Chapter 4

Carbon and the Molecular Diversity of Life

Lectures by
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Overview: Carbon: The Backbone of Life

- Living organisms consist mostly of carbon-based compounds.
- Carbon is unparalleled in its ability to form large, complex, and diverse molecules.
- Proteins, DNA, carbohydrates, and other molecules that distinguish living matter are all composed of carbon compounds.
Concept 4.1: Organic chemistry is the study of carbon compounds

- **Organic chemistry** is the study of compounds that contain carbon
- Organic compounds range from simple molecules to colossal ones
- Most organic compounds contain hydrogen atoms in addition to carbon atoms
Concept 4.2: Carbon atoms can form diverse molecules by bonding to four other atoms

- Electron configuration is the key to an atom’s 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 ability makes large, complex molecules possible
• 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

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<table>
<thead>
<tr>
<th>Name and Comment</th>
<th>Molecular Formula</th>
<th>Structural Formula</th>
<th>Ball-and-Stick Model</th>
<th>Space-Filling Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Methane</td>
<td>CH$_4$</td>
<td>H(\text{H--C--H})</td>
<td><img src="#" alt="Ball-and-Stick Model" /></td>
<td><img src="#" alt="Space-Filling Model" /></td>
</tr>
<tr>
<td>(b) Ethane</td>
<td>C$_2$H$_6$</td>
<td>H(\text{H--C--C--H})</td>
<td><img src="#" alt="Ball-and-Stick Model" /></td>
<td><img src="#" alt="Space-Filling Model" /></td>
</tr>
<tr>
<td>(c) Ethene (ethene)</td>
<td>C$_2$H$_4$</td>
<td>H(\text{C=C--H})</td>
<td><img src="#" alt="Ball-and-Stick Model" /></td>
<td><img src="#" alt="Space-Filling Model" /></td>
</tr>
</tbody>
</table>
• The electron configuration of carbon gives it covalent compatibility with many different elements
• The valences of carbon and its most frequent partners (hydrogen, oxygen, and nitrogen) are the “building code” that governs the architecture of living molecules
Figure 4.4

Hydrogen (valence = 1)

Oxygen (valence = 2)

Nitrogen (valence = 3)

Carbon (valence = 4)
• Carbon atoms can partner with atoms other than hydrogen; for example:
  – Carbon dioxide: \( \text{CO}_2 \)
    \[
    \text{O} &= \text{C} &= \text{O}
    \]
  – Urea: \( \text{CO(NH}_2\text{)}_2 \)
Figure 4.UN01

Urea

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Molecular Diversity Arising from Carbon Skeleton Variation

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

Animation: Carbon Skeletons
Figure 4.5

(a) Length
- Ethane
- Propane

(b) Branching
- Butane
- 2-Methylpropane (isobutane)

(c) Double bond position
- 1-Butene
- 2-Butene

(d) Presence of rings
- Cyclohexane
- Benzene

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(a) Length

Ethane

Propane
(b) Branching

Butane

2-Methylpropane (commonly called isobutane)
(c) Double bond position

1-Butene

2-Butene

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(d) Presence of rings

Cyclohexane

Benzene
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

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Figure 4.6a

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** have the same covalent bonds but differ in spatial arrangements
  - **Enantiomers** are isomers that are mirror images of each other
(a) Structural isomers

(b) Cis-trans isomers

(c) Enantiomers
(a) Structural isomers
(b) *Cis-trans* isomers

**cis** isomer: The two Xs are on the same side.

**trans** isomer: The two Xs are on opposite sides.
(c) Enantiomers

L isomer

\[
\text{CH}_3 \quad \text{NH}_2 \quad \text{H} \quad \text{CO}_2\text{H}
\]

D isomer

\[
\text{CH}_3 \quad \text{NH}_2 \quad \text{H} \quad \text{CO}_2\text{H}
\]
Enantiomers are important in the pharmaceutical industry. Two enantiomers of a drug may have different effects. Usually only one isomer is biologically active. Differing effects of enantiomers demonstrate that organisms are sensitive to even subtle variations in molecules.
The Chemical Groups Most Important in the Processes of Life

• **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
• The seven functional groups that are most important in the chemistry of life:
  – Hydroxyl group
  – Carbonyl group
  – Carboxyl group
  – Amino group
  – Sulfhydryl group
  – Phosphate group
  – Methyl group
<table>
<thead>
<tr>
<th>CHEMICAL GROUP</th>
<th>Hydroxyl</th>
<th>Carbonyl</th>
<th>Carboxyl</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURE</td>
<td>(may be written HO—)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAME OF COMPOUND</td>
<td>Alcohols (Their specific names usually end in -ol.)</td>
<td>Ketones if the carbonyl group is within a carbon skeleton</td>
<td>Carboxylic acids, or organic acids</td>
</tr>
<tr>
<td>EXAMPLE</td>
<td>Ethanol</td>
<td>Acetone</td>
<td>Acetic acid</td>
</tr>
</tbody>
</table>
| FUNCTIONAL PROPERTIES | • Is polar as a result of the electrons spending more time near the electronegative oxygen atom. • Can form hydrogen bonds with water molecules, helping dissolve organic compounds such as sugars. | • A ketone and an aldehyde may be structural isomers with different properties, as is the case for acetone and propanal. • Ketone and aldehyde groups are also found in sugars, giving rise to two major groups of sugars: ketoses (containing ketone groups) and aldoses (containing aldehyde groups). | • Acts as an acid; can donate an $H^+$ because the covalent bond between oxygen and hydrogen is so polar: \[
\text{Nonionized} \quad \text{Carboxyl} \quad \text{Ionized} \\
\begin{align*}
\text{OH} & \Rightarrow \quad \text{O}^- + H^+ \\
\end{align*}
\] • Found in cells in the ionized form with a charge of 1- and called a carboxylate ion. |
Amino

