3 | BIOLOGICAL MACROMOLECULES

Figure 3.1 Foods such as bread, fruit, and cheese are rich sources of biological macromolecules. (credit: modification of work by Bengt Nyman)

Chapter Outline

Introduction

Food provides the body with the nutrients it needs to survive. Many of these critical nutrients are biological macromolecules, or large molecules, necessary for and built by living things. For example, the amino acids found in protein are needed to build healthy bone and muscle. The body uses fat molecules to build new cells, store energy, and for proper digestion. Carbohydrates are the primary source of the body's energy. Nucleic acids contain genetic information.

While all living things, including humans, need macromolecules in their daily diet, an imbalance of any one of them can lead to health problems. For example, eating too much fat can lead to cardiovascular problems, and too much protein can lead to problems with the kidneys. Some people think that removing whole grains, such as wheat, from one's diet can be beneficial. However, scientists have found that to not be true for the majority of people. In fact, just the opposite may be true, because whole wheat contains more dietary fiber than other types of grains. The full research review can be found **here (http://openstaxcollege.org/l/32wholegrain)** .

3.1 | Synthesis of Biological Macromolecules

In this section, you will explore the following questions:

- How are complex macromolecule polymers synthesized from monomers?
- What is the difference between dehydration (or condensation) and hydrolysis reactions?

Connection for AP® Courses

Living organisms need food to survive as it contains critical nutrients in the form of biological macromolecules. These large molecules are composed mainly of six elements—sulfur, phosphorus, oxygen, nitrogen, carbon, and hydrogen (SPONCH)—in different quantities and arrangements. Complex polymers are built from combinations of smaller monomers by dehydration synthesis, a chemical reaction in which a molecule of water is removed between two linking monomers. (Think of a train: each boxcar, including the caboose, represents a monomer, and the entire train is a polymer.) During digestion, polymers can be broken down by hydrolysis, or the addition of water. Both dehydration and hydrolysis reactions in cells are catalyzed by specific enzymes. Dehydration reactions typically require an investment of energy for new bond formation, whereas hydrolysis reactions typically release energy that can be used to power cellular processes. The four categories of macromolecules are carbohydrates, lipids, proteins, and nucleic acids. Evidence supports scientists' claim that the organic precursors of these biological molecules were present on primitive Earth.

Information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in Big Idea 1 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® Exam questions. A learning objective merges required content with one or more of the seven Science Practices.

Big Idea 1	The process of evolution drives the diversity and unity of life.
Enduring Understanding 1.D	The origin of living systems is explained by natural processes.
Essential Knowledge	**1.D.1** There are several hypotheses about the natural origin of life on Earth, each with supporting scientific evidence.
Science Practice	**1.2** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**1.27** The student is able to describe a scientific hypothesis about the origin of life on Earth.
Essential Knowledge	**1.D.1** There are several hypotheses about the natural origin of life on Earth, each with supporting scientific evidence.
Science Practice	**3.3** The student can evaluate scientific questions.
Learning Objective	**1.28** The student is able to evaluate scientific questions based on hypotheses about the origin of life on Earth.

Dehydration Synthesis

As you've learned, **biological macromolecules** are large molecules, necessary for life, that are built from smaller organic molecules. There are four major classes of biological macromolecules (carbohydrates, lipids, proteins, and nucleic acids); each is an important cell component and performs a wide array of functions. Combined, these molecules make up the majority of a cell's dry mass (recall that water makes up the majority of its complete mass). Biological macromolecules are organic, meaning they contain carbon. In addition, they may contain hydrogen, oxygen, nitrogen, and additional minor elements.

Most macromolecules are made from single subunits, or building blocks, called **monomers**. The monomers combine with each other using covalent bonds to form larger molecules known as **polymers**. In doing so, monomers release water molecules as byproducts. This type of reaction is known as **dehydration synthesis**, which means "to put together while losing water."

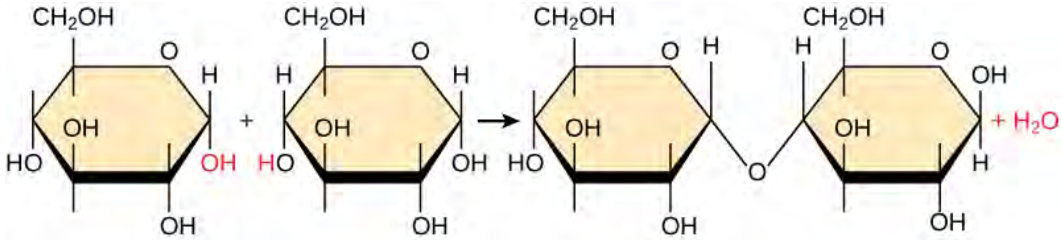

Figure 3.2 In the dehydration synthesis reaction depicted above, two molecules of glucose are linked together to form the disaccharide maltose. In the process, a water molecule is formed.

In a dehydration synthesis reaction (**Figure 3.2**), the hydrogen of one monomer combines with the hydroxyl group of another monomer, releasing a molecule of water. At the same time, the monomers share electrons and form covalent bonds. As additional monomers join, this chain of repeating monomers forms a polymer. Different types of monomers can combine in many configurations, giving rise to a diverse group of macromolecules. Even one kind of monomer can combine in a variety of ways to form several different polymers: for example, glucose monomers are the constituents of starch, glycogen, and cellulose.

Hydrolysis

Polymers are broken down into monomers in a process known as hydrolysis, which means "to split with water." Hydrolysis is a reaction in which a water molecule is used during the breakdown of another compound (**Figure 3.3**). During these reactions, the polymer is broken into two components: one part gains a hydrogen atom (H+) and the other gains a hydroxyl molecule (OH–) from a split water molecule.

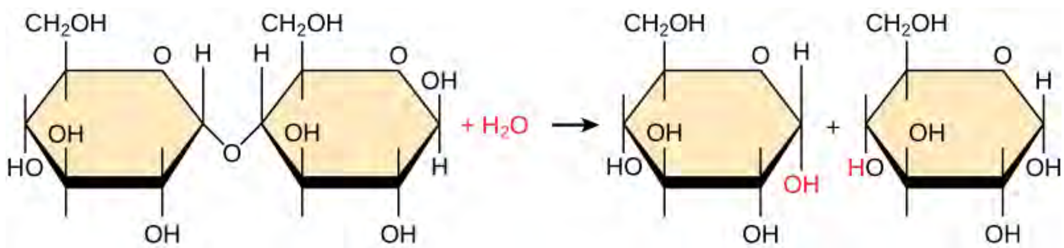

Figure 3.3 In the hydrolysis reaction shown here, the disaccharide maltose is broken down to form two glucose monomers with the addition of a water molecule. Note that this reaction is the reverse of the synthesis reaction shown in Figure 3.2.

Dehydration and **hydrolysis reactions** are catalyzed, or "sped up," by specific enzymes; dehydration reactions involve the formation of new bonds, requiring energy, while hydrolysis reactions break bonds and release energy. These reactions are similar for most macromolecules, but each monomer and polymer reaction is specific for its class. For example, in our bodies, food is hydrolyzed, or broken down, into smaller molecules by catalytic enzymes in the digestive system. This allows for easy absorption of nutrients by cells in the intestine. Each macromolecule is broken down by a specific enzyme. For instance, carbohydrates are broken down by amylase, sucrase, lactase, or maltase. Proteins are broken down by the enzymes pepsin and peptidase, and by hydrochloric acid. Lipids are broken down by lipases. Breakdown of these macromolecules provides energy for cellular activities.

LINK TO LEARNING

Visit **this site (http://openstaxcollege.org/l/hydrolysis)** to see visual representations of dehydration synthesis and hydrolysis.

What role do electrons play in dehydration synthesis and hydrolysis?

a. Sharing of electrons between monomers occurs in both dehydration synthesis and hydrolysis.

b. The sharing of electrons between monomers occurs in hydrolysis only.

c. H^+ and OH^- ions share electrons with the respective monomers in dehydration synthesis.

d. H^+ and OH^- ions share electrons with the respective monomers in hydrolysis.

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Recreating Primordial Earth

Many people wonder how life formed on Earth. In 1953, Stanley Miller and Harold Urey developed an apparatus like the one shown in **Figure 3.4** to model early conditions on earth. They wanted to test if organic molecules could form from inorganic precursors believed to exist very early in Earth's history. They used boiling water to mimic early Earth's oceans. Steam from the "ocean" combined with methane, ammonia, and hydrogen gases from the early Earth's atmosphere and was exposed to electrical sparks to act as lightning. As the gas mixture cooled and condensed, it was found to contain organic compounds, such as amino acids and nucleotides. According to the abiogenesis theory, these organic molecules came together to form the earliest form of life about 3.5 billion years ago. (credit: Yassine Mrabet)

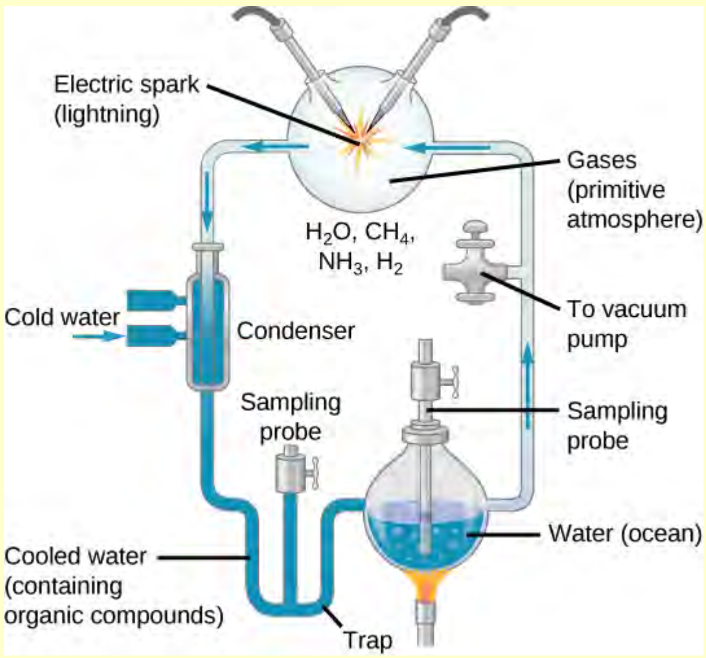

Figure 3.4

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Think About It

How does Stanley Miller's and Harold Urey's model support the claim that organic precursors present on early Earth could have assembled into large, complex molecules necessary for life? What chemical "ingredients" were present on early Earth?

3.2 | Carbohydrates

By the end of this section, you will be able to:

- What is the role of carbohydrates in cells and in the extracellular materials of animals and plants?
- What are the different classifications of carbohydrates?
- How are monosaccharide building blocks assembled into disaccharides and complex polysaccharides?

Connection for AP® Courses

Carbohydrates provide energy for the cell and structural support to plants, fungi, and arthropods such as insects, spiders, and crustaceans. Consisting of carbon, hydrogen, and oxygen in the ratio CH_2O or carbon hydrated with water, carbohydrates are classified as monosaccharides, disaccharides, and polysaccharides depending on the number of monomers in the macromolecule. Monosaccharides are linked by glycosidic bonds that form as a result of dehydration synthesis. Glucose, galactose, and fructose are common isomeric monosaccharides, whereas sucrose or table sugar is a disaccharide. Examples of polysaccharides include cellulose and starch in plants and glycogen in animals. Although storing glucose in the form of polymers like starch or glycogen makes it less accessible for metabolism, this prevents it from leaking out of cells or creating a high osmotic pressure that could cause excessive water uptake by the cell. Insects have a hard outer skeleton made of chitin, a unique nitrogen-containing polysaccharide.

