Chapter 4

Carbon and the Molecular Diversity of Life

Lecture Outline

Overview: Carbon—The Backbone of Life

- 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 CO_2 into organic molecules, which are taken in by plant-eating animals.
- 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 CH_4, to complex molecules such as proteins, with thousands of atoms.
    - Most organic compounds contain hydrogen atoms as well as carbon.
- 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, thought 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. A few years later, Hermann Kolbe, a student of Wöhler's, made the organic compound acetic acid from inorganic substances prepared directly from pure elements.
- 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 abiotic synthesis of organic compounds, possibly near volcanoes, 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.
- The ability of carbon to form four covalent bonds 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 as the carbons.

    - 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 (CO_2), one carbon atom forms two double bonds with two 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, $CO(NH_2)_2$, is another simple organic molecule in which each atom forms covalent bonds to complete its valence shell.
    - In urea, one carbon atom is involved in both single and double bonds.

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.
- ***Cis-trans* 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.
  - Consider a simple molecule with two double-bonded carbons, each of which has an H and an X attached to it. The arrangement with both Xs on the same side of the double bond is called a *cis* isomer; the arrangement with the Xs on opposite sides is called a *trans* isomer.
  - The biochemistry of vision involves a light-induced change in the structure of rhodopsin in the retina from the *cis* isomer to the *trans* isomer.
- **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, methamphetimine occurs in two enantiomers with very different effects. One is a highly addictive street drug called "crank", while the other is sold for treatment of nasal congestion.

Concept 4.3 A few chemical groups are key to the functioning of biological molecules

- 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 *di*phosphate, or ADP.
- In a sense, ATP "stores" the potential to react with water, releasing energy that can be used by the cell.