

# Lecture Outline: Chemical Fundamentals

## I. Basic Chemistry Fundamentals

### A. Atoms and Subatomic Particles

1. All material things in the universe are made out of **atoms**, which are inconceivably small particles.
2. A single cell, too small to see with the naked eye, contains billions of atoms.
3. Atoms themselves are made of even smaller things called **subatomic particles**.
  - a. The three main subatomic particles discussed are **electrons**, **protons**, and **neutrons**.
4. Atoms have distinct three-dimensional regions:
  - a. The **nucleus** is the central part of the atom, occupied only by neutrons and protons.
  - b. The space around the nucleus is occupied only by electrons.
5. The **planetary model** of the atom, depicting electrons revolving around a nucleus like planets around a star, is a simplified cartoon and not an accurate representation of how atoms truly are.

### B. Properties of Subatomic Particles

1. **Protons** and **neutrons** are almost identical in their size and mass.
2. **Neutrons** are named for the fact that they are **neutral** with respect to electrical charge, meaning they have a zero charge.
3. **Protons** are charged subatomic particles, and each individual proton has a **full positive one charge**.
4. Every atom must feature at least one proton; without it, it is not considered an atom.
5. Neutrons may or may not be present in an atom; for instance, the

normal version of a hydrogen atom is just a proton and an electron with no neutrons.

6. **Electrons** are much, much tinier than protons and neutrons.
7. Despite their tiny size, electrons have just as big a charge as protons, but in the **opposite direction**, meaning they are negatively charged (a full negative one charge).

### C. Elements and Atomic Number

1. An **element** is a substance that is made out of only one kind of atom.
2. The fact that there are different kinds of atoms is determined by the **number of protons** they possess.
  - a. This is the only thing that defines an element; the number of other particles (neutrons or electrons) can change without changing the element.
3. The **atomic number**, listed on the periodic table, is the number of protons that a specific type of atom has.
  - a. For example, hydrogen is atomic number one (has one proton), and helium is atomic number two (has two protons).
4. The vast majority of substances in the world are **compounds**, which are combinations of two or more different kinds of atoms (e.g., water is a compound made of hydrogen and oxygen).

### D. Isotopes and Ions

1. When we use the word **atom**, we are generally referring to an electrically **neutral** atom, meaning it has the same number of electrons as protons, resulting in an overall zero charge.
2. **Isotopes** are different versions of the same element that differ in their **number of neutrons**.
  - a. For example, hydrogen has isotopes like deuterium (one neutron) and tritium (two neutrons), which are considered "heavy hydrogen."
  - b. Additional neutrons make isotopes more massive.
  - c. Isotopes are important in medicine, such as in tracer solutions for imaging.
3. An **ion** is an atom that has an overall electrical charge.

- a. Under normal chemical reaction conditions, the number of protons in an atom does not change.
- b. However, the **number of electrons can be increased or decreased**, which will change the atom's charge.
- c. If a neutral atom gains an electron, it becomes a **negatively charged ion** (anion).
- d. If a neutral atom loses an electron, it becomes a **positively charged ion** (cation).

## II. Chemical Reactions and Bonds

### A. Introduction to Chemical Reactions

1. **Chemical reactions** are defined as rearrangements of electrons when atoms encounter each other.
2. The nuclei (protons and neutrons) generally stay put and are not directly involved in chemical reactions.
3. In a chemical reaction, **reactants** (on the left of an arrow) are transformed into **products** (on the right).
4. These transformations can result in profoundly different substances with new properties (e.g., dangerous sodium and poisonous chlorine reacting to form harmless and essential table salt).

### B. Atomic Stability and Electron Shells

1. Chemical reactions occur because atoms seek to achieve **stability**, which is attained when their **outer electron shells** are full.
2. The electron shell closest to the nucleus can contain a maximum of **two electrons**.
3. The next shell can hold a maximum of **eight electrons**.
4. Elements in the rightmost group of the periodic table, known as **noble gases** (e.g., helium, neon), are **inert** (do not react) because their outer electron shells are already completely filled, making them very stable.
  - a. Helium has two electrons, filling its first and only shell.
  - b. Neon has 10 electrons: two fill its first shell, and eight fill its second (outer) shell.
5. The **valence shell** is the outermost electron shell that contains at least

one electron.

6. **Valence electrons** are the electrons located in this outermost shell.
7. The vast majority of elements are not perfectly stable because they do not have a completely filled outer shell.

### C. Metals and Non-metals in Reactivity

1. Most elements are **metals**, found to the left and underneath the stair-step shape on the periodic table.
2. **Non-metals** are found above the stair-step in the upper-right corner, and hydrogen, though on the left, is also a non-metal.
3. **Metals** generally become stable by **losing electrons** from their outer shells, which are usually mostly empty. When they lose electrons, they become **positive ions (cations)**.
4. **Non-metals**, conversely, have outer shells that are almost full. They become stable by **accepting (gaining) electrons**, which is easier than losing all the electrons in their outer shell. When they gain electrons, they become **negative ions (anions)**.

