Biomolecules and Cells

Introduction

Biochemistry is the science dedicated to understanding life at the molecular level, examining the chemical processes and structures that occur within living organisms. The basic unit of this study is the cell, which is fundamentally built from four major classes of macromolecule: proteins, nucleic acids, carbohydrates, and lipids. Their unique structures and interactions, governed by the crucial solvent properties of water, form the foundational concepts for understanding all biological processes.

- Biochemistry is the study of the chemical processes within and relating to living organisms.
- The fundamental unit of life is the cell.
- Life maintains a **"steady state"** far from equilibrium, requiring constant energy input to counteract entropy.
- The composition and organization of the cell, along with the unique properties of water, are essential foundational concepts for understanding all biochemical processes.

Learning Objectives

By the end of this module, you will be able to:

- Identify the two main types of cells and differentiate their structures.
- Describe the structure, organization, and supramolecular assemblies within a eukaryotic cell.
- Identify the major biochemical composition and specific function of key cell organelles.
- **Identify key functional groups** (hydroxyl, carboxyl, amino, etc.) that dictate biomolecular reactivity.
- Review the unique properties of water, explain acid-base equilibria, and describe the function of buffers in biological systems.

Key Concepts and Definitions

Term	Definition
Prokaryotic Cell	A simple cell lacking a nucleus and other membrane-bound organelles (e.g., bacteria).
Eukaryotic Cell	A complex cell containing a membrane-bound nucleus and numerous organelles (e.g., animal, plant, fungal cells).
Organelle	A membrane-bound structure within a eukaryotic cell that performs a specific, compartmentalized function
Biomolecules	The four major classes of organic molecules essential for life: Proteins, Nucleic Acids, Carbohydrates, and Lipids.
Hydrophilic	"Water-loving" substances, typically polar or ionic, that interact well with water and dissolve readily.
Hydrophobic	"Water-fearing" substances, typically non-polar, that do not dissolve in water; their separation is driven by entropy.
Buffer	An aqueous system, usually a weak acid and its conjugate base, that resists drastic changes in pH upon the addition of acid or base.
Steady State	A condition where the rate of formation of a substance equals its rate of breakdown, maintaining constant internal conditions despite external changes.

Detailed Discussion

The Chemical Language: Functional Groups

The reactivity of the four major biomolecules is determined by specific clusters of atoms called functional groups. According to Campbell & Farrell, the most critical for biochemistry are:

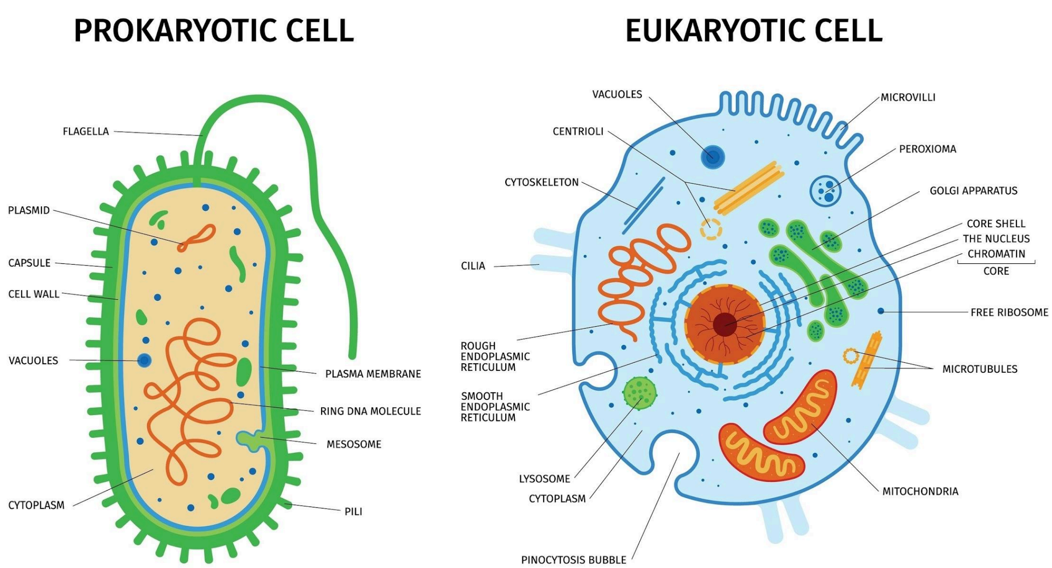
- **Hydroxyl (-OH):** Found in alcohols and sugars; increases water solubility.
- **Carbonyl (C=O):** Found in aldehydes and ketones; central to energy metabolism.
- **Carboxyl (-COOH):** Acts as an acid; found in amino acids and fatty acids.
- **Amino ($-NH_2$):** Acts as a base; found in amino acids and nucleic acids.
- **Phosphate ($-PO_4^{3-}$):** Essential for energy transfer (ATP) and the backbone of DNA/RNA.

