

THE CHEMISTRY OF LIFE

The Chemical Context of Life (Chapters 2 and 3)

YOU MUST KNOW...

- The three subatomic particles and their significance.
- The types of chemical bonds and how they form.
- The importance of hydrogen bonding to the properties of water.
- Four unique properties of water, and how each contributes to life on Earth.
- How to interpret the pH scale.
- How changes in pH can alter biological systems. The importance of buffers in biological systems.

Matter consists of chemical elements in pure form and in combinations called compounds (2.1)

- **Matter** is anything that takes up space and has mass.
- An **element** is a substance that cannot be broken down to other substances by chemical reactions. *Examples:* gold, copper, carbon, and oxygen.
- A **compound** is a substance consisting of two or more elements combined in a fixed ratio. *Examples:* water (H₂O) and table salt (NaCl).
- **C, H, O, N** make up 96% of living matter. About 25 of the 92 natural elements are known to be essential to life.
- **Trace elements** are those required by an organism in only minute quantities. *Examples:* iron and iodine.

An element's properties depend on the structure of its atoms (2.2)

- **Atoms** are the smallest unit of an element that still retains the property of the element. Atoms are made up of neutrons, protons, and electrons.
- **Protons** are positively charged particles found in the nucleus of the atom.
- **Electrons** are negatively charged particles that are found in electron shells around the nucleus. They determine the chemical properties and reactivity of the element.
- **Neutrons** are particles with no charge. They are found in the nucleus. Their number can vary in the same element, resulting in isotopes.
- **Isotopes** are forms of an element with differing numbers of neutrons. *Example:* ¹²C and ¹⁴C are isotopes of carbon. Both have 6 protons, but ¹²C has 6 neutrons, whereas ¹⁴C has 8 neutrons.

- The **atomic number** is the number of protons an element possesses. This number is unique to every element. (See Figure 2.7)
- The **mass number** of an element is the sum of its protons and neutrons.

The formation and function of molecules depend on chemical bonding between atoms (2.3)

- **Chemical bonds** are defined as interactions between the valence electrons of different atoms. Atoms are held together by chemical bonds to form molecules.
- A **covalent bond** occurs when valence electrons are shared by two atoms.
 - **Nonpolar covalent bonds** occur when the electrons being shared are shared equally between the two atoms. *Examples:* $O \equiv O$, $H - H$.
 - Atoms vary in their *electronegativity*, a tendency to attract electrons of a covalent bond. Oxygen and nitrogen are strongly electronegative.
 - In **polar covalent bonds**, one atom has greater electronegativity than the other, resulting in an unequal sharing of the electrons. This results in the region of the oxygen atom being slightly negative, whereas the regions about the hydrogen atoms are slightly positive. *Example:* Refer to Figure 3.2 and note that within each molecule of H_2O the electrons are shared unequally.
- **Ionic bonds** are ones in which atoms attract valence electrons so unequally that the more electronegative atom steals the electron away from the less electronegative atom.
 - An **ion** is the resulting charged atom or molecule.
 - **Ionic bonds** occur because these ions will be either positively or negatively charged and will be attracted to each other by these opposite charges.
- **Hydrogen bonds** are relatively weak bonds that form between the partial positively charged hydrogen atom of one molecule and the strongly electronegative oxygen or nitrogen of *another* molecule. Hydrogen bonds play a major role in the three-dimensional shape of proteins and nucleic acids.
- **Van der Waals interactions** are very weak, transient connections that are the result of asymmetrical distribution of electrons within a molecule. These weak interactions contribute to the three-dimensional shape of molecules.

Chemical reactions make and break chemical bonds (2.4)

- A **chemical reaction** shows the **reactants**, which are the starting materials, and an arrow to indicate their conversion into the **products**, the ending materials. *Example:* $6 CO_2 + 6 H_2O \rightarrow C_6H_{12}O_6 + 6 O_2$.
- The chemical reaction above also shows the number of molecules involved. This is the coefficient in front of each molecule. Note that the number of atoms of each element is the same on each side of the reaction.
- Some chemical reactions are reversible, which is indicated with a double-headed arrow: $3 H_2 + N_2 \leftrightarrow 2 NH_3$.

