

Chapter 4

Carbon and the Molecular Diversity of Life

Lecture Outline

Overview: Carbon—The Backbone of Biological Molecules

- Although cells are 70–95% water, the rest consists of mostly carbon-based compounds.
- Carbon enters the biosphere when photosynthetic organisms use the sun's energy to transform CO₂ into organic molecules, which are transferred to primary consumers.
- Carbon accounts for the diversity of biological molecules, which has made possible the wide variety 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).

Concept 4.1 Organic chemistry is the study of carbon compounds.

- **Organic chemistry** focuses on organic compounds containing carbon.
 - Organic compounds can range from simple molecules, such as CH₄, to complex molecules such as proteins, which may have molecular masses greater than 100,000 daltons.
 - Most organic compounds contain hydrogen atoms.
- 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 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 individuals of a single species.
- The science of organic chemistry began with attempts to purify and improve the yield of products obtained from 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 in only living organisms and inorganic compounds that were found in the nonliving world.
- Early organic chemists proposed **vitalism**, the belief that physical and chemical laws do not apply to living things.
 - Support for vitalism waned as organic chemists learned to synthesize complex organic compounds in the laboratory.
 - In the early 1800s, the German chemist Friedrich Wöhler and his students synthesized urea from totally inorganic materials.

- In 1953, Stanley Miller at the University of Chicago set up a laboratory simulation of possible chemical conditions on the primitive Earth and demonstrated the spontaneous synthesis of organic compounds.
 - The mixture of gases Miller created probably did not accurately represent the atmosphere of the primitive Earth.
 - However, similar experiments using more accurate atmospheric conditions also led to the formation of organic compounds.
 - Spontaneous synthesis of organic compounds may have been an early stage in the origin of life on Earth.
- Organic chemists finally rejected vitalism and embraced **mechanism**, the belief 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 produce the majority of organic compounds.
 - The laws of chemistry apply to both inorganic and organic compounds.
- The foundation of organic chemistry is not a mysterious life force but rather the unique versatility of carbon-based compounds.

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

- A carbon atom has a total of 6 electrons: 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.
- Carbon usually completes its valence shell by sharing electrons with other atoms in four covalent bonds, which may include single and double bonds.
- Carbon's **tetravalence** makes large, complex molecules possible.
 - When a carbon atom forms covalent bonds with four other atoms, they are arranged at the corners of an imaginary tetrahedron with bond angles of 109.5° .
 - In molecules with multiple carbon atoms, every carbon atom bonded to four other atoms has a tetrahedral shape.
 - 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 electron configuration of carbon enables it to form 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.
- Although 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.
 - CO_2 is usually fixed into organic molecules by the process of photosynthesis.

- Urea, $\text{CO}(\text{NH}_2)_2$, is another simple organic molecule in which each atom forms covalent bonds to complete its valence shell.

Molecular diversity arises from variations in the carbon skeleton.

- Carbon chains form the skeletons of most organic molecules.
 - Carbon skeletons vary in length and may be straight, branched, or arranged in closed rings.
 - 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-hydrogen bonds.
- Hydrocarbons can undergo reactions that release a relatively large amount of energy.
- **Isomers** are compounds that have the same molecular formula but different structures and, therefore, different chemical properties.
- **Structural isomers** have the same molecular formula but differ in the covalent arrangement of atoms.
 - Structural isomers may also differ in the location of the double bonds.
- **Geometric isomers** have the same covalent partnerships but differ in the spatial arrangement of atoms around a carbon-carbon double bond.
 - The double bond does not allow the 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 an **asymmetric carbon**.
 - The four groups can be arranged in space in two different ways that are mirror images of each other.
 - 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 may have important functional significance because of emergent properties from specific arrangements of atoms.
 - For example, one enantiomer of the drug thalidomide reduced morning sickness, the desired effect, but the other isomer caused severe birth defects.

Concept 4.3 Characteristic chemical groups help determine how biological molecules function.

- The distinctive properties of an organic molecule depend not only on the arrangement of its carbon skeleton but also on the chemical groups attached to that skeleton.
- If we start with hydrocarbons as the simplest organic molecules, characteristic chemical groups can replace one or more of the hydrogen atoms bonded to the carbon skeleton of a hydrocarbon.
- These chemical groups may be involved in chemical reactions or may contribute to the shape and function of the organic molecule in a characteristic way, giving it 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 the hormones differ in the chemical groups attached to the rings.
 - As a result, testosterone and estradiol have different shapes, causing them to interact differently with many targets throughout the body.
- In other cases, chemical groups known as **functional groups** affect molecular function through their direct involvement in chemical reactions.
- Seven chemical groups are most important to the chemistry of life: hydroxyl, carbonyl, carboxyl, amino, sulfhydryl, phosphate, and methyl groups.
- The first six chemical groups are functional groups. They are hydrophilic and increase the solubility of organic compounds in water.
- Methyl groups are not reactive but may serve as important markers on organic molecules.
- In a **hydroxyl** group (—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 *-ol*.
- A **carbonyl** group (>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, the compound is a **ketone**.
 - Isomers with aldehydes and those with ketones have different properties.
- A **carboxyl** group (—COOH) consists of a carbon atom with a double bond to an oxygen atom and a single bond to the oxygen atom 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 chance of dissociation of hydrogen as an ion (H^+).
- An **amino** group (—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 it can pick up a hydrogen ion (H^+) from the solution.

- Amino acids, the building blocks of proteins, have amino and carboxyl groups.
- A **sulfhydryl** group (—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.
- A **phosphate** group (—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 because 2 protons dissociate from the oxygen atoms.
 - One function of phosphate groups is to transfer energy between organic molecules.

ATP is an important source of energy for cellular processes.

- Adenosine triphosphate, or ATP, is the primary energy transfer molecule in living cells.
- ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups.
- When one inorganic phosphate ion is split off as a result of a reaction with water, ATP becomes adenosine *d*iphosphate, or ADP.
- In a sense, ATP “stores” the potential to react with water, releasing energy that can be used by the cell.