The Chemical Level of Organization

Objectives

- Describe atomic structure
- Compare the ways atoms combine to form molecules and compounds
- Distinguish among the major types of chemical reactions
- Describe the role of enzymes in metabolism
- Distinguish between organic and inorganic compounds
- Describe pH and the role of buffers in the body
- Describe the structures and functions of each organic and inorganic compound

Chemistry is the foundation of all living organisms. All basic physiological processes of life take place at the chemical level

Atoms, Molecules and Bonds

- The physical world (matter) is made up of atoms, which join together to form chemicals with different characteristics. These chemical characteristics determine the physiology of living organisms at the molecular and cellular level.

- Atoms are the smallest units of matter with their own chemical characteristics.

- Atoms are divided into 2 basic regions:
  1. the central nucleus, contains heavy particles
  2. the electron cloud, contains very light, moving particles

- Atoms have 3 major types of smaller or subatomic particles. Particles are defined by electrical charge (positive or negative), weight or mass, and location within the atom.
  1. protons (p⁺): positive charge, about 1 unit of mass, in the central nucleus
  2. neutrons (n): no electrical charge (neutral), about 1 unit of mass, in the central nucleus
  3. electrons (e⁻): negative charge, very small mass, spin rapidly in a cloud around the central nucleus

Atomic Structure

- Atoms are also elements, the basic chemicals found in the Periodic Table.

- Elements are defined by their atomic number, which is the number of protons in the nucleus. The number of protons is the positive electrical charge of the atom.

- Electrons, rapidly orbiting the nucleus in a spherical electron cloud, contain the negative charge. In our atomic diagram, this is called the electron shell. The number of electron is the negative electrical charge of the atom.

- An element’s mass number is determined by adding together the number of
protons and neutrons in the nucleus. Although neutrons have no electrical charge, they have significant mass.

- **Isotopes** are atoms of the same element that have different mass numbers due to different numbers of neutrons.

- Some isotopes, called radioisotopes, emit radiation in the form of subatomic particles. The amount of radiation decreases over time, or decays, at a rate that is specific to that isotope, called the half-life.

- Accurately determining atomic weight is important in chemical reactions. Chemists use atomic weight in measuring chemicals. A mole (mol) is the quantity of an element with a weight in grams equal to that element’s atomic weight.

- Chemical properties of an individual atom or element depend upon several factors, such as its electrical charge.

- Any atom with an equal number of protons (positive) and electrons (negative) has a neutral charge. If the atom loses or gains electrons, it will have a net positive or negative charge. Atoms with positive or negative charges are called ions.

- Electrons orbit around the nucleus in patterns called energy levels, which are like shells or steps.

- Each energy level holds a specific number of electrons. Level 1 holds 2 electrons. Levels 2 and 3 each hold 8 electrons. Electrons must fill the lowest available energy level first. When a lower level is full, higher levels can be occupied.

- The outermost energy level is the “surface” of the atom. The number of electrons in the outermost level determines the chemical properties of the atom.
  - Atoms with unfilled outer levels are unstable -- they react with other elements.
  - Atoms with filled outer levels do not react with other atoms -- they are inert.

**Chemical Bonds**

- Reactive atoms become more stable by gaining, losing or sharing electrons to fill their outer energy levels. Interaction between the outer electrons of two atoms forms a chemical bond which holds the atoms together.

- Chemical bonds can be strong or weak. Two or more atoms joined together with strong bonds are molecules. A compound is two or more elements joined together by any chemical bond, strong or weak.

- There are 3 basic types of chemical bonds: ionic, covalent and hydrogen.
(1) **Ionic bonds** form between atoms with opposite electrical charges (ions).
- An atom that loses electrons (electron donor) has a net *positive* charge, and is called a **cation**.
- An atom that gains electrons (electron acceptor) has a net *negative* charge, and is an **anion**.
- Ions in solution can conduct electricity – These are called **electrolytes**

Table salt (sodium chloride) is an example of an ionic compound.
- The **sodium atom** (Na) has only 1 electron in its outer energy level, which is easily lost, resulting in a *positive* sodium ion (Na⁺).
- **Chlorine** (Cl) has 7 electrons in its outer level. Adding 1 electron forms a *negative* chloride ion (Cl⁻).
- A sodium ion and a chloride ion join together in an *ionic bond* to form a **neutral ionic compound**, sodium chloride (NaCl).

(2) **Covalent bonds** occur when atoms share, rather than gain or lose electrons, forming **molecules**.

