Anatomy and Physiology: Chemical Fundamentals

AI-Generated Study Guide

(Based on lectures delivered by Dr. Ty C.M. Hoffman)

I. Fundamental Chemistry

- **A. Atoms and Subatomic ParticlesDefinition of an atom:** The basic unit of all material things in the universe.
- **Components of an atom:Protons:** Positively charged subatomic particles, located in the nucleus. Determine the element (atomic number).
- **Neutrons:** Neutrally charged subatomic particles, located in the nucleus. Contribute to mass but not charge.
- **Electrons:** Negatively charged subatomic particles, orbiting the nucleus in a probability cloud (though often depicted in a planetary model). Much smaller than protons and neutrons, but carry an equal and opposite charge to protons.
- **Atomic Regions:Nucleus:** Central part of the atom containing protons and neutrons.
- **Electron Cloud/Shells:** Space around the nucleus where electrons are found.
- **Charge Neutrality:** In a neutral atom, the number of protons (positive charges) equals the number of electrons (negative charges), resulting in an overall zero charge.
- **B. Elements, Isotopes, and IonsElement:** A substance made of only one kind of atom, defined by the number of protons (atomic number).
- **Atomic Number:** The number of protons in an atom, unique to each element.
- **Isotopes:** Different versions of the same element that have the same number of protons but different numbers of neutrons, leading to different masses (e.g., heavy hydrogen: deuterium, tritium).
- **Ions:** Atoms that have gained or lost electrons, resulting in an overall electrical charge.
- **Cation:** Positively charged ion (lost electrons).
- **Anion:** Negatively charged ion (gained electrons).
- **C. Electron Shells and StabilityElectron Shells/Subshells:** Specific energy levels or regions where electrons are located around the nucleus. Each shell has a maximum number of electrons it can hold.
- **Valence Shell:** The outermost electron shell of an atom that contains at least one electron.
- **Valence Electrons:** Electrons in the valence shell.

- **Stability (Octet Rule/Duet Rule):** Atoms achieve stability when their outermost electron shell is completely filled (e.g., 2 electrons for the first shell, 8 for the second). Noble gases (Group 18 elements like Helium and Neon) have full valence shells and are therefore inert (non-reactive).
- **Reactivity:** Atoms that do not have full valence shells are unstable and tend to react with other atoms to achieve stability by gaining, losing, or sharing electrons.
- **Metals vs. Non-metals:Metals:** Tend to lose electrons to achieve stability, forming cations. Their valence shells are mostly empty.
- **Non-metals:** Tend to gain electrons to achieve stability, forming anions, or share electrons. Their valence shells are almost full. Hydrogen is an exception, being a non-metal despite its position.
- **D. Chemical BondsDefinition:** Form when atoms interact and rearrange electrons to form new substances.
- **Ionic Bonds:**Form between a metal and a non-metal.
- Involve the **transfer** of electrons from one atom to another.
- Results in the formation of oppositely charged ions (cations and anions) that are attracted to each other.
- Weaker than covalent bonds. (e.g., Sodium Chloride, NaCl)
- **Covalent Bonds:**Form between two non-metals.
- Involve the **sharing** of valence electrons between atoms.
- Stronger than ionic bonds.
- Represented by dashes (one dash = two shared electrons).
- Can be single, double, or triple bonds.
- **Valence (of an atom):** The number of bonds an atom typically forms to achieve stability (e.g., Oxygen has a valence of 2, Carbon has a valence of 4).
- **Electronegativity:** A measure of an atom's "greediness" for shared electrons.
- **Types of Covalent Bonds:Nonpolar Covalent Bond:** Involves **equal sharing** of electrons between atoms with similar electronegativity values (e.g., O2, CO2 due to symmetry). No partial charges.
- **Polar Covalent Bond:** Involves **unequal sharing** of electrons between atoms with significantly different electronegativity values. Results in partial positive (δ+) and partial negative (δ-) charges on different parts of the molecule (e.g., H2O).
- **Hydrogen Bonds:**Weak attractive forces between polar molecules (not chemical bonds because they don't form new substances).
- Occur when a partially positive hydrogen atom in one molecule is attracted to a partially negative atom (like oxygen or nitrogen) in another molecule.
- Crucial for the special properties of water (e.g., surface tension, solvent capabilities).

