Chapter 4
Carbon and the Molecular Diversity of Life

Key Concepts

4.1 Organic chemistry is the study of carbon compounds
4.2 Carbon atoms can form diverse molecules by bonding to four other atoms
4.3 Functional groups are the parts of molecules involved in chemical reactions

Framework

![Framework Diagram]

4.2 Carbon atoms can form diverse molecules by bonding to four other atoms

Formation of Bonds with Carbon
Carbon has six electrons. To complete its valence shell, carbon forms four covalent bonds with other atoms. This tetrahedral structure is at the center of carbon’s ability to form large and complex molecules with characteristic three-dimensional shapes and properties. When carbon forms four single covalent bonds, its hybrid orbitals create a tetrahedral shape. When two carbons are joined by a double bond, the other carbon bonds are in the same plane, forming a flat molecule.

Molecular Diversity Arising from Carbon Skeleton Variation
Carbon atoms readily bond with each other, producing chains or rings of carbon atoms. These molecular backbones can vary in length, branching, placement of double bonds, and location of atoms of other elements. The simplest organic molecules are hydrocarbons, consisting of only carbon and hydrogen. The nonpolar C—H bonds in hydrocarbon chains account for their hydrophobic properties.

Isomers are compounds with the same molecular formula but different structural arrangements and, thus, different properties. Structural isomers differ in the covalent arrangement of atoms and often in the location of double bonds. Geometric isomers have the same sequence of covalently bonded atoms but differ in spatial arrangement due to the inflexibility of double bonds. A cis isomer has non-hydrogen atoms attached to double-bonded carbons on the same side of the double bond; a trans isomer has these atoms on opposite sides of the double bond. Enantiomers are left- and right-handed versions of each other and can
differ greatly in their biological activity. An asymmetric carbon is one that is covalently bonded to four different kinds of atoms or groups of atoms. Due to the tetrahedral shape of the asymmetric carbon, the four groups can be attached in spatial arrangements that are not superimposable on each other.

**INTERACTIVE QUESTION 4.1**

Identify the structural isomers, geometric isomers, and enantiomers from the following compounds. Which of the geometric isomers is the cis isomer?

<table>
<thead>
<tr>
<th>COOH</th>
<th>H H</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂C−C−H−OH</td>
<td>H C−C−OH</td>
</tr>
<tr>
<td>L-lactic acid</td>
<td>ethanol</td>
</tr>
<tr>
<td>COOH</td>
<td>H C−C−OH</td>
</tr>
<tr>
<td>H−C−CH₃ OH</td>
<td>HO−C−C−H</td>
</tr>
<tr>
<td>D-lactic acid</td>
<td>fumaric acid</td>
</tr>
<tr>
<td>H H H H</td>
<td>H C−C−OH</td>
</tr>
<tr>
<td>H−C−O−C−H</td>
<td>H C−C−OH</td>
</tr>
<tr>
<td>dimethyl ether</td>
<td>maleic acid</td>
</tr>
</tbody>
</table>

**Carbonyl groups** consist of a carbon double-bonded to an oxygen (≥CO). If the carbonyl group is at the end of the carbon skeleton, the compound is called an aldehyde. Otherwise, the compound is called a ketone.

A **carboxyl group** consists of a carbon double-bonded to an oxygen and also attached to a hydroxyl group (−COOH). Compounds with a carboxyl group are called **carboxylic acids** or organic acids because they tend to dissociate to release H⁺, becoming —COO⁻.

An **amino group** consists of a nitrogen atom bonded to two hydrogens (−NH₂) and to the carbon skeleton. Compounds with an amino group, called **amines**, can act as bases. The nitrogen, with its pair of unshared electrons, can attract a hydrogen ion, becoming —NH₃⁺.

The **sulphydryl group** consists of a sulfur atom bonded to a hydrogen (—SH). **Thiols** are compounds containing sulphydryl groups.

A **phosphate group** is bonded to the carbon skeleton by an oxygen attached to PO₃²⁻, a phosphorus atom that is bonded to three other oxygen atoms (—OPO₃²⁻). It is an ionized form of a phosphoric acid group (—PO₃H₂). Compounds containing phosphate groups are called **organic phosphates**. The group is an anion due to the dissociation of hydrogen ions.

**The chemical elements of life: a review**

Carbon, oxygen, hydrogen, nitrogen, and smaller quantities of sulfur and phosphorus, all capable of forming strong covalent bonds, are combined into the complex organic molecules of living matter. The versatility of carbon in forming four covalent bonds, linking readily with itself to produce chains and rings, and binding with other elements and functional groups makes possible the incredible diversity of organic molecules.

**Word Roots**

hydro- = water *(hydrocarbon: an organic molecule consisting only of carbon and hydrogen)*

iso- = equal *(isomer: one of several organic compounds with the same molecular formula but different structures and, therefore, different properties)*

enanti- = opposite *(enantiomer: molecules that are mirror images of each other)*

carb- = coal *(carboxyl group: a functional group present in organic acids, consisting of a carbon atom double-bonded to an oxygen atom and a hydroxyl group)*

sulf- = sulfur *(sulphydryl group: a functional group that consists of a sulfur atom bonded to an atom of hydrogen)*

thio- = sulfur *(thiol: organic compounds containing sulphydryl groups)*
1. Construct a concept map that illustrates your understanding of the characteristics and significance of the three types of isomers. A suggested map is in the answer section. Comparing and discussing your map with that of a study partner would be most helpful.

