CHAPTER 3
THE CHEMISTRY OF ORGANIC MOLECULES

3.1 Organic Molecules

The chemistry of **carbon** accounts for the diversity of organic molecules found in living things. Carbon has six electrons, four of which are valence electrons. Thus, carbon forms covalent bonds and can share electrons with as many as four other atoms, usually H, O, N, S, and P. Carbon can form a combination of single, double, or triple bonds.

Carbon can also bond with itself and hydrogen to form both chains and rings called hydrocarbons. Because the covalent bond between carbon and hydrogen is nonpolar, these carbon skeletons are hydrophobic. **Functional groups** can be added to carbon skeletons to make them more hydrophilic. Differences in the carbon skeleton and attached functional groups cause organic molecules to have different chemical properties. The chemical properties of a molecule determine how it interacts with other molecules and the role the molecule plays in the cell. Some functional groups are hydrophobic and others are hydrophilic. Take a moment to review six functional groups that are important for life.

Functional Groups

Group	Structure	Compound	Significance
Hydroxyl	R—OH	Alcohol as in ethanol	Polar, forms hydrogen bond Present in sugars, some amino acids
Carbonyl	R—C(=O)—H	Aldehyde as in formaldehyde	Polar Present in sugars
	R—C(=O)—R	Ketone as in acetone	Polar Present in sugars
Carboxyl (acidic)	R—C(=O)—OH	Carboxylic acid as in acetic acid	Polar, acidic; Present in fatty acids, amino acids
Amino	R—N(—H)—H	Amine as in tryptophan	Polar, basic, forms hydrogen bonds Present in amino acids
Sulfhydryl	R—SH	Thiol as in ethanethiol	Forms disulfide bonds Present in some amino acids
Phosphate	R—O—P(=O)(—OH)—OH	Organic phosphate as in phosphorylated molecules	Polar, acidic; Present in nucleotides, phospholipids

R = remainder of molecule

Functional groups

There are four classes of **biomolecules** in cells: carbohydrates, lipids, proteins, and nucleic acids. Polysaccharides, the largest of the carbohydrates, are polymers of simple sugars called monosaccharides. The polypeptides of proteins are polymers of amino acids, and nucleic acids are polymers of nucleotides. Polymers are formed by the joining together of monomers. Dehydration reactions, in which a molecule of water is removed, connect monomers together.

In order to break up a polymer, a molecule of water is added in a hydrolysis reaction.

> **Take Note:** *You should understand the characteristics of carbon that make it so versatile and allow it to be the basis of organic molecules. You should also be able to identify the functional groups that can be attached to hydrocarbons.*

3.2 Carbohydrates

Carbohydrates are made of carbon, hydrogen, and oxygen in a 1:2:1 ratio. Monosaccharides, disaccharides, and polysaccharides are all carbohydrates. **Monosaccharides** are simple sugars with three to six carbon atoms in the carbon skeleton. Examples of monosaccharides are glucose, fructose, and galactose, which each have six carbons. Glucose ($C_6H_{12}O_6$) is the immediate energy source of cells. Examples of five-carbon sugars include ribose and deoxyribose, found in the nucleic acids RNA and DNA, respectively. Disaccharides are formed from the dehydration reaction between two monosaccharides, as in sucrose or lactose.

Polysaccharides such as starch, glycogen, and cellulose are polymers of glucose. Starch in plants and glycogen in animals are energy storage compounds. Starch is found in the stems and roots of plants, and glycogen is found in the liver of animals. The structural polysaccharides are cellulose in plant cell walls, and chitin in arthropods and the cell walls of fungi. Chitin's monomer is glucose with an amino group attached. The structural polysaccharide of bacteria is peptidoglycan.