Information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in Big Idea 4 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® Exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**7.1** The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	**4.1** The student is able to refine representations and models to explain how the subcomponents of a biological polymer and their sequence determine the properties of that polymer.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**1.3** The student can refine representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	**4.2** The student is able to refine representations and models to explain how the subcomponents of a biological polymer and their sequence determine the properties of that polymer.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**6.1** The student can justify claims with evidence.

Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.3** The student is able to use models to predict and justify that changes in the subcomponents of a biological polymer affect the functionality of the molecules.

The Science Practice Challenge Questions contain additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 4.15] [APLO 2.5]

Molecular Structures

Most people are familiar with carbohydrates, one type of macromolecule, especially when it comes to what we eat. To lose weight, some individuals adhere to "low-carb" diets. Athletes, in contrast, often "carb-load" before important competitions to ensure that they have enough energy to compete at a high level. Carbohydrates are, in fact, an essential part of our diet; grains, fruits, and vegetables are all natural sources of carbohydrates. Carbohydrates provide energy to the body, particularly through glucose, a simple sugar that is a component of **starch** and an ingredient in many staple foods. Carbohydrates also have other important functions in humans, animals, and plants.

Carbohydrates can be represented by the stoichiometric formula $(CH_2O)_n$, where n is the number of carbons in the molecule. In other words, the ratio of carbon to hydrogen to oxygen is 1:2:1 in carbohydrate molecules. This formula also explains the origin of the term "carbohydrate": the components are carbon ("carbo") and the components of water (hence, "hydrate"). Carbohydrates are classified into three subtypes: monosaccharides, disaccharides, and polysaccharides.

Monosaccharides

Monosaccharides (mono- = "one"; sacchar- = "sweet") are simple sugars, the most common of which is glucose. In monosaccharides, the number of carbons usually ranges from three to seven. Most monosaccharide names end with the suffix -ose. If the sugar has an aldehyde group (the functional group with the structure R-CHO), it is known as an aldose, and if it has a ketone group (the functional group with the structure RC(=O)R'), it is known as a ketose. Depending on the number of carbons in the sugar, they also may be known as trioses (three carbons), pentoses (five carbons), and or hexoses (six carbons). See **Figure 3.5** for an illustration of the monosaccharides.

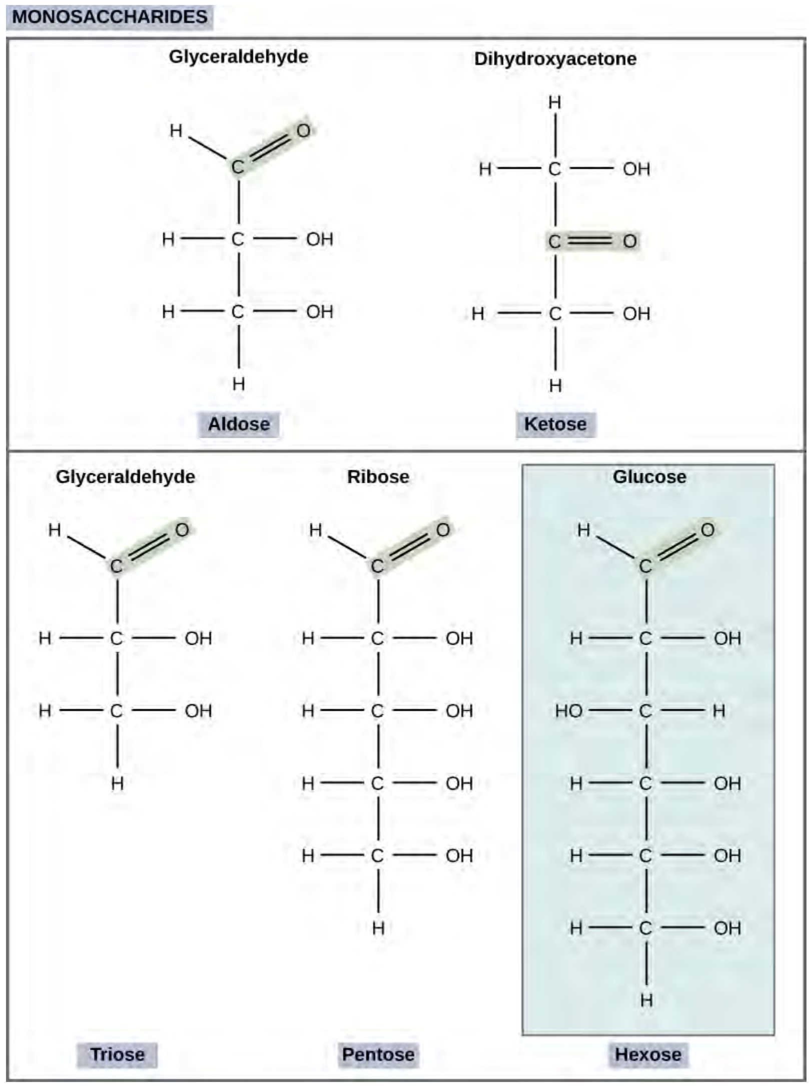


Figure 3.5 Monosaccharides are classified based on the position of their carbonyl group and the number of carbons in the backbone. Aldoses have a carbonyl group (indicated in green) at the end of the carbon chain, and ketoses have a carbonyl group in the middle of the carbon chain. Trioses, pentoses, and hexoses have three-, five-, and six-carbon backbones, respectively.

The chemical formula for glucose is $C_6H_{12}O_6$. In humans, glucose is an important source of energy. During cellular respiration, energy is released from glucose, and that energy is used to help make adenosine triphosphate (ATP). Plants synthesize glucose using carbon dioxide and water, and glucose in turn is used for energy requirements for the plant. Excess glucose is often stored as starch that is catabolized (the breakdown of larger molecules by cells) by humans and other animals that feed on plants.

Galactose (part of lactose, or milk sugar) and fructose (found in sucrose, in fruit) are other common monosaccharides. Although glucose, galactose, and fructose all have the same chemical formula ($C_6H_{12}O_6$), they differ structurally and chemically (and are known as isomers) because of the different arrangement of functional groups around the asymmetric carbon; all of these monosaccharides have more than one asymmetric carbon (**Figure 3.6**).

visual CONNECTION

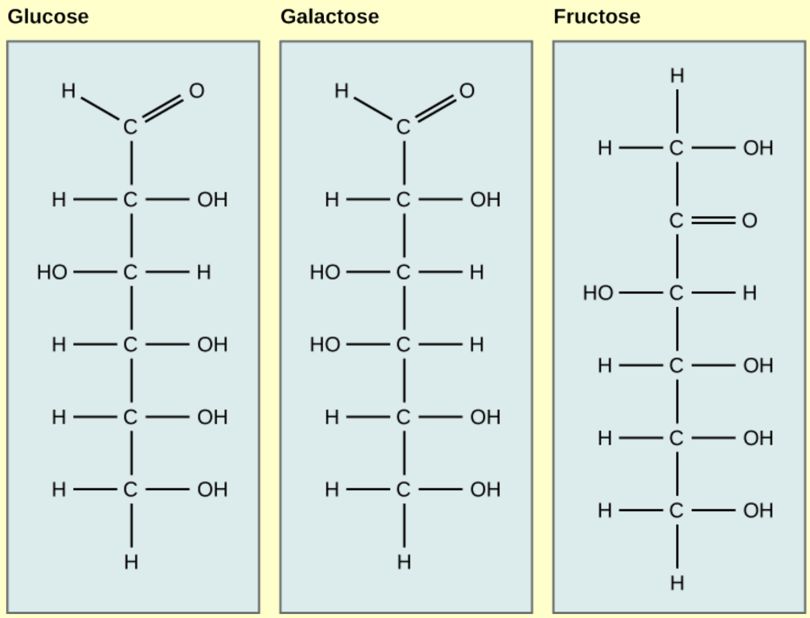


Figure 3.6 Glucose, galactose, and fructose are all hexoses. They are structural isomers, meaning they have the same chemical formula ($C_6H_{12}O_6$) but a different arrangement of atoms.

Identify each sugar as an aldose or ketose.

1. fructose
2. galactose
3. glucose
    a. Glucose and galactose are aldoses. Fructose is a ketose
    b. Glucose and fructose are aldoses. Galactose is a ketose.
    c. Galactose and fructose are ketoses. Glucose is an aldose.
    d. Glucose and fructose are ketoses. Galactose is an aldose.

Glucose, galactose, and fructose are isomeric monosaccharides (hexoses), meaning they have the same chemical formula but have slightly different structures. Glucose and galactose are aldoses, and fructose is a ketose.

Monosaccharides can exist as a linear chain or as ring-shaped molecules; in aqueous solutions they are usually found in ring forms (Figure 3.7). Glucose in a ring form can have two different arrangements of the hydroxyl group (OH) around the anomeric carbon (carbon 1 that becomes asymmetric in the process of ring formation). If the hydroxyl group is below carbon number 1 in the sugar, it is said to be in the alpha (α) position, and if it is above the plane, it is said to be in the beta (β) position.

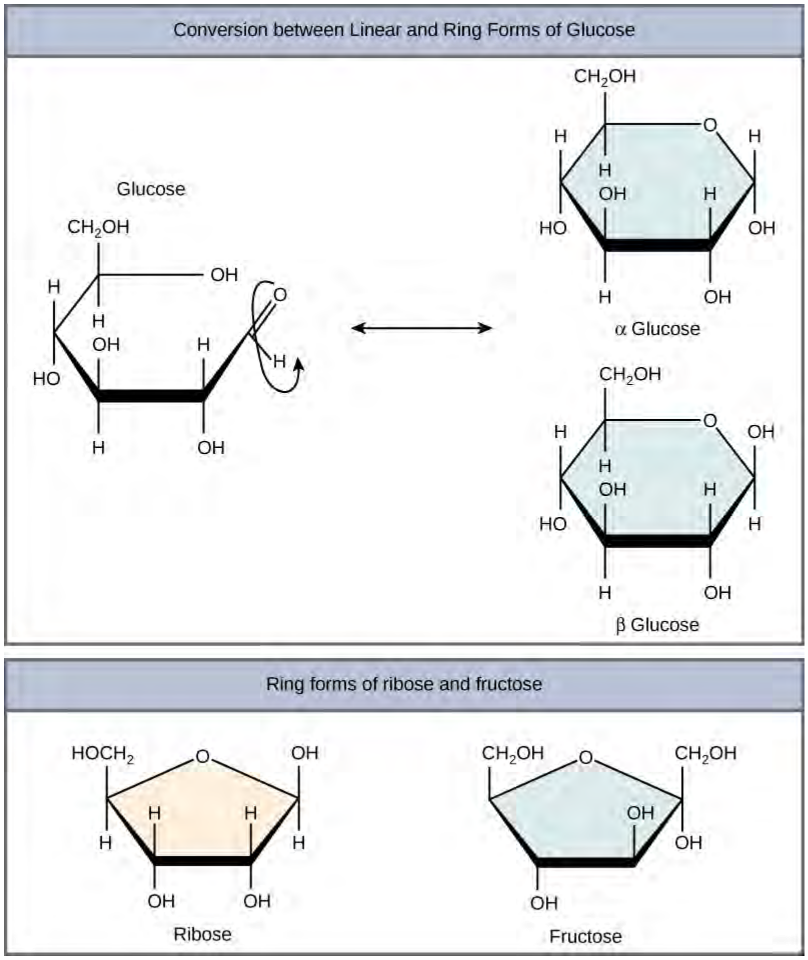


Figure 3.7 Five and six carbon monosaccharides exist in equilibrium between linear and ring forms. When the ring forms, the side chain it closes on is locked into an *α* or *β* position. Fructose and ribose also form rings, although they form five-membered rings as opposed to the six-membered ring of glucose.

