I. Atoms, Ions, and Chemical Bonds

Body Chemistry

• A general understanding of chemistry is necessary for understanding human physiology.
  – Physiological processes are based on chemical interactions.

Atoms

• An atom is the smallest unit of an element. It has:
  – A nucleus with positively charged protons and uncharged neutrons
  – Orbiting electrons with negative charges
  – An atomic mass equal to the number of protons plus the number of neutrons
  – An atomic number equal to the number of protons

Electron Orbitals

• Orbitals (or shells) are energy levels that surround the nucleus of an atom.
• Electrons fill the shells, starting with the one closest to the nucleus.
  – The first shell holds 2 electrons.
  – Each shell thereafter holds 8 electrons. (Nonbiological elements fill distant shells that hold more than 8.)
  – Atoms are most stable when the outer shell is filled. Electrons in unfilled outer shells participate in bonding; they are called valence electrons.
Common Biological Atoms

Isotopes

- Sometimes atoms do not have the same number of neutrons as protons.
  - Their atomic number is the same, but the atomic mass is different.
  - Some isotopes are radioactive and used in medical testing and physiological research.

Chemical Bonds

- A molecule forms when electrons of several atoms interact to form chemical bonds.
  - The number of bonds an atom can form is determined by the number of valence electrons.
    - Hydrogen has one electron; it needs one more to fill the inner shell so that it can form one bond.
    - Carbon has 6 electrons; 2 fill the inner shell and 4 are in the next shell. It needs 4 more electrons so that it can form 4 bonds.

Covalent Bonds

- Valence electrons are shared.
  - Nonpolar electrons are shared equally.
    - Example: 2 hydrogen atoms
  - Polar electrons are not shared equally; they have positive and negative ends.
    - Example: water

Covalent Bonds

Water

- Polar molecule
- Good solvent (substances dissolve in it)
- When split, it can contribute to the pH of a substance.
In an ionic bond, one atom gives electrons to another so that both have filled valence shells.

- The electron donor becomes positively charged.
- Atom now called a cation.
- The electron receiver becomes negatively charged.
- Atom now called an anion.
- Cations and anions form ionic compounds.

Much weaker than covalent bonds
- They easily dissociate when dissolved in water.
  - The negative side of water is attracted to the cation, and the positive side of water is attracted to the anion.
  - Molecules that dissolve in water are considered hydrophilic.
  - Fat is made up of nonpolar covalent bonds and will not dissolve in water. It is hydrophobic.

Sodium + chlorine →
Sodium ions (Na⁺)
+ Chloride ions (Cl⁻)

These free ions are critical to many physiological processes.
Hydrogen bond

- Weak bond formed between two polar molecules based on opposite charges attracting (not based on electron sharing)
  - Forms between water molecules
  - Forms between amino acids on a protein to produce the 3D structure of the protein
  - Holds the two strands of the DNA molecule together.

Acids, Bases, and pH

- Some water molecules break to form free hydrogen ions (H\(^+\)) and hydroxide ions (OH\(^-\)).

- When this happens, there are the same number of H\(^+\) ions as OH\(^-\) ions in solution, so the solution is neutral.

- A neutral solution is said to have a pH of 7 (which means 10\(^{-7}\) molar concentration H\(^+\)).

Acids, Bases, and pH

- Sometimes a solution has more H\(^+\) ions than OH\(^-\) ions. This is called an acid, and its pH is below 7.
  - Often called a proton donor

- Sometimes a solution has more OH\(^-\) ions than H\(^+\) ions. This is called a base, and its pH is above 7. (Such solutions are also called alkaline.)
  - Often called a proton acceptor

pH Scale

- Runs from 0 to 14, with 0 the strongest acid and 14 the strongest base.

\[
pH = \log \frac{H^+ \text{ concentration}}{10^{-7}}
\]

- Pure water has a H\(^+\) concentration of 10\(^{-7}\), so the pH is 7. A pH 6 solution actually has 10 times the number of H\(^+\) ions.

