Chapter 5

The Structure and Function of Large Biological Molecules

Key Concepts

5.1 Macromolecules are polymers, built from monomers
5.2 Carbohydrates serve as fuel and building materials
5.3 Lipids are a diverse group of hydrophobic molecules
5.4 Proteins include a diversity of structures, resulting in a wide range of functions
5.5 Nucleic acids store, transmit, and help express hereditary information

Chapter Review

Smaller organic molecules are joined together to form carbohydrates, lipids, proteins, and nucleic acids. These molecules, many of which are giant macromolecules, have emergent properties that arise from their complex and unique structures.

5.1 Macromolecules are polymers, built from monomers

Polymers are chainlike molecules formed from the linking together of many similar or identical small molecules, called monomers.

Synthesis and Breakdown of Polymers Monomers are joined by a dehydration reaction, in which one monomer provides a hydroxyl group (—OH) and the other contributes a hydrogen (—H) to release a water molecule. In hydrolysis, the bond between monomers is broken by the addition of water. The hydroxyl group of a water molecule is joined to one monomer while the hydrogen is bonded with the other. Enzymes catalyze both dehydration reactions and hydrolysis.

Framework

A small number of monomers or subunits joined into unique sequences and forming three-dimensional structures create a huge variety of large molecules with diverse functions. The following table briefly summarizes the major characteristics of the four classes of biological molecules.

<table>
<thead>
<tr>
<th>Class</th>
<th>Monomers or Components</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrates</td>
<td>Monosaccharides</td>
<td>Energy source, raw materials, energy storage, structural compounds</td>
</tr>
<tr>
<td>Lipids</td>
<td>Glycerol and fatty acids → fats; phospholipids; steroids</td>
<td>Energy storage, membrane components, hormones</td>
</tr>
<tr>
<td>Proteins</td>
<td>Amino acids</td>
<td>Enzymes, transport, movement, receptors, defense, structure</td>
</tr>
<tr>
<td>Nucleic acids</td>
<td>Nucleotides</td>
<td>Heredity, various functions in gene expression</td>
</tr>
</tbody>
</table>
Diversity of Polymers  Polymers are constructed from about 40 to 50 common monomers and a few rarer molecules. The seemingly endless variety of macromolecules arises from the essentially infinite number of possibilities in the sequencing and arrangement of these basic building blocks.

**INTERACTIVE QUESTION 5.1**

Monomers are linked into polymers by ________, which involve the ________ of a water molecule.

Polymers are broken down to monomers by ________, which involves the ________ of a water molecule.

5.2 Carbohydrates serve as fuel and building materials

Carbohydrates include sugars and their polymers.

**Sugars**  Monosaccharides have the general formula of \((\text{CH}_2\text{O})_n\). The number \((n)\) of these units forming a sugar varies from three to seven, with hexoses \((\text{C}_6\text{H}_{12}\text{O}_6)\), trioses, and pentoses being most common. Sugar molecules may also vary due to the spatial arrangement of parts around asymmetric carbons.

**INTERACTIVE QUESTION 5.2**

Fill in the blanks to review monosaccharides.

You can recognize a monosaccharide by its multiple (a) ________ groups and its one (b) ________ group, whose location determines whether the sugar is an (c) ________ or a (d) ________. In aqueous solutions, most five- and six-carbon sugars form (e) ________.

Glucose is broken down to yield energy in cellular respiration. Monosaccharides also serve as the raw materials for the synthesis of other organic molecules. Two monosaccharides are joined by a glycosidic linkage to form a disaccharide.

**Polysaccharides**  Polysaccharides are storage or structural macromolecules. Starch, a storage molecule in plants, is a polymer made of glucose molecules joined by 1–4 glycosidic linkages that give starch a helical shape. Animals use glycogen, a highly branched polymer of glucose, as their energy storage molecule.

**Cellulose**, the major component of plant cell walls, is the most abundant organic compound on Earth. It differs from starch by the configuration of the ring form of glucose (beta instead of alpha) and the resulting geometry of the glycosidic bonds. In a plant cell wall, hydrogen bonds between hydroxyl groups hold parallel cellulose molecules together to form strong microfibrils.

Enzymes that digest the α linkages of starch are unable to hydrolyze the β linkages of cellulose: Only a few organisms (some prokaryotes and fungi) have enzymes that can digest cellulose.