Disaccharides

Disaccharides (di- = "two") form when two monosaccharides undergo a dehydration reaction (also known as a condensation reaction or dehydration synthesis). During this process, the hydroxyl group of one monosaccharide combines with the hydrogen of another monosaccharide, releasing a molecule of water and forming a covalent bond. A covalent bond formed between a carbohydrate molecule and another molecule (in this case, between two monosaccharides) is known as a **glycosidic bond** (Figure 3.8). Glycosidic bonds (also called glycosidic linkages) can be of the alpha or the beta type.

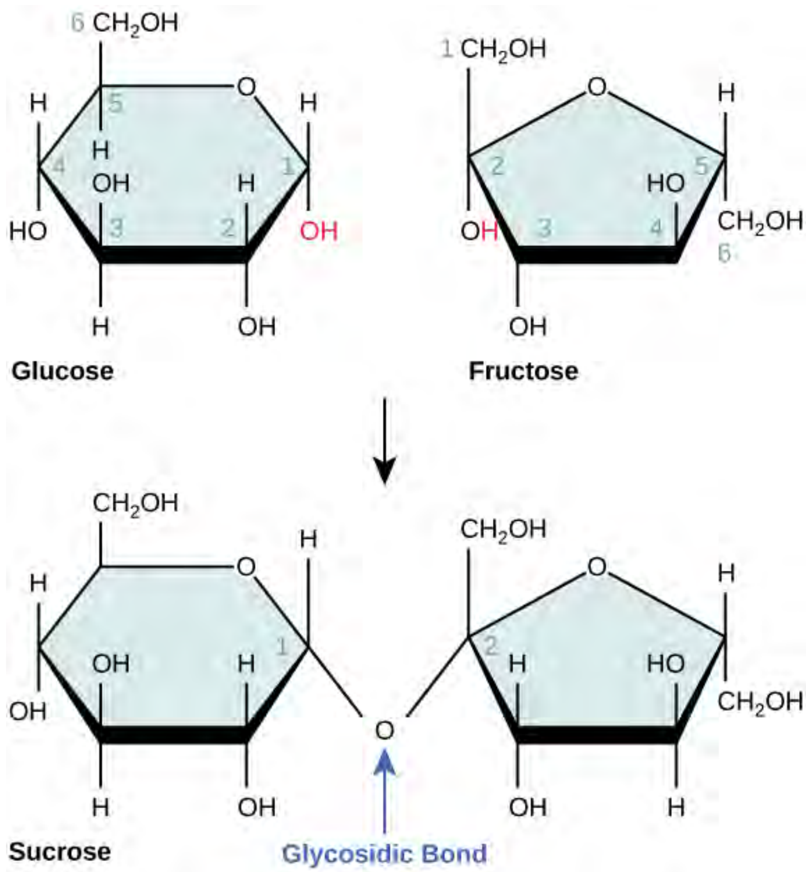


Figure 3.8 Sucrose is formed when a monomer of glucose and a monomer of fructose are joined in a dehydration reaction to form a glycosidic bond. In the process, a water molecule is lost. By convention, the carbon atoms in a monosaccharide are numbered from the terminal carbon closest to the carbonyl group. In sucrose, a glycosidic linkage is formed between carbon 1 in glucose and carbon 2 in fructose.

Common disaccharides include lactose, maltose, and sucrose (**Figure 3.9**). Lactose is a disaccharide consisting of the monomers glucose and galactose. It is found naturally in milk. Maltose, or malt sugar, is a disaccharide formed by a dehydration reaction between two glucose molecules. The most common disaccharide is sucrose, or table sugar, which is composed of the monomers glucose and fructose.

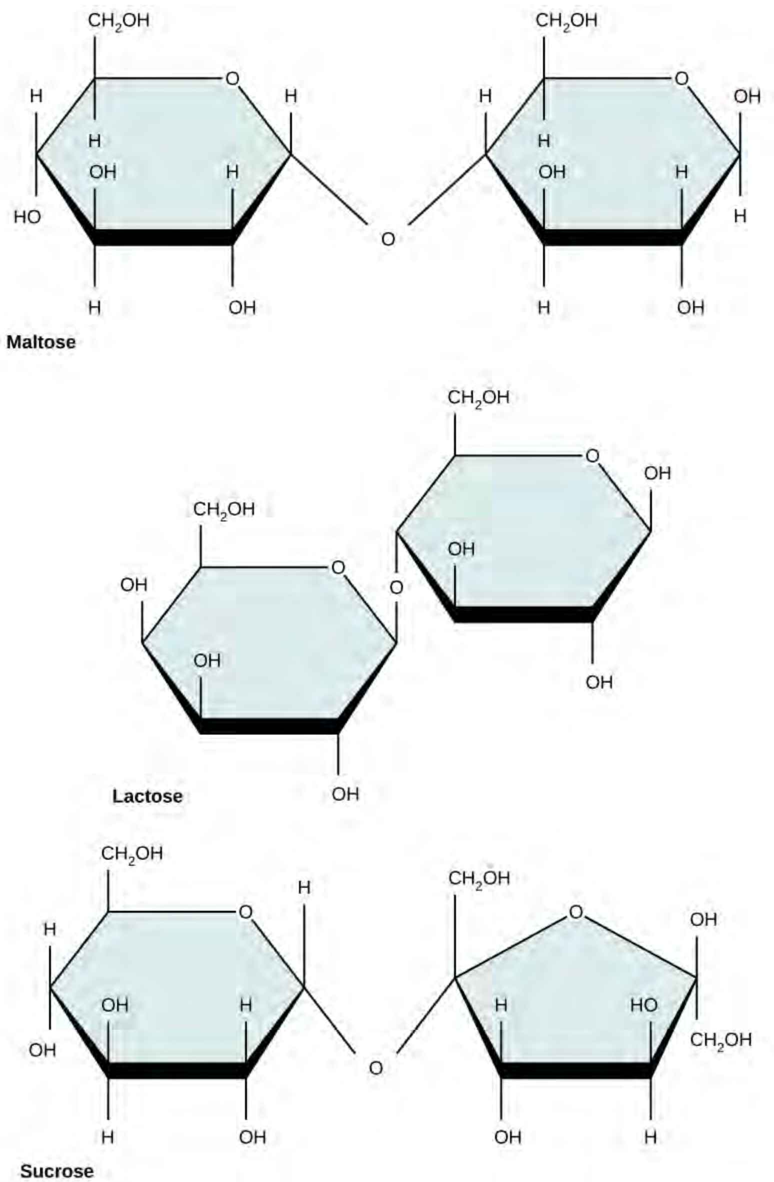


Figure 3.9 Common disaccharides include maltose (grain sugar), lactose (milk sugar), and sucrose (table sugar).

Polysaccharides

A long chain of monosaccharides linked by glycosidic bonds is known as a **polysaccharide** (poly- = “many”). The chain may be branched or unbranched, and it may contain different types of monosaccharides. The molecular weight may be 100,000 daltons or more depending on the number of monomers joined. Starch, glycogen, cellulose, and chitin are primary examples of polysaccharides.

Starch is the stored form of sugars in plants and is made up of a mixture of amylose and amylopectin (both polymers of glucose). Plants are able to synthesize glucose, and the excess glucose, beyond the plant’s immediate energy needs, is stored as starch in different plant parts, including roots and seeds. The starch in the seeds provides food for the embryo as it germinates and can also act as a source of food for humans and animals. The starch that is consumed by humans is broken down by enzymes, such as salivary amylases, into smaller molecules, such as maltose and glucose. The cells can then absorb the glucose.

Starch is made up of glucose monomers that are joined by α 1-4 or α 1-6 glycosidic bonds. The numbers 1-4 and 1-6 refer to the carbon number of the two residues that have joined to form the bond. As illustrated in **Figure 3.10**, amylose is starch formed by unbranched chains of glucose monomers (only α 1-4 linkages), whereas amylopectin is a branched polysaccharide (α 1-6 linkages at the branch points).

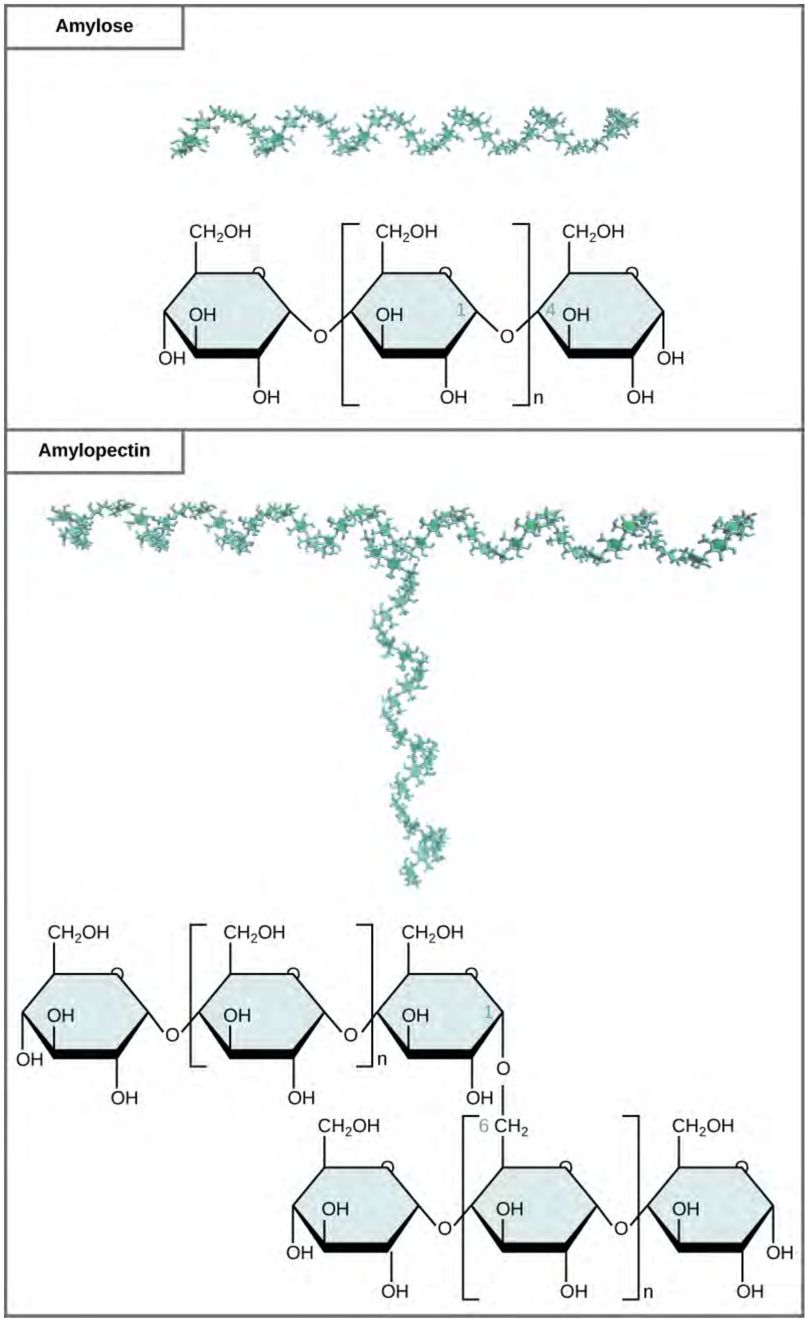


Figure 3.10 Amylose and amylopectin are two different forms of starch. Amylose is composed of unbranched chains of glucose monomers connected by α 1,4 glycosidic linkages. Amylopectin is composed of branched chains of glucose monomers connected by α 1,4 and α 1,6 glycosidic linkages. Because of the way the subunits are joined, the glucose chains have a helical structure. Glycogen (not shown) is similar in structure to amylopectin but more highly branched.

Glycogen is the storage form of glucose in humans and other vertebrates and is made up of monomers of glucose. Glycogen is the animal equivalent of starch and is a highly branched molecule usually stored in liver and muscle cells. Whenever blood glucose levels decrease, glycogen is broken down to release glucose in a process known as glycogenolysis.