II. Water and pH

- **A. Water (H2O): A Polar Molecule**Oxygen is highly electronegative, pulling shared electrons closer to itself, making the oxygen end partially negative and the hydrogen ends partially positive.

- **Special Properties due to Polarity:Surface Tension:** Hydrogen bonds create a "skin-like" effect on the water's surface.
- **Excellent Solvent:** Water's polarity allows it to dissolve many polar and ionic substances (solutes) by surrounding and separating them.
- **B. pH ScalePurpose:** Measures the acidity or basicity (alkalinity) of a solution.
- **Logarithmic Scale:** Each unit change represents a tenfold change in hydrogen ion concentration.
- **Acids:** Hydrogen-containing compounds that dissociate in water, releasing hydrogen ions (H+). Higher H+ concentration = lower pH = more acidic. (pH < 7)
- **Bases (Alkaline):** Compounds that reduce hydrogen ion concentration (often by releasing hydroxide ions or accepting H+). Lower H+ concentration = higher pH = more basic/alkaline. (pH > 7)
- **Neutrality:** pH of 7 (equal H+ and OH- concentration).
- **Biological Importance:** Maintaining a stable pH (homeostasis) is critical for cell survival and proper bodily function (e.g., blood pH, stomach acid exception).

III. Macromolecules of Life

- **A. Synthesis and BreakdownMonomers:** Small molecular subunits.
- **Polymers:** Large molecules formed by linking many monomers together.
- **Dehydration Synthesis (Condensation Reaction):**Builds larger molecules (polymers) from smaller ones (monomers).
- Involves the **removal of a water molecule** for each bond formed between monomers.
- **Hydrolysis:**Breaks down larger molecules (polymers) into smaller ones (monomers).
- Involves the **addition of a water molecule**, which is split to break the bond.
- Essential for digestion.
- **B. Four Categories of Organic Macromolecules**These four categories are **organic** (carbon-containing) and essential for all organisms.
- All contain Carbon, Oxygen, and Hydrogen. Proteins and Nucleic Acids also contain Nitrogen.
- **1. Polysaccharides (Carbohydrates):Monomer:** Monosaccharides (simple sugars, e.g., glucose, fructose).
- **Polymer:** Polysaccharide (many sugars hooked together).
- **Function:** Primary energy source (glucose is the master fuel), energy storage (starch in plants, glycogen in animals), structural support.
- **Examples:Starch:** Storage polysaccharide in plants.
- **Glycogen:** Storage polysaccharide in animals (stored in liver and muscles).
- **Cellulose, Chitin** (not explicitly detailed, but implied as structural).
- **2. Lipids:Not polymers** in the same way as the others, but still macromolecules.
- **Characteristics:** Tend to be non-polar (hydrophobic - "water-fearing").
- **Examples:Fats (Triglycerides):**Structure: Glycerol molecule + three fatty acids.
- Function: Efficient energy storage (high energy density).
- Types:

