Lecture Outline: Overview of Organic Chemistry

I. **Specialness of Carbon**

A. **Organic vs. Inorganic Chemistry**

1. Chemistry is divided into organic and inorganic branches.
2. Original definition of "organic": of organs, referring to living material. Early belief that organic and non-living substances were fundamentally different and could not be interconverted.
3. Current definition: **carbon-containing**.
    a. Exceptions: graphite, diamond (pure carbon), and carbon dioxide are not considered organic.
    b. Requirement: Must be a **compound** (elemental carbon is not organic).
    c. Typical composition: Organic compounds must contain carbon, usually include hydrogen, and often oxygen and nitrogen.
4. All organisms are composed of **organic compounds**.
    a. Not every molecule in an organism is organic (e.g., water).
    b. Cells contain numerous organic compounds, including all four macromolecules.

B. **Hydrocarbons**

1. Definition: Compounds consisting **only** of **hydrogen** and **carbon** atoms.
2. Valence and Bonding:
    a. Carbon's Valence:
        (1) Has four valence electrons.
        (2) Valence is four, meaning it must form four bonds.
        (3) Termed **tetravalence**.

(4) Carbon is the **smallest tetravalent atom**, making it highly versatile in bonding (e.g., four single bonds, two double bonds, one triple and one single bond).

f. Hydrogen's Valence: One, meaning it forms one bond.

3. Types of Hydrocarbons (based on bond types):
    a. **Alkanes**: Contain **only single bonds**. Names end in "-ane" (e.g., methane, ethane).
    b. **Alkenes**: Contain **at least one double bond**. Names end in "-ene" (e.g., ethene).
    c. **Alkynes**: Contain **at least one triple bond**. Names end in "-yne".
4. Nomenclature Prefixes (indicate carbon count): Meth- (1), Eth- (2), Prop- (3), But- (4), Pent- (5), Hex- (6), Hept- (7), Oct- (8), Non- (9).
5. Hydrocarbons as Fuel Sources:
    a. Excellent fuels (e.g., gasoline) due to high energy content.
    b. Undergo combustion reactions, both outside (e.g., engines) and inside the body.
6. Nature of Carbon-Hydrogen Bonds:
    a. Form **nonpolar covalent bonds**.
    b. Involve **equal sharing of electrons**.
    c. Reason: Carbon and hydrogen have **very similar (low) electronegativity values**.
    d. This makes hydrocarbons nonpolar, which is why they do not mix with polar substances like water.

C. **Important Non-metal Elements for Molecules**

1. Hydrogen, Oxygen, Nitrogen, and Carbon are the most abundant non-metals in organisms.
2. All are non-metals (located in the upper right of the periodic table, plus hydrogen).
3. These elements typically form **covalent bonds**, leading to the creation of **molecules**.

D. **Urea as an Organic Compound Example**

1. An organic compound that does not have direct carbon-hydrogen bonds.
2. Produced in the body to eliminate toxic ammonia, a byproduct of protein breakdown.
3. Historically significant as the first organic compound artificially synthesized from inorganic precursors, demonstrating that organic molecules could be created in the laboratory.

E. **Classification of Hydrocarbons**

1. Based on the **length of the carbon skeleton** (e.g., ethane vs. propane).
2. Based on the **presence of double or triple bonds** (alkanes, alkenes, alkynes).
3. Based on the **branching of the carbon skeleton** (linear vs. branched).
   a. More carbons allow for more branching possibilities.
   b. Can lead to **structural isomers** (e.g., butane and 2-methylpropane have the same formula but different arrangements).
4. Based on the **presence of rings** (carbon skeletons connecting back on themselves, e.g., cyclohexane, benzene).
   a. Chemists use shorthand notation where angles represent carbon atoms and hydrogens are implied.

F. **Lipids: Fats (Triglycerides/Triacylglycerol)**

1. Fats are a type of lipid, but not all lipids are fats.
2. Structure: Composed of a glycerol molecule attached to three fatty acid tails.
3. High Energy Density:
   a. Fatty acid tails are long hydrocarbon chains (excellent fuels).
   b. Fats store more than twice the energy per gram compared to carbohydrates and proteins.
   c. The body stores excess energy as fat to minimize weight, facilitating movement.

G. **Isomers**

1. Definition: Chemicals that have the **same exact chemical formula** but are **different substances** due to different arrangements of atoms.
2. Types of Isomers:
   a. **Structural Isomers**: Differ in the arrangement of their carbon skeleton (e.g., branching vs. non-branching). Example: pentane and 2-methylbutane (both C5H12).

   b. **Geometric Isomers**: Involve a **double bond**, which prevents rotation, holding atoms in fixed positions.

      (1) **Cis isomer**: Two specific groups are on the **same side** of the double bond.

      (2) **Trans isomer**: Two specific groups are on **opposite sides** of the double bond.

      (3) These are distinct molecules with unique properties.

   f. **Enantiomers (Stereoisomers)**:

      (1) Examples of **chiral compounds**, meaning "handed" (like a left and right hand).

