

## Chapter 4

# Carbon and the Molecular Diversity of Life

### *Lecture Outline*

#### Overview

##### **A. Carbon—The Backbone of Biological Molecules**

- Although cells are 70–95% water, the rest consists mostly of carbon-based compounds.
- Carbon is unparalleled in its ability to form large, complex, and diverse molecules.
- Carbon accounts for the diversity of biological molecules and has made possible the great diversity of living things.
- Proteins, DNA, carbohydrates, and other molecules that distinguish living matter from inorganic material are all composed of carbon atoms bonded to each other and to atoms of other elements.
- These other elements commonly include hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and phosphorus (P).

##### **1. Organic chemistry is the study of carbon compounds.**

- The study of carbon compounds, **organic chemistry**, deals with any compound with carbon (organic compounds).
- Organic compounds can range from simple molecules, such as CO<sub>2</sub> or CH<sub>4</sub>, to complex molecules such as proteins, which may weigh more than 100,000 daltons.
- The overall percentages of the major elements of life (C, H, O, N, S, and P) are quite uniform from one organism to another.
- However, because of carbon's versatility, these few elements can be combined to build an inexhaustible variety of organic molecules.
- Variations in organic molecules can distinguish even between individuals of a single species.
- The science of organic chemistry began in attempts to purify and improve the yield of products obtained from other organisms.
- Initially, chemists learned to synthesize simple compounds in the laboratory, but had no success with more complex compounds.
- 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 nonliving world.
- This led early organic chemists to propose **vitalism**, the belief that physical and chemical laws did not apply to living things.
- Support for vitalism began to wane as organic chemists learned to synthesize complex organic compounds in the laboratory.

- 1
- In the early 1800s, the German chemist Friedrich Wöhler and his students were able to synthesize urea from totally inorganic materials.
  - In 1953, Stanley Miller at the University of Chicago set up a laboratory simulation of chemical conditions on the primitive Earth and demonstrated the spontaneous synthesis of organic compounds.
  - Such spontaneous synthesis of organic compounds may have been an early stage in the origin of life.
  - Organic chemists finally rejected vitalism and embraced **mechanism**, accepting that the same physical and chemical laws govern all natural phenomena including the processes of life.
  - Organic chemistry was redefined as the study of carbon compounds regardless of their origin.
  - Organisms do produce the majority of organic compounds.
  - The laws of chemistry apply to inorganic and organic compounds alike.

2. ***Carbon atoms can form diverse molecules by bonding to four other atoms.***

- 2
- With a total of 6 electrons, a carbon atom has 2 in the first electron shell and 4 in the second shell.
  - Carbon has little tendency to form ionic bonds by losing or gaining 4 electrons to complete its valence shell.
  - Instead, carbon usually completes its valence shell by sharing electrons with other atoms in four covalent bonds.
  - This **tetravalence** by carbon makes large, complex molecules possible.
  - When carbon forms covalent bonds with four other atoms, they are arranged at the corners of an imaginary tetrahedron with bond angles of  $109.5^\circ$ .
  - In molecules with multiple carbons, every carbon bonded to four other atoms has a tetrahedral shape.
  - However, when two carbon atoms are joined by a double bond, all bonds around those carbons are in the same plane and have a flat, three-dimensional structure.
  - The three-dimensional shape of an organic molecule determines its function.
  - The electron configuration of carbon makes it capable of forming covalent bonds with many different elements.
  - The valences of carbon and its partners can be viewed as the building code that governs the architecture of organic molecules.
  - In carbon dioxide, one carbon atom forms two double bonds with two different oxygen atoms.
  - In the structural formula,  $O=C=O$ , each line represents a pair of shared electrons. This arrangement completes the valence shells of all atoms in the molecule.
  - While  $CO_2$  can be classified as either organic or inorganic, its importance to the living world is clear.
  - $CO_2$  is the source of carbon for all organic molecules found in organisms. It is usually fixed into organic molecules by the process of photosynthesis.
  - Urea,  $CO(NH_2)_2$ , is another simple organic molecule in which each atom forms covalent bonds to complete its valence shell.

3 (3. ***Variation in carbon skeletons contributes to the diversity of organic molecules.***