**Chitin** is a structural polysaccharide formed from glucose monomers with a nitrogen-containing group. Chitin is found in the exoskeleton of arthropods and the cell walls of many fungi.

**INTERACTIVE QUESTION 5.3**

Number the carbons in the following glucose molecules (each unlabeled corner of the ring represents a carbon). Circle the atoms that will be removed by a dehydration reaction. Then draw the resulting maltose molecule with its 1–4 glycosidic linkage.

![Glucose and Maltose](image)
5.3 Lipids are a diverse group of hydrophobic molecules

Fats, phospholipids, and steroids are part of a diverse assemblage of biological molecules that are grouped together as lipids based on their hydrophobic behavior. Lipids do not form polymers.

**Fats** Fats are composed of fatty acids attached to the three-carbon alcohol, glycerol. A fatty acid consists of a long hydrocarbon chain with a carboxyl group at one end. The nonpolar hydrocarbons make a fat hydrophobic.

A triacylglycerol, or fat, consists of three fatty acid molecules, each linked to glycerol by an ester linkage, a bond that forms between a hydroxyl and a carboxyl group. Triglyceride is another name for fats.

Fatty acids with double bonds in their carbon chain are called unsaturated fatty acids. The cis double bonds create a kink in the hydrocarbon chain and prevent fat molecules with unsaturated fatty acids from packing closely together and becoming solidified at room temperature. The fats of plants and fish are generally unsaturated and are called oils. Saturated fatty acids have no double bonds in their carbon chains. Most animal fats are saturated and solid at room temperature. Diets rich in saturated fats and in trans fats made in the process of hydrogenating vegetable oils have been linked to cardiovascular disease.

Fats are excellent energy storage molecules, containing twice the energy reserves of carbohydrates such as starch. Adipose tissue, made of fat storage cells, also cushions organs and insulates the body.

**Phospholipids** Phospholipids consist of a glycerol linked to two fatty acids and a negatively charged phosphate group, to which other small molecules are attached. The phosphate head of this molecule is hydrophilic and water soluble, whereas the two fatty acid chains are hydrophobic. The unique structure of phospholipids makes them ideal constituents of cell membranes.

**Steroids** Steroids are a class of lipids distinguished by four connected carbon rings with various chemical groups attached. Cholesterol is a common component of animal cell membranes and a precursor for other steroids, including many hormones.
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INTERACTIVE QUESTION 5.6

Fill in this concept map to help you organize your understanding of lipids.

![Lipid Concept Map]

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

Proteins are central to almost every function of life. Most enzymes, which function as catalysts that selectively speed up the chemical reactions of a cell, are proteins.

Polypeptides A polypeptide is a polymer of amino acids. A protein is a functional molecule that consists of one or more polypeptides, each folded into a specific three-dimensional shape.

Amino acids are composed of an asymmetric carbon (called the alpha [α] carbon) bonded to a hydrogen atom, a carboxyl group, an amino group, and a variable side chain called the R group. At the pH in a cell, the amino and carboxyl groups are usually ionized. The R group confers the unique physical and chemical properties of each amino acid. Side chains may be either nonpolar and hydrophobic, or polar or charged (acidic or basic) and thus hydrophilic.

A peptide bond links the carboxyl group of one amino acid with the amino group of another.

INTERACTIVE QUESTION 5.7

a. Draw the amino acids alanine (R group: —CH₃) and serine (R group: —CH₂OH) and then show how a dehydration reaction will form a peptide bond between them.

b. Which of these amino acids has a polar R group? a nonpolar R group?

c. What does the following molecule segment represent? (Note the N–C–C–N–C–C sequence.)

![Amino Acid Segment]
**Protein Structure and Function**  A protein has a unique three-dimensional shape, or structure, created by the twisting or folding of one or more polypeptide chains. Protein structure usually arises spontaneously as the protein is synthesized in the cell. The unique structure of a protein enables it to recognize and bind to other molecules. **Globular proteins** are roughly spherical; **fibrous proteins** are long fibers.

**Primary structure** is the genetically coded sequence of amino acids within a protein.

**Secondary structure** involves the coiling or folding of the polypeptide backbone, stabilized by hydrogen bonds between the oxygen (with a partial negative charge) of one peptide bond and the partially positive hydrogen attached to the nitrogen of another peptide bond. An α helix is a coil produced by hydrogen bonding between every fourth amino acid. A β pleated sheet is held by repeated hydrogen bonds along regions of the polypeptide backbone lying parallel to each other.