      (2) Are **mirror images** of each other that cannot be superimposed.

      (3) Require a central carbon atom bonded to **four different groups**.

      (4) Biological Importance: Many chemical signals (e.g., drugs, hormones) are enantiomers. Only one "handed" version typically works by binding to a specific receptor that also has a corresponding "handedness."

      (5) Notations: L (levo = left) and D (dextro = right), or S (sinestral = left) and R (recto = right).

      (6) Examples: S-ibuprofen is effective, R-albuterol is effective, L-dopa is produced by the body.

H. **Steroid Hormones (e.g., Estradiol, Testosterone)**

1. All steroid hormones are derived from **cholesterol**.
2. Small structural modifications to cholesterol lead to vastly different

biological effects.

3. Their distinct functions arise from specific **functional groups** attached to the main ring structure, which allow for unique interactions with other molecules.

II. **Functional Groups**

A. Definition and General Characteristics:

1. Small collections of atoms that are part of a larger molecule.
2. Impart specific **chemical functions** to the molecule by enabling interactions with other substances.
3. Not complete molecules themselves; they connect to the "residue" (R), which represents the rest of the molecule.

B. Specific Functional Groups (common in biology):

1. **Hydroxyl Group (-OH)**:
   a. Structure: An oxygen atom bonded to a hydrogen atom and to the rest of the molecule (R-OH).
   b. Compounds containing a hydroxyl group are called **alcohols** (names often end in "-ol").
   c. **Polar** due to the high electronegativity of oxygen compared to hydrogen, leading to unequal sharing of electrons.
2. **Carbonyl Group (>C=O)**:
   a. Structure: A carbon atom double-bonded to an oxygen atom.
   b. Two categories of carbonyl-containing compounds based on placement in the carbon skeleton:
      (1) **Ketones**: The carbonyl group is located **within the carbon skeleton**, not at a tip. Names end in "-one" (e.g., acetone).
      (2) **Aldehydes**: The carbonyl group is located **at a tip** of the carbon skeleton. Names end in "-al" (e.g., propanal).
   e. Important as major fuels in biology (e.g., in sugars).
3. **Carboxyl Group (-COOH)**:
   a. Structure: A carbon atom double-bonded to an oxygen (carbonyl) and also bonded to a hydroxyl group, specifically configured

together.

b. Considered a single functional group.

c. Compounds containing a carboxyl group are called **carboxylic acids** (or organic acids) because they exhibit acidic behavior.

d. Biological Importance: All **amino acids** (protein building blocks) contain a carboxyl group.

4. **Amino Group (-NH2)**:

   a. Structure: A nitrogen atom bonded to two hydrogen atoms and to the rest of the molecule (R-NH2).

   b. Nitrogen has a valence of three, forming three bonds.

   c. Compounds containing an amino group are called **amines**.

   d. Biological Importance: All **amino acids** contain an amino group. The name "amino acid" refers to the presence of both amino and carboxyl groups.

5. **Sulfhydryl Group (-SH)**:

   a. Structure: A sulfur atom bonded to a hydrogen atom and to the rest of the molecule (R-SH).

   b. Similar to a hydroxyl group, but with sulfur instead of oxygen (sulfur is in the same periodic table group as oxygen and also has a valence of two).

   c. Compounds containing sulfhydryl groups are called **thiols** ("sulfur alcohols").

   d. Biological Importance:

      (1) Present in the amino acid **cysteine**.

      (2) In proteins, two sulfhydryl groups from different cysteine residues can react to form a **disulfide bridge** (S-S bond), which stabilizes and strengthens the protein's three-dimensional shape (e.g., in human hair).

6. **Phosphate Group ($-OPO_3^{2-}$)**:

   a. Structure: A central phosphorus atom bonded to four oxygen atoms, one of which connects to the rest of the molecule.

b. A **charged functional group**, highly significant in biology.

c. Compounds containing a phosphate group are called **organic phosphates**.

d. Biological Importance:

(1) **Phospholipids**: Major components of cellular plasma membranes.

(2) **ATP (Adenosine Triphosphate)**: The primary temporary energy storage molecule in all cells.

(3) **Nucleotides**: Every nucleotide (monomer of nucleic acids like DNA and RNA) contains a phosphate group.

(4) **Phosphorylation and Dephosphorylation**: The addition or removal of phosphate groups from proteins. This process changes protein shape, serving as a major mechanism for cells to **control protein function** (e.g., switching enzymes on or off quickly without destroying them).

7. **Methyl Group (-CH3)**:

a. Structure: A carbon atom bonded to three hydrogen atoms and to the rest of the molecule (R-CH3).

b. Are ubiquitous ("space fillers") in molecules.

c. Compounds containing methyl groups are called **methylated compounds**.

d. Biological Importance:

(1) **Methylation and Demethylation of DNA**: Used to **control gene expression**.

(2) Methylation can make DNA inaccessible and unreadable to the cell, effectively turning genes off (can be permanent or reversible).