Cellulose is the most abundant natural biopolymer. The cell wall of plants is mostly made of cellulose; this provides structural support to the cell. Wood and paper are mostly cellulosic in nature. Cellulose is made up of glucose monomers that are linked by β 1-4 glycosidic bonds (**Figure 3.11**).

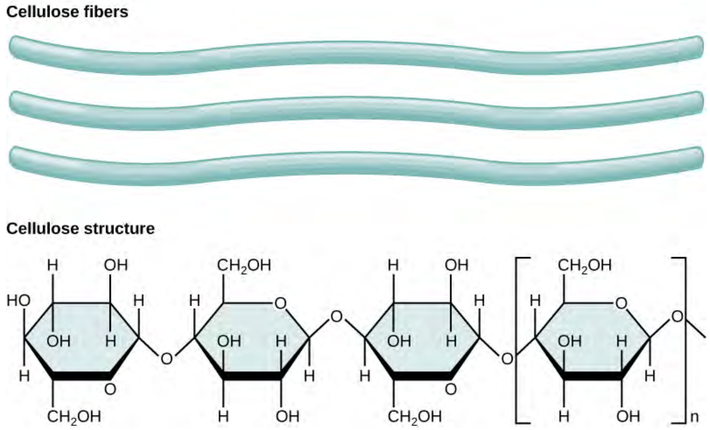


Figure 3.11 In cellulose, glucose monomers are linked in unbranched chains by β 1-4 glycosidic linkages. Because of the way the glucose subunits are joined, every glucose monomer is flipped relative to the next one resulting in a linear, fibrous structure.

As shown in **Figure 3.11**, every other glucose monomer in cellulose is flipped over, and the monomers are packed tightly as extended long chains. This gives cellulose its rigidity and high tensile strength—which is so important to plant cells. While the β 1-4 linkage cannot be broken down by human digestive enzymes, herbivores such as cows, koalas, and buffalos are able, with the help of the specialized flora in their stomach, to digest plant material that is rich in cellulose and use it as a food source. In these animals, certain species of bacteria and protists reside in the rumen (part of the digestive system of herbivores) and secrete the enzyme cellulase. The appendix of grazing animals also contains bacteria that digest cellulose, giving it an important role in the digestive systems of ruminants. Cellulases can break down cellulose into glucose monomers that can be used as an energy source by the animal. Termites are also able to break down cellulose because of the presence of other organisms in their bodies that secrete cellulases.

Carbohydrates serve various functions in different animals. Arthropods (insects, crustaceans, and others) have an outer skeleton, called the exoskeleton, which protects their internal body parts (as seen in the bee in **Figure 3.12**). This exoskeleton is made of the biological macromolecule **chitin**, which is a polysaccharide-containing nitrogen. It is made of repeating units of N-acetyl-β-d-glucosamine, a modified sugar. Chitin is also a major component of fungal cell walls; fungi are neither animals nor plants and form a kingdom of their own in the domain Eukarya.

Figure 3.12 Insects have a hard outer exoskeleton made of chitin, a type of polysaccharide. (credit: Louise Docker)

career CONNECTION

Registered dietitians help plan nutrition programs for individuals in various settings. They often work with patients in health care facilities, designing nutrition plans to treat and prevent diseases. For example, dietitians may teach a patient with diabetes how to manage blood sugar levels by eating the correct types and amounts of carbohydrates. Dietitians may also work in nursing homes, schools, and private practices.

To become a registered dietitian, one needs to earn at least a bachelor’s degree in dietetics, nutrition, food technology, or a related field. In addition, registered dietitians must complete a supervised internship program and pass a national exam. Those who pursue careers in dietetics take courses in nutrition, chemistry, biochemistry, biology, microbiology, and human physiology. Dietitians must become experts in the chemistry and physiology (biological functions) of food (proteins, carbohydrates, and fats).

Benefits of Carbohydrates

Are carbohydrates good for you? People who wish to lose weight are often told that carbohydrates are bad for them and should be avoided. Some diets completely forbid carbohydrate consumption, claiming that a low-carbohydrate diet helps people to lose weight faster. However, carbohydrates have been an important part of the human diet for thousands of years; artifacts from ancient civilizations show the presence of wheat, rice, and corn in our ancestors’ storage areas.

Carbohydrates should be supplemented with proteins, vitamins, and fats to be parts of a well-balanced diet. Calorie-wise, a gram of carbohydrate provides 4.3 Kcal. For comparison, fats provide 9 Kcal/g, a less desirable ratio. Carbohydrates contain soluble and insoluble elements; the insoluble part is known as fiber, which is mostly cellulose. Fiber has many uses; it promotes regular bowel movement by adding bulk, and it regulates the rate of consumption of blood glucose. Fiber also helps to remove excess cholesterol from the body: fiber binds to the cholesterol in the small intestine, then attaches to the cholesterol and prevents the cholesterol particles from entering the bloodstream, and then cholesterol exits the body via the feces. In addition, a meal containing whole grains and vegetables gives a feeling of fullness. As an immediate source of energy, glucose is broken down during the process of cellular respiration, which produces ATP, the energy currency of the cell. Without the consumption of carbohydrates, the availability of “instant energy” would be reduced. Eliminating carbohydrates from the diet is not the best way to lose weight. A low-calorie diet that is rich in whole grains, fruits, vegetables, and lean meat, together with plenty of exercise and plenty of water, is the more sensible way to lose weight.

LINK TO LEARNING

For an additional perspective on carbohydrates, explore “Biomolecules: the Carbohydrates” through this **interactive animation (http://openstaxcollege.org/l/carbohydrates)** .

Fiber is not really a nutrient, because it passes through our body undigested. Why can't fiber be digested and why is it important to our diet?

a. The enzymes required to digest cellulose are not produced in human body; undigested fiber adds bulk to the food easing bowel movements.

b. The enzymes that digests cellulose cannot bind to the cellulose due to altered active sites; undigested fiber adds bulk to the food easing bowel movements.

c. The enzymes required to digest cellulose are not produced in human body; fiber produces energy for the metabolism.

d. Competitive inhibitors are not the reason that fiber is indigestible.

science practices CONNECTION for AP® Courses

Activity

Use a molecular model kit to construct a polysaccharide from several different monosaccharide monomers. Explain how the structure of the polysaccharide determines its primary function as an energy storage molecule. Then use your model to describe how changes in structure result in changes in function.

Think About It

- Explain why athletes often “carb-load” before a big game or tournament.
- Explain why it is difficult for some animals, including humans, to digest cellulose. Describe a structural difference between cellulose and starch, which is easily digested by humans. How are cows and other ruminants able to digest cellulose?

3.3 | Lipids

In this section, you will explore the following questions:

- What are the four major types of lipids?
- What are functions of fats in living organisms?
- What is the difference between saturated and unsaturated fatty acids?
- What is the molecular structure of phospholipids, and what is the role of phospholipids in cells?
- What is the basic structure of a steroid, and what are examples of their functions?
- How does cholesterol help maintain the fluid nature of the plasma membrane of cells?

Connection for AP® Courses

Lipids also are sources of energy that power cellular processes. Like carbohydrates, lipids are composed of carbon, hydrogen, and oxygen, but these atoms are arranged differently. Most lipids are nonpolar and hydrophobic. Major types include fats and oils, waxes, phospholipids, and steroids. A typical fat consists of three fatty acids bonded to one molecule of glycerol, forming triglycerides or triacylglycerols. The fatty acids may be saturated or unsaturated, depending on the presence or absence of double bonds in the hydrocarbon chain; a saturated fatty acid has the maximum number of hydrogen atoms bonded to carbon and, thus, only single bonds. In general, fats that are liquid at room temperature (e.g., canola oil) tend to be more unsaturated than fats that are solid at room temperature. In the food industry, oils are artificially hydrogenated to make them chemically more appropriate for use in processed foods. During this hydrogenation process, double bonds in the cis- conformation in the hydrocarbon chain may be converted to double bonds in the trans-conformation; unfortunately, trans fats have been shown to contribute to heart disease. Phospholipids are a special type of lipid associated with cell membranes and typically have a glycerol (or sphingosine) backbone to which two fatty acid chains and a phosphate-containing group are attached. As a result, phospholipids are considered amphipathic because they have both hydrophobic and hydrophilic components. (In Chapters 4 and 5 we will explore in more detail how the amphipathic nature of phospholipids in plasma cell membranes helps regulate the passage of substances into and out of the cell.) Although the molecular structures of steroids differ from that of triglycerides and phospholipids, steroids are classified as lipids based on their hydrophobic properties. Cholesterol is a type of steroid in animal cells’ plasma membrane. Cholesterol is also the precursor of steroid hormones such as testosterone.

Information presented and the examples highlighted in the section, support concepts outlined in Big Idea 4 of the AP® Biology Curriculum Framework. The learning objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**7.1** The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	**4.1** The student is able to explain the connection between the sequence and the subcomponents of a biological polymer and its properties.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**1.3** The student can refine representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	**4.2** The student is able to refine representations and models to explain how the subcomponents of a biological polymer and their sequence determine the properties of that polymer.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**6.1** The student can justify claims with evidence.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.3** The student is able to use models to predict and justify that changes in the subcomponents of a biological polymer affect the functionality of the molecules.

The Science Practice Challenge Questions contain additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 2.9] [APLO 2.10] [APLO 2.12] [APLO 2.13][APLO 2.14][APLO 4.14]

Fats and Oils

Lipids include a diverse group of compounds that are largely nonpolar in nature. This is because they are hydrocarbons that include mostly nonpolar carbon–carbon or carbon–hydrogen bonds. Non-polar molecules are hydrophobic (“water fearing”), or insoluble in water. Lipids perform many different functions in a cell. Cells store energy for long-term use in the form of fats. Lipids also provide insulation from the environment for plants and animals (**Figure 3.13**). For example, their water-repellant hydrophobic nature can help keep aquatic birds and mammals dry by forming a protective layer over fur or feathers. Lipids are also the building blocks of many hormones and an important constituent of all cellular membranes. Lipids include fats, waxes, phospholipids, and steroids.

Figure 3.13 Hydrophobic lipids in the fur of aquatic mammals, such as this river otter, protect them from the elements. (credit: Ken Bosma)

A fat molecule consists of two main components—glycerol and fatty acids. Glycerol is an organic compound (alcohol) with three carbons, five hydrogens, and three hydroxyl (OH) groups. Fatty acids have a long chain of hydrocarbons to which a carboxyl group is attached, hence the name “fatty acid.” The number of carbons in the fatty acid may range from 4 to 36; most common are those containing 12–18 carbons. In a fat molecule, the fatty acids are attached to each of the three carbons of the glycerol molecule with an ester bond through an oxygen atom (**Figure 3.14**).