In covalent bonding, each atom contributes the same number of electrons to the bond, called **electron pairs**.
- A **single covalent bond** shares 1 electron pair, signified in chemical notation by a single line (→).
- A **double covalent bond** shares 2 electron pairs, indicated by a double line (==).
- **Carbon dioxide** has 2 double covalent bonds.

Molecules that share electrons equally (such as oxygen, O₂) have symmetrical shapes, and a uniform electrical charge over the surface of the molecule. This is called a **nonpolar covalent bond**.

Molecules that share electrons unequally (such as water, H₂O) have an asymmetrical shape, **polarizing** the positive and negative charge around the molecule like a magnet. Although the water molecule is neutral overall, the hydrogen side of the molecule is more positive and the oxygen side is more negative.

Because water is a **polar molecule**, it interacts chemically with both positive and negative ions, **dissolving** ionic compounds such as NaCl.

(3) **Hydrogen bonds** are weak attractions between the positive, hydrogen side of one polar molecule and the negative side of another polar molecule. Hydrogen bonds influence the shape of larger molecules, which is important to molecules such as proteins and DNA.
Hydrogen bonds between water molecules cause surface tension, which repels small particles.

**Chemical Reactions**

- The functions and structures of life all depend on chemical reactions making and breaking chemical bonds.

- Chemicals that go into reactions are reactants. Chemicals that come out are products. All reactions taking place in an organism’s cells and tissues are its metabolism.

**Basic Energy Concepts**

- Chemical reactions involve energy.

- The chemical energy in a molecular bond is a form of potential energy.

- Energy cannot be created or destroyed. It can only be changed from one form to another.

- Each time energy changes form, some energy is lost in the form of heat. This is why our bodies are warm, and car engines get hot.

**Types of Chemical Reactions**

- Three types of chemical reactions are important to physiology: decomposition, synthesis, and exchange reactions.

  (1) **Decomposition reactions** break larger molecules into smaller parts.

    - **Hydrolysis** (hydro = water; -lysis = breaking down) is a decomposition reaction in which the components of water molecules (H⁺ and OH⁻) added to the ends of the fragments. Hydrolysis is one of the reactions used in digestion.

    - When chemical bonds are broken, energy is released. Catabolism is work done by cells using kinetic energy from decomposition reactions.

  (2) **Synthesis reactions** are the opposite of decomposition. Small molecules join together to form larger molecules.

    - **Dehydration synthesis** (condensation) removes the water components (H⁺, OH⁻) from the ends of molecular fragments so they can join together, releasing water.
- Synthesis reactions require energy. Anabolism (opposite of catabolism) is the use of energy to synthesize molecules.

(3) Exchange reactions are paired decomposition and synthesis reactions. The reactants exchange components to produce new products.

Reversible Reactions

- Synthesis reactions can reverse to become decomposition reactions, and decomposition reactions can reverse to become synthesis reactions.

Enzymes, Energy and Chemical Reactions

- The amount of energy needed to get a reaction started can be reduced by a helper chemical called an enzyme. Enzymes reduce the activation energy for a reaction. Enzymes are not used up in a reaction, they are just facilitators or catalysts.

Inorganic Compounds

- Nutrients and metabolites are classified chemically as:
  (1) organic compounds: based on carbon and hydrogen atoms, e.g. carbohydrates, lipids, proteins, nucleic acids
  (2) inorganic compounds: not based on carbon and hydrogen atoms, e.g. carbon dioxide (CO2), oxygen (O2), water (H2O)

Water and Its Properties

- Water is the most important molecule in the body. Water makes up 2/3 of our body weight; and is required for most chemical and physiological reactions.

- Water has some special properties resulting from its polar nature and hydrogen-bonding capabilities:
  (1) solubility: A solution is a uniform distribution of one substance (the solute) in a medium (the solvent). Many organic and inorganic compounds dissolve in water (an aqueous solution).
  (2) reactivity: In our bodies, most reactions either involve water (e.g. hydrolysis, condensation), or occur in water.
  (3) high heat capacity: The ability to absorb and retain heat. Because water has a high heat capacity, it remains a liquid over a broad range of temperatures.
  (4) lubrication: Friction between water molecules is low.

- Water is called the universal solvent because of its ability to form solutions.

- In water, ionic compounds such as sodium chloride (NaCl) disassociate or
separate into ions. The **positive pole** of the water molecule attracts the negative Cl- ion, and the **negative pole** attracts the positive Na+ ion, creating **hydrations spheres** which help keep the ions in solution.

- **Electrolytes** are soluble inorganic ions which conduct electricity in solution, such as NaCl.

- These are the electrolytes important in body fluids. An imbalance in concentration of these electrolytes seriously disturbs vital body functions.

- Organic molecules that have polar covalent bonds also dissolve in water. They are called **hydrophilic** or water-loving molecules (*hydro* = water, *philos* = loving), e.g. sugar.

- Other organic molecules are nonpolar and do not react with water. These are called **hydrophobic** or water-fearing molecules (*phobos* = fear), e.g. fats and oils.

- Hydrogen atoms are of particular importance to chemical reactions because they lose their electrons very easily. Since the components of a hydrogen atom are only one proton and one electron, a **hydrogen ion** (H+) is the same as a proton. One hydrogen ion and 1 hydroxide ion (OH-) make up a water molecule.

- Hydrogen ions are very reactive and essential to most physiological processes. The concentration of hydrogen ions in body fluids is called **pH** and must be carefully regulated.

- The **pH scale** has an *inverse* relationship with the concentration of hydrogen ions. More H+ ions means lower pH, less H+ ions means higher pH.

- Since pure water consists of a balance between H+ ions and OH- ions, the pH of water is **neutral**, and is assigned a pH of 7.0
  - A pH lower than 7.0 (*high* H+ concentration, *low* OH-concentration) is **acidic**.
  - A pH higher than 7.0 (*low* H+ concentration, *high* OH-concentration) is **basic**.

- (*) The pH of body fluids measures free H+ ions in solution. Excess H+ ions (low pH) damage cells and tissues, alters proteins and interferes with normal physiological functions. An excess of OH- ions (high pH) also causes problems, but occurs rarely.

*Inorganic Acids and Bases*

- An **acid** is any solute that **releases** hydrogen ions (H+) in solution, lowering the pH. Since H+ is a proton, acids are also called **proton donors**. Excess acidity in body fluids causes **acidosis**.
• A base is any solute that removes hydrogen ions from solution (raising the pH), or a proton acceptor. Excess hydroxide ions (OH⁻) in body fluids cause alkalosis.

**Salts**

• Only compounds that contain H⁺ or OH⁻ ions affect acidity.

• Other compounds, which disassociate into positive and negative ions (cations and anions) in solution but contain no H⁺ or OH⁻, such as NaCl, are salts. Most salts have little or no effect on the pH of a solution.

**Buffers and pH Control**

• Compounds which contain both a weak acid and a weak base can stabilize the pH of a solution by removing or replacing H⁺ ions in a reversible reaction. These buffer systems can help neutralize either a strong acid or a strong base.

**Organic Compounds**

• Organic compounds are usually very large molecules containing carbon, hydrogen and oxygen atoms.

• The 4 major classes of organic compounds are carbohydrates, lipids, proteins, and nucleic acids.

• Though complex and varied, all organic compounds have certain active molecular groups, called functional groups, which allow them to interact with other molecules. The major functional groups are: carboxyl (-COOH); amino (-NH₂); hydroxyl (-OH); and phosphate (-PO₄).

**Carbohydrates**

• Carbohydrates are organic molecules with a carbon/hydrogen/oxygen ratio of about 1:2:1, including sugars and starches. There are 3 main categories of carbohydrates:
  1. Monosaccharides: simple sugars, glucose, fructose.
  2. Disaccharides: two simple sugars condensed by dehydration synthesis. Disaccharides (such as sucrose) must be broken down by hydrolysis before the body can use them.
  3. Polysaccharides: large molecular chains of many simple sugars. Polysaccharides include:
     - cellulose (plant fiber): an indigestible polysaccharide.
     - starches (plant starch): digestible chains of glucose molecules
     - glycogen (animal starch): the way animals store glucose
**Lipids**

- **Lipids** are mainly hydrophobic molecules (such as fats, oils, and waxes) made mostly of carbon and hydrogen atoms.

- The 5 main classes of lipids are fatty acids, eicosanoids, glycerides, steroids, and phospholipids & glycolipids.
  1. **Fatty Acids**: carbon chains with hydrogen and carboxyl groups.
     - **saturated**: no covalent bonds in the carbon chain
     - **monounsaturated**: 1 double bond in the carbon chain
     - **polyunsaturated**: many double bonds in the carbon chain
  2. **Eicosanoids**: derived from arachidonic acid
     - **leukotrienes**: active in injury and disease
     - **prostaglandins**: local hormones
  3. **Glycerides**: fatty acids attached to a **glycerol** molecule
     - 1. **monoglyceride**: one fatty acid
     - 2. **diglyceride**: two fatty acids
     - 3. **triglyceride** (triacylglycerols): three fatty acids
       - energy source
       - insulation
       - protection
  4. **Steroids**: 4 carbon rings.
     - **cholesterol**: found in all cell membranes
     - **estrogens** and **testosterone**: sex hormones
     - **corticosteroids** and **calcitrol**: metabolic regulation
     - **bile salts**: derived from steroids
  5. **Phospholipids** and **glycolipids**:
     - have hydrophilic heads and hydrophobic tails
     - form **micelles** in water
     - structural lipids, major components of cell membranes

**Proteins**

- **Proteins** (components carbon, hydrogen, oxygen, nitrogen) are the most abundant and most important class of molecules in the human body. All body functions require proteins. **Cells are essentially protein factories.**

- Seven major functions of proteins are:
  1. Support: **structural proteins**
  2. Movement: **contractile proteins**
  3. Transport: **transport proteins**
  4. Buffering: regulation of pH
  5. Metabolic Regulation: **enzymes**
  6. Coordination and Control: **hormones**
  7. Defense: antibodies

- **(*) Proteins are the key to anatomical structure and physiological function. They determine cell shape and tissue properties. Almost all cell functions are performed by proteins.**
• The building blocks of proteins are **amino acids**. Each amino acid has 5 parts:
  1. central carbon
  2. hydrogen
  3. **amino group** (-NH2)
  4. **carboxylic acid group** (-COOH)
  5. variable side chain or **R group**

• The **amino group** of one amino acid bonds with the **carboxylic acid group** of another amino acid (a **peptide bond**) by dehydration synthesis to form a **peptide**. A long chain of amino acids linked by peptide bonds is a **polypeptide**.

• For the polypeptide chain to become a protein, it must be folded into a unique shape.

• Proteins have 4 levels of shape:
  1. **primary structure**: the order of amino acids
  2. **secondary structure**: hydrogen bonds form
  3. **tertiary structure**: folds the secondary structure
  4. **quaternary structure**: several tertiary structures together

• The shape of a protein determines its function.

• **Enzymes** are proteins that make cells function. Every enzyme is shaped to facilitate a particular chemical reaction.

**Nucleic Acids**

• **Nucleic acids** are large organic molecules (made of carbon, hydrogen, oxygen, nitrogen, phosphorus) which **store and process information** at the molecular level.

• The 2 classes of nucleic acids are:
  1. **Deoxyribonucleic acid (DNA)**
     - determines inherited characteristics
     - directs protein synthesis
     - controls enzyme production
     - controls metabolism
  2. **Ribonucleic acid (RNA)**
     - codes for intermediate steps in protein synthesis

• (*) DNA in the cell nucleus contains the information needed to construct all of the proteins in the body.
• **Nucleic acids** are chains of building blocks called nucleotides. **Nucleotides** are made up of 3 basic units:
  1. **nitrogenous base**
     - adenine (A)
     - guanine (G)
     - cytosine (C)
     - thymine (T): DNA only
     - uracil (U): RNA only
  2. **deoxyribose sugar**
  3. **phosphate group**

• RNA is a single chain of nucleotides. There are 3 types of RNA involved in protein synthesis:
  1. **messanger RNA** (mRNA)
  2. **transfer RNA** (tRNA)
  3. **ribosomal RNA** (rRNA)

• In DNA, each base in the nucleotide chain hydrogen-bonds with a matching base to form **complementary base pairs**. Adenine always pairs with thymine, cytosine with guanine.

• The result is a DNA **double helix** resembling a spiral staircase, with sugars and phosphates as the side rails and nucleotide pairs as the steps. The two halves of the DNA spiral are **complementary strands**.

*High-Energy Compounds*

• Cells require energy to function. Specific molecules called **high-energy compounds** store and transfer energy. Energy is stored in **high-energy bonds** connecting a phosphate group to an organic molecule.

• The most important energy-storing organic molecule is **adenosine diphosphate** (ADP), which has 2 phosphate groups. Adding a third phosphate group to ADP (the **endergonic** process of phosphorylation) requires the enzyme **ATPase**, and produces the high-energy-compound **adenosine triphosphate** (ATP).

• Breaking off ATP’s third phosphate releases the stored energy of the phosphate bond, providing energy for work. The molecule reverts to ADP, and must go through the phosphorylation cycle again to be recharged as an ATP molecule.