### D. Types of Chemical Bonds

1. A **chemical bond** is formed when atoms interact in a way that creates a new chemical substance (e.g., sodium chloride is a new chemical, not just separate sodium and chlorine).
  - a. Bonds like hydrogen bonds, which loosely hold things together without changing their chemical identity, are not considered chemical bonds.
2. **Ionic Bonds:**
  - a. Form through the **transfer of electrons** from one atom to another.
  - b. Typically occur between a **metal** and a **non-metal**, both of which become ions of opposite charges.
  - c. The oppositely charged ions then attract each other, holding them together.
  - d. Ionic bonds are considered the weakest type of chemical bond.
3. **Covalent Bonds:**
  - a. Involve the **sharing of valence electrons** between two atoms.

- b. The shared electrons spend time around both atomic nuclei involved in the bond.
- c. Typically form between two **non-metals** (which can be the same or different elements).
- d. Covalent bonds are much stronger and harder to break than ionic bonds.
- e. A **single covalent bond** involves the sharing of **two electrons** (one from each atom), represented by a single dash (e.g., H-H).
- f. A **double covalent bond** involves the sharing of **four electrons** (two from each atom), represented by a double dash (e.g., O=O).
- g. The **valence** of an atom indicates how far away from fullness its outer shell is, and thus how many bonds it needs to form to become stable. For example, oxygen has a valence of two and forms two bonds.

#### E. Special Properties of Carbon (Tetravalence)

- 1. Carbon is the fundamental element for life on Earth ("carbon-based life").
- 2. Carbon has **four valence electrons**, giving it a **valence of four**, also known as **tetravalence**.
- 3. This tetravalence makes carbon extremely **versatile** in how it can form bonds and create compounds.
  - a. It can form four single bonds, two double bonds, or a triple bond and a single bond, all adding up to four total bonds for stability.
  - b. This versatility allows carbon to bond with a wide variety of other atoms and form complex structures.
- 4. As the smallest tetravalent atom in its group, carbon is uniquely suited to be the basis for biological molecules.
- 5. **Organic compounds** are defined in chemistry as carbon-containing compounds.

#### F. Polarity in Covalent Bonds

- 1. Covalent bonds can be further categorized into **non-polar covalent bonds** and **polar covalent bonds**.

2. The term "polar" refers to having different ends, typically related to differences in electrical charge.
3. In a **non-polar covalent bond**, the shared electrons are **equally shared** between the two atoms, meaning they spend equal time around both nuclei.
  - a. This occurs when the two atoms have similar or identical **electronegativity**, which is a measure of how greedily an atom wants electrons for itself.
  - b. Examples include the bonds in an oxygen molecule (O<sub>2</sub>) and, due to symmetry, the carbon-oxygen bonds in carbon dioxide (CO<sub>2</sub>).
4. In a **polar covalent bond**, the shared electrons are **unequally shared**.
  - a. This happens when the two atoms involved have significantly different electronegativity values.
  - b. The electrons spend more time around the atom with higher electronegativity, making that part of the molecule slightly negatively charged (indicated by  $\delta^-$ ).
  - c. The other atom, from which the electrons are drawn away, becomes slightly positively charged (indicated by  $\delta^+$ ).

#### G. The Importance of Water's Polarity

1. Water (H<sub>2</sub>O) is a prime example of a **polar covalent compound**. Each bond in water is polar because oxygen is significantly more electronegative than hydrogen.
2. This polarity is of paramount importance to biology, making life possible.
3. **Hydrogen bonding** occurs between polar water molecules: the partially negative oxygen of one water molecule is attracted to the partially positive hydrogen of another. This gives water a "stickiness."
4. One special property due to hydrogen bonding is **surface tension**, where water molecules at the surface are pulled inward, creating a dense, skin-like layer that allows some things (like insects) to walk on water.

5. Water's polarity also makes it an **excellent solvent**.
  - a. In a solution, the **solvent** dissolves the **solute(s)**.
  - b. Water's polar nature allows it to effectively dissolve many substances, including salts like sodium chloride, by surrounding and separating individual ions.