- Acts as a base; can pick up an H⁺ from the surrounding solution (water, in living organisms):

\[ H^+ + \ce{NH} \rightarrow \ce{NH}\_3^+ \]

- Found in cells in the ionized form with a charge of 1⁺.

Sulfhydryl

- Two sulfhydryl groups can react, forming a covalent bond. This “cross-linking” helps stabilize protein structure.

- Cross-linking of cysteines in hair proteins maintains the curliness or straightness of hair. Straight hair can be “permanently” curled by shaping it around curlers and then breaking and re-forming the cross-linking bonds.

Phosphate

- Contributes negative charge to the molecule of which it is a part (2⁻ when at the end of a molecule, as above; 1⁻ when located internally in a chain of phosphates).

- Molecules containing phosphate groups have the potential to react with water, releasing energy.

Methyl

- Addition of a methyl group to DNA, or to molecules bound to DNA, affects the expression of genes.

- Arrangement of methyl groups in male and female sex hormones affects their shape and function.

Amines

- Glycine

Thiols

- Cysteine

Organic phosphates

- Glycerol phosphate

Methylated compounds

- 5-Methyl cytidine
Alcohols (Their specific names usually end in -ol.)

Ethanol

- Is polar as a result of the electrons spending more time near the electronegative oxygen atom.
- Can form hydrogen bonds with water molecules, helping dissolve organic compounds such as sugars.
**Carbonyl**

**STRUCTURE**

Ketones if the carbonyl group is within a carbon skeleton

Aldehydes if the carbonyl group is at the end of the carbon skeleton

**EXAMPLE**

- **Acetone**
  - A ketone and an aldehyde may be structural isomers with different properties, as is the case for acetone and propanal.

- **Propanal**
  - Ketone and aldehyde groups are also found in sugars, giving rise to two major groups of sugars: ketoses (containing ketone groups) and aldoses (containing aldehyde groups).
Carboxylic acids, or organic acids

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<th>FUNCTIONAL PROPERTIES</th>
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</table>
| Acetic acid      | • Acts as an acid; can donate an H⁺ because the covalent bond between oxygen and hydrogen is so polar:  
                                 \[ -\overset{\text{C-\text{O}}}{}\text{OH} \overset{\text{H⁺}}{\rightleftharpoons} -\overset{\text{C-\text{O}}}{}\text{O⁻} \]  
                                 Nonionized ↔ Ionized  
                                 • Found in cells in the ionized form with a charge of 1⁻ and called a carboxylate ion. |
Amino

**STRUCTURE**

![Structure of Glycine](image)

**EXAMPLE**

Glycine

**FUNCTIONAL PROPERTIES**

- Acts as a base; can pick up an H\(^+\) from the surrounding solution (water, in living organisms):

\[
H^+ + \text{Glycine} \rightleftharpoons \text{Glycine}^+ + H\]

- Found in cells in the ionized form with a charge of 1+. 
Sulfhydryl (may be written HS—)

**EXAMPLE**

- Two sulfhydryl groups can react, forming a covalent bond. This “cross-linking” helps stabilize protein structure.

  - Cross-linking of cysteines in hair proteins maintains the curliness or straightness of hair. Straight hair can be “permanently” curled by shaping it around curlers and then breaking and re-forming the cross-linking bonds.
Figure 4.9f

**Phosphate**

**STRUCTURE**

- Organic phosphates

**EXAMPLE**

- Glycerol phosphate

**NAME OF COMPOUND**

**FUNCTIONAL PROPERTIES**

- Contributes negative charge to the molecule of which it is a part (2– when at the end of a molecule, as at left; 1– when located internally in a chain of phosphates).

- Molecules containing phosphate groups have the potential to react with water, releasing energy.
Methylated compounds

- Addition of a methyl group to DNA, or to molecules bound to DNA, affects the expression of genes.
- Arrangement of methyl groups in male and female sex hormones affects their shape and function.

**Methylated compounds**

**NAME OF COMPOUND**

**FUNCTIONAL PROPERTIES**

**EXAMPLE**

5-Methyl cytidine

**STRUCTURE**

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ATP: An Important Source of Energy for Cellular Processes

- One phosphate molecule, adenosine triphosphate (ATP), is the primary energy-transferring molecule in the cell
- ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups
Figure 4. UN05

Adenosine

Reacts with $\text{H}_2\text{O}$

$\text{P}_i$ + ADP + Energy

ATP

Inorganic phosphate

ADP

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