Chapter 2: The Chemical Level of Organization

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

I. Atoms, Molecules and Bonds, p. 27

- (* 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.

- Figure 2-1 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, p. 27

- Table 2-1 Atoms are also elements, the basic chemicals found in the Periodic Table. Here we see the most common elements found in the human body.

- 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.

• Although mass number approximately equals the weight of an atom, we calculate a precise atomic weight by adding up the total mass in daltons of all the protons, neutrons, electrons and other subatomic particles.

• 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.

• Figure 2-2 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_, p. 30

• Reactive atoms, such as hydrogen and oxygen, 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.

• The chemical activity of a molecule or compound is different from that of the
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.

   Figure 2-3 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.

   Figure 2-4 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.

   Figure 2-5 Within one molecule, atoms can share electrons equally or unequally, creating molecules of different shapes.

   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.

*Figure 2-6* Hydrogen bonds between water molecules cause surface tension, which repels small particles.

• Molecules can exist in any of 3 states of matter, from less random to more random:
  o **solids** have constant shape and volume
  o **liquids** have constant volume but change shape easily
  o **gases** change shape and volume freely

• Matter changes states with changes in **temperature** and **pressure**. For example, water changes from solid ice, to liquid, to gaseous water vapor.

II. Chemical Reactions, p. 35

• 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, p. 35

• Chemical reactions involve **energy**, which is defined as the *power or capacity to do work*. Work is measured by any *change in mass or motion*. Chemical reactions in a cell are work.

• The 2 major types of energy are **kinetic energy**, the *energy of motion*; and **potential energy**, or *stored 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.

• (*) **When energy is exchanged, heat is produced, but cells cannot capture it or use it for work.**
Types of Chemical Reactions, p. 35

- 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 bonds of large molecules are broken, and 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 within the cell.

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

Reversible Reactions, p. 36

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

- (*) **Reversible reactions tend to reach an equilibrium in which the opposing reaction rates are balanced. If reactants are added or removed, reaction rates adjust until a new equilibrium is reached.**

Enzymes, Energy and Chemical Reactions, p. 36

- **Figure 2-7** Most chemical reactions in cells cannot occur without help. The energy needed to get a reaction started is called **activation energy.**
• The amount of energy needed to get a reaction started can be reduced by a helper chemical called an enzyme. One specific enzyme reduces the activation energy for one specific reaction. Enzymes are not used up in a reaction, they are just facilitators or catalysts.

• A chemical reaction which releases more energy than it uses to get started is an exergonic reaction (exo = outside). When the activation energy of a reaction is greater than the energy it produces, it is an endergonic reaction (endo = inside).

• (*) Most chemical reactions that sustain life cannot occur unless the right enzymes are present.

III. Inorganic Compounds, p.37

• The elements found in the human body combine to form thousands of chemical compounds. Two important categories are:
  (1) nutrients: essential elements and molecules obtained only from food
  (2) metabolites (metabole = change), molecules synthesized or broken down by the body

• 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, p. 37

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

• 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.
• (* Most of our body weight is water. Water is the key structural and functional component of cells and their control mechanisms, the nucleic acids.

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

• Figure 2-8 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.

• Table 2-3 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.

• The amount of a solute in a specific amount of solvent is its concentration; e.g. concentration might be expressed in moles per liter (mol/L or M) or milligrams per milliliter (mg/mL).

• A solution of very large organic molecules, such as proteins, is a colloid (e.g. liquid gelatin).

• When the particles mixed into a solute are so large that they settle to the bottom of the container, rather than dissolving, it is not a solution but a suspension.

• 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.

• Figure 2-9 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, p. 41

- 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, p.41

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

- Other compounds, which disassociate into positive and negative ions 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, p. 41

- Compounds which contain both a weak acid and a related salt which acts as a weak base (such as carbonic acid and sodium bicarbonate) 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.

IV. Organic Compounds, p. 42

- 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). These functional groups determine the physiological activity of an organic molecule.