- Carbon chains form the skeletons of most organic molecules.
- The skeletons vary in length and may be straight, branched, or arranged in closed rings.
- The carbon skeletons may include double bonds.
- Atoms of other elements can be bonded to the atoms of the carbon skeleton.
- **Hydrocarbons** are organic molecules that consist of only carbon and hydrogen atoms.
- Hydrocarbons are the major component of petroleum, a fossil fuel that consists of the partially decomposed remains of organisms that lived millions of years ago.
- Fats are biological molecules that have long hydrocarbon tails attached to a nonhydrocarbon component.
- Petroleum and fat are hydrophobic compounds that cannot dissolve in water because of their many nonpolar carbon-to-hydrogen bonds.
- **Isomers** are compounds that have the same molecular formula but different structures and, therefore, different chemical properties.
- For example, butane and isobutane have the same molecular formula,  $C_4H_{10}$ , but butane has a straight skeleton and isobutane has a branched skeleton.
- The two butanes are **structural isomers**, molecules that have the same molecular formula but differ in the covalent arrangement of atoms.
- **Geometric isomers** are compounds with the same covalent partnerships that differ in the spatial arrangement of atoms around a carbon-carbon double bond.
- The double bond does not allow atoms to rotate freely around the bond axis.
- The biochemistry of vision involves a **light-induced change** in the structure of rhodopsin in the retina from one geometric isomer to another.
- **Enantiomers** are molecules that are mirror images of each other.
- Enantiomers are possible when four different atoms or groups of atoms are bonded to a carbon.
- In this case, the four groups can be arranged in space in two different ways that are mirror images.
- They are like left-handed and right-handed versions of the molecule.
- Usually one is biologically active, while the other is inactive.
- Even subtle structural differences in two enantiomers have important functional significance because of emergent properties from specific arrangements of atoms.
- One enantiomer of the drug thalidomide reduced morning sickness, the desired effect, but the other isomer caused severe birth defects.
- The L-dopa isomer is an effective treatment of Parkinson's disease, but the D-dopa isomer is inactive.

## B. Functional Groups

1. **Functional groups are involved in chemical reactions and contribute to the molecular diversity of life.**

- The components of organic molecules that are most commonly involved in chemical reactions are known as **functional groups**.

- 8
- If we consider hydrocarbons to be the simplest organic molecules, we can view functional groups as attachments that replace one or more of the hydrogen atoms bonded to the carbon skeleton of the hydrocarbon.
  - Each functional group behaves consistently from one organic molecule to another.
  - The number and arrangement of functional groups help give each molecule its unique properties.
  - As an example, the basic structure of testosterone (a male sex hormone) and estradiol (a female sex hormone) is the same.
  - Both are steroids with four fused carbon rings, but they differ in the functional groups attached to the rings.
  - These functional groups interact with different targets in the body.
  - There are six functional groups that are most important to the chemistry of life: hydroxyl, carbonyl, carboxyl, amino, sulfhydryl, and phosphate groups.
  - All are hydrophilic and increase the solubility of organic compounds in water.

- 9
- In a **hydroxyl group** ( $\text{—OH}$ ), a hydrogen atom forms a polar covalent bond with an oxygen atom, which forms a polar covalent bond to the carbon skeleton.
  - Because of these polar covalent bonds, hydroxyl groups increase the solubility of organic molecules.
  - Organic compounds with hydroxyl groups are alcohols, and their names typically end in  $\text{—ol}$ .

- 10
- A **carbonyl group** ( $\text{>CO}$ ) consists of an oxygen atom joined to the carbon skeleton by a double bond.
  - If the carbonyl group is on the end of the skeleton, the compound is an **aldehyde**.
  - If the carbonyl group is within the carbon skeleton, then the compound is a **ketone**.
  - Isomers with aldehydes versus ketones have different properties.

- 11
- A **carboxyl group** ( $\text{—COOH}$ ) consists of a carbon atom with a double bond to an oxygen atom and a single bond to the oxygen of a hydroxyl group.
  - Compounds with carboxyl groups are **carboxylic acids**.
  - A carboxyl group acts as an acid because the combined electronegativities of the two adjacent oxygen atoms increase the dissociation of hydrogen as an ion ( $\text{H}^+$ ).

- 12
- An **amino group** ( $\text{—NH}_2$ ) consists of a nitrogen atom bonded to two hydrogen atoms and the carbon skeleton.
  - Organic compounds with amino groups are **amines**.
  - The amino group acts as a base because the amino group can pick up a hydrogen ion ( $\text{H}^+$ ) from the solution.
  - Amino acids, the building blocks of proteins, have amino and carboxyl groups.

- 13
- A **sulfhydryl group** ( $\text{—SH}$ ) consists of a sulfur atom bonded to a hydrogen atom and to the backbone.
  - This group resembles a hydroxyl group in shape.
  - Organic molecules with sulfhydryl groups are **thiols**.
  - Two sulfhydryl groups can interact to help stabilize the structure of proteins.

- 14
- A **phosphate group** ( $\text{—OPO}_3^{2-}$ ) consists of a phosphorus atom bound to four oxygen atoms (three with single bonds and one with a double bond).
  - A phosphate group connects to the carbon backbone via one of its oxygen atoms.
  - Phosphate groups are anions with two negative charges, as two protons have dissociated from the oxygen atoms.
  - One function of phosphate groups is to transfer energy between organic molecules.
  - Adenosine triphosphate, or ATP, is the primary energy-transferring molecule in living cells.

## 2. *These are the chemical elements of life.*

- Living matter consists mainly of carbon, oxygen, hydrogen, and nitrogen, with smaller amounts of sulfur and phosphorus.
- These elements are linked by strong covalent bonds.
- Carbon, with its four covalent bonds, is the **basic building block in molecular architecture**.
- The great diversity of organic molecules with their special properties emerges from the unique arrangement of the carbon skeleton and the functional groups attached to the skeleton.