> **Take Note:** *You should be able to identify the structures of glucose (and the polymers it forms), ribose, deoxyribose, and sucrose.*

3.3 Lipids

Lipids include a wide variety of compounds that are insoluble in water. Like carbohydrates, fats are also made of carbon, hydrogen, and oxygen, though not in the same fixed ratio. Fats and oils, also called **triglycerides**, allow long-term energy storage and are formed from the dehydration reaction between one **glycerol** and three **fatty acids**.

Both glycerol and fatty acids have polar groups, but fats and oils are nonpolar, and this accounts for their insolubility in water. Fats tend to contain **saturated** fatty acids, and oils tend to contain **unsaturated** fatty acids. Saturated fatty acids do not have carbon–carbon double bonds, but unsaturated fatty acids do have double bonds in their hydrocarbon chain. The double bond causes a kink in the molecule that accounts for the liquid nature of oils.

Phospholipids are similar to fats, except that one of the fatty acids attached to the glycerol is replaced by a phosphate group. In the presence of water, phospholipids form a bilayer because the head of each molecule is hydrophilic and the tails are hydrophobic. The hydrophobic fatty acid tails will orient themselves away from the water, while the phosphate heads interact with the water. The cell membrane and the membranes of the organelles are all phospholipid bilayers, thus phospholipids are crucial for organisms.

Steroids have the same four-ring structure as cholesterol, but each differs by the groups attached to these rings. Cholesterol is found in the cell membrane, where it plays a role in stabilizing the structure of the membrane. It is also the basis for the steroid hormones, estrogen and testosterone.

Waxes are composed of a fatty acid with a long hydrocarbon chain bonded to an alcohol, also with a long hydrocarbon chain. As with carbohydrates and fats, waxes are formed by dehydration reactions. Waxes are important for water retention in plants. In animals, wax found in the ear prevents foreign substances from entering the body. Bees use wax to make honeycombs.

> **Take Note:** *You should be able to identify the structures of triglycerides, phospholipids, and steroids.*

3.4 Proteins

Proteins carry out many diverse functions in cells and organisms, including support, metabolism, transport, defense, regulation, and motion. Proteins are polymers of **amino acids**. A polypeptide is a long chain of amino acids joined by **peptide bonds**. An amino acid consists of a hydrogen, a carboxyl group, an amino group, and a variable *R* group that are all attached to a central carbon atom. There are 20 different amino acids in cells, and they differ only by their *R* groups. The presence or absence of polarity is an important aspect of the *R* groups, because they determine the structure of proteins.

A polypeptide can have up to four levels of structure. The **primary structure** is the sequence of the amino acids. **Secondary structure** contains **α-helices** and **β-pleated sheets** in place by hydrogen bonding between amino acids along the backbone of the polypeptide chain. The **tertiary structure** is the final folding of the polypeptide, which is held in place by interactions between *R* groups. Proteins that contain more than one polypeptide chain have a **quaternary structure**. The structure of a protein is important to its function. Both high temperatures and a change in pH can cause proteins to **denature** and lose their shape, causing a loss of function that can be detrimental to an organism.

> **Take Note:** *You should be able to identify the structure of an amino acid. You should also be able to explain the different levels of protein structure and relate the importance of structure to function.*

3.5 Nucleic Acids

The nucleic acids **DNA** and **RNA** are polymers of **nucleotides**. Variety is possible because the nucleotides can be in any order. Each nucleotide has three components: a phosphate group, a 5-carbon sugar, and a nitrogen-containing base. DNA contains a deoxyribose sugar, while RNA contains a ribose sugar.

DNA is the genetic material that stores information for its own replication and for the order in which amino acids are to be sequenced in proteins. DNA, with the help of mRNA, specifies protein synthesis. DNA is a double-stranded helix in which A pairs with T and C pairs with G through hydrogen bonding. RNA—containing phosphate, the sugar ribose, and the bases A, U, C, and G—is single stranded.

ATP (adenosine triphosphate) is a nucleotide that has three phosphate groups attached. ATP has unstable phosphate bonds and is the energy currency of cells. Hydrolysis of ATP to ADP + P_i releases energy, which is used by the cell to make a product or do any other type of metabolic work.