**Carbohydrates, p. 42**

- **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:
  - **Figure 2-10** (1) **Monosaccharides**: simple sugars with 3 to 7 carbon atoms (including glucose, the body’s most important metabolic fuel, and its isomer, fructose).
  - **Figure 2-11** (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.
  - **Figure 2-12** (3) **Polysaccharides**: large molecular chains of many simple sugars. **Table 2-5** Polysaccharides include:
    a. cellulose (plant fiber): an indigestible polysaccharide.
    b. starches (plant starch): digestible chains of glucose molecules
    c. glycogen (animal starch): the way animals store glucose

**Lipids, p. 44**

- (*) **Carbohydrates are quick energy sources and components of membranes.** Lipids have many functions, including membrane structure and energy storage.
- **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.

**Figure 2-13** (1) **Fatty Acids**: carbon chains with hydrogen and carboxyl groups. Increasing the number of double bonds in a carbon chain changes the shape and function of the molecule.
  - 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

- Table 2-6 Examples of 5 lipid types and their functions.

Proteins, p. 49

- 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.

- 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.

- Figure 2-18 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

• **Figure 2-19** 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*.

• **Figure 2-20** For the polypeptide chain to become a protein, it must be folded into a unique *shape*.

Proteins have 4 levels of shape:

- **Figure 2-20a** (1) *primary structure*: the order of amino acids
- **Figure 2-20b** (2) *secondary structure*: hydrogen bonds form
- **Figure 2-20c** (3) *tertiary structure*: folds the secondary structure
- **Figure 2-20d** (4) *quaternary structure*: several tertiary structures together

• Proteins can be divided into 2 classes based on shape:
  - (1) *fibrous proteins*: structural sheets or strands
  - (2) *globular proteins*: soluble spheres with active functions

• The shape of a protein determines its function. A protein’s final shape is determined by the original sequence of amino acids in the polypeptide chain. Environmental factors such as temperature can affect protein shape and therefore its function.

• **Figure 2-21** Enzymes are proteins that make cells function. Every enzyme is shaped to facilitate a particular chemical reaction.
  - Small reactant molecules, called *substrates*, bind to a specific area of the enzyme called the *active site* like a key fitting into a lock.
  - When the reaction is finished, the enzyme releases the product and is ready to process more substrates.

• All enzymes share 3 basic characteristics:
  - (1) *specificity*: one enzyme for one reaction
  - (2) *saturation limits*: the enzyme’s maximum work rate
  - (3) *regulation*: the ability to turn off and on

• Enzymes can be *activated* or *deactivated* by the presence of *cofactors* or *coenzymes*.
  - Cofactors are inorganic molecules or ions such as Ca++.  
  - Coenzymes are organic molecules such as vitamins.

• An enzyme’s function depends on its shape. All proteins are sensitive to
environmental factors. If heat changes the shape of an enzyme so it will not function, it has been denatured. Some enzymes require a specific pH to function.

- **Glycoproteins** and **proteoglycans** are combinations of protein and carbohydrate molecules.
  - glycoproteins: include enzymes, antibodies, hormones, mucus production
  - proteoglycans: link polysaccharide molecules for viscosity

**Nucleic Acids**, p. 54

- **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.

*Figure 2-22* 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

*Figure 2-23* To form a nucleic acid molecule, the phosphates and sugars of the nucleotides condense to form a chain.

- RNA is a single chain of nucleotides. There are 3 types of RNA involved in protein synthesis:
  1. **messenger 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* p. 56

• 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.

• *Figure 2-24* 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.

• *Table 2-8* summarizes the organic and inorganic compounds important to physiology.

*Chemicals and Cells* p. 57

• Each individual cell is like a miniature organism, responding to its environment, performing the chemical processes of life, removing and replacing components, and adapting to stimuli in the process of **metabolic turnover**.

• *Table 2-9* shows the **turnover rate** of components in different kinds of cells.

• (*) **As cellular parts wear out, your body must recycle and renew all of its chemical components at intervals ranging from minutes to years. Metabolic turnover lets your body grow, change and adapt to new conditions and activities.**

**SUMMARY**

In Chapter 2 we learned:

• The importance of atoms, molecules and bonds to cellular physiology
• How metabolism and energy work within the cell
• The importance of organic and inorganic nutrients and metabolites
• The role of water and solubility in metabolism and cell structure
• The chemistry of acids and bases, pH and buffers
• The structure and function of carbohydrates, lipids, proteins and nucleic acids