### III. pH and Biological Reactions

#### A. The pH Scale

1. The **pH scale** is a **logarithmic scale** used to measure the degree of **acidity** or **basicity (alkalinity)** of solutions.
  - a. Each step on the pH scale represents a 10-fold difference in concentration.
2. The "H" in pH stands for the concentration of **hydrogen ions (H<sup>+</sup>)**.
3. An **acid** is a compound that dissociates in water, giving up hydrogen ions, thus increasing their concentration.
4. The **lower the pH value**, the higher the concentration of hydrogen ions, and the more **acidic** the solution is.
5. A pH of **7 is neutral**. Values above 7 are basic/alkaline.
6. Maintaining a narrow range of pH is critical for the survival of organisms, a process known as **homeostasis**.
  - a. Most body cells require a pH close to 7.
  - b. The stomach is an exception, secreting hydrochloric acid to achieve a very low pH, which helps kill bacteria.
  - c. The brain constantly monitors blood pH; for example, holding one's breath causes carbon dioxide to build up and acidify the blood, triggering an involuntary breath to restore pH balance.

#### B. Building and Breaking Down Molecules in Biology

1. Cells continuously engage in two major categories of biological chemical reactions:
2. **Dehydration Reaction (Synthesis Reaction):**
  - a. This process builds larger, more complex molecules, known as **polymers**, by linking together smaller subunits called **monomers**.

- b. It involves the **removal of a water molecule (H<sub>2</sub>O)** (an -OH group from one monomer and an -H atom from another) to form a new bond between the monomers.
- c. This is how the body's cells construct macromolecules like polysaccharides, nucleic acids, and proteins.

### 3. **Hydrolysis Reaction:**

- a. This is the exact opposite of a dehydration reaction, involving "water splitting."
- b. It breaks down a large molecule into smaller pieces by **adding a water molecule**, which is split into -H and -OH and attached to the separated fragments.
- c. Hydrolysis is crucial during **digestion**, breaking down large food molecules (e.g., proteins) into smaller, absorbable subunits (e.g., amino acids).
- d. These smaller subunits can then be absorbed into the body and used to build new macromolecules through dehydration reactions.

## IV. **Major Categories of Macromolecules**

### A. **Polysaccharides (Carbohydrates)**

- 1. Polysaccharides are one of the four main types of organic macromolecules and are officially categorized as **polymers**.
- 2. Their individual building blocks (monomers) are called **monosaccharides**, or simple sugars.
  - a. **Glucose** is the most important monosaccharide, serving as the master fuel for all cells.
  - b. Other important monosaccharides include fructose.
- 3. Polysaccharides are formed by hooking together many monosaccharides.
  - a. A **disaccharide** (e.g., table sugar, which is glucose and fructose combined) consists of two sugars but is not large enough to be called a polysaccharide.
- 4. Many polysaccharides serve as **storage molecules** for glucose:
  - a. **Starch** is the storage polysaccharide used by **plants** to store



excess glucose.

- b. **Glycogen** is the storage polysaccharide used by **animals** (including humans) for the same purpose, particularly in the liver.
- c. The liver continuously builds glycogen (via dehydration) to store excess blood glucose after a meal and breaks it down (via hydrolysis) to release glucose when blood sugar levels drop, maintaining homeostasis.

## B. Lipids

- 1. Lipids are a category of organic macromolecules, but they are **not technically polymers** because they are not built from repeating monomer subunits in the same way as the other three categories.
- 2. **Fats** are a specific type of lipid. (Not all lipids are fats).
  - a. Fats are highly efficient for storing energy due to their **high energy density**.
  - b. A typical fat molecule consists of one **glycerol** molecule attached to three individual **fatty acids**.
  - c. The high energy density of fats comes from the many carbon-hydrogen bonds within the fatty acids.
- 3. **Fatty Acids** can be classified into two major types:
  - a. **Saturated fatty acids** are "saturated" with hydrogen atoms, meaning they have only single bonds between their carbon atoms, allowing them to hold the maximum number of hydrogens.
    - (1) They have **straight chains**.
    - (2) Due to their straight shape, they can stack neatly and tend to be **solids at room temperature** (e.g., butter, lard), commonly produced by animals.
  - d. **Unsaturated fatty acids** are not saturated with hydrogen because they contain at least one **double bond** between carbon atoms.
    - (1) These double bonds introduce a characteristic **bend** in the fatty acid chain.
    - (2) Due to their bent shape, they do not stack neatly and tend to be **liquids at room temperature** (e.g., oils), commonly

produced by plants.

4. **Phospholipids** are extremely important lipids.

- a. Their structure is similar to a fat, but they have only **two fatty acids** and a **phosphate group** attached to the glycerol.
- b. Phospholipids are **amphopathic** molecules, meaning they have dual preferences:
  - (1) The "head" region, containing the phosphate group, is **polar** and hydrophilic (attracts water).
  - (2) The "tails," consisting of the fatty acids (made of carbons and hydrogens with equal electronegativity), are **non-polar** and hydrophobic (repel water).
- e. This amphopathic nature causes phospholipids to spontaneously self-assemble in water to form a **phospholipid bilayer**, which is the main structural component of the plasma membrane of all cells, making them essential for the existence of life.