Multiple Choice Questions

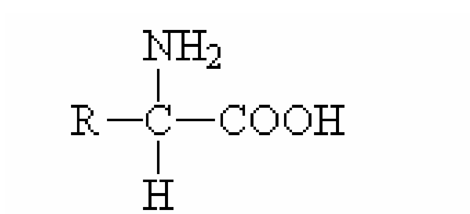
1. Which of the following atoms has four electrons available for covalent bonding and can form rings, long chains, and double bonds—making it the building block of the most versatile complex biological molecules?
   A. carbon
   B. silicon
   C. hydrogen
   D. oxygen
   E. nitrogen

2. Hydrocarbons do NOT vary in
   A. length.
   B. ring structure.
   C. branching.
   D. bonding patterns.
   E. composition.

3. Structural isomers
   A. may differ in their spatial arrangements.
   B. are mirror images of each other.
   C. may differ in the location of their double bonds.
   D. create left-handed and right-handed versions of the same molecule.
   E. create one active and one inactive molecule.

4. The polysaccharide stored in plastids enabling plants to store glucose is
   A. cellulose.
   B. glycogen.
   C. sucrose.
   D. starch.
   E. chitin.

5. The following molecule



   A. consists of a carbon atom joined to an oxygen atom by a double bond and is frequently found in carbohydrates.
   B. can transfer energy between organic molecules.
   C. consists of an amino group and a carboxyl group and is found in polypeptides.
   D. is the building block of lipids.
   E. is an alcohol and dissolves organic compounds such as sugars.

6. A dehydration reaction in the synthesis of a fat
   A. creates glycosidic linkages between the glycerol and the fatty acids.
   B. removes one molecule of water for each fatty acid joined to the glycerol.
   C. bonds water to the glycerol molecule to form a triacylglycerol.
   D. causes the glycerol molecules to separate from water and exclude the fatty acids.
   E. requires water to form peptide bonds.

7. A change in which of the following structural components will consequently the function of each amino acid?
   A. amino group
   B. α carbon
   C. carboxyl group
   D. functional group
   E. hydrocarbon

8. The level of protein structure that involves interactions between the side chains of the amino acids rather than the interactions between molecules within the backbone is
   A. primary.
   B. helical.
   C. secondary.
   D. tertiary.
   E. quaternary.

9. Which of the following statements is true regarding chaperonins?
   A. They specify the correct structure of a polypeptide.
   B. They are carbohydrates that bond with proteins to maintain proper shape.
   C. They are organic molecules that protect against disease.
   D. They transport oxygen from the lungs to other parts of the body.
   E. They are protein molecules that assist in the proper folding of other proteins.

10. Ribonucleic acid (RNA) and deoxyribonucleic acid (DNA) differ structurally in that
   A. RNA is composed of a pentose sugar and DNA is composed of a triose sugar.
   B. DNA contains uracil.
   C. RNA bonds purines to purines and DNA bonds pyrimidines to pyrimidines.
   D. DNA contains a sugar which lacks an oxygen atom and RNA does not.
   E. DNA is single stranded and RNA is double stranded.

Free Response Question

Diabetes is a disorder in which uncontrollable blood glucose levels become extremely dangerous. After eating, blood glucose levels can become very high, resulting in hyperglycemia and tissue damage. One way to monitor the level of blood glucose is to determine the amount of glucose that becomes bonded to hemoglobin, a protein on red blood cells. This is often more accurate than routine blood sugar tests as it is not as affected by short term blood glucose level changes due to exercise, eating or medications.

A. **Identify** and **describe** the levels of protein structure.

B. **Explain** how the structure of hemoglobin affects its function.

C. **Explain** how glucose may become attached to the hemoglobin and **hypothesize** as to what conditions may affect this test.