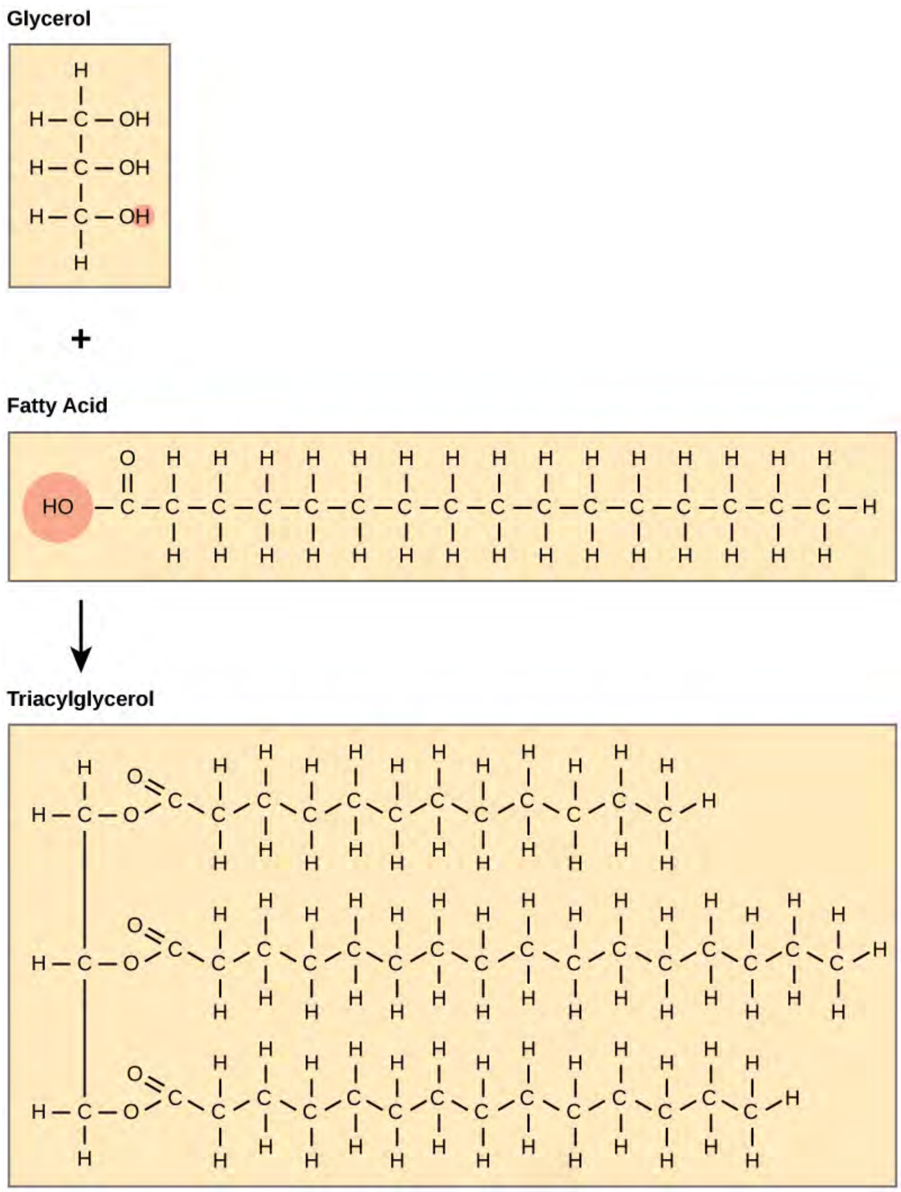


Figure 3.14 Triacylglycerol is formed by the joining of three fatty acids to a glycerol backbone in a dehydration reaction. Three molecules of water are released in the process.

During this ester bond formation, three water molecules are released. The three fatty acids in the triacylglycerol may be similar or dissimilar. Fats are also called **triacylglycerols** or **triglycerides** because of their chemical structure. Some fatty acids have common names that specify their origin. For example, palmitic acid, a **saturated fatty acid**, is derived from the palm tree. Arachidic acid is derived from *Arachis hypogea*, the scientific name for groundnuts or peanuts.

Fatty acids may be saturated or unsaturated. In a fatty acid chain, if there are only single bonds between neighboring carbons in the hydrocarbon chain, the fatty acid is said to be saturated. Saturated fatty acids are saturated with hydrogen; in other words, the number of hydrogen atoms attached to the carbon skeleton is maximized. Stearic acid is an example of a saturated fatty acid (**Figure 3.15**)

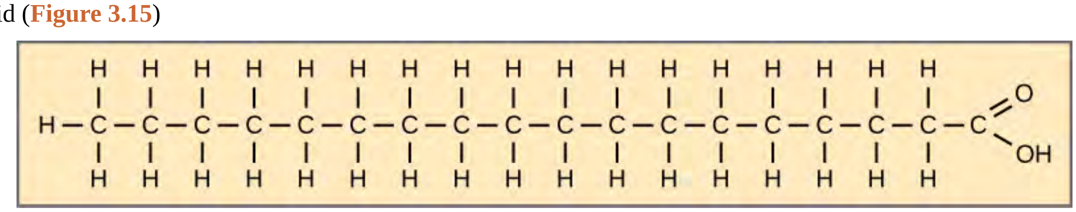


Figure 3.15 Stearic acid is a common saturated fatty acid.

When the hydrocarbon chain contains a double bond, the fatty acid is said to be **unsaturated**. Oleic acid is an example of an unsaturated fatty acid (**Figure 3.16**).

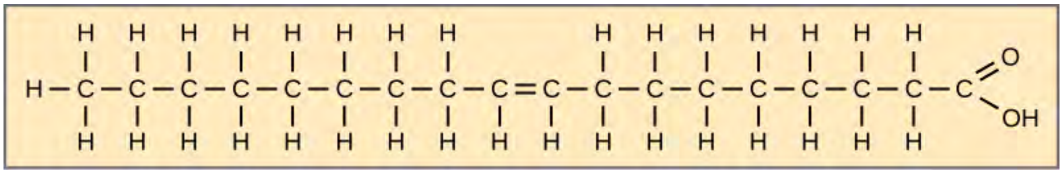


Figure 3.16 Oleic acid is a common unsaturated fatty acid.

Most unsaturated fats are liquid at room temperature and are called oils. If there is one double bond in the molecule, then it is known as a monounsaturated fat (e.g., olive oil), and if there is more than one double bond, then it is known as a polyunsaturated fat (e.g., canola oil).

When a fatty acid has no double bonds, it is known as a saturated fatty acid because no more hydrogen may be added to the carbon atoms of the chain. A fat may contain similar or different fatty acids attached to glycerol. Long straight fatty acids with single bonds tend to get packed tightly and are solid at room temperature. Animal fats with stearic acid and palmitic acid (common in meat) and the fat with butyric acid (common in butter) are examples of saturated fats. Mammals store fats in specialized cells called adipocytes, where globules of fat occupy most of the cell's volume. In plants, fat or oil is stored in many seeds and is used as a source of energy during seedling development. Unsaturated fats or oils are usually of plant origin and contain *cis* unsaturated fatty acids. *Cis* and *trans* indicate the configuration of the molecule around the double bond. If hydrogens are present in the same plane, it is referred to as a cis fat; if the hydrogen atoms are on two different planes, it is referred to as a **trans fat**. The *cis* double bond causes a bend or a "kink" that prevents the fatty acids from packing tightly, keeping them liquid at room temperature (**Figure 3.17**). Olive oil, corn oil, canola oil, and cod liver oil are examples of unsaturated fats. Unsaturated fats help to lower blood cholesterol levels whereas saturated fats contribute to plaque formation in the arteries.

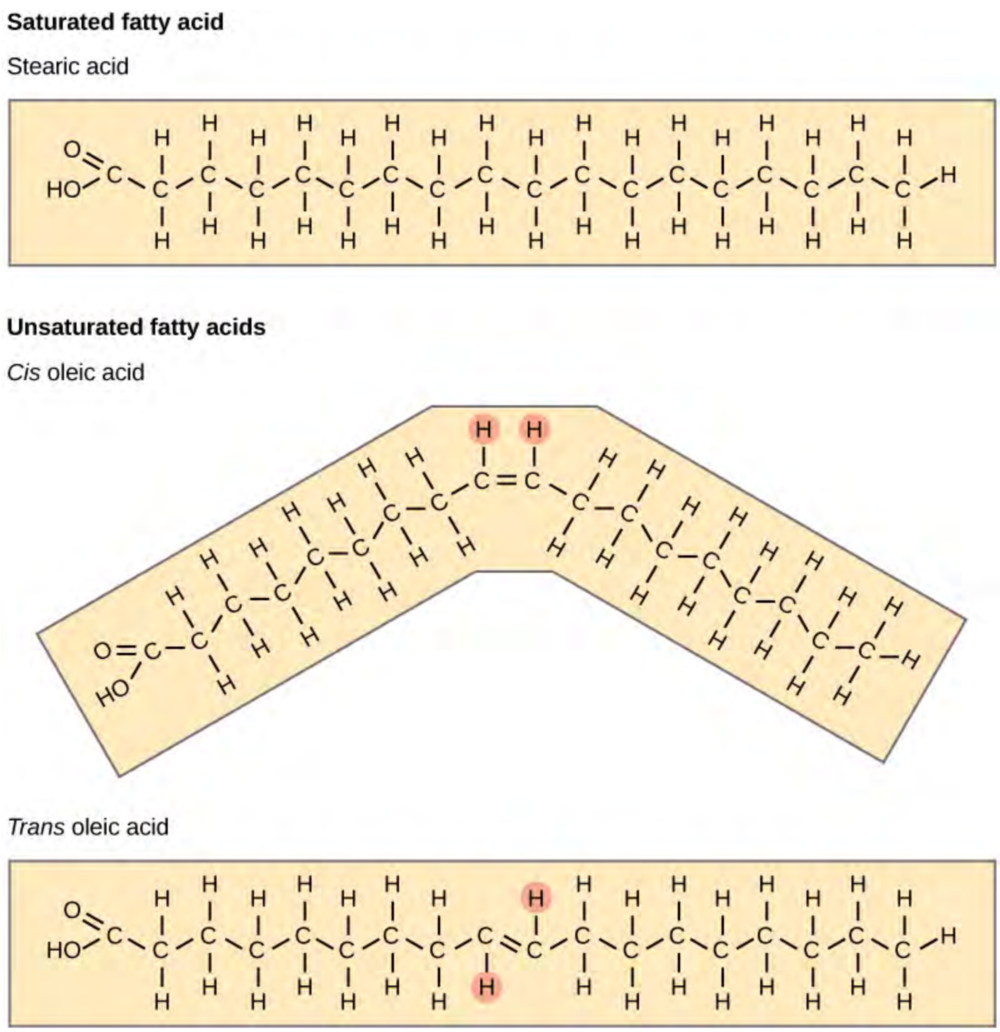


Figure 3.17 Saturated fatty acids have hydrocarbon chains connected by single bonds only. Unsaturated fatty acids have one or more double bonds. Each double bond may be in a *cis* or *trans* configuration. In the *cis* configuration, both hydrogens are on the same side of the hydrocarbon chain. In the *trans* configuration, the hydrogens are on opposite sides. A *cis* double bond causes a kink in the chain.

Trans Fats

In the food industry, oils are artificially hydrogenated to make them semi-solid and of a consistency desirable for many processed food products. Simply speaking, hydrogen gas is bubbled through oils to solidify them. During this hydrogenation process, double bonds of the *cis*- conformation in the hydrocarbon chain may be converted to double bonds in the trans-conformation.

Margarine, some types of peanut butter, and shortening are examples of artificially hydrogenated trans fats. Recent studies have shown that an increase in trans fats in the human diet may lead to an increase in levels of low-density lipoproteins (LDL), or “bad” cholesterol, which in turn may lead to plaque deposition in the arteries, resulting in heart disease. Many fast food restaurants have recently banned the use of trans fats, and food labels are required to display the trans fat content.

Omega Fatty Acids

Essential fatty acids are fatty acids required but not synthesized by the human body. Consequently, they have to be supplemented through ingestion via the diet. **Omega**-3 fatty acids (like that shown in Figure 3.18) fall into this category and are one of only two known for humans (the other being omega-6 fatty acid). These are polyunsaturated fatty acids and are called omega-3 because the third carbon from the end of the hydrocarbon chain is connected to its neighboring carbon by a double bond.

