# Chapter 2

# The Chemical Level of Organization

## An Introduction to the Chemical Level of Organization

- Chemistry
  - Is the science of change
  - Topics of this chapter include:
    - The structure of atoms
    - The basic chemical building blocks
    - How atoms combine to form increasingly complex structures

## 2-1 Atoms and Atomic Structure

- Matter
  - Is made up of **atoms**
    - Atoms join together to form chemicals with different characteristics
    - Chemical characteristics determine physiology at the molecular and cellular levels

## 2-1 Atoms and Atomic Structure

- Subatomic Particles
  - Proton
    - Positive charge, 1 mass unit
  - Neutron
    - Neutral, 1 mass unit
  - Electron
    - Negative charge, low mass

## 2-1 Atoms and Atomic Structure

- Atomic Structure
  - Atomic number
    - Number of protons
  - Nucleus
    - Contains protons and neutrons
  - Electron cloud
    - Contains electrons

## 2-1 Atoms and Atomic Structure

- Elements and Isotopes
  - **Elements** are determined by the atomic number of an atom
    - Remember, atomic number = number of protons

        - Elements are the most basic chemicals

## 2-1 Atoms and Atomic Structure

- Elements and Isotopes
    - **Isotopes** are the specific version of an element based on its **mass number**
        - Mass number = number of protons plus the number of neutrons
        - Only neutrons are different because the number of protons determines the element

## 2-1 Atoms and Atomic Structure

- Atomic Weight
    - Exact mass of all particles
        - Measured in **moles**
    - Average of the mass numbers of the isotopes

## 2-1 Atoms and Atomic Structure

- Electrons and Energy Levels
    - Electrons in the electron cloud determine the reactivity of an atom
    - The electron cloud contains shells, or energy levels, that hold a maximum number of electrons
        - Lower shells fill first
        - Outermost shell is the **valence shell**, and it determines bonding
        - The number of electrons per shell corresponds to the number of atoms in that row of the periodic table

## 2-2 Molecules and Compounds

- **Chemical Bonds**
    - Involve the sharing, gaining, and losing of electrons in the valence shell
    - Three major types of chemical bonds
        1. **Ionic bonds**
            - Attraction between **cations** (electron donor) and **anions** (electron acceptor)
        2. **Covalent bonds**
            - Strong electron bonds involving shared electrons
        3. **Hydrogen bonds**
            - Weak polar bonds based on partial electrical attractions

## 2-2 Molecules and Compounds

- Chemical Bonds
    - Form molecules and/or compounds
        - **Molecules**

        - Two or more atoms joined by strong bonds
    - **Compounds**
        - Two or more atoms *OF DIFFERENT ELEMENTS* joined by strong or weak bonds
    - Compounds are all molecules, but not all molecules are compounds
        - $H_2$ = molecule only
        - $H_2O$ = molecule and compound

## 2-2 Molecules and Compounds

- **Ionic Bonds**
    - One atom—*the electron donor*—loses one or more electrons and becomes a cation, with a positive charge
    - Another atom—*the electron acceptor*—gains those same electrons and becomes an anion, with a negative charge
    - Attraction between the opposite charges then draws the two ions together

## 2-2 Molecules and Compounds

- **Covalent Bonds**
    - Involve the sharing of pairs of electrons between atoms
        - One electron is donated by each atom to make the pair of electrons
        - Sharing one pair of electrons is a **single covalent bond**
        - Sharing two pairs of electrons is a **double covalent bond**
        - Sharing three pairs of electrons is a triple covalent bond

## 2-2 Molecules and Compounds

- **Covalent Bonds**
    - **Nonpolar covalent bonds**
        - Involve *equal* sharing of electrons because atoms involved in the bond have equal pull for the electrons
    - **Polar covalent bonds**
        - Involve the *unequal* sharing of electrons because one of the atoms involved in the bond has a disproportionately strong pull on the electrons
        - Form *polar molecules* — like water

## 2-2 Molecules and Compounds

- **Hydrogen Bonds**
    - Bonds between adjacent molecules, not atoms
    - Involve slightly positive and slightly negative portions of polar molecules being attracted to one another
    - Hydrogen bonds between $H_2O$ molecules cause **surface tension**

## 2-2 Molecules and Compounds

- States of Matter
  - *Solid*
    - Constant volume and shape
  - *Liquid*
    - Constant volume but changes shape
  - *Gas*
    - Changes volume and shape

## 2-3 Chemical Reactions

- In a **Chemical Reaction**
  - Either new bonds are formed or existing bonds are broken
    - **Reactants**
      - Materials going into a reaction
    - **Products**
      - Materials coming out of a reaction
    - **Metabolism**
      - All of the reactions that are occurring at one time