- **Saturated Fatty Acids:** No double bonds between carbons; "saturated" with hydrogen; straight shape; tend to be solid at room temperature (e.g., animal fats like butter, lard).
- **Unsaturated Fatty Acids:** One or more double bonds between carbons; "unsaturated" with hydrogen; bent shape (kinks); tend to be liquid at room temperature (oils, typically from plants).
- **Phospholipids:**Structure: Glycerol + two fatty acids + a phosphate group.
- Amphipathic: Has both a polar (hydrophilic) head (phosphate group) and nonpolar (hydrophobic) tails (fatty acids).
- Function: Primary component of cell membranes (phospholipid bilayer), crucial for the formation of cells and life itself.
- **Steroids:**Structure: Characterized by four fused carbon rings.
- Example: Cholesterol (a precursor for other steroids like sex hormones: estrogen, testosterone, progesterone).
- Function: Hormones, component of cell membranes.
- **3. Proteins:Monomer:** Amino acids (20 common types in nature).
- **Polymer:** Polypeptide (string of amino acids linked by peptide bonds). Proteins can consist of one or more polypeptides.
- **Structure/Confirmation (Four Levels):Primary Structure:** Unique sequence of amino acids in a polypeptide chain.
- **Secondary Structure:** Localized folding patterns (e.g., alpha helices, beta-pleated sheets) formed by hydrogen bonds.
- **Tertiary Structure:** Overall three-dimensional shape of a single polypeptide, determined by interactions between amino acid side chains.
- **Quaternary Structure:** (For proteins with multiple polypeptides) The arrangement of multiple polypeptide chains to form a functional protein (e.g., hemoglobin).
- **Shapes:Fibrous Proteins:** Long, fiber-like; often have structural functions (e.g., collagen, keratin).
- **Globular Proteins:** Compact, spherical shape; diverse functions.
- **Functions (Diverse and numerous):** Enzymes (catalysts), structural support, transport (e.g., hemoglobin), defense, regulation (hormones), movement.
- **Enzymes:** Biological catalysts (mostly proteins) that speed up chemical reactions without being consumed in the reaction; highly specific and reusable.
- **4. Nucleic Acids:Monomer:** Nucleotides.
- **Polymer:** Polynucleotide.
- **Structure of a Nucleotide:**Five-carbon sugar (deoxyribose in DNA, ribose in RNA).
- Nitrogenous base (A, T, C, G in DNA; A, U, C, G in RNA).
- Phosphate group(s).
- **Examples:DNA (Deoxyribonucleic Acid):**Structure: Double helix (two polynucleotide strands held together by hydrogen bonds between nitrogenous bases).
- Function: Stores genetic information, self-replication (copying itself), transcription (template for RNA synthesis).
- **RNA (Ribonucleic Acid):**Typically single-stranded.
- Function: Involved in protein synthesis (carries genetic information from DNA).

- **ATP (Adenosine Triphosphate):**A modified nucleotide (adenine, ribose, and three phosphate groups).
- Function: The primary energy currency of the cell, providing energy for various cellular processes (chemical work, transport work, mechanical work) by breaking the bond between its second and third phosphate groups (hydrolysis).

Quiz

1. Describe the three main subatomic particles, their location within an atom, and their electrical charge.
2. Explain the difference between an element, an isotope, and an ion. Provide an example for each.
3. What is a valence shell and why is its fullness (or lack thereof) crucial for determining an atom's reactivity?
4. Compare and contrast ionic bonds and covalent bonds in terms of how electrons are involved and what types of atoms typically form them.
5. What is electronegativity, and how does it determine whether a covalent bond will be polar or nonpolar? Give an example of each.
6. Explain how water's polarity contributes to its ability to act as an excellent solvent for substances like salt.
7. Define dehydration synthesis and hydrolysis. How are these two reactions central to the building up and breaking down of macromolecules in living organisms?
8. Briefly describe the general structure of a fat molecule. How do saturated and unsaturated fatty acids differ structurally, and what is a key consequence of this difference at room temperature?
9. List the four levels of protein structure. Why is the overall three-dimensional shape (confirmation) of a protein so important?
10. What are the three components of a nucleotide? Name two important nucleic acids and briefly state their primary function in a cell.

Answer Key

1. **Protons** are positively charged and located in the nucleus. **Neutrons** are neutral (no charge) and also located in the nucleus. **Electrons** are negatively charged and orbit the nucleus in electron shells or a probability cloud.
2. An **element** is a substance made of only one kind of atom, defined by its number of protons (e.g., Hydrogen always has one proton). An **isotope** is a version of an element with the same number of protons but a different number of neutrons (e.g., Deuterium is an isotope of hydrogen with one neutron). An **ion** is an atom that has gained or lost electrons, resulting in an overall electrical charge (e.g., a sodium ion, Na+, has lost an electron).
3. The **valence shell** is the outermost electron shell of an atom that contains electrons. Its fullness determines an atom's reactivity because atoms strive for stability, which is

achieved when their valence shell is completely filled (like noble gases). Atoms with incomplete valence shells will react to gain, lose, or share electrons to achieve this full, stable configuration.