2. Fill in the following table on the functional groups.

<table>
<thead>
<tr>
<th>Functional Group</th>
<th>Molecular Formula</th>
<th>Names and Characteristics of Organic Compounds Containing Functional Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>—OH</td>
<td></td>
<td>Aldehyde or ketone; polar group</td>
</tr>
<tr>
<td>Carboxyl</td>
<td></td>
<td>Thiols; cross-links stabilize protein structure</td>
</tr>
<tr>
<td>—NH₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

d. they store energy in the many C—H bonds along the carbon backbone.
e. they are lighter than water.

3. Which of the following is not true of an asymmetric carbon atom?
   a. It is attached to four different atoms or groups.
b. It results in right- and left-handed versions of a molecule.
c. It can be a part of enantiomers.
d. Its configuration is in the shape of a tetrahedron.
e. It can be a part of geometric isomers.

4. A reductionist approach to considering the structure and function of organic molecules would be based on
   a. mechanism.
b. holism.
c. determinism.
d. vitalism.
e. evolution.

5. The functional group that can cause an organic molecule to act as a base is
   a. —COOH.      c. —SH.        e. —OPO₃²⁻.
b. —OH.        d. —NH₂.

6. The functional group that confers acidic properties to organic molecules is
   a. —COOH.      c. —SH.        e. >C = O.
b. —OH.        d. —NH₂.

7. Which is not true about structural isomers?
   a. They have different chemical properties.
b. They have the same molecular formula.
c. Their atoms and bonds are arranged in different sequences.
d. They are a result of restricted movement around a carbon double bond.
e. Their possible numbers increase as carbon skeletons increase in size.

8. The fats stored in your body consist mostly of
   a. amino acids.
b. alcohols.
c. carboxylic acids.
d. hydrocarbons.
e. organic phosphates.
9. How many asymmetric carbons are there in the sugar ribose?
   a. 1  c. 3  e. 5  
   b. 2  d. 4  
   
   MATCHING: Match the formulas (a–f) to the terms at the right. Choices may be used more than once; more than one right choice may be available.
   
   a.  
   b.  
   c.  
   d.  
   e.  
   f.  
   
   1. structural isomers  
   2. geometric isomers  
   3. can have enantiomers  
   4. carboxylic acid  
   5. can make cross-link in protein  
   6. hydrophilic  
   7. hydrocarbon  
   8. amino acid  
   9. organic phosphate  
   10. aldehyde  
   11. amine  
   12. ketone
1. Although cells are 70-95% water, the rest consists mostly of ____________ compounds.

2. Carbon is unparalleled in its ability to form large, ____________, and diverse molecules.

3. Carbon accounts for the diversity of ____________ molecules and has made possible the great diversity of living things.

4. Proteins, DNA, carbohydrates, and other molecules that distinguish living matter from ____________ material are all composed of carbon atoms bonded to each other and to atoms of other elements.

5. These other elements commonly include hydrogen (H), oxygen (O), nitrogen (N), ____________, and phosphorus (P).

6. The study of carbon compounds, ________________ , deals with any compound with carbon (organic compounds).

7. Organic compounds can range from simple molecules, such as CO2 or CH4, to complex molecules such as ____________, which may weigh more than 100,000 daltons.

8. The overall ____________ of the major elements of life (C, H, O, N, S, and P) are quite uniform from one organism to another.

9. However, because of carbon's ____________, these few elements can be combined to build and inexhaustible variety of organic molecules.

10. Variations in organic molecules can distinguish between individuals of a ____________ species.

11. The science of organic chemistry began in attempts to ____________ and improve the yield of products obtained from other organisms.

12. Initially, chemists learned to ____________ simple compounds in the laboratory, but had no success with more complex compounds.

13. The Swedish chemist Jons Jacob Berzelius was the first to make a distinction between organic compounds that seemed to arise only in living organisms and inorganic compounds that were found in the ____________ world.

14. This led early organic chemists to propose ____________, the belief that physical and chemical laws did not apply to living things.

15. Support for vitalism began to wane as organic chemists learned to synthesize complex organic compounds in the ____________.

16. In the early 1800s, the German chemist Friedich Wohler and his students were able to synthesize ____________ from totally inorganic materials.

17. In 1953, Stanley Miller at the University of Chicago set up a laboratory ____________ of chemical conditions on the primitive Earth and demonstrated the spontaneous synthesis of organic compounds.

18. Such ____________ synthesis of organic compounds may have been an early stage in the origin of life.

19. Organic chemists finally rejected vitalism and embraced ____________, accepting that the same physical and chemical laws govern all natural phenomena including the processes of life.

20. Organic chemistry was redefined as the study of carbon compounds ____________ of their origin.

21. Organisms do produce the ____________ of organic compounds.

22. The laws of ____________ apply to inorganic and organic compounds alike.