Buffers

- Buffers stabilize H\(^+\) concentration in a solution.
  - In blood, two molecules stabilize pH: bicarbonate ion (HCO\(_3^-\)) and carbonic acid (H\(_2\)O\(_3\)).

\[
HCO_3^- + H^+ \leftrightarrow H_2O_3
\]

- If blood falls below pH 7.35, the condition is called acidosis.
- If blood rises above pH 7.45, the condition is called alkalosis.
Organic Molecules

- Contain carbon and hydrogen
  - Because carbon must form 4 bonds to satisfy the valence shell, it can form chains and rings of carbons while still bonding with other atoms.
  - Two carbons can share 1 or 2 electrons. If 2 are shared, it is a double bond and can bond with 2 additional atoms. If 1 electron is shared, it can bond with 3 additional atoms.

Carbon Rings

- Carbons are not shown but are understood to be at the corners of the molecule. Some show double bonds.
- Carbon rings form backbones for more reactive groups of atoms called functional groups.

Functional Groups

- Classes of molecules are named after their functional group.
Stereoisomers

- Two molecules can have exactly the same atoms arranged in exactly the same sequence, but still differ in the spatial organization of their functional groups.
  - This characteristic is critical to function. A given enzyme may interact with one stereoisomer but not with another.
  - The sugars glucose, galactose, and fructose are stereoisomers.

II. Carbohydrates

Carbohydrates

- Organic molecules that contain carbon, hydrogen, and oxygen in a 1:2:1 ratio.
- Serve as a major source of energy in the body
- Include sugars and starches

Carbohydrates

- Monosaccharide: simple sugar, one carbon ring
  - Examples: glucose, fructose, galactose
- Disaccharide: two monosaccharides joined by a covalent bond
  - Examples: sucrose, maltose, lactose
- Polysaccharide: several monosaccharides joined together
  - Example: starch (composed of thousands of glucose molecules)

Carbohydrates

- Glycogen: another polysaccharide formed to store sugar in a cell
  - Glycogen does not pull in water via osmosis as simple sugars do.
- Cellulose: a polysaccharide made by plants
  - Cellulose is not digestible by humans.
Glycogen

Dehydration Synthesis and Hydrolysis

• Covalent bonds that hold monosaccharides together are formed via dehydration synthesis.
  – A hydrogen atom is removed from one molecule, and a hydroxyl group is removed from another to form water.
• Hydrolysis breaks bonds between monosaccharides.
  – Water is split and used to complete the individual molecules.
  • These processes are also used to build/break fats, proteins, and nucleic acids.

Dehydration Synthesis

Hydrolysis

III. Lipids

Lipids

• Lipids consist of nonpolar hydrocarbon chains and rings.
  – This makes them hydrophobic (insoluble in water).
• There are several categories of lipids.
Triglycerides (Triglycerols)

- Include fats and oils
- Composed of one molecule of glycerol and three molecules of fatty acids

Saturated and Unsaturated Fats

- If every carbon on the fatty acid chain shares a single electron, the fatty acid is saturated.
- If there are double bonds between carbons, the fatty acid is unsaturated.

Ketone Bodies

- Hydrolysis of triglycerides forms free fatty acids in the blood. These can be used for energy or converted into ketone bodies by the liver.
  - Strict low-carbohydrate diets and uncontrolled diabetes can result in elevated ketone levels, called ketosis.
  - Ketone levels low enough to lower pH can cause ketoacidosis, which can lead to coma and death.
Phospholipids

- Lipids with a phosphate group, which makes them polar.
  - Major component of cell membranes as a double layer, with hydrophilic phosphates pointing outward on each side and hydrophobic fatty acids and glycerol pointing inward.
  - As micelles, phospholipids can act as surfactants. The polar nature of the molecule decreases the surface tension of water.
    - Surfactant keeps lungs from collapsing.

Micelles and Water

Steroids

- A steroid is structurally very different from a triglyceride but nonpolar, so considered a lipid.
  - 3 six-carbon rings + 1 five-carbon ring + functional groups

Steroids

- Cholesterol is a steroid used (1) as a precursor to steroid hormones, such as testosterone, estrogen, and aldosterone, and (2) to make molecules such as vitamin D and bile salts.