4. **Ionic bonds** involve the *transfer* of electrons from one atom to another, typically occurring between a metal and a non-metal. This transfer creates oppositely charged ions that are then attracted to each other. **Covalent bonds** involve the *sharing* of valence electrons between two atoms, usually two non-metals, allowing both atoms to achieve a stable electron configuration.
5. **Electronegativity** is an atom's measure of "greediness" or attraction for shared electrons in a covalent bond. If two atoms in a covalent bond have similar electronegativity values, they share electrons equally, forming a **nonpolar covalent bond** (e.g., O2). If they have significantly different electronegativity values, the electrons are shared unequally, resulting in a **polar covalent bond** with partial positive and negative charges (e.g., H2O).
6. Water is a **polar molecule** because its oxygen atom is more electronegative than its hydrogen atoms, leading to an unequal sharing of electrons. This creates a partially negative oxygen end and partially positive hydrogen ends. When ionic substances like salt (sodium chloride) are added to water, the charged ends of water molecules are attracted to the oppositely charged ions, surrounding and pulling them apart, effectively dissolving the salt.
7. **Dehydration synthesis** is a reaction that builds larger molecules (polymers) from smaller subunits (monomers) by *removing* a molecule of water for each bond formed. **Hydrolysis** is the opposite reaction, breaking down large molecules into smaller ones by *adding* a molecule of water, which splits the bond. These processes are fundamental for constructing complex molecules needed for growth and function, and for breaking down food for energy and absorption.
8. A fat molecule typically consists of a **glycerol** molecule bonded to three **fatty acids**. **Saturated fatty acids** have only single bonds between their carbon atoms, allowing them to be "saturated" with the maximum number of hydrogen atoms; they are straight. **Unsaturated fatty acids** contain one or more double bonds between carbon atoms, which create kinks or bends in their structure. This structural difference causes saturated fats to pack tightly and be solid at room temperature (e.g., butter), while unsaturated fats cannot pack as densely and are liquid at room temperature (e.g., oils).
9. The four levels of protein structure are: **primary** (sequence of amino acids), **secondary** (localized folding like alpha helices and beta-pleated sheets), **tertiary** (overall 3D shape of a single polypeptide), and **quaternary** (arrangement of multiple polypeptides in a multi-subunit protein). A protein's specific three-dimensional shape, or **confirmation**, is absolutely crucial because it dictates the protein's function; if the shape is altered, the protein often cannot perform its job.
10. A nucleotide consists of three parts: a **five-carbon sugar**, a **nitrogenous base**, and one or more **phosphate groups**. Two important nucleic acids are **DNA** (Deoxyribonucleic Acid), which stores genetic information and serves as a template for its own replication and RNA synthesis, and **ATP** (Adenosine Triphosphate), which serves as the primary energy currency of the cell, providing energy for various cellular activities.

Essay Format Questions

1. Discuss the critical role of electrons in both atomic stability and chemical reactions. Explain how the behavior of valence electrons dictates whether an atom will form ionic or covalent bonds, and elaborate on the implications of polar versus nonpolar covalent bonds for molecular properties.
2. Water is often called the "solvent of life." Explain how the atomic structure of a water molecule leads to its unique properties, focusing on polarity and hydrogen bonding. Illustrate how these properties are essential for biological processes, including solvent action and surface tension.
3. Trace the journey of a complex carbohydrate, such as starch, from ingestion to its utilization by your cells. Explain the roles of hydrolysis and dehydration synthesis in this process, connecting it to the concepts of monomers, polymers, and energy storage/release.
4. Compare and contrast the structure and functions of the four major categories of biological macromolecules: polysaccharides, lipids, proteins, and nucleic acids. For each category, discuss their primary building blocks (monomers, if applicable), general structural characteristics, and at least two vital roles they play in a living organism.
5. Explain how the pH scale works, including its logarithmic nature and the significance of hydrogen ion concentration. Discuss the importance of pH regulation (homeostasis) in the human body, providing examples of how deviations from optimal pH can be detrimental and how the body compensates.