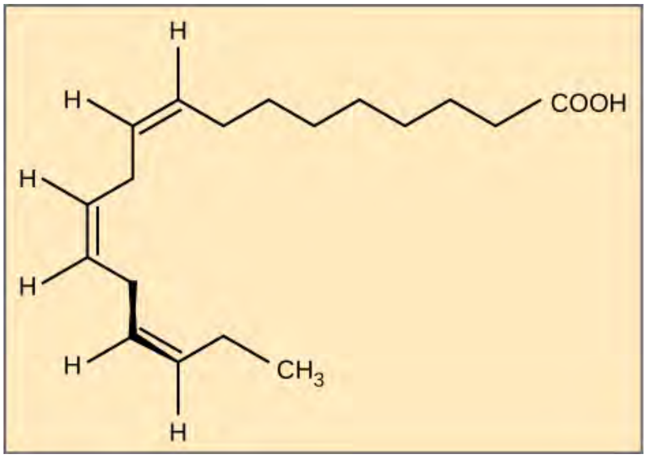


Figure 3.18 Alpha-linolenic acid is an example of an omega-3 fatty acid. It has three *cis* double bonds and, as a result, a curved shape. For clarity, the carbons are not shown. Each singly bonded carbon has two hydrogens associated with it, also not shown.

The farthest carbon away from the carboxyl group is numbered as the omega (ω) carbon, and if the double bond is between the third and fourth carbon from that end, it is known as an omega-3 fatty acid. Nutritionally important because the body does not make them, omega-3 fatty acids include alpha-linoleic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), all of which are polyunsaturated. Salmon, trout, and tuna are good sources of omega-3 fatty acids. Research indicates that omega-3 fatty acids reduce the risk of sudden death from heart attacks, reduce triglycerides in the blood, lower blood pressure, and prevent thrombosis by inhibiting blood clotting. They also reduce inflammation, and may help reduce the risk of some cancers in animals.

Like carbohydrates, fats have received a lot of bad publicity. It is true that eating an excess of fried foods and other “fatty” foods leads to weight gain. However, fats do have important functions. Many vitamins are fat soluble, and fats serve as a long-term storage form of fatty acids: a source of energy. They also provide insulation for the body. Therefore, “healthy” fats in moderate amounts should be consumed on a regular basis.

science practices CONNECTION for AP® Courses

Think About It

Explain why trans fats have been banned from some restaurants. How are trans fats made, and what effect does a simple chemical change have on the properties of the lipid?

Waxes

Wax covers the feathers of some aquatic birds and the leaf surfaces of some plants. Because of the hydrophobic nature of waxes, they prevent water from sticking on the surface (**Figure 3.19**). Waxes are made up of long fatty acid chains esterified to long-chain alcohols.

Figure 3.19 Waxy coverings on some leaves are made of lipids. (credit: Roger Griffith)

Phospholipids

Phospholipids are major constituents of the plasma membrane, the outermost layer of all living cells. Like fats, they are composed of fatty acid chains attached to a glycerol or sphingosine backbone. Instead of three fatty acids attached as in triglycerides, however, there are two fatty acids forming diacylglycerol, and the third carbon of the glycerol backbone is occupied by a modified phosphate group (**Figure 3.20**). A phosphate group alone attached to a diaglycerol does not qualify as a phospholipid; it is phosphatidate (diacylglycerol 3-phosphate), the precursor of phospholipids. The phosphate group is modified by an alcohol. Phosphatidylcholine and phosphatidylserine are two important phospholipids that are found in plasma membranes.

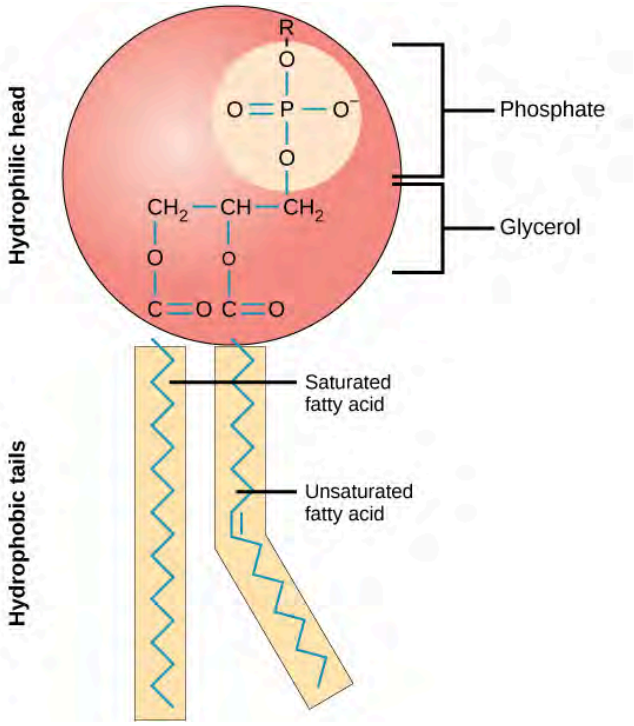


Figure 3.20 A phospholipid is a molecule with two fatty acids and a modified phosphate group attached to a glycerol backbone. The phosphate may be modified by the addition of charged or polar chemical groups.

A phospholipid is an amphipathic molecule, meaning it has a hydrophobic and a hydrophilic part. The fatty acid chains are hydrophobic and cannot interact with water, whereas the phosphate-containing group is hydrophilic and interacts with water (**Figure 3.21**).

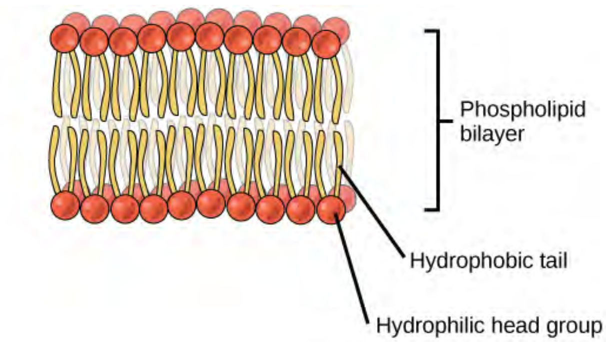


Figure 3.21 The phospholipid bilayer is the major component of all cellular membranes. The hydrophilic head groups of the phospholipids face the aqueous solution. The hydrophobic tails are sequestered in the middle of the bilayer.

The head is the hydrophilic part, and the tail contains the hydrophobic fatty acids. In a membrane, a bilayer of phospholipids forms the matrix of the structure, the fatty acid tails of phospholipids face inside, away from water, whereas the phosphate group faces the outside, aqueous side (**Figure 3.21**).

Phospholipids are responsible for the dynamic nature of the plasma membrane. If a drop of phospholipids is placed in water, it spontaneously forms a structure known as a micelle, where the hydrophilic phosphate heads face the outside and the fatty acids face the interior of this structure.

everyday CONNECTION for AP® Courses

Fats are amphiphilic molecules. In other words, the long hydrocarbon tail is hydrophobic, and the glycerol part of the molecule is hydrophilic. When in water, fats will arrange themselves into a ball called a **micelle** so that the hydrophilic "heads" are on the outer surface, and the hydrophobic "tails" are on the inside where they are protected from the surrounding water.

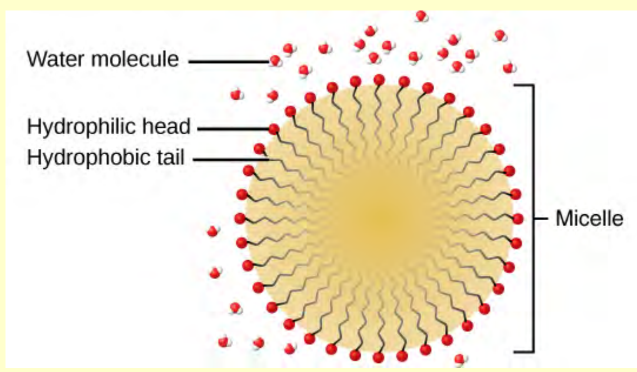
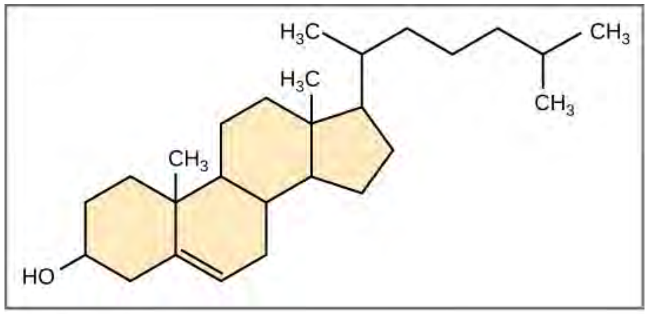


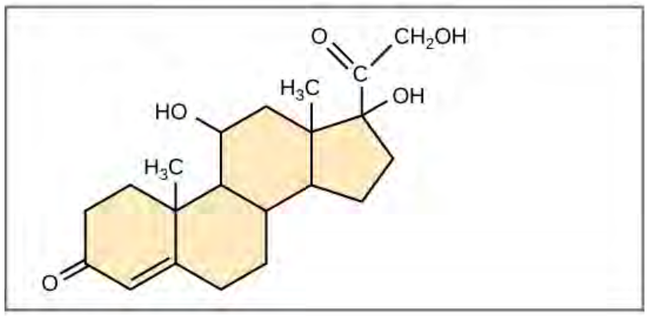
Figure 3.22

Steroids

Unlike the phospholipids and fats discussed earlier, **steroids** have a fused ring structure. Although they do not resemble the other lipids, they are grouped with them because they are also hydrophobic and insoluble in water. All steroids have four linked carbon rings and several of them, like cholesterol, have a short tail (**Figure 3.23**). Many steroids also have the –OH functional group, which puts them in the alcohol classification (sterols).



Cholesterol



Cortisol

Figure 3.23 Steroids such as cholesterol and cortisol are composed of four fused hydrocarbon rings.

Cholesterol is the most common steroid. Cholesterol is mainly synthesized in the liver and is the precursor to many steroid hormones such as testosterone and estradiol, which are secreted by the gonads and endocrine glands. It is also the precursor to Vitamin D. Cholesterol is also the precursor of bile salts, which help in the emulsification of fats and their subsequent absorption by cells. Although cholesterol is often spoken of in negative terms by lay people, it is necessary for proper functioning of the body. It is a component of the plasma membrane of animal cells and is found within the phospholipid bilayer. Being the outermost structure in animal cells, the plasma membrane is responsible for the transport of materials and cellular recognition and it is involved in cell-to-cell communication.

LINK TO LEARNING

For an additional perspective on lipids, explore the interactive animation **"Biomolecules: The Lipids" (http://openstaxcollege.org/l/lipids)** .

What is cholesterol specifically classified as?

a. a lipid

b. a phospholipid

c. a steroid

d. a wax

3.4 | Proteins

In this section, you will investigate the following questions:

- What are functions of proteins in cells and tissues?
- What is the relationship between amino acids and proteins?
- What are the four levels of protein organization?
- What is the relationship between protein shape and function?

Connection for AP® Courses

Proteins are long chains of different sequences of the 20 amino acids that each contain an amino group (-NH_2), a carboxyl group (-COOH), and a variable group. (Think of how many protein “words” can be made with 20 amino acid “letters”). Each amino acid is linked to its neighbor by a peptide bond formed by a dehydration reaction. A long chain of amino acids is known as a polypeptide. Proteins serve many functions in cells. They act as enzymes that catalyze chemical reactions, provide structural support, regulate the passage of substances across the cell membrane, protect against disease, and coordinate cell signaling pathways. Protein structure is organized at four levels: primary, secondary, tertiary, and quaternary. The primary structure is the unique sequence of amino acids. A change in just one amino acid can change protein structure and function. For example, sickle cell anemia results from just one amino acid substitution in a hemoglobin molecule consisting of 574 amino acids. The secondary structure consists of the local folding of the polypeptide by hydrogen bond formation; leading to the α helix and β pleated sheet conformations. In the tertiary structure, various interactions, e.g., hydrogen bonds, ionic bonds, disulfide linkages, and hydrophobic interactions between R groups, contribute to the folding of the polypeptide into different three-dimensional configurations. Most enzymes are of tertiary configuration. If a protein is denatured, loses its three-dimensional shape, it may no longer be functional. Environmental conditions such as temperature and pH can denature proteins. Some proteins, such as hemoglobin, are formed from several polypeptides, and the interactions of these subunits form the quaternary structure of proteins.