Prostaglandins

- Type of fatty acid with a cyclic hydrocarbon group
  - Serve as communication molecules between cells in the same organ
  - Help regulate blood vessel diameter, ovulation, uterine contractions, inflammatory reactions, blood clotting, etc.
IV. Proteins

Proteins

- Composed of an amino acid chain
  - There are 20 different amino acids that can be combined in an endless number of ways.
  - Amino acids are charged, so they attract each other to form kinks and folds in the protein.
  - The sequence of amino acids in a chain is determined by DNA.

Amino Acids

- An amino acid has an amino group, a carboxyl group, and a functional group.
  - The functional group is what differentiates the 20 amino acids.

Making a Protein

- When amino acids are joined, a H is stripped from the amino end and a OH is stripped from the carboxyl end in dehydration synthesis. This is called a peptide bond.
Making a Protein

Protein Structure

- A chain of amino acids is called a *polypeptide chain*.
  - The chain varies in length from 3 to 4,500 amino acids.
  - The chain is called the *primary structure* of the protein.
- Weak hydrogen bonds may form between neighboring amino acids.
  - This may form an alpha helix or a beta fold.
  - This is called the *secondary structure* of the protein.

Protein Structure

- Attraction to amino acids further away produces bends and folds, creating a specific 3D shape.
  - This is the *tertiary structure* of the protein.
  - This structure dictates function.
  - Since weak bonds hold tertiary structure together, a protein is easily denatured (unfolded) by changes in pH or temperature.

Protein Structure

- Some functional proteins are composed of multiple polypeptide chains covalently bonded together.
  - This is called the *quaternary structure* of the protein.
  - Examples are the hemoglobin in blood and the hormone insulin.
Conjugated Proteins

• Sometimes proteins are combined with other molecules:
  – Glycoprotein = Protein + Carbohydrate
    • Examples: some hormones
  – Lipoprotein = Protein + Lipid
    • Example: in cell membranes, carrier molecules in blood

Protein Functions

• Structural: collagen fibers in connective tissues; keratin in skin
• Enzymes: assist every chemical process in the body
• Antibodies: part of the immune system
• Receptors: receive communication from other cells for regulation of cell activity
• Carriers: across cell membranes or in blood

V. Nucleic Acids

Nucleotides

• Building blocks for nucleic acids
  – Composed of a five-carbon sugar, a phosphate group, and a nitrogenous base
  – Nitrogenous bases fall into two categories:
    • Pyrimidine: a single carbon ring + nitrogen
    • Purine: 2 carbon rings + nitrogen

Deoxyribonucleic Acid (DNA)

• The sugar in this molecule is called deoxyribose and can bind to one of four nitrogenous bases:
  – Guanine
  – Thymine
  – Cytosine
  – Adenine
**Deoxyribonucleic Acid (DNA)**

- Deoxyribose bonds with a phosphate group (via dehydration synthesis) to form a long chain, which serves as the backbone of the molecule.
- Each nitrogenous base can form a hydrogen bond with another to result in a double-stranded molecule.
  - Cytosine can only bind with guanine.
  - Tyrosine can only bind with adenine.
- The two chains of DNA are twisted, forming a double helix.

**DNA Structure**

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<tr>
<th>DNA Structure</th>
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<tr>
<td><img src="image1.png" alt="Diagram of DNA structure" /></td>
<td><img src="image2.png" alt="Diagram of DNA structure" /></td>
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**Ribonucleic Acid (RNA)**

- Similar to DNA except:
  - Has ribose sugar instead of deoxyribose
  - Is single-stranded instead of double-stranded
  - Has uracil instead of thymine

**Ribonucleic Acid (RNA)**

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<td><img src="image4.png" alt="Diagram of DNA nucleotides" /></td>
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Types of RNA

- Three types of RNA are used to take information for assembling a protein out of the nucleus and to actually assemble it:
  - Messenger RNA
  - Transfer RNA
  - Ribosomal RNA

- Other RNA-related molecules serve important functions in the body: ATP, cAMP, NAD, FAD.