Glossary of Key Terms

- **Acid:** A hydrogen-containing compound that, when added to water, dissociates to give up hydrogen ions (H+), increasing the solution's acidity.
- **Alkaline (Basic):** Solutions with a pH greater than 7, indicating a lower concentration of hydrogen ions.
- **Amino Acid:** The monomer subunit that makes up proteins.
- **Amphipathic:** A molecule having both a hydrophilic (polar) part and a hydrophobic (nonpolar) part, such as a phospholipid.
- **Anion:** A negatively charged ion, formed when an atom gains electrons.
- **Atom:** The smallest unit of matter that retains an element's chemical identity; the fundamental building block of all material things.
- **Atomic Number:** The number of protons in an atom's nucleus, which determines the element.
- **ATP (Adenosine Triphosphate):** A modified nucleotide that serves as the primary energy currency of the cell.
- **Base:** A compound that, when added to water, reduces the concentration of hydrogen ions, making the solution more alkaline.
- **Cation:** A positively charged ion, formed when an atom loses electrons.

- **Chemical Bond:** An attractive force that holds atoms together to form molecules or compounds, involving rearrangements of electrons.
- **Cholesterol:** A type of lipid (steroid) that is an essential component of animal cell membranes and a precursor for steroid hormones.
- **Compound:** A substance formed when two or more different elements are chemically bonded together (e.g., water, sodium chloride).
- **Confirmation:** The specific three-dimensional shape of a protein, which is critical for its function.
- **Covalent Bond:** A chemical bond formed by the sharing of valence electrons between two atoms, typically between two non-metals.
- **Dehydration Synthesis (Condensation Reaction):** A chemical reaction in which two molecules are covalently bonded together with the removal of a water molecule; used to build polymers from monomers.
- **DNA (Deoxyribonucleic Acid):** A nucleic acid polymer (double helix) that carries genetic instructions for the development, functioning, growth, and reproduction of all known organisms.
- **Double Helix:** The twisted ladder-like structure of DNA, consisting of two polynucleotide strands.
- **Electronegativity:** A measure of the attraction of an atom for the electrons in a chemical bond.
- **Electron:** A negatively charged subatomic particle that orbits the nucleus of an atom.
- **Element:** A pure substance consisting only of atoms that all have the same numbers of protons in their atomic nuclei.
- **Enzyme:** A biological catalyst, usually a protein, that speeds up the rate of specific biochemical reactions without being consumed in the process.
- **Fat:** A type of lipid composed of a glycerol molecule and three fatty acids; functions primarily in long-term energy storage.
- **Fatty Acid:** A component of fats and phospholipids, consisting of a long hydrocarbon chain. Can be saturated or unsaturated.
- **Fibrous Protein:** A protein characterized by a long, fiber-like shape, often serving structural functions (e.g., collagen).
- **Globular Protein:** A protein characterized by a compact, spherical shape, typically performing a wide variety of functions (e.g., enzymes, hemoglobin).
- **Glycerol:** A three-carbon molecule that forms the backbone of fats and phospholipids.
- **Glycogen:** A branched polysaccharide of glucose that serves as the primary form of glucose storage in animals (primarily liver and muscle cells).
- **Hydrogen Bond:** A weak attractive force between a partially positive hydrogen atom in one polar molecule and a partially negative atom (like oxygen or nitrogen) in another polar molecule. Not a chemical bond.
- **Hydrolysis:** A chemical reaction that breaks a covalent bond by adding a water molecule; used to break down polymers into monomers.
- **Ion:** An atom or molecule that has gained or lost one or more electrons, resulting in a net electrical charge.