Information presented and the examples highlighted in the section, support concepts and Learning Objectives outlined in Big Idea 4 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A Learning Objective merges required content with one or more of the seven science practices.

Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**7.1** The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	**4.1** The student is able to explain the connection between the sequence and the subcomponents of a biological polymer and its properties.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**1.3** The student can refine representations and models of natural or man-made phenomena and systems in the domain.

Learning Objective	**4.2** The student is able to refine representations and models to explain how the subcomponents of a biological polymer and their sequence determine the properties of that polymer.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**6.1** The student can justify claims with evidence.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.3** The student is able to use models to predict and justify that changes in the subcomponents of a biological polymer affect the functionality of the molecules.

The Science Practice Challenge Questions contain additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 1.14] [APLO 2.12] [APLO 4.1] [APLO 4.3][APLO 4.15][APLO 4.22]

Types and Functions of Proteins

Proteins are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. Proteins may be structural, regulatory, contractile, or protective; they may serve in transport, storage, or membranes; or they may be toxins or enzymes. Each cell in a living system may contain thousands of proteins, each with a unique function. Their structures, like their functions, vary greatly. They are all, however, polymers of amino acids, arranged in a linear sequence.

Enzymes, which are produced by living cells, are catalysts in biochemical reactions (like digestion) and are usually complex or conjugated proteins. Each enzyme is specific for the substrate (a reactant that binds to an enzyme) it acts on. The enzyme may help in breakdown, rearrangement, or synthesis reactions. Enzymes that break down their substrates are called catabolic enzymes, enzymes that build more complex molecules from their substrates are called anabolic enzymes, and enzymes that affect the rate of reaction are called catalytic enzymes. It should be noted that all enzymes increase the rate of reaction and, therefore, are considered to be organic catalysts. An example of an enzyme is salivary amylase, which hydrolyzes its substrate amylose, a component of starch.

Hormones are chemical-signaling molecules, usually small proteins or steroids, secreted by endocrine cells that act to control or regulate specific physiological processes, including growth, development, metabolism, and reproduction. For example, insulin is a protein hormone that helps to regulate the blood glucose level. The primary types and functions of proteins are listed in **Table 3.1**.

Protein Types and Functions

Type	Examples	Functions
Digestive Enzymes	Amylase, lipase, pepsin, trypsin	Help in digestion of food by catabolizing nutrients into monomeric units
Transport	Hemoglobin, albumin	Carry substances in the blood or lymph throughout the body
Structural	Actin, tubulin, keratin	Construct different structures, like the cytoskeleton
Hormones	Insulin, thyroxine	Coordinate the activity of different body systems
Defense	Immunoglobulins	Protect the body from foreign pathogens
Contractile	Actin, myosin	Effect muscle contraction
Storage	Legume storage proteins, egg white (albumin)	Provide nourishment in early development of the embryo and the seedling

Table 3.1

Proteins have different shapes and molecular weights; some proteins are globular in shape whereas others are fibrous in nature. For example, hemoglobin is a globular protein, but collagen, found in our skin, is a fibrous protein. Protein shape is critical to its function, and this shape is maintained by many different types of chemical bonds. Changes in temperature, pH, and exposure to chemicals may lead to permanent changes in the shape of the protein, leading to loss of function, known as **denaturation**. All proteins are made up of different arrangements of the most common 20 types of amino acids.

Amino Acids

Amino acids are the monomers that make up proteins. Each amino acid has the same fundamental structure, which consists of a central carbon atom, also known as the alpha (α) carbon, bonded to an amino group (NH_2), a carboxyl group (COOH), and to a hydrogen atom. Every amino acid also has another atom or group of atoms bonded to the central atom known as the R group (**Figure 3.24**).

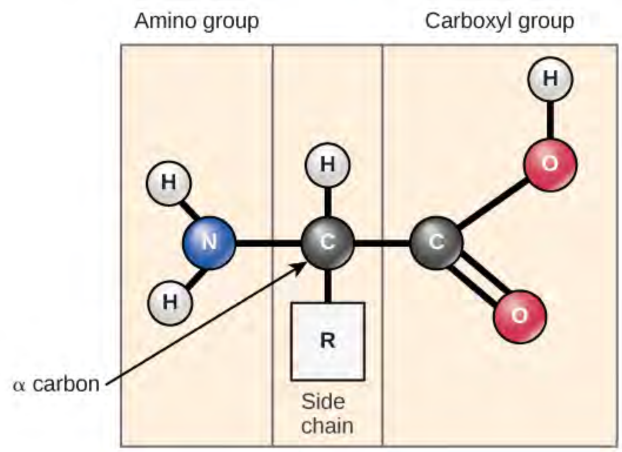


Figure 3.24 Amino acids have a central asymmetric carbon to which an amino group, a carboxyl group, a hydrogen atom, and a side chain (R group) are attached.

The name "amino acid" is derived from the fact that they contain both amino group and carboxyl-acid-group in their basic structure. As mentioned, there are 20 common amino acids present in proteins. Nine of these are considered essential amino acids in humans because the human body cannot produce them and they are obtained from the diet. For each amino acid, the R group (or side chain) is different (**Figure 3.25**).

visual CONNECTION

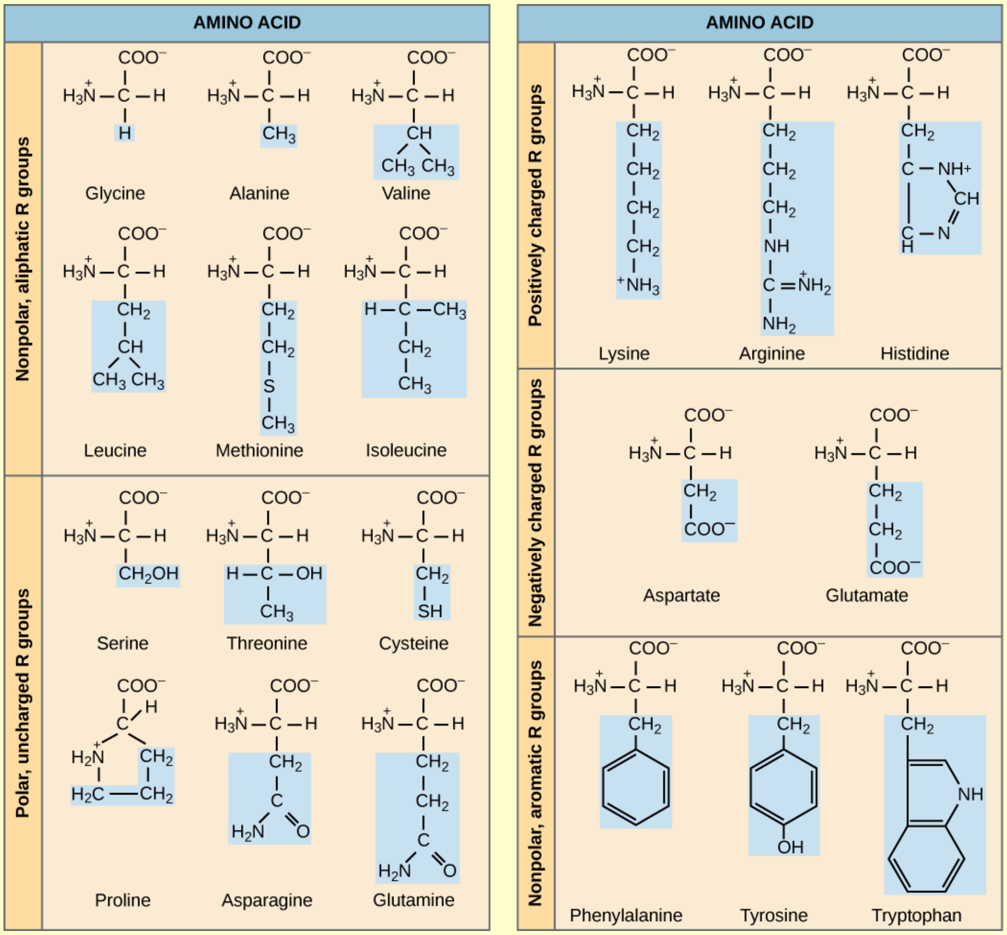


Figure 3.25 There are typically 20 common amino acids commonly found in proteins, each with a different R group (variant group) that determines its chemical nature.

Which categories of amino acid would you expect to find on the surface of a soluble protein, and which would you expect to find in the interior?

a. Polar and charged amino acids will be found on the surface. Non-polar amino acids will be found in the interior.

b. Polar and charged amino acids will be found in the interior. Non-polar amino acids will be found on the surface.

c. Non-polar and uncharged proteins will be found on the surface as well as in the interior.

The chemical nature of the side chain determines the nature of the amino acid (that is, whether it is acidic, basic, polar, or nonpolar). For example, the amino acid glycine has a hydrogen atom as the R group. Amino acids such as valine, methionine, and alanine are nonpolar or hydrophobic in nature, while amino acids such as serine, threonine, and cysteine are polar and have hydrophilic side chains. The side chains of lysine and arginine are positively charged, and therefore these amino acids are also known as basic amino acids. Proline has an R group that is linked to the amino group, forming a ring-like structure. Proline is an exception to the standard structure of an animo acid since its amino group is not separate from the side chain (**Figure 3.25**).

Amino acids are represented by a single upper case letter or a three-letter abbreviation. For example, valine is known by the letter V or the three-letter symbol val. Just as some fatty acids are essential to a diet, some amino acids are necessary as well. They are known as essential amino acids, and in humans they include isoleucine, leucine, and cysteine. Essential amino acids refer to those necessary for construction of proteins in the body, although not produced by the body; which amino acids are essential varies from organism to organism.

The sequence and the number of amino acids ultimately determine the protein's shape, size, and function. Each amino acid is attached to another amino acid by a covalent bond, known as a **peptide bond**, which is formed by a dehydration reaction. The carboxyl group of one amino acid and the amino group of the incoming amino acid combine, releasing a molecule of water. The resulting bond is the peptide bond (**Figure 3.26**).

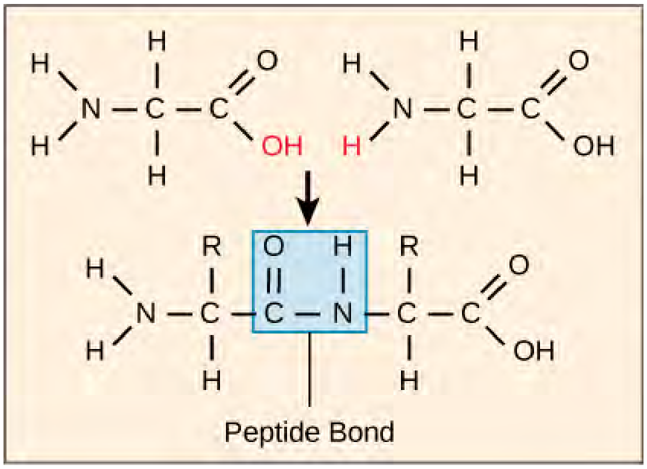


Figure 3.26 Peptide bond formation is a dehydration synthesis reaction. The carboxyl group of one amino acid is linked to the amino group of the incoming amino acid. In the process, a molecule of water is released.

The products formed by such linkages are called peptides. As more amino acids join to this growing chain, the resulting chain is known as a polypeptide. Each polypeptide has a free amino group at one end. This end is called the N terminal, or the amino terminal, and the other end has a free carboxyl group, also known as the C or carboxyl terminal. While the terms polypeptide and protein are sometimes used interchangeably, a polypeptide is technically a polymer of amino acids, whereas the term protein is used for a polypeptide or polypeptides that have combined together, often have bound non-peptide prosthetic groups, have a distinct shape, and have a unique function. After protein synthesis (translation), most proteins are modified. These are known as post-translational modifications. They may undergo cleavage or phosphorylation, or may require the addition of other chemical groups. Only after these modifications is the protein completely functional.

LINK TO LEARNING

Click through the steps of protein synthesis in this **interactive tutorial (http://openstaxcollege.org/l/protein_synth)** .

Why is the process of protein synthesis critical to life?

a. Protein is the body’s preferred source for energy for rapid energy production.

b. Protein is stored in the liver and muscles to supply energy for future use.

c. Protein is required for tissue formation and constitutes hormones and enzymes.

d. Proteins are required for the absorption of all fat soluble vitamins.

evolution CONNECTION

Cytochrome c is an important component of the electron transport chain, a part of cellular respiration, and it is normally found in the cellular organelle, the mitochondrion. This protein has a heme prosthetic group, and the central ion of the heme gets alternately reduced and oxidized during electron transfer. Because this essential protein's role in producing cellular energy is crucial, it has changed very little over millions of years. Protein sequencing has shown that there is a considerable amount of cytochrome c amino acid sequence homology among different species; in other words, evolutionary kinship can be assessed by measuring the similarities or differences among various species' DNA or protein sequences.

Scientists have determined that human cytochrome c contains 104 amino acids. For each cytochrome c molecule from different organisms that has been sequenced to date, 37 of these amino acids appear in the same position in all samples of cytochrome c. This indicates that there may have been a common ancestor. On comparing the human and chimpanzee protein sequences, no sequence difference was found. When human and rhesus monkey sequences were compared, the single difference found was in one amino acid. In another comparison, human to yeast sequencing shows a difference in the 44th position.

The protein sequence of cytochrome c from chimpanzees and humans is identical. The protein sequence of cytochrome c from rhesus monkeys differs from the human sequence by one amino acid. What do these comparisons suggest?

a. Rhesus monkeys are more closely related to humans than chimpanzees.
b. Chimpanzees are more closely related to rhesus monkeys than to humans.
c. Humans are related to chimpanzees, but are not related to rhesus monkeys.
d. Chimpanzees are more closely related to humans than rhesus monkeys.

Protein Structure

As discussed earlier, the shape of a protein is critical to its function. For example, an enzyme can bind to a specific substrate at a site known as the active site. If this active site is altered because of local changes or changes in overall protein structure, the enzyme may be unable to bind to the substrate. To understand how the protein gets its final shape or conformation, we need to understand the four levels of protein structure: primary, secondary, tertiary, and quaternary.

Primary Structure

The unique sequence of amino acids in a polypeptide chain is its **primary structure**. For example, the pancreatic hormone insulin has two polypeptide chains, A and B, and they are linked together by disulfide bonds. The N terminal amino acid of the A chain is glycine, whereas the C terminal amino acid is asparagine (**Figure 3.27**). The sequences of amino acids in the A and B chains are unique to insulin.

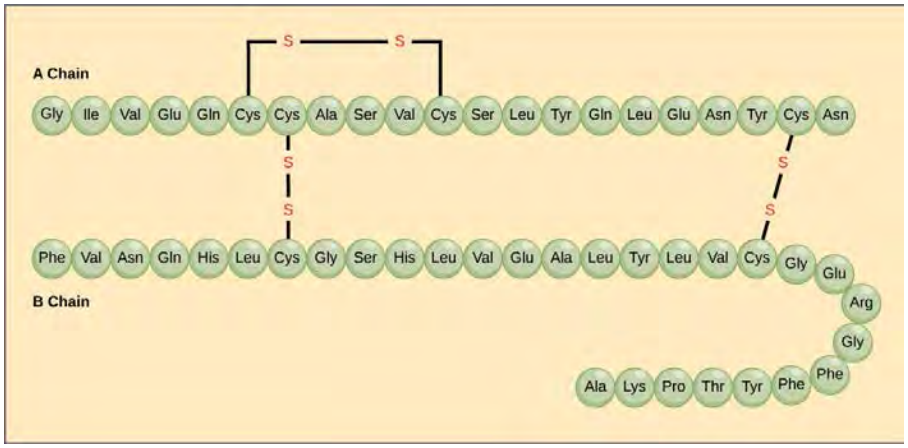


Figure 3.27 Bovine serum insulin is a protein hormone made of two peptide chains, A (21 amino acids long) and B (30 amino acids long). In each chain, primary structure is indicated by three-letter abbreviations that represent the names of the amino acids in the order they are present. The amino acid cysteine (cys) has a sulfhydryl (SH) group as a side chain. Two sulfhydryl groups can react in the presence of oxygen to form a disulfide (S-S) bond. Two disulfide bonds connect the A and B chains together, and a third helps the A chain fold into the correct shape. Note that all disulfide bonds are the same length, but are drawn different sizes for clarity.

The unique sequence for every protein is ultimately determined by the gene encoding the protein. A change in nucleotide sequence of the gene's coding region may lead to a different amino acid being added to the growing polypeptide chain, causing a change in protein structure and function. In sickle cell anemia, the hemoglobin β chain (a small portion of which is shown in **Figure 3.28**) has a single amino acid substitution, causing a change in protein structure and function. Specifically, the amino acid glutamic acid is substituted by valine in the β chain. What is most remarkable to consider is that a hemoglobin molecule is made up of two alpha chains and two beta chains that each consist of about 150 amino acids. The molecule, therefore, has about 600 amino acids. The structural difference between a normal hemoglobin molecule and a sickle cell molecule—which dramatically decreases life expectancy—is a single amino acid of the 600. What is even more remarkable is that those 600 amino acids are encoded by three nucleotides each, and the mutation is caused by a single base change (point mutation), 1 in 1800 bases.

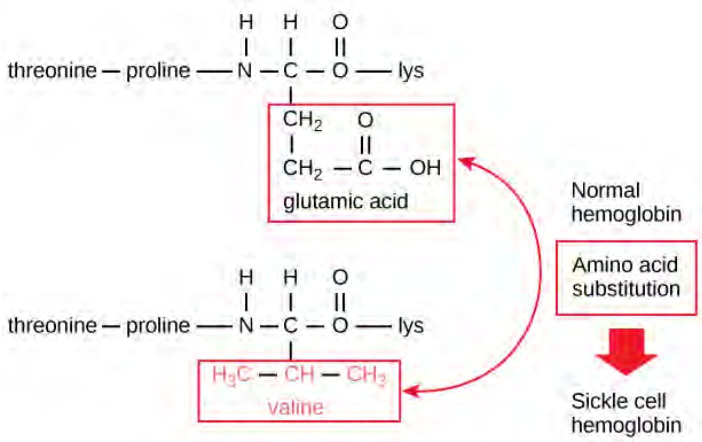


Figure 3.28 The beta chain of hemoglobin is 147 residues in length, yet a single amino acid substitution leads to sickle cell anemia. In normal hemoglobin, the amino acid at position seven is glutamate. In sickle cell hemoglobin, this glutamate is replaced by a valine.

Because of this change of one amino acid in the chain, hemoglobin molecules form long fibers that distort the biconcave, or disc-shaped, red blood cells and cause them to assume a crescent or "sickle" shape, which clogs blood vessels (**Figure 3.29**). This can lead to myriad serious health problems such as breathlessness, dizziness, headaches, and abdominal pain for those affected by this disease.

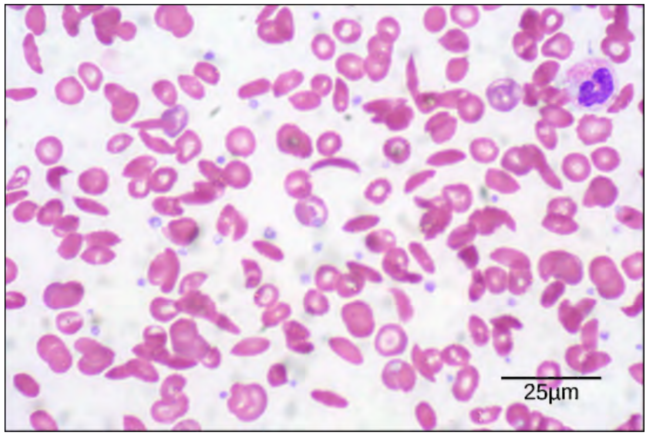


Figure 3.29 In this blood smear, visualized at 535x magnification using bright field microscopy, sickle cells are crescent shaped, while normal cells are disc-shaped. (credit: modification of work by Ed Uthman; scale-bar data from Matt Russell)

Secondary Structure

The local folding of the polypeptide in some regions gives rise to the **secondary structure** of the protein. The most common are the ***α*-helix** and ***β*-pleated sheet** structures (Figure 3.30). Both structures are held together by hydrogen bonds. In the *α*-helix structure, the hydrogen bonds form between the oxygen atom in the carbonyl group in one amino acid and another amino acid that is four amino acids farther along the chain.

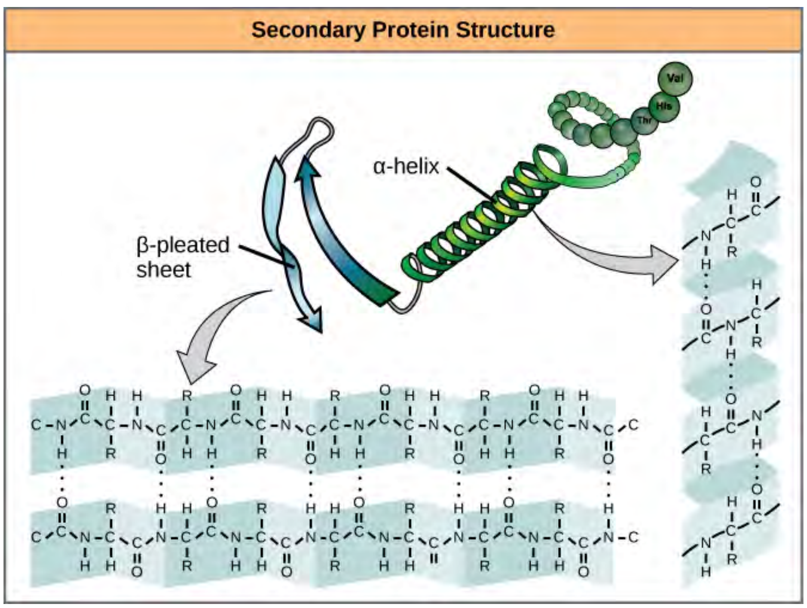


Figure 3.30 The *α*-helix and *β*-pleated sheet are secondary structures of proteins that form because of hydrogen bonding between carbonyl and amino groups in the peptide backbone. Certain amino acids have a propensity to form an *α*-helix, while others have a propensity to form a *β*-pleated sheet.

Every helical turn in an alpha helix has 3.6 amino acid residues. The R groups (the variant groups) of the polypeptide protrude out from the *α*-helix chain. In the *β*-pleated sheet, the "pleats" are formed by hydrogen bonding between atoms on the backbone of the polypeptide chain. The R groups are attached to the carbons and extend above and below the folds of the pleat. The pleated segments align parallel or antiparallel to each other, and hydrogen bonds form between the partially positive nitrogen atom in the amino group and the partially negative oxygen atom in the carbonyl group of the peptide backbone. The *α*-helix and *β*-pleated sheet structures are found in most globular and fibrous proteins and they play an important structural role.

Tertiary Structure

The unique three-dimensional structure of a polypeptide is its **tertiary structure** (Figure 3.31). This structure is in part due to chemical interactions at work on the polypeptide chain. Primarily, the interactions among R groups creates the complex three-dimensional tertiary structure of a protein. The nature of the R groups found in the amino acids involved can counteract the formation of the hