CHAPTER 3

The Molecules of Cells

Objectives

Introduction Explain how spider silk is produced. Describe the special properties of spider silk that help spiders capture prey.

Introduction to Organic Compounds and Their Polymers

3.1 Explain why carbon is unparalleled in its ability to form large, diverse molecules.
3.1 Define organic compounds, hydrocarbons, a carbon skeleton, and an isomer.
3.2 Describe the properties of and distinguish between the four functional groups of organic molecules.
3.3 List the four classes of macromolecules, explain the relationship between monomers and polymers, and compare the processes of dehydration synthesis and hydrolysis.

Carbohydrates

3.4–3.7 Describe the structures, functions, properties, and types of carbohydrate molecules.

Lipids

3.8–3.10 Describe the structures, functions, properties, and types of lipid molecules.

Proteins

3.11–3.18 Describe the structures, functions, properties, and types of proteins.
3.19 Describe the major achievements of Linus Pauling.

Nucleic Acids

3.20 Compare the structures and functions of DNA and RNA.

Key Terms

organic compound
hydrocarbon
carbon skeleton
isomer
functional group
hydrophilic
hydroxyl group
carbonyl group
carboxyl group
carboxylic acid
amino group
amine
macromolecule
polymer
monomer
dehydration synthesis
hydrolysis
carbohydrate
monosaccharide
disaccharide
polysaccharide
starch
glycogen
cellulose
lipid
hydrophobic
fat
triglyceride
unsaturated
saturated
phospholipid
wax
steroid
anabolic steroid
protein
enzyme

amino acid
peptide bond
polypeptide
denaturation
primary structure
secondary structure
alpha helix
pleated sheet
tertiary structure
quaternary structure
nucleic acid
deoxyribonucleic acid (DNA)
ribonucleic acid (RNA)
gene
nucleotide
phosphate group
nitrogenous base
double helix

Word Roots

carb- = coal (*carboxyl group:* a functional group present in organic acids, consisting of a carbon atom double-bonded to an oxygen atom)

di- = two (*disaccharide:* two monosaccharides joined together)

glyco- = sweet (*glycogen:* a polysaccharide sugar used to store energy in animals)

hydro- = water (*hydrocarbon:* an organic molecule consisting only of carbon and hydrogen)

iso- = equal (*isomer:* one of several organic compounds with the same molecular formula but different structures and therefore different properties)

macro- = large (*macromolecule:* a large molecule)

mono- = single; **-sacchar** = sugar (*monosaccharide:* simplest type of sugar)

poly- = many (*polysaccharide:* many monosaccharides joined together)

tri- = three (*triacylglycerol:* three fatty acids linked to one glycerol molecule)

Lecture Outline

Introduction *Spider Silk: Stronger Than Steel*

A. Life's beauty and properties begin to emerge at the macromolecular level.

B. The central topic of this chapter is how smaller molecular units are assembled into larger ones.

C. Figure 3.0 is a good starting example of macromolecular structure and function.

I. Introduction to Organic Compounds and Their Polymers

Module 3.1 Life's molecular diversity is based on the properties of carbon.

A. **Organic compounds** contain at least one carbon atom (Figure 3.1).

B. Carbon has 4 electrons in the outer shell; therefore carbon has a strong tendency to fill the shell to 8 by forming covalent bonds with other atoms, particularly hydrogen, oxygen, and nitrogen. The 4 electrons in the outermost shell of carbon allow it to form complex structures (e.g., long, branched chains, ring structures). This is a major reason why carbon is the structural backbone of organic compounds. A compound composed only of carbon and hydrogen is called a **hydrocarbon.**
Review: Covalent bonds (Module 2.8).
NOTE: At this point you might want to ask the class if any of them have ever seen the episode of the original *Star Trek* in which the Horta, a silicon-based life form, appeared; ask if silicon-based life makes chemical sense.

C. Point out the double bond in Figure 3.1, explaining that it represents 4 shared electrons. *NOTE:* Although the topic is not introduced here, you might mention that triple bonds—which occur in molecular nitrogen, among other places—are represented by three lines (6 shared electrons).

D. The way bonding occurs among atoms in molecules determines an overall shape.

E. **Isomers** are molecules with the same numbers of each atom but with different structural arrangements of the atoms.

Module 3.2 Functional groups help determine the properties of organic compounds.

A. Functional groups are generally attached to the carbon backbone of different macromolecules and exhibit predictable chemical properties.

B. Functional groups are the atoms of an organic compound directly participating in chemical reactions.

C. Go over Figure 3.2, discussing a few of the examples.

D. All of these functional groups have polar characteristics. Therefore, most of the molecules they are found on are polar molecules.

Module 3.3 Cells make a huge number of large molecules from a small set of small molecules.

A. **Monomers** are the fundamental molecular unit. **Polymers** are **macromolecules** made by linking many of the same kind of fundamental units.

B. Types of reactions (note that water is involved in both; Figure 3.3A, B): **dehydration synthesis**—molecules synthesized by loss of a water molecule between reacting monomers, the most common way organic polymers are synthesized; **hydrolysis**—literally, "breaking apart with water"—the most common way organic polymers are degraded.

C. The study of molecular reactions in living systems is a broad topic that will be a theme throughout the course. The two reactions reviewed in this module are ones involved in the formation of molecular structures introduced in the remaining modules.

D. Life's chemical reactions occur in particular intracellular and extracellular environments and under controlled conditions.

E. *Preview:* Chapter 4 will discuss the cellular framework on which and in which molecular reactions occur.

F. *Preview:* Chapters 5–7 discuss metabolism, i.e., cellular reactions involving energy uptake, storage, and release.

II. Carbohydrates

Module 3.4 Monosaccharides are the simplest **carbohydrates.**

NOTE: The word "carbohydrate" indicates that these compounds are made of carbon (*carbo,* C) and water (*hydrate,* H_2O). This is reiterated in the general formula $(CH_2O)_n$ for monosaccharides.

A. Show examples of the isomers glucose and fructose (Figure 3.4B).

B. The suffix "ose" indicates that the molecule is a sugar.

C. In solution, many monosaccharides form ring-shaped molecules (Figure 3.4C).

D. *Preview:* The basic roles of simple sugars are as fuel to do work, as raw material for carbon backbones, and as the monomers from which disaccharides and polysaccharides are synthesized.

Module 3.5 Cells link single sugars to form **disaccharides.**

- A. Two monosaccharides are put together to form a disaccharide via a glycosidic bond (Figure 3.5).
- B. Disaccharide formation is an example of dehydration synthesis (Module 3.3).
- C. The most common disaccharide is sucrose (table sugar), which is composed of glucose and fructose.

Module 3.6 Connection: How sweet is sweet?

- A. There are four well-documented taste receptors on the tongue: bitter, salty, sour, and sweet.
- B. Humans perceive a sweet taste when a chemical binds to the sweet receptor on the tongue. The chemical can be a sugar or other chemicals like aspartame.
- C. The stronger the binding by a chemical to the sweet receptor, the sweeter the chemical is perceived to be. Fructose is considered 4 times sweeter than sucrose.
- D. *Preview:* The discussion in this module continues with additional material on nutrition in Chapter 21.

Module 3.7 Polysaccharides are long chains of sugar units.

- A. Different organisms use monosaccharides, such as glucose, to build several different polymers: **starch, glycogen,** and **cellulose** (Figure 3.7).
  NOTE: Hydrogen atoms and functional groups are not shown in the figure.
- B. Each of these molecules is synthesized by dehydration synthesis, but there are subtle differences in the covalent bonds that lead to different overall structures and functions.
  Review: Covalent bonds (Module 2.8).
- C. Starch is used for long-term energy storage only in plants. Starch molecules are helical and may be either unbranched or branched. Animals can hydrolyze this polymer to obtain glucose.
  NOTE: The unbranched form of starch is called *amylose.* The branched form is called *amylopectin.* Starches rich in amylopectin retain water and are often used in frozen foods. This can also be used to illustrate the convention used for naming enzymes—the starch amylose is broken down by the enzyme amylase.
- D. Glycogen has the same kind of bond between monomers as starch, but it is highly branched. Glycogen also is used for long-term energy storage, but only in animals. Animals can hydrolyze this polymer to obtain glucose.
- E. Cellulose has a different kind of bond between monomers, forming linear polymers that are cross-linked by hydrogen bonds with other linear chains. Cellulose is the principal structural molecule in the cell walls of plants and algae. Since animals cannot hydrolyze this polymer to obtain glucose (only certain bacteria, protozoans, and fungi can) it is referred to as a *fiber.*

III. Lipids

Module 3.8 Lipids include fats, which are mostly energy-storage molecules.

- A. In lipids, carbon and hydrogen predominate; there is very little oxygen. General molecular formula for fatty acid: $(CH_2)_n$.
- B. Diverse types of lipids have different roles, but all are more or less **hydrophobic.**
- C. **Fats** are polymers of fatty acids (usually three) and one glycerol molecule, formed by dehydration synthesis reactions, and are called triglycerides or triacylglycerides (Figure 3.8B, C).

D. **Saturated** fatty acids have no double bonds between carbons (the carbons are "saturated" with hydrogen atoms). The molecular backbones are flexible and tend to ball up into tight globules. Saturated fats like butter and lard are solid at room temperature.

E. **Unsaturated** fats may include several double bonds between carbons. This causes the molecules to be less flexible and they do not pack into solid globules. Unsaturated fats like olive oil and corn oil are liquid at room temperature.

F. Most plant fats are unsaturated, whereas animal fats are richer in saturated fats.

Preview: There are two types of unsaturated fats (Chapter 21). Polyunsaturated fats include the essential fatty acids. Monounsaturated fats (in moderation), contrary to the general reputation of "fat," have cardiovascular benefits. Omega fats in fish are a good example of a healthy fat.

NOTE: By "hydrogenating" unsaturated oils, the double bonds are removed and the molecules become more solid at room temperature. These structurally modified (trans) fats are as detrimental as their naturally saturated counterparts in leading to atherosclerotic plaques.

Module 3.9 Phospholipids, waxes, and steroids are lipids with a variety of functions.

A. Phospholipids are a major component of cell membranes, but have two fatty acid molecules instead of three and a phosphate group.

B. **Waxes** are effective hydrophobic coatings formed by many organisms (insects, plants, even humans) to ward off water. They consist of a single fatty acid linked to an alcohol.

C. **Steroids** are lipids with backbones bent into rings. Cholesterol is an important steroid formed by animals (Figure 3.9; notice that the diagram omits carbons and hydrogens at each intersection in the rings and just shows the backbone shape). Among other things, cholesterol is the precursor to bile acids that functions in the digestion of fats and as starting material for the synthesis of female and male sex hormones.

NOTE: Despite its reputation, cholesterol plays many vital roles in the body.

D. *Preview:* The structural roles of phospholipid-containing membranes are introduced in Chapter 4, on cell structure; their molecular structure and function are discussed in Chapter 5, with other topics relating to cellular work. Like fats, they are polymers of fatty acids and glycerol, but include a PO_4 group in place of one fatty acid. This gives them the unique property of having a hydrophobic "tail" and a hydrophilic "head."

Module 3.10 Connection: Anabolic steroids and related substances pose health risks.

A. **Anabolic steroids** are synthetic and natural variants of the male hormone testosterone, which, among other roles, causes the buildup of muscle and bone mass during puberty in men.

NOTE: Since college-age body builders may be tempted to use steroids, you might want to point out some of the medical problems such use could lead to, including problems such as: testicular atrophy, liver cancer, breast development in males, masculinization of females, and antisocial behavior.

IV. Proteins

Module 3.11 Proteins are essential to the structures and activities of life.

A. **Proteins** are constructed from amino acids.

B. The structure of the protein determines its function.

C. The seven major classes of protein are:
   1. Structural: hair, cell cytoskeleton
   2. Contractile: as part of muscle and other motile cells, produce movement
   3. Storage: sources of amino acids, such as egg white
   4. Defense: antibodies, membrane proteins, complement proteins
   5. Transport: hemoglobin, membrane proteins
   6. Signaling: hormones, membrane proteins
   7. **Enzymatic:** decrease the rate of a biochemical reaction much like a chemical catalyst

Module 3.12 Proteins are made from just 20 kinds of amino acids.

A. **Amino acids** are characterized by having an alpha carbon atom covalently bonded to one hydrogen, one amino group (NH_2), one carboxyl group (COOH), and one functional group symbolized by an R (Figure 3.12A).
Review: Covalent bonds (Module 2.8).

B. Each naturally occurring amino acid has one of 20 functional groups (Figure 3.12B), which determines the chemical characteristics of each amino acid.

Module 3.13 Amino acids can be linked by peptide bonds.

A. Organisms use amino acids as the monomer to build polypeptides by dehydration synthesis. The bond between each amino acid is called a **peptide bond** (Figure 3.13).

B. Protein peptide bonds can be broken down by hydrolysis, to release free amino acids.

C. **Polypeptides** are from several to over a thousand amino acids long and the specific sequence determines the function of the protein (a polypeptide with more than 20 amino acids is classified as a protein).
NOTE: Add a reverse arrow to Figure 3.13 and label it "Hydrolysis."

Module 3.14 Overview: A protein's specific shape determines its function.

A. Long polypeptide chains include numerous and various amino acids.

B. The final structure of a protein, and thus its potential role, depends on the way these long, linear molecules fold up.

C. Each sequence of amino acids folds in a different way spontaneously (Figure 3.14A).

D. Changes in heat, ionic strength, salinity, and so on can cause proteins to unfold (this is called **denaturation**).

E. The four levels of structure are shown in the protein transthyretin in Figures 3.15–3.18.
NOTE: At each level in the diagrams, details are hidden to show the essential structure added at that level.

Module 3.15 A protein's primary structure is its amino acid sequence.

A. Transthyretin is found in blood and is important in the transport of a thyroid hormone and vitamin A.

B. Three-letter abbreviations represent amino acids; each amino acid is in a precise order in the chain (Figure 3.15).

C. In transthyretin, there are four polypeptide chains, each with 127 amino acids.

D. Changes in the **primary structure** of a protein (the amino acid sequence) can affect its overall structure and thus its ability to function.

Module 3.16 **Secondary structure** is polypeptide coiling or folding produced by hydrogen bonding.

A. Hydrogen bonds occur between —NH and —C=O groups of amino acids in sequence along each polypeptide chain.
Review: Hydrogen bonds (Module 2.10).

B. Depending on where the groups are relative to one another, the secondary structure takes the shape of an **alpha helix** or a **pleated sheet** (Figure 3.16).

C. The R groups usually do not play a role in secondary structure and are not diagrammed.
NOTE: Diagramming the secondary structures of proteins uses cylinders, flat arrows, and lines to represent helical regions, beta pleated sheets, and nonhydrogen-bonded regions (also called random coils), respectively.

Module 3.17 Tertiary structure is the overall shape of a polypeptide.

A. **Tertiary structure** results from the clustering of hydrophobic and hydrophilic R groups and bond formation (hydrogen and ionic) between certain R groups along the coils and pleats (Figure 3.17). An important and often overlooked covalent bond that maintains tertiary structure is the disulfide bond that forms between two cysteine amino acids.

B. In transthyretin, the tertiary shape is essentially globular.

Module 3.18 **Quaternary structure** is the relationship among multiple polypeptides of a protein.

A. Many (but not all) proteins consist of more than one primary chain.

B. Transthyretin consists of four chains, each identical (Figure 3.18). Other proteins might have all chains different or be additionally complexed with other atoms or molecules. Another good example of a protein with quaternary structure is hemoglobin: 4 subunits (2 + 2) and 4 heme prosthetic groups.
NOTE: Quaternary bonding is largely by polar and hydrophobic interaction.

Module 3.19 Talking About Science: Linus Pauling contributed to our understanding of the chemistry of life.

A. Dr. Pauling felt that there was value in reductionism when studying biology in an attempt to answer questions about whole organisms.

B. He was the first to describe the coiled and pleated-sheet secondary structure of protein and the first to describe the structure of hemoglobin and the abnormal form found in the red blood cells of those with sickle-cell disease.

C. Later in his life, Pauling was most noted for his work on the role of vitamin C in maintaining health, which has not been substantiated.

D. Pauling also had a lifelong interest in the biology of aging.

E. As are many scientists, Pauling was politically active, being an advocate for a ban on the testing of nuclear weapons.

V. Nucleic Acids

Module 3.20 **Nucleic acids** are information-rich polymers of nucleotides.

A. **Nucleotides** are complex molecules composed of three functional parts (Figure 3.20A, B): phosphate group, five-carbon sugar (deoxyribose in **DNA;** ribose in **RNA**), nitrogenous base.

B. There are five basic types of nitrogenous bases: A, T, G, C in DNA and A, U, G, C in RNA (Figure 10.2B, C).

   NOTE: DNA nucleotide sequences encode the information required for production of the primary structure of proteins; such sequences are called genes (Modules 10.7 and 10.8).

C. Nucleotide monomers join by dehydration synthesis between the nucleotide parts (phosphate to sugar) to form polynucleotides with a linear structure of sugar-phosphate repeats (Figures 3.20A, B; Figure 10.2A).

D. Hydrogen bonding between **nitrogenous bases** (A to T and G to C) causes the final structure of the nucleic acid.

   Preview: The mechanisms by which these structures determine gene expression are discussed in Chapters 10 and 11.

E. In DNA, two linear chains are held together in an antiparallel **double helix** (Figure 3.20C).

F. In RNA, one linear chain may be wrapped around itself in places, forming one of three types of RNA: transfer RNA (tRNA), ribosomal RNA (rRNA), or messenger RNA (mRNA). See Chapter 10 for structural details.

Class Activities

1. Present your students with hydrocarbons of various lengths and hydrogen content. Ask them to see how many different isomers they can construct from these hydrocarbons. Point out to your class how the *cis* versus *trans* position of hydrogens relates to the hydrogenation of fatty acids.

2. To show that the polysaccharide starch is composed of smaller sugars, pass out grains of wheat, and have students chew on them for 5–10 minutes. As they chew, explain how the hydrolysis of plant starch produces the disaccharide maltose, which is noticeably sweet. Also point out that this only occurs in the presence of the right environment, including the enzyme salivary amylase (take this opportunity to illustrate the "ase" convention of naming enzymes: The starch amylose is broken down by the enzyme amylase) and the proper pH. The exact chemical role of this enzyme need not be introduced at this point. In larger classes, you might want to restrict this activity to discussion groups.

3. On a per gram basis, sugar alcohols are not as sweet as sucrose, yet sufficient amounts are used to achieve a comparable degree of sweetness in gums and candies that are labeled as being "dietetic" and "sugarless." Ask students what might account for the apparent contradiction.

   You might want to point out to your students that sugars are not the only compounds that are perceived as being sweet. For example, proteins known as thaumatins are 2000 times sweeter than sucrose.

4. Ask your students to consider, based on what they have learned in this chapter, the role of fever as a mechanism for restoring homeostasis.

Transparency Acetates

Figure 3.1	Variations in carbon skeletons
Table 3.2	Some common functional groups
Figure 3.3A	Dehydration synthesis of a polymer

Figure 3.3B	Hydrolysis of a polymer
Figure 3.4B	Structures of glucose and fructose
Figure 3.4C	Linear and ring forms of glucose
Figure 3.5	Disaccharide formation
Table 3.6	Sweetness scale
Figure 3.7	Polysaccharides
Figure 3.8B	Dehydration synthesis linking a fatty acid to glycerol
Figure 3.8C	A fat molecule
Figure 3.9	Cholesterol, a steroid
Figure 3.12A	General structure of an amino acid
Figure 3.12B	Examples of amino acids
Figure 3.13	Peptide bond formation
Figure 3.15–18	Levels of protein structure: primary, secondary, tertiary, and quaternary
Figure 3.20A	A nucleotide
Figure 3.20B	Part of a polynucleotide
Figure 3.20C	DNA double helix

Describing, Comparing, and Explaining Question 5: Sucrose molecule

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Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

Animations and Videos	**File Name**
Macromolecules Animation	03-03-MacromoleculesAnim.mov
Disaccharides Animation	03-05-DisaccharidesAnim.mov
Polysaccharides Animation	03-07-PolysaccharidesAnim.mov
Fats Animation	03-08-FatsAnim.mov
Contractile Proteins Animation	03-11-ContractProteinsAnim.mov
Defensive Proteins Animation	03-11-DefensiveProteinsAnim.mov
Enzymes Animation	03-11-EnzymesAnim.mov
Signal Proteins Animation	03-11-SignalProteinsAnim.mov
Storage Proteins Animation	03-11-StorageProteinsAnim.mov
Structural Proteins Animation	03-11-StructuralProtAnim.mov
Transport Proteins Animation	03-11-TransportProtAnim.mov
Protein Structure Introduction Animation	03-14-ProteinStructureAnim.mov
Primary Protein Structure Animation	03-15-PrimaryStructureAnim.mov
Secondary Protein Structure Animation	03-16-SecondStructureAnim.mov
Tertiary Protein Structure Animation	03-17-TertiaryStructureAnim.mov
Quaternary Protein Structure Animation	03-18-QuatStructureAnim.mov

Activities and Thinking as a Scientist	Module Number
Web/CD Activity 3A: *Diversity of Carbon-Based Molecules*	3.1
Web/CD Thinking as a Scientist: *Connection: What Factors Determine the Effectiveness of Drugs?*	3.1
Web/CD Activity 3B: *Functional Groups*	3.2
Biology Labs On-Line: *HemoglobinLab*	3.2
Web/CD Activity 3C: *Making and Breaking Polymers*	3.3
Web/CD Activity 3D: *Models of Glucose*	3.4
Web/CD Activity 3E: *Carbohydrates*	3.7
Web/CD Activity 3F: *Lipids*	3.9
Web/CD Activity 3G: *Protein Functions*	3.11
Web/CD Activity 3H: *Protein Structure*	3.18
Web/CD Activity 3I: *Nucleic Acid Functions*	3.20
Web/CD Activity 3J: *Nucleic Acid Structure*	3.20