Water and its properties due to hydrogen bonding helps make life on Earth possible (3.1-3.3)

- The **structure of water** is the key to its special properties. Water is made up of one atom of oxygen and two atoms of hydrogen, bonded to form a molecule.
- Water molecules are **polar**. The oxygen region of the molecule has a partial negative charge, and each hydrogen has a partial positive charge.
- **Hydrogen bonds** form between water molecules. The slightly negative oxygen atom from one water molecule is attracted to the slightly positive hydrogen end of *another* water molecule.
- Each water molecule can form a maximum of four hydrogen bonds at one time. (Refer to Figure 3.2.)
- **Hydrogen bonds** are the key to each of the following properties of water and what makes water so unique.
 1. **Cohesion**. Cohesion is the linking of like molecules. Think “water molecule joined to water molecule” and visualize a water strider walking on top of a pond due to the *surface tension* that is the result of this property.
 - **Adhesion** is the clinging of one substance to another. Think “water molecule attached to some other molecule” such as water droplets adhering to a glass windshield.
 - **Transpiration** is the movement of water molecules up the very thin xylem tubes and their evaporation from the stomata in plants. The water molecules cling to each other by *cohesion* and to the walls of the xylem tubes by *adhesion*.
 2. Moderation of temperature is possible because of water’s high specific heat.
 - **Specific heat** is the amount of heat required to raise or lower the temperature of a substance by 1°C. Relative to most other materials, the temperature of water changes less when a given amount of heat is lost or absorbed. This high specific heat makes the temperature of Earth’s oceans relatively stable and able to support vast quantities of both plant and animal life.
 3. Insulation of bodies of water by floating ice.
 - Water is less dense as a solid than in its liquid state, whereas the opposite is true of most other substances. Because ice is less dense than liquid water, ice floats. This keeps larger bodies of water from freezing solid, allowing life to exist in ponds, lakes, and even oceans.
 4. Water is an important *solvent*. (The substance that something is dissolved in is called the *solvent*, whereas the substance being dissolved is the *solute*. Together they are called the *solution*.)
- Acidic and basic conditions affect living organisms
 - The **pH** scale runs between 0 and 14 and measures the relative acidity and alkalinity of aqueous solutions. (See Figure 3.10.)
 - **Acids** have an excess of H^+ ions and a pH below 7.0. $[H^+] > [OH^-]$
 - **Bases** have an excess of OH^- ions, and a pH above 7.0. $[H^+] < [OH^-]$
 - Pure water is neutral, which means it has a pH of 7. $[H^+] = [OH^-]$

- **Buffers** are substances that minimize changes in pH. They accept H^+ from solution when they are in excess and donate H^+ when they are depleted. Buffering compounds are essential in living tissues to minimize pH changes.
- **Carbonic acid (H_2CO_3)** is an important buffer in living systems. It moderates pH changes in blood plasma and the ocean.

Carbon and the Molecular Diversity of Life (Chapters 4 and 5)

YOU MUST KNOW...

- The properties of carbon that make it so important.
- The role of dehydration reactions in the formation of organic compounds and hydrolysis in the digestion of organic compounds.
- How the sequence and subcomponents of the four groups of organic compounds determine their properties.
- The cellular functions of carbohydrates, lipids, proteins, and nucleic acids.
- How changes in these organic molecules would affect their function.
- The four structural levels of proteins and how changes at any level can affect the activity of the protein.
- How proteins reach their final shape (conformation), the denaturing impact that heat and pH can have on protein structure, and how these changes may affect the organism.
- Directionality influences structure and function of polymers, such as nucleic acids (5' and 3' ends) and proteins (amino and carboxyl ends).

Carbon and molecular diversity (4.1-4.3)

- The major elements of life are C, H, O, N, S, and P.
- All **organic compounds** contain carbon, and most also contain hydrogen.
- Carbon is unparalleled in its ability to form molecules that are large, complex, and diverse. Why?
 - It has 4 valence electrons.
 - It can form up to 4 covalent bonds.
 - These can be single, double, or triple covalent bonds.
 - It can form large molecules.
 - These molecules can be chains, ring-shaped, or branched.
- **Isomers** are molecules that have the same molecular formula but differ in their arrangement of these atoms. These differences can result in molecules that are very different in their biological activities. *Examples:* glucose and fructose (both have the molecular formula of $C_6H_{12}O_6$).
- **Functional groups** attached to the carbon skeleton have diverse properties. The behavior of organic molecules is dependent on the identity of their functional groups.
- Some common functional groups are listed in Figure 4.9.

Macromolecules are polymers, built from monomers (5.1)

- **Polymers** are long chain molecules made of repeating subunits called **monomers**. *Examples:* Starch is a polymer composed of glucose monomers. (See Figure 5.2.)
- **Dehydration reactions** create polymers from monomers. Two monomers are joined by removing one molecule of water. *Example:* $C_6H_{12}O_6 + C_6H_{12}O_6 \rightarrow C_{12}H_{22}O_{11} + H_2O$.
- **Hydrolysis** occurs when water is added to split large molecules. This occurs in the reverse of the above reaction.

Carbohydrates serve as fuel and building material (5.2)

- **Carbohydrates** include both simple sugars (glucose, fructose, galactose, etc.) and polymers such as starch made from these and other subunits. All carbohydrates exist in a ratio of 1 carbon: 2 hydrogen: 1 oxygen or CH_2O .
- **Monosaccharides** are the monomers of carbohydrates. *Examples:* glucose ($C_6H_{12}O_6$) and ribose ($C_5H_{10}O_5$). Notice the 1:2:1 ratio discussed above.
- **Polysaccharides** are polymers of monosaccharides. *Examples:* starch, cellulose, and glycogen.
- Starches and cellulose are both composed of glucose monomers, but the different ring forms (alpha and beta) and linkages between them result in very different functions. For example, you can digest starch, which has 1-4 alpha linkages, and not cellulose, which has 1-4 beta linkages. Keep this in mind: *Change the structure, change the function!*
- Two functions of polysaccharides are **energy storage** and **structural support**.
 1. **Energy-storage polysaccharides**
 - **Starch** is a storage polysaccharide found in plants (for example, potatoes).
 - **Glycogen** is a storage polysaccharide found in animals, vertebrate muscle cells, and liver cells.
 2. **Structural support polysaccharides**
 - **Cellulose** is a major component of plant cell walls.
 - **Chitin** is found in the exoskeleton of arthropods, such as lobsters and insects, and the cell walls of fungi. It gives cockroaches their “crunch”.

Lipids are a diverse group of hydrophobic molecules (5.3)

- Lipids are all **hydrophobic**. They aren't polymers because they are assembled from a variety of components. *Examples:* **waxes, oils, fats, and steroids**.
- **Fats** (also called triglycerides) are made up of a **glycerol** molecule and three **fatty acid** molecules.
- **Fatty acids** include hydrocarbon chains of variable lengths. These chains are nonpolar and therefore hydrophobic.
- **Saturated fatty acids**
 - have no double bonds between carbons
 - tend to pack solidly at room temperature

- are linked to cardiovascular disease
- are commonly produced by animals
- *Examples:* butter and lard
- **Unsaturated fatty acids**
 - have some C = C (carbon double bonds); this results in kinks
 - tend to be liquid at room temperature
 - are commonly produced by plants
 - *Examples:* corn oil and olive oil
- **Functions of lipids**
 - **Energy storage.** Fats store twice as many calories/gram as carbohydrates!
 - *Protection* of vital organs and *insulation*. In humans and other mammals, fat is stored in adipose cells.
- **Phospholipids** make up cell membranes. They
 - have a hydrophilic (polar) head that includes a phosphate group.
 - have two fatty acid tails, which are hydrophobic.
 - are arranged in a bilayer in forming the cell membrane, with the hydrophilic heads pointing toward the watery cytosol or extracellular environment, and hydrophobic tails sandwiched in between (Figure 5.11).
- **Steroids** are made up of four rings that are fused together.
 - **Cholesterol** is a steroid. It is a common component of cell membranes.
 - **Estrogen** and **testosterone** are steroid hormones.

Proteins include a diversity of structures, resulting in a wide range of functions (5.4)

- **Proteins** are polymers made up of amino acid monomers.
- **Amino acids** contain a central carbon bonded to a carboxyl group (COOH) at one end, an amino group (NH₂) at the other end, a hydrogen atom, and an R group (variable group or side chain). (See the figure on p. 75 of your book.)
- **Peptide bonds** link amino acids. They are formed by dehydration synthesis between the amino and carboxyl groups of adjacent monomers.
- **There are four levels of protein structure** (Figure 5.18):
 - **Primary structure** is the unique sequence in which amino acids are joined.
 - **Secondary structure** refers to one of two three-dimensional shapes that are the result of hydrogen bonding between members of the polypeptide backbone (not the amino acid side chains).
 - **Alpha (α) helix** is a coiled shape, much like a slinky.
 - **Beta (β) pleated sheet** is an accordion shape.
 - **Tertiary structure** results in a complex globular shape due to interactions between the side chains (R groups), such as hydrophobic interactions, van der Waals interactions, hydrogen bonds, and disulfide bridges.
 - Globular proteins such as enzymes are held in position by these R group interactions.

- **Quaternary structure** refers to the association of two or more polypeptide chains into one large protein. Hemoglobin is a globular protein with quaternary structure because it is composed of four chains.
- **Protein shape is crucial to protein function.** When a protein does not fold properly, its function is changed. This can be the result of a single amino acid substitution, such as that seen in the abnormal hemoglobin typical of sickle-cell disease.
- A protein is **denatured** when it loses its shape and ability to function due to **heat**, a change in **pH**, or some other disturbance. Keep this in mind: *change the structure, change the function!*

CONNECT WITH THE CURRICULUM FRAMEWORK

Consider each category of organic compound. Describe a specific change that might occur in a molecule in each category, and describe how this might affect the original function of the molecule. Justify your response.

Nucleic acids store, transmit, and help express hereditary information (5.5)

- **DNA** (deoxyribonucleic acid) and **RNA** (ribonucleic acid) are the two nucleic acids. Their monomers are nucleotides.
- **Nucleotides** are made up of three parts (Figure 5.24b):
 - **Nitrogenous base** (adenine, thymine, cytosine, and guanine in DNA; adenine, uracil, cytosine, and guanine in RNA)
 - **Pentose** (5-carbon) sugar (deoxyribose in DNA or ribose in RNA)
 - **Phosphate group**
- **DNA** is the molecule of heredity.
 - It is a double-stranded helix.
 - Its nucleotides are adenine, thymine, cytosine, and guanine.
 - Adenine nucleotides will hydrogen bond to thymine nucleotides; cytosine nucleotides will hydrogen bond to guanine nucleotides.
- **RNA** is single-stranded. Its nucleotides are adenine, uracil, cytosine, and guanine. Note that it does not have thymine.
- Nucleic acids have directionality, determined by the 3' and 5' carbons of the sugar. This will determine the direction of DNA replication and transcription (5' to 3').

An Introduction to Metabolism (Enzymes) (Chapter 8)

YOU MUST KNOW...

- That enzymes work by lowering the energy of activation.
- The catalytic cycle of an enzyme that results in the production of a final product.
- Factors that change enzyme shape and how they influence enzyme activity.
- How the shape of enzymes, their active sites, and interaction with specific molecules affect their function.
- How feedback inhibition is used to maintain appropriate levels of enzymes in a pathway.

Enzymes speed up metabolic reactions by lowering energy barriers (8.4)

- **Catalysts** are substances that can change the rate of a reaction without being altered in the process.
- **Enzymes** are macromolecules that are biological catalysts.
- The **activation energy** of a reaction is the amount of energy it takes to start a reaction – the amount of energy it takes to break the bonds of the reactant molecules. Enzymes speed up reactions *by lowering the activation energy* of the reaction – but without changing the free-energy change of the reaction. The reactant that the enzyme acts on is called a **substrate**. Figure 8.14 graphically depicts how enzymes function.
- The **active site** is the part of the enzyme that binds to the substrate. The enzyme and substrate form a complex called an **enzyme-substrate complex** that is generally held together by weak interactions. The substrate is then converted into **products**, and the products are released from the enzyme. Use Figure 8.16 to locate each step in the catalytic cycle of an enzyme.
- The activity of an enzyme can be affected by several factors:
 - Protein enzymes have complicated three-dimensional shapes that are dramatically affected by changes in pH and temperature. Changes in the precise shape of an enzyme usually mean the enzyme will not be as effective (Figure 8.17). Note how the rate of the reaction is altered in the graphs in Figure 8.17 when temperature and pH are not optimal.
 - Many enzymes require non-protein helpers, termed **cofactors**, to function properly. Cofactors include metal ions like zinc, iron, and copper and function in some crucial way to allow catalysis to occur. If the cofactor is organic, it is more properly referred to as a coenzyme. **Coenzymes** are organic cofactors; vitamins are examples of coenzymes.

- **Competitive inhibitors** are reversible inhibitors that *compete with the substrate for the active site* on the enzyme. Competitive inhibitors are often chemically very similar to the normal substrate molecule and reduce the efficiency of the enzyme as it competes for the active site.
- **Noncompetitive inhibitors** do not directly compete with the substrate molecule; instead, they impede enzyme activity by binding to another part of the enzyme. This causes the enzyme to change its shape, rendering the active site nonfunctional.

STUDY TIP: Enzymes are a key topic in biology. Know why certain factors such as pH and temperature affect enzyme action. Be able to pose a question about enzyme function, design an experiment to test this question, predict results, and analyze data from an enzyme experiment.

Regulation of enzyme activity helps control metabolism (8.5)

- Many enzyme regulators bind to an **allosteric** site on the enzyme, which is a specific binding site, but not the active site. Once bound, the shape of the enzyme is changed, and this can either stimulate or inhibit enzyme activity.
- The end product on an enzymatic pathway can switch off its pathway by binding to the allosteric site of an enzyme in the pathway. This type of allosteric inhibition is termed **feedback inhibition**. Feedback inhibition increases the efficiency of the pathway by turning it off when the end product accumulates in the cell.