Types of Cells, Structure, and Organization

- Explanation: Organisms are grouped into prokaryotes (Bacteria and Archaea) and eukaryotes (Protists, Fungi, Plants, and Animals). Prokaryotic cells are simpler, with DNA concentrated in a nucleoid region and lacking true membrane-bound organelles. Eukaryotic cells are defined by the presence of a nucleus and a complex internal organization of organelles.

Prokaryotes vs. Eukaryotes

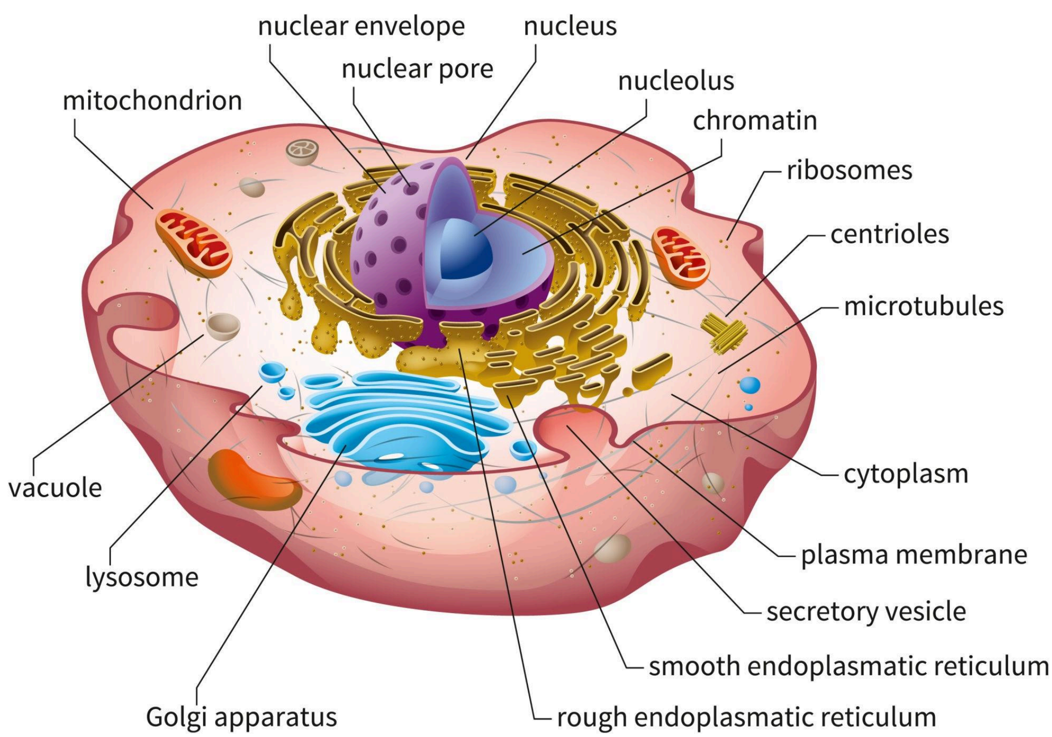
- **Prokaryotic Cells:** Smaller, lack a membrane-bound nucleus. Their "genome" is located in a **nucleoid**. They contain **ribosomes** (70S) for protein synthesis but lack membrane-bound organelles like mitochondria.
- **Eukaryotic Cells:** Characterized by **compartmentalization**. Membranes create distinct microenvironments (organelles) where specific pH levels or enzyme concentrations can be maintained.



- Supramolecular Assemblies: Within a cell, biomolecules self-assemble into large, complex structures. For instance, phospholipids spontaneously assemble into the plasma membrane (a lipid bilayer), which separates the cell's interior (intracellular fluid) from the exterior (extracellular fluid) and controls substance exchange.

Biochemical Composition and Function of Cell Organelles

- Explanation: Cells are approximately 70% water, with the remaining mass comprising inorganic ions and organic macromolecules. These macromolecules form the structure and machinery of the organelles:



  - Nucleus: Stores the cell's genetic information (DNA), which is structured as chromatin. The DNA (nucleic acid) and associated histone proteins form the core composition. Site of DNA replication and RNA synthesis (Transcription).
  - Mitochondria : The site of cellular respiration; it converts energy from food into the chemical energy molecule ATP. The inner membrane contains the protein complexes for the electron transport chain.
  - Ribosomes: Synthesize proteins (translation) by reading RNA. They are composed of ribosomal RNA (rRNA) and protein.

- Endoplasmic Reticulum (ER):
- Rough ER (RER): Studded with ribosomes; involved in synthesizing, folding, and modifying proteins, especially those destined for secretion or membranes.
- Smooth ER (SER): Synthesis of lipids and steroids, and detoxification.
- Golgi Apparatus: Modifies, sorts, and packages proteins and lipids received from the ER, preparing them for transport to other parts of the cell or for secretion.
- Lysosomes: Contain powerful enzymes (proteins) that break down ingested materials, foreign substances, and worn-out cell parts.