III. **ATP (Adenosine Triphosphate) and Energy**

A. Structure and Components:

1. ATP is the acronym for **Adenosine Triphosphate**.

2. Composed of Adenosine (a nucleoside) with three phosphate groups attached.

B. Nucleic Acids and Nucleotides:

1. Nucleotide: A building block or monomer of nucleic acids (DNA and RNA).
2. Components of a Nucleotide (three pieces):
   a. A **pentose sugar**: Ribose (in RNA nucleotides) or Deoxyribose (in DNA nucleotides).
   b. A **nitrogenous base**: (e.g., Adenine, Guanine, Cytosine, Thymine, Uracil).
   c. A **phosphate group**.
3. Macromolecule Classification:
   a. Nucleic acids (DNA and RNA) are **macromolecules** and are classified as **polymers** (specifically, polynucleotides).
   b. Three of the four major macromolecules are polymers: Nucleic Acids (polynucleotides from nucleotides), Polysaccharides (from monosaccharides), and Proteins (polypeptides from amino acids).
   c. **Lipids** are macromolecules but **not polymers**.

C. ATP as Energy Currency:

1. Analogy: Functions like a "debit card" for energy within the cell.
2. Energy Storage and Release:
   a. AMP (adenosine monophosphate) has one phosphate.
   b. ADP (adenosine diphosphate) has two phosphates.
   c. ATP has three phosphates, representing a high energy balance.
   d. **Conversion of AMP to ADP to ATP requires energy**, which is derived from the chemical bonds in food.
   e. **Breaking down ATP to ADP and inorganic phosphate (Pi) releases energy**, which powers various cellular activities (e.g., moving molecules, muscle contraction).
   f. This is a **reversible reaction**, constantly cycling in cells.
3. Recycling and Regulation:
   a. The body maintains a continuous pool of adenosine-based nucleotides (ATP, ADP, AMP).

    b. A buildup of AMP signals high energy demand, prompting the cell to increase cellular respiration in the mitochondria to produce more ATP.
    c. High ATP levels signal a decrease in energy production.

D. Inorganic Phosphate (Pi):
  1. Refers to a phosphate group that is not connected to a carbon skeleton (i.e., cleaved from an organic molecule like ATP).
  2. It is continuously recycled, being reattached to ADP or ATP.

IV. **Review of Related Chemical Concepts**

A. **Entropy**:
  1. Roughly defined as **disorder**.
  2. Organisms are highly ordered structures, possessing low entropy compared to their surroundings.
  3. In accordance with the **Second Law of Thermodynamics** (entropy of the universe is always increasing), organisms maintain their high order by increasing the disorder of their non-living surroundings.

B. **Orbitals and Electron Shells**:
  1. **Orbitals**: The smallest spaces where electrons are found; they are members of subshells.
  2. Subshells are larger spaces composed of orbitals, and subshells themselves make up even larger spaces called **shells** or **energy levels**.
  3. Types discussed: **s-orbitals** (spherical shape) and **p-orbitals** (dumbbell shape).
  4. Each orbital can hold at most **two electrons**.
  5. **Electron Shells/Energy Levels**: Correspond to **periods (rows)** on the periodic table.
    a. First shell (Period 1) contains one s-orbital, holding a maximum of 2 electrons.
    b. Second shell (Period 2) contains one s-orbital and three p-orbitals (total of four orbitals), holding a maximum of 8 electrons.

C. **Valence Electrons vs. Valence**:

1. **Valence electrons**: The electrons located in the outermost shell of an atom.
2. **Valence**: The number of additional electrons an atom needs to fill its outer shell. For non-metals, it also indicates the number of **covalent bonds** the atom will typically form.
   a. Example: Oxygen has six valence electrons and a valence of two, meaning it forms two covalent bonds.

D. **Ions**:

1. **Charged atoms**.
2. **Anion**: A **negatively charged ion**, formed when an atom **gains** one or more electrons.
3. **Cation**: A **positively charged ion**, formed when an atom **loses** one or more electrons.
4. Metals typically form cations by losing their valence electrons (e.g., Group 1 metals lose one electron to form a +1 cation; Group 2 metals lose two electrons to form a +2 cation).

E. **Ionic Bonds and Salts**:

1. **Salt**: Another term for an ionic compound.
2. The smallest possible bit of a salt is called a **formula unit** (in contrast to a molecule for covalent compounds).
3. Example: Magnesium fluoride (MgF_2) has a formula unit consisting of one magnesium ion (Mg^{2+}) and two fluoride ions (F^-).

F. **Autoionization of Water**:

1. Refers to the **self-ionization** of water molecules.
2. A small fraction of water molecules (H_2O) spontaneously split into a **hydrogen ion (H^+)** (also called a proton) and a **hydroxide ion (OH^-)**.
3. This process is reversible.
4. In pure water at a specific temperature, the concentration of both H^+ and OH^- is 1×10^{-7} M, which is the basis for pH 7 on the pH scale.