5. **Cholesterol** is another vital type of lipid.

- a. It is characterized by its distinct structural formula of **four interconnected rings**.
- b. Cholesterol serves as a **precursor molecule for all steroid hormones** in the body, including sex steroids like estrogens, progesterones, and testosterone.
- c. All animals require cholesterol for survival and produce their own, even if not consumed in the diet.
- d. It is also an important component of the plasma membrane.

C. **Proteins**

1. Proteins are essential organic macromolecules and are categorized as **polymers**.
2. Their individual building blocks (monomers) are called **amino acids**. There are 20 different amino acids commonly used by all organisms in nature.
3. Amino acids are linked together by **peptide bonds** to form a long, unbranched chain called a **polypeptide**.

4. The specific three-dimensional **shape (or confirmation)** of a protein is critical because it directly determines the protein's specific job or function.
5. Protein structure is described in four hierarchical levels:
  - a. **Primary structure**: Refers to the particular, linear sequence of amino acids within a polypeptide chain.
  - b. **Secondary structure**: Involves common, often repeated, local folding patterns within the polypeptide, such as the corkscrew-shaped **alpha helices** and the folded **pleated sheets**.
  - c. **Tertiary structure**: Describes the overall, complex **three-dimensional shape** of a single polypeptide chain, resulting from further folding and interactions. For proteins made of only one polypeptide, this is the highest level of structure.
  - d. **Quaternary structure**: Applies to proteins made of at least two different polypeptide chains (multimeric proteins). It describes how these multiple polypeptide chains are assembled together to form the complete, functional protein (e.g., hemoglobin, which has four polypeptides).
6. Proteins can be broadly classified by their overall shape:
  - a. **Fibrous proteins** are long and fiber-like, typically having **structural functions** (acting like ropes or cables).
  - b. **Globular proteins** have a more compact, "globular" shape and perform a **huge variety of functions**.
7. A crucial type of globular protein is an **enzyme**.
  - a. An enzyme acts as a **catalyst**, which is a substance that speeds up the rate of a chemical reaction without being consumed in the process.
  - b. Enzymes are reusable after a reaction, continuing to catalyze more reactions.
  - c. They are indispensable in biology because thousands of chemical reactions within cells would occur too slowly to sustain life without their catalytic action.

## D. Nucleic Acids

1. Nucleic acids are the fourth major category of organic macromolecules and are also classified as **polymers**.
2. The two main types of nucleic acids are **DNA** (Deoxyribonucleic Acid) and **RNA** (Ribonucleic Acid). They are called "nucleic acids" because DNA was first discovered in the nucleus of eukaryotic cells.
3. The monomer subunits that are linked together to form nucleic acids are called **nucleotides**.
4. A long strand of nucleotides is also referred to as a **polynucleotide**.
5. Each **nucleotide** consists of three components:
  - a. A **five-carbon sugar** (deoxyribose in DNA, ribose in RNA).
  - b. A **nitrogenous base** (there are four different types used in DNA and four different types used in RNA).
  - c. A **phosphate group** (composed of a phosphorus atom and four oxygen atoms).
6. **DNA (Deoxyribonucleic Acid):**
  - a. Is arguably the most famous molecule in the world, known for carrying genetic information.
  - b. It is an enormously long molecule, consisting of millions of nucleotides in a single chromosome.
  - c. DNA is typically composed of **two polynucleotide strands**.
  - d. These two strands are associated with each other via **hydrogen bonds** formed between their nitrogenous bases (adenine, guanine, cytosine, and thymine).
  - e. This structure results in a characteristic **double helix** shape, which can be thought of as a twisted ladder.
  - f. The two primary functions of DNA are **replication** (copying itself) and **transcription** (acting as a template for RNA synthesis).
7. **ATP (Adenosine Triphosphate):**
  - a. ATP is a specific type of **nucleotide** that is critically important by itself, serving as a versatile **energy-carrying molecule** in all cells.

- b. It is often described as the "**energy currency of the cell**" because it temporarily stores and transfers energy.
- c. Energy from food is extracted and stored in the bonds of ATP molecules.
- d. This stored energy is released through a **hydrolysis reaction**, specifically by breaking a bond between its outermost two phosphate groups, converting ATP (triphosphate) into ADP (diphosphate) and a free phosphate group.
- e. The energy released from ATP hydrolysis powers three main types of cellular work:
  - (1) **Chemical work**: Driving energy-requiring (uphill) chemical reactions that would not occur spontaneously.
  - (2) **Transport work**: Powering **transmembrane transport**, which involves moving substances across cell membranes, either into or out of the cell.
  - (3) **Mechanical work**: Enabling the movement of cellular parts, most notably muscle contraction in the body.