Water: The Solvent of Life

Water is not just a "filler"; it is an active participant in biochemical reactions.

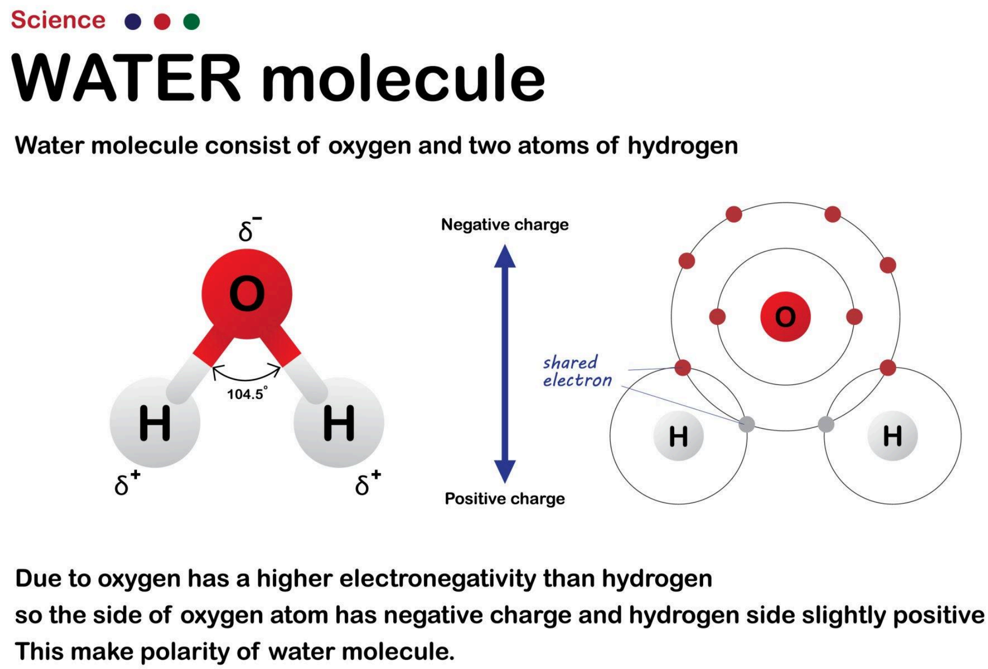
1. Non-Covalent Interactions

While individual non-covalent bonds are weak, their cumulative effect provides stability to DNA and proteins.

- **Hydrogen Bonds:** Formed between a hydrogen atom covalently bonded to an electronegative atom (O, N) and another electronegative atom.
- **Ionic Interactions:** Electrostatic attractions between permanently charged species.
- **Van der Waals Forces:** Weak, short-range attractions between all atoms due to transient dipoles.
- **Hydrophobic Effect:** The tendency of non-polar molecules to aggregate in water. This is driven by **entropy**; when non-polar molecules cluster, fewer water molecules are "ordered" in clathrate cages, increasing the overall randomness of the system.

Properties of Water, Acid-Base Equilibria, and Buffers

- Explanation (Water): Water is uniquely essential for life due to its polarity and ability to form extensive hydrogen bonds. The oxygen atom is highly electronegative, creating partial negative and positive charges, which allows water to act as the universal solvent. This polarity drives the structure of biomolecules: hydrophilic molecules interact with water, while hydrophobic molecules cluster away from water (the hydrophobic effect), which is crucial for protein folding and membrane stability.



- Explanation (Acid-Base Equilibria): Biological processes are extremely sensitive to the concentration of hydrogen ions (H+), measured by the pH scale.
  - Acids release H+, and bases consume H+.
  - The degree of dissociation for a weak acid (HA) is governed by the Henderson-Hasselbalch Equation:

$$\mathrm{pH} = \mathrm{p}K_a + \log \frac{[\text{Conjugate Base, } A^-]}{[\text{Weak Acid, } HA]}$$

- **Example (Buffers): Buffers** are vital for maintaining **homeostasis**. For example, blood pH must remain within a narrow range (7.35–7.45).
  - The major extracellular buffer is the **bicarbonate buffer system** $(\mathrm{H_2CO_3}/\mathrm{HCO_3^-})$.
  - The major intracellular buffer is the **phosphate buffer system**.
  - These systems use the $\log(\frac{[A^-]}{[HA]})$ ratio to resist large shifts in pH when metabolic acids or bases are produced.

Biological Buffer Systems

- Phosphate Buffer System: Primarily intracellular. The active species are $H_2PO_4^-$ (acid) and HPO_4^{2-} (base). $pK_a \approx 7.2$
- .Bicarbonate Buffer System: The primary blood buffer. It is an "open system" because the concentration of CO_2 is regulated by respiration:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

Hyperventilation decreases CO_2, shifting the equilibrium to the left and increasing blood pH (Respiratory Alkalosis).

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