Annotated Answer Key (MC)

1. **A**; Carbon is the most versatile element in terms of its ability to form many different structures. It has four valence electrons, as does silicon. Hydrogen, oxygen, and nitrogen all have differing numbers of valence electrons. Silicon, however, is not capable of creating long chains of molecules due to its size.

2. **E**; Hydrocarbons contain hydrogen atoms and carbon atoms. While they may vary in their length, structure, branching, and bonding patterns, they must consist entirely of hydrogen and carbon.

3. **C**; Organic molecules are very specialized in the fact that they may contain the same numbers of specific atoms, but their arrangement defines their function. Enantiomers are mirror images of each other and create left-handed and right-handed versions of the same molecule. Often this creates one active and one inactive molecule. In a structural isomer, the location of the bonds may change, whereas in a geometric isomer there are the same covalent partnerships.

4. **C**; Cellulose, glycogen, starch, and chitin are all polysaccharides. Sucrose is a disaccharide. However, these polysaccharides differ in their functions. Cellulose and chitin are *structural* polysaccharides of plants and insects, respectively. Glycogen is the primary *storage* polysaccharide in animals, whereas starch is the primary *storage* polysaccharide in plants and is found in plastids.

5. **C**; This molecule contains an amino group (NH_2), a carboxyl group (COOH), a functional group (R), and a basic amino acid, the building block of polypeptides. Amino acids differ only in their R groups. It is not an alcohol and is not frequently found in lipids or carbohydrates.

6. **B**; Dehydration reactions *remove* water from molecules in order to create bonds between components. In carbohydrates, the bonds that hold the monomers of glucose together are called glycosidic linkages, but not in lipids. Water is removed, not added to the molecules and forms ester linkages, not peptide bonds.

7. **D**; Amino acids are composed of a carboxyl group, an amino group, a central carbon, and a functional group. This functional group, or side chain, can differ in their polarity and their pH properties, greatly influencing their biological function.

8. **D**; Primary structure involves the amino acid sequence of the protein structure. The bonds that hold these amino acids together are peptide bonds. In secondary structure, highly regular structures such as α helices or β pleated sheets result due to the hydrogen bonds within the backbone. However, in tertiary structure, interactions between atoms of the functional groups as well as the backbone occur (including but not limited to disulfide bridges, hydrophobic interactions, and ionic bonds).

9. **E**; Chaperonins are protein molecules that assist in the proper folding. Hemoglobin is the protein that transports oxygen from the lungs to other parts of the body, and antibodies protect against disease. Often, protein molecules end in the suffix *–in* as a hint in this question.

10. **D**; RNA and DNA both bond purines (adenine and guanine; double ring structures) to pyrimidines (cytosine and thymine; single ring structures). RNA contains uracil and bonds it to adenine in place of thymine. DNA is a double-stranded molecule, whereas RNA is a single-stranded molecule. Deoxyribose is a sugar in DNA derived from ribose, the sugar in RNA, but it lacks an oxygen atom, thus the prefix *deoxy-*.

Answer to FRQ

PART A (MAX 8 POINTS)
One point identification, one point definition.

- Primary: peptide bonds
- Secondary: hydrogen bonds
- Additional point for identification of beta pleated sheets and alpha helix structures
- Tertiary: interactions between R or functional groups
- Additional point for identification of Van der Waals, hydrophobic interactions, disulfide bridges, ionic interactions, etc.
- Quaternary: interaction between polypeptide chains

PART B (MAX 2 Function POINTS and MAX 2 Structure POINTS)

- Function: bind to oxygen in the bloodstream
- Function: carry it to outlying tissues
- Structure: can bond to between 1 and 4 molecules OR composed of four subunits
- Structure: porphyrin ring (Fe/N) for oxygen binding

PART C (MAX 4 POINTS)

- Irreversible covalent bond
- Blood transfusion
- Anemia
- Sickle cell anemia
- Pregnancy
- Kidney disease