- **Ionic Bond:** A chemical bond formed by the electrostatic attraction between oppositely charged ions, typically formed by the transfer of electrons between a metal and a non-metal.
- **Isotope:** Atoms of the same element that have the same number of protons but different numbers of neutrons, resulting in different atomic masses.
- **Lipid:** A diverse group of organic macromolecules that are largely nonpolar and hydrophobic; includes fats, phospholipids, and steroids.
- **Macromolecules:** Large, complex organic molecules essential for life (polysaccharides, lipids, proteins, nucleic acids).
- **Monomer:** The small, repeating molecular unit that makes up a polymer.
- **Monosaccharide:** The simplest form of carbohydrate; a single sugar unit (e.g., glucose, fructose). The monomer for polysaccharides.
- **Neutron:** An uncharged (neutral) subatomic particle found in the nucleus of an atom.
- **Nonpolar Covalent Bond:** A type of covalent bond in which electrons are shared equally between two atoms due to similar electronegativity.
- **Nucleic Acid:** A macromolecule (polymer) that carries genetic information or is involved in its expression; includes DNA and RNA.
- **Nucleotide:** The monomer subunit of nucleic acids, consisting of a five-carbon sugar, a nitrogenous base, and a phosphate group.
- **Nucleus (Atomic):** The dense central core of an atom, containing protons and neutrons.
- **Organic Compound:** A chemical compound that contains carbon, typically bonded to hydrogen, oxygen, and/or nitrogen.
- **pH Scale:** A logarithmic scale (0-14) used to specify the acidity or basicity of an aqueous solution, based on the concentration of hydrogen ions.
- **Phospholipid:** A type of lipid that is the main component of cell membranes; characterized by a polar head and two nonpolar fatty acid tails, making it amphipathic.
- **Polar Covalent Bond:** A type of covalent bond in which electrons are shared unequally between two atoms due to differing electronegativity, creating partial positive and negative charges on the molecule.
- **Polymer:** A large molecule (macromolecule) composed of many repeated smaller subunits (monomers) linked together.
- **Polypeptide:** A linear chain of amino acids linked by peptide bonds; a protein typically consists of one or more polypeptides.
- **Polysaccharide:** A complex carbohydrate (polymer) made up of many monosaccharide units linked together (e.g., starch, glycogen).
- **Primary Structure (Protein):** The unique linear sequence of amino acids in a polypeptide chain.
- **Protein:** A highly versatile organic macromolecule (polymer of amino acids) essential for virtually every function in living cells, including structural support, enzymatic activity, transport, and signaling.
- **Proton:** A positively charged subatomic particle found in the nucleus of an atom.
- **Quaternary Structure (Protein):** The arrangement of multiple polypeptide chains in a protein that consists of more than one polypeptide subunit.

- **Replication:** The biological process of producing two identical copies of DNA from one original DNA molecule.
- **RNA (Ribonucleic Acid):** A nucleic acid polymer, typically single-stranded, involved in various roles in gene expression and regulation.
- **Saturated Fatty Acid:** A fatty acid with no double bonds between carbon atoms in its hydrocarbon chain, allowing it to hold the maximum number of hydrogen atoms. Tend to be solid at room temperature.
- **Secondary Structure (Protein):** Localized, repeating folding patterns within a polypeptide chain, such as alpha helices and beta-pleated sheets, stabilized by hydrogen bonds.
- **Solute:** A substance dissolved in a solvent to form a solution.
- **Solution:** A homogeneous mixture composed of two or more substances, typically a solvent and one or more solutes.
- **Solvent:** A substance that dissolves a solute, resulting in a solution.
- **Starch:** A storage polysaccharide in plants, composed of many glucose units.
- **Steroid:** A type of lipid characterized by a carbon skeleton consisting of four fused rings (e.g., cholesterol, sex hormones).
- **Subatomic Particles:** Particles smaller than an atom (protons, neutrons, electrons).
- **Tertiary Structure (Protein):** The overall three-dimensional shape of a single polypeptide chain, resulting from interactions between amino acid side chains.
- **Transcription:** The process by which genetic information from DNA is copied into RNA.
- **Unsaturated Fatty Acid:** A fatty acid with one or more double bonds between carbon atoms in its hydrocarbon chain, leading to kinks in its structure. Tend to be liquid at room temperature.
- **Valence Electron:** An electron in the outermost shell of an atom.
- **Valence Shell:** The outermost electron shell of an atom, where chemical bonding typically occurs.