such as the following:
  - Carbon dioxide: \( \text{CO}_2 \)
    \[
    \text{O} = \text{C} = \text{O}
    \]
  - Urea: \( \text{CO(NH}_2)_2 \)
Molecular Diversity Arising from Variation in Carbon Skeletons

– Carbon atoms can also be linked into chains as shown for $C_3H_8$
Molecular Diversity Arising from Variation in Carbon Skeletons

- Carbon chains form the skeletons of most organic molecules
- Carbon chains vary in length and shape

![Carbon skeletons diagram](image)

**Figure 4.5**

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Hydrocarbons

- **Hydrocarbons** are organic molecules consisting of only carbon and hydrogen.

- Many organic molecules, such as fats, have hydrocarbon components.

- Hydrocarbons can undergo reactions that release a large amount of energy.
Figure 4.6

(a) Part of a human adipose cell

(b) A fat molecule

Nucleus
Fat droplets

10 μm
Isomers

- **Isomers** are compounds with the same molecular formula but different structures and properties

  - **Structural isomers** have different covalent arrangements of their atoms

  - **Cis-trans isomers** (also called geometric isomers) have the same covalent bonds but differ in their spatial arrangements

  - **Enantiomers** are isomers that are mirror images of each other
Figure 4.7

(a) Structural isomers

Pentane

2-Methylbutane

(c) Enantiomers

L isomer

D isomer

(b) Cis-trans isomers (also known as geometric isomers)

\[ \text{cis isomer: The two } Xs \text{ are on the same side.} \]

\[ \text{trans isomer: The two } Xs \text{ are on opposite sides.} \]
**Enantiomers**

1. Enantiomers are important in the pharmaceutical industry
2. Two enantiomers of a drug may have different effects
3. Often only one enantiomer is biologically active
4. Differing effects of enantiomers demonstrate that organisms are sensitive to even subtle variations in molecules

<table>
<thead>
<tr>
<th>Drug</th>
<th>Effects</th>
<th>Effective Enantiomer</th>
<th>Ineffective Enantiomer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ibuprofen</td>
<td>Reduces inflammation and pain</td>
<td>S-Ibuprofen</td>
<td>R-Ibuprofen</td>
</tr>
<tr>
<td>Albuterol</td>
<td>Relaxes bronchial (airway) muscles, improving airflow in asthma patients</td>
<td>R-Albuterol</td>
<td>S-Albuterol</td>
</tr>
</tbody>
</table>
CONCEPT 4.3: A few chemical groups are key to molecular function

• Distinctive properties of organic molecules depend on the carbon skeleton and the chemical groups attached to it

• These groups help give each molecule its unique properties
The Chemical Groups Most Important in the Processes of Life

- Estradiol and testosterone are both steroids with a common carbon skeleton, in the form of four fused rings.
- These sex hormones differ only in the chemical groups attached to the rings of the carbon skeleton.
**Functional Groups**

- *Functional groups* are the components of organic molecules that are most commonly involved in chemical reactions.

- The number and arrangement of functional groups give each molecule its unique properties.
Functional Groups

- The seven functional groups that are most important in the chemistry of life are the following:
  - Hydroxyl group
  - Carbonyl group
  - Carboxyl group
  - Amino group
  - Sulfhydryl group
  - Phosphate group
  - Methyl group
ATP: An Important Source of Energy for Cellular Processes

- An important organic phosphate is **adenosine triphosphate (ATP)**
- ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups
- ATP stores the potential to react with water
- This reaction releases energy that can be used by the cell
The Chemical Elements of Life: A Review

• The versatility of carbon makes possible the great diversity of organic molecules
• Variation at the molecular level lies at the foundation of all biological diversity on our planet
<table>
<thead>
<tr>
<th>Product Compound</th>
<th>Molecular Formula</th>
<th>Molar Ratio (Relative to Glycine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycine</td>
<td>C$_2$H$_5$NO$_2$</td>
<td>1.0</td>
</tr>
<tr>
<td>Serine</td>
<td>C$_3$H$_7$NO$_3$</td>
<td>3.0 × 10^{-2}</td>
</tr>
<tr>
<td>Methionine</td>
<td>C$<em>5$H$</em>{11}$NO$_2$S</td>
<td>1.8 × 10^{-3}</td>
</tr>
<tr>
<td>Alanine</td>
<td>C$_3$H$_7$NO$_2$</td>
<td>1.1</td>
</tr>
</tbody>
</table>

March 24, 1958  Run #22

CH₄  25.8
CO₂  8.7
H₂S  10.0

NH₃  2.5° (3.5 ml of 10% NH₃)

300 ml H₂ S

Started spark at 5:30 P.M. Monday, March 24, 1958.

After 6-7 minutes there was yellowing of the coal but no flame.
Figure 4.UN09
Figure 4.UN10

Structure of a molecule with labeled atoms A, B, C, and D.
Figure 4.UN11

L-dopa

D-dopa