## 2-3 Chemical Reactions

- Basic Energy Concepts
  - **Energy**
    - The power to do work
  - **Work**
    - A change in mass or distance
  - **Kinetic energy**
    - Energy of motion
  - **Potential energy**
    - Stored energy
  - Chemical energy
    - Potential energy stored in chemical bonds

## 2-3 Chemical Reactions

- Types of Chemical Reactions
  - **Decomposition reaction (catabolism)**
  - **Synthesis reaction (anabolism)**
  - **Exchange reaction**
  - **Reversible reaction**

## 2-3 Chemical Reactions

- **Decomposition Reaction (Catabolism)**
  - Breaks chemical bonds

    - $AB \rightarrow A + B$
    - Hydrolysis $A\text{-}B + H_2O \rightarrow A\text{-}H + HO\text{-}B$
- **Synthesis Reaction (Anabolism)**
    - Forms chemical bonds
    - $A + B \rightarrow AB$
    - Dehydration synthesis (*condensation reaction*)
- $A\text{-}H + HO\text{-}B \rightarrow A\text{-}B + H_2O$

## 2-3 Chemical Reactions

- **Exchange Reaction**
    - Involves decomposition first, then synthesis
    - $AB + CD \rightarrow AD + CB$

## 2-3 Chemical Reactions

- **Reversible Reaction**
    - $A + B \leftrightarrow AB$
    - At equilibrium the amounts of chemicals do not change even though the reactions are still occurring
        - Reversible reactions seek equilibrium, balancing opposing reaction rates
        - Add or remove reactants
            - Reaction rates adjust to reach a new equilibrium

## 2-4 Enzymes

- Chemical Reactions
    - In cells, cannot start without help
        - **Activation energy** is the amount of energy needed to get a reaction started
        - **Enzymes** are protein **catalysts** that lower the activation energy of reactions

## 2-4 Enzymes

- **Exergonic** (Exothermic) Reactions
    - Produce more energy than they use
- **Endergonic** (Endothermic) Reactions
    - Use more energy than they produce

## 2-5 Inorganic and Organic Compounds

- **Nutrients**
    - Essential molecules obtained from food
- **Metabolites**

    - Molecules made or broken down in the body
- **Inorganic Compounds**
    - Molecules not based on carbon and hydrogen
    - Carbon dioxide, oxygen, water, and inorganic acids, bases, and salts
- **Organic Compounds**
    - Molecules based on carbon and hydrogen
    - Carbohydrates, proteins, lipids, and nucleic acids

## 2-6 Properties of Water

- Water
    - Accounts for up to two-thirds of your total body weight
    - A **solution** is a uniform mixture of two or more substances
        - It consists of a **solvent**, or medium, in which atoms, ions, or molecules of another substance, called a **solute**, are individually dispersed

## 2-6 Properties of Water

- *Solubility*
    - Water's ability to dissolve a **solute** in a **solvent** to make a **solution**
- *Reactivity*
    - Most body chemistry occurs in water
- *High Heat Capacity*
    - Water's ability to absorb and retain heat
- *Lubrication*
    - To moisten and reduce friction

## 2-6 Properties of Water

- The Properties of Aqueous Solutions
    - Ions and polar compounds undergo **ionization**, or **dissociation**, in water
    - Polar water molecules form *hydration spheres* around ions and small polar molecules to keep them in solution

## 2-6 Properties of Water

- The Properties of Aqueous Solutions
    - Electrolytes and body fluids
        - **Electrolytes** are inorganic ions that conduct electricity in solution
        - Electrolyte imbalance seriously disturbs vital body functions

## 2-6 Properties of Water

- The Properties of Aqueous Solutions
    - Hydrophilic and hydrophobic compounds
        - **Hydrophilic**

        - *hydro-* = water, *philos* = loving
        - Interacts with water
        - Includes ions and polar molecules
    - **Hydrophobic**
        - *phobos* = fear
        - Does NOT interact with water
        - Includes nonpolar molecules, fats, and oils

## 2-6 Properties of Water

- Colloids and Suspensions
    - **Colloid**
        - A solution of very large organic molecules
        - For example, blood plasma
    - **Suspension**
        - A solution in which particles settle (sediment)
        - For example, whole blood
    - **Concentration**
        - The amount of solute in a solvent (mol/L, mg/mL)

## 2-7 pH and Homeostasis

- **pH**
    - The concentration of hydrogen ions ($H^+$) in a solution
- **Neutral pH**
    - A balance of $H^+$ and $OH^-$
    - Pure water = 7.0

## 2-7 pH and Homeostasis

- **Acidic** pH Lower Than 7.0
    - High $H^+$ concentration
    - Low $OH^-$ concentration
- **Basic** (or *alkaline*) pH Higher Than 7.0
    - Low $H^+$ concentration
    - High $OH^-$ concentration
- pH of Human Blood
    - Ranges from 7.35 to 7.45

## 2-7 pH and Homeostasis

- pH Scale
    - Has an *inverse* relationship with $H^+$ concentration
        - More $H^+$ ions means *lower* pH, fewer $H^+$ ions means *higher* pH

## 2-8 Inorganic Compounds

- **Acid**
  - A solute that adds hydrogen ions to a solution
  - *Proton donor*
  - *Strong acids* dissociate completely in solution
- Base
  - A solute that removes hydrogen ions from a solution
  - *Proton acceptor*
  - *Strong bases* dissociate completely in solution
- *Weak Acids* and *Weak Bases*
  - Fail to dissociate completely
  - Help to balance the pH

## 2-8 Inorganic Compounds

- **Salts**
  - Solutes that dissociate into cations and anions other than hydrogen ions and hydroxide ions

## 2-8 Inorganic Compounds

- Buffers and pH Control
  - **Buffers**
    - Weak acid/salt compounds
    - Neutralize either strong acid or strong base
    - Sodium bicarbonate is very important in humans
  - Antacids
    - Basic compounds that neutralize acid and form a salt
    - Alka-Seltzer, Tums, Rolaids, etc.

## 2-9 Carbohydrates

- Organic Molecules
  - Contain H, C, and usually O
  - Are covalently bonded
  - Contain functional groups that determine chemistry
    - **Carbohydrates**
    - Lipids
    - Proteins (or amino acids)
    - Nucleic acids

## 2-9 Carbohydrates

- Carbohydrates
  - Contain carbon, hydrogen, and oxygen in a 1:2:1 ratio
    - *Monosaccharide — simple* sugar

        - *Disaccharide* — two sugars
        - *Polysaccharide* — many sugars

## 2-9 Carbohydrates

- **Monosaccharides**
    - Simple sugars with 3 to 7 carbon atoms
    - Glucose, *fructose*, galactose
- **Disaccharides**
    - Two simple sugars condensed by dehydration synthesis
    - *Sucrose*, maltose
- **Polysaccharides**
    - Many monosaccharides condensed by dehydration synthesis
    - **Glycogen**, *starch*, *cellulose*

## 2-10 Lipids

- Lipids
    - Mainly hydrophobic molecules such as fats, oils, and waxes
    - Made mostly of carbon and hydrogen atoms
    - Include:
        - *Fatty acids*
        - *Eicosanoids*
        - *Glycerides*
        - *Steroids*
        - *Phospholipids and glycolipids*

## 2-10 Lipids

- **Fatty Acids**
    - Long chains of carbon and hydrogen with a *carboxyl group* (COOH) at one end
    - Are relatively nonpolar, *except* the carboxyl group
    - Fatty acids may be:
        - *Saturated* with hydrogen (no covalent bonds)
        - *Unsaturated* (one or more double bonds)
            - *Monounsaturated* = one double bond
            - *Polyunsaturated* = two or more double bonds

## 2-10 Lipids

- **Eicosanoids**
    - Derived from the fatty acid called *arachidonic acid*
    - *Leukotrienes*
        - Active in immune system
    - **Prostaglandins**
        - *Local hormones*, short-chain fatty acids

## 2-10 Lipids

- **Glycerides**
  - Fatty acids attached to a **glycerol** molecule
  - **Triglycerides** are the three fatty-acid tails
    - Also called *triacylglycerols* or *neutral fats*
    - Have three important functions
      1. Energy source
      2. Insulation
      3. Protection

## 2-10 Lipids

- **Steroids**
  - Four rings of carbon and hydrogen with an assortment of functional groups
  - Types of steroids
    - **Cholesterol**
      - Component of plasma (cell) membranes
    - *Estrogens* and *testosterone*
      - Sex hormones
    - *Corticosteroids* and *calcitriol*
      - Metabolic regulation
    - *Bile salts*
      - Derived from steroids

## 2-10 Lipids

- **Phospholipids** and **Glycolipids**
  - Diglycerides attached to either a *phosphate group* (*phospho*lipid) or a sugar (*glyco*lipid)
  - Generally, both have hydrophilic heads and hydrophobic tails and are *structural lipids*, components of plasma (cell) membranes

## 2-11 Proteins

- **Proteins**
  - Are the most abundant and important organic molecules
  - Contain basic elements
    - Carbon (C), hydrogen (H), oxygen (O), and nitrogen (N)
  - Basic building blocks
    - 20 amino acids

## 2-11 Proteins

- Seven Major Protein Functions
  1. *Support*
     - *Structural proteins*

2. *Movement*
    - *Contractile proteins*
3. *Transport*
    - *Transport (*carrier*) proteins*
4. *Buffering*
    - *Regulation of pH*
5. *Metabolic Regulation*
    - *Enzymes*
6. *Coordination and Control*
    - *Hormones*
7. *Defense*
    - *Antibodies*

## 2-11 Proteins

- Protein Structure
    - Long chains of **amino acids**
    - Five components of amino acid structure
        1. Central carbon atom
        2. Hydrogen atom
        3. *Amino group* (—$NH_2$)
        4. *Carboxyl group* (—COOH)
        5. Variable *side chain* or *R group*

## 2-11 Proteins

- Hooking Amino Acids Together
    - Requires a dehydration synthesis between:
        - The amino group of one amino acid and the carboxyl group of another amino acid
        - Forms a **peptide bond**
            - Resulting molecule is a **peptide**

## 2-11 Proteins

- Protein Shape
    - **Primary structure**
        - The sequence of amino acids along a polypeptide
    - **Secondary structure**
        - Hydrogen bonds form spirals or pleats
    - **Tertiary structure**
        - Secondary structure folds into a unique shape
    - **Quaternary structure**
        - Final protein shape — several tertiary structures together

## 2-11 Proteins

- **Fibrous Proteins**
  - Structural sheets or strands
- **Globular Proteins**
  - Soluble spheres with active functions
  - Protein function is based on shape
- Shape is based on sequence of amino acids

## 2-11 Proteins

- Enzyme Function
  - Enzymes are catalysts
    - Proteins that lower the activation energy of a chemical reaction
    - Are not changed or used up in the reaction
    - Enzymes also exhibit:
      1. *Specificity* — will only work on limited types of **substrates**
      2. *Saturation Limits* — by their concentration
      3. *Regulation* — by other cellular chemicals

## 2-11 Proteins

- Cofactors and Enzyme Function
  - **Cofactor**
    - An ion or molecule that binds to an enzyme before substrates can bind
  - **Coenzyme**
    - Nonprotein organic cofactors (vitamins)
  - Isozymes
    - Two enzymes that can catalyze the same reaction

## 2-11 Proteins

- Effects of Temperature and pH on Enzyme Function
  - **Denaturation**
    - Loss of shape and function due to heat or pH

## 2-11 Proteins

- Glycoproteins and Proteoglycans
  - **Glycoproteins**
    - Large protein + small carbohydrate
      - Includes enzymes, antibodies, hormones, and **mucus** production
  - **Proteoglycans**
    - Large polysaccharides + polypeptides
      - Promote viscosity

## 2-12 Nucleic Acids

- **Nucleic Acids**
  - Are large organic molecules, found in the nucleus, which *store and process information* at the molecular level
    - **Deoxyribonucleic acid** (**DNA**)
      - Determines inherited characteristics
      - Directs protein synthesis
      - Controls enzyme production
      - Controls metabolism
    - **Ribonucleic acid** (**RNA**)
      - Controls intermediate steps in protein synthesis

## 2-12 Nucleic Acids

- Structure of Nucleic Acids
  - DNA and RNA are strings of nucleotides
  - **Nucleotides**
    - Are the building blocks of DNA and RNA
    - Have three molecular parts
      1. A *pentose* sugar (*deoxyribose* or *ribose*)
      2. Phosphate group
      3. **Nitrogenous base** (A, G, T, C, or U)

## 2-12 Nucleic Acids

- DNA and RNA
  - DNA is double stranded, and the bases form hydrogen bonds to hold the DNA together
  - Sometimes RNA can bind to itself but is usually a single strand
  - DNA forms a twisting double helix
  - **Complementary base pairs**
    - Purines pair with pyrimidines
      - DNA
        - Adenine (A) and thymine (T)
        - Cytosine (C) and guanine (G)
      - RNA
        - Uracil (U) replaces thymine (T)

## 2-12 Nucleic Acids

- Types of RNA
  - *Messenger RNA (mRNA)*
  - *Transfer RNA (tRNA)*
  - *Ribosomal RNA (rRNA)*

## 2-13 High-Energy Compounds

- Nucleotides Can Be Used to Store Energy
    - Adenosine diphosphate (ADP)
        - Two phosphate groups; *di-* = 2
    - Adenosine triphosphate (ATP)
        - Three phosphate groups; *tri-* = 3
- **Phosphorylation**
    - Adding a phosphate group to ADP with a high-energy bond to form the high-energy compound ATP
- **Adenosine triphosphatase** (**ATPase**)
    - The enzyme that catalyzes the conversion of ATP to ADP

## 2-14 Chemicals and Cells

- Chemicals and Cells
    - Biochemical building blocks form functional units called cells
    - **Metabolic turnover** lets your body grow, change, and adapt to new conditions and activities
    - Your body recycles and renews all of its chemical components at intervals ranging from minutes to years