**Tertiary structure**, the overall shape of a protein, results from interactions between the various side chains (R groups) of the constituent amino acids. The following chemical interactions help produce the stable and unique shape of a protein: **hydrophobic interactions** between nonpolar side groups clumped in the center of the molecule due to their repulsion by water, van der Waals interactions among those non-polar side chains, hydrogen bonds between polar side chains, and ionic bonds between negatively and positively charged side chains. Strong covalent bonds, called **disulfide bridges**, may occur between the sulfhydryl side groups of cysteine monomers that have been brought close together by the folding of the polypeptide.

**Quaternary structure** occurs in proteins that are composed of more than one polypeptide. The individual polypeptide subunits are held together in a precise structural arrangement to form a functional protein.

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**Interactive Question 5.8**

In the following diagram of a portion of a protein, label the types of interactions that are shown. What level of structure are these interactions producing?

In the inherited blood disorder sickle-cell disease, a change in one amino acid affects the structure of a hemoglobin molecule, causing red blood cells to deform into a sickle shape that clogs tiny blood vessels.

The bonds and interactions that maintain the three-dimensional shape of a protein may be disrupted by changes in pH, salt concentration, or temperature, causing a protein to unravel. **Denaturation** also occurs if a protein is transferred to an organic solvent; in that case, its hydrophilic regions cluster on the inside while its hydrophobic regions are on the outside interacting with the nonpolar solvent.

The primary structure (sequence of amino acids) determines where the interactions and bonds that maintain a protein’s shape can form. Within a cell, **chaperonins**, or chaperone proteins, assist newly made polypeptides during the folding process, perhaps by providing a sheltered environment.

Using the techniques of **X-ray crystallography**, nuclear magnetic resonance (NMR) spectroscopy, and bioinformatics, biochemists have identified the structure of thousands of proteins. These structures can then be related to the specific functions of different regions of a protein.
5.5 Nucleic acids store, transmit, and help express hereditary information

Genes are the units of inheritance that determine the primary structure of proteins. Nucleic acids are the polymers that carry and transmit this information.

The Roles of Nucleic Acids DNA, deoxyribonucleic acid, is the genetic material that is inherited from one generation to the next and is replicated whenever a cell divides so that all cells of an organism contain identical DNA. The instructions coded in DNA are transcribed to RNA, ribonucleic acid, which directs the synthesis of proteins, the ultimate enactors of the genetic program. In a eukaryotic cell, DNA resides in the nucleus. Messenger RNA (mRNA) carries the instructions for protein synthesis to ribosomes located in the cytoplasm. Recent research has revealed other important functions of RNA.

The Components of Nucleic Acids Polynucleotides are polymers of nucleotides—monomers that consist of a pentose (five-carbon sugar) covalently bonded to a phosphate group and a nitrogenous (nitrogen-containing) base. A nucleotide may contain more than one phosphate group; without the phosphate group it is called a nucleoside.

There are two families of nitrogenous bases. Pyrimidines, including cytosine (C), thymine (T), and uracil (U), are characterized by six-membered rings of carbon and nitrogen atoms. Purines, adenine (A) and guanine (G), add a five-membered ring to the pyrimidine ring. Thymine is only in DNA; uracil is only in RNA. In DNA, the sugar is deoxyribose; in RNA, it is ribose.

Nucleotide Polymers Nucleotides are linked together into a polynucleotide by phosphodiester linkages, which join the sugar of one nucleotide with the phosphate of the next. The polymer has two distinct ends: a 5' end with a phosphate attached to the 5' carbon of a sugar, and a 3' end with a hydroxyl group on the 3' carbon of a sugar. The nitrogenous bases extend from this backbone of repeating sugar-phosphate units. The unique sequence of bases in a gene codes for the specific amino acid sequence of a protein.

The Structure of DNA and RNA Molecules DNA molecules consist of two polynucleotides (strands) spiraling in a double helix. The two sugar-phosphate backbones run in opposite 5' to 3' directions, an arrangement called antiparallel. In 1953, Watson and Crick first proposed the double helix structure, with the nitrogenous bases pairing and hydrogen-bonding together in the inside of the molecule. Adenine pairs only with thymine; guanine always pairs with cytosine. Thus, the sequences of nitrogenous bases on the two strands of DNA are complementary. Because of this specific base-pairing property, DNA can replicate itself and precisely copy the genes of inheritance.

RNA molecules are usually single polynucleotides, although base-pairing within or between RNA molecules is common. For example, the functional shape of transfer RNA (tRNA), an RNA involved in protein synthesis, involves four regions of complementary base-pairing.

DNA and Proteins as Tape Measures of Evolution Genes form the hereditary link between generations. Closely related members of the same species share many common DNA sequences and proteins. More closely related species have a larger proportion of their DNA and proteins in common. This "molecular genealogy" provides evidence of evolutionary relationships.
INTERACTIVE QUESTION 5.11

Take the time to create a concept map that summarizes what you have just reviewed about nucleic acids. Compare your map with that of a study partner or explain it to a friend. Refer to Figures 5.26 and 5.27 in your textbook to help you visualize polynucleotides and the three-dimensional structures of DNA and RNA.

The Theme of Emergent Properties in the Chemistry of Life: A Review. At each stage in the hierarchy from atoms through large biological molecules, we have seen that novel properties arise with increasing structural organization.

Word Roots

di- = two; sacchar = sugar (disaccharide: two monosaccharides [simple sugars] joined through a dehydration reaction)
glyco- = sweet (glycogen: an extensively branched glucose polysaccharide that stores energy in animals)
hydro- = water; lyse = break (hydrolysis: a chemical reaction that breaks bonds between two molecules by the addition of water)
macro- = large (macromolecule: a giant molecule formed by the joining of smaller molecules, such as a polysaccharide, a protein, or a nucleic acid)
poly- = many; meros- = part (polymer: a long molecule consisting of many similar or identical monomers)
tri- = three (triacylglycerol: three fatty acids linked to one glycerol molecule; also called a fat or triglyceride)

Structure Your Knowledge

1. Describe the four structural levels in the functional shape of a protein.

2. Identify the type of monomer or group shown by the formulas a–g. Then match the chemical formulas with their description. Answers may be used more than once.

1. molecules that would combine to form a fat
2. molecule that would be attached to other monomers by a peptide bond
3. molecules or groups that would combine to form a nucleotide
4. molecules that are carbohydrates
5. molecule that is a purine
6. monomer of a protein
7. groups that would be joined by phosphodiester bonds
8. most nonpolar (hydrophobic) molecule

a. __________________
b. __________________
c. __________________
d. __________________
e. __________________
f. __________________
g. __________________
Test Your Knowledge

MATCHING: Match the molecule with its class of molecule.

1. glycogen  A. carbohydrate
2. cholesterol  B. lipid
3. RNA  C. protein
4. collagen  D. nucleic acid
5. hemoglobin
6. a gene
7. triacylglycerol
8. enzyme
9. cellulose
10. chitin

d. Few organisms have enzymes that hydrolyze its glycosidic linkages.
e. Its monomers are glucose with nitrogen-containing appendages.

5. Plants store most of their energy for later use as
   a. unsaturated fats.
   b. glycogen.
   c. starch.
   d. sucrose.
   e. cellulose.

6. Sucrose is made from joining a glucose molecule and a fructose molecule in a dehydration reaction. What is the molecular formula for this disaccharide?
   a. C\(_{12}\)H\(_{22}\)O\(_{11}\)
   b. C\(_{10}\)H\(_{20}\)O\(_{10}\)
   c. C\(_{12}\)H\(_{22}\)O\(_{13}\)
   d. C\(_{12}\)H\(_{24}\)O\(_{12}\)

7. A cow can derive nutrients from cellulose because
   a. it can produce the enzymes that break the β linkages between glucose molecules.
   b. it chews and rechews its cud so that cellulose fibers are finally broken down.
   c. its rumen contains prokaryotes that can hydrolyze the bonds of cellulose.
   d. its intestinal tract contains termites, which harbor microbes that hydrolyze cellulose.
   e. it can convert cellulose to starch and then hydrolyze starch to glucose.

8. Which of the following substances is the major component of the cell membrane of a fungus?
   a. cellulose
   b. chitin
   c. unsaturated fatty acids
   d. phospholipids
   e. cholesterol

9. A fatty acid that has the formula C\(_{16}\)H\(_{32}\)O\(_{2}\) is
   a. saturated.
   b. unsaturated.
   c. branched.
   d. hydrophilic.
   e. part of a steroid molecule.

10. Three molecules of the fatty acid in question 9 are joined to a molecule of glycerol (C\(_3\)H\(_8\)O\(_3\)). The resulting molecule has the formula
    a. C\(_{46}\)H\(_{90}\)O\(_{9}\)
    b. C\(_{46}\)H\(_{94}\)O\(_{9}\)
    c. C\(_{51}\)H\(_{102}\)O\(_{9}\)

11. What are trans fats?
    a. hydrogenated fish oils that have been identified with health risks
    b. fats made from cholesterol that are components of plaques in the walls of blood vessels
    c. fats that are derived from animal sources and are associated with cardiovascular disease
    d. fats that contain trans double bonds and may contribute to atherosclerosis
    e. polyunsaturated fats produced by removing H from fatty acids and forming cis double bonds.
12. Which of the following molecules is the most hydrophobic?
   a. cholesterol  
   b. nucleotide  
   c. chitin  
   d. phospholipid  
   e. glucose

13. Which of the following molecules provides the most energy (kcal/g) when eaten and digested?
   a. glucose  
   b. starch  
   c. glycogen  
   d. fat  
   e. protein

14. Which of the following is not one of the many functions performed by proteins?
   a. acting as signals and receptors  
   b. acting as an enzymatic catalyst for metabolic reactions  
   c. providing protection against disease  
   d. serving as contractile components of muscle  
   e. forming primary structural component of membranes

15. What happens when a protein denatures?
   a. Its primary structure is disrupted.  
   b. Its secondary and tertiary structures are disrupted.  
   c. It always flips inside out.  
   d. It hydrolyzes into component amino acids.  
   e. Its hydrogen bonds, ionic bonds, hydrophobic interactions, disulfide bridges, and peptide bonds are disrupted.

16. The alpha helix of proteins is
   a. part of the protein’s tertiary structure and is stabilized by disulfide bridges.  
   b. a double helix.  
   c. stabilized by hydrogen bonds and is commonly found in fibrous proteins.  
   d. found in some regions of globular proteins and is stabilized by hydrophobic interactions.  
   e. a complementary sequence to messenger RNA.

17. Beta pleated sheets are characterized by
   a. disulfide bridges between cysteine amino acids.  
   b. parallel regions of the polypeptide chain held together by hydrophobic interactions.  
   c. folds stabilized by hydrogen bonds between segments of the polypeptide backbone.  
   d. membrane sheets composed of phospholipids.  
   e. hydrogen bonds between adjacent cellulose molecules.

18. What is the best description of the following molecule?

19. Which number(s) in the molecule in question 18 refer(s) to a peptide bond?
   a. 1  
   b. 2  
   c. 3  
   d. both 2 and 4  
   e. both 2 and 3

20. What determines the sequence of the amino acids in a particular protein?
   a. its primary structure  
   b. the sequence of nucleotides in RNA, which was determined by the sequence of nucleotides in the gene for that protein  
   c. the sequence of nucleotides in DNA, which was determined by the sequence of nucleotides in RNA  
   d. the sequence of RNA nucleotides making up the ribosome  
   e. the three-dimensional shape of the protein

21. Both hydrophobic and hydrophilic interactions are important for which of the following types of molecules?
   a. proteins  
   b. saturated fats  
   c. glycogen and cellulose  
   d. polynucleotides  
   e. all of the above

22. How are nucleotide monomers connected to form a polynucleotide?
   a. by hydrogen bonds between complementary nitrogenous base pairs  
   b. by ionic attractions between phosphate groups  
   c. by disulfide bridges between cysteines  
   d. by covalent bonds between the sugar of one nucleotide and the phosphate of the next  
   e. by ester linkages between the carboxyl group of one nucleotide and the hydroxyl group on the ribose of the next

23. If the nucleotide sequence of one strand of a DNA helix is 5’GCCTAA3’, what would be the 3’–5’ sequence on the complementary strand?
   a. GCCTAA  
   b. CGGAUU  
   c. CGATT  
   d. ATTCG  
   e. TAAGCC

24. Monkeys and humans share many of the same DNA sequences and have similar proteins, indicating that
   a. the two groups belong to the same species.  
   b. the two groups share a relatively recent common ancestor.  
   c. humans evolved from monkeys.  
   d. monkeys evolved from humans.  
   e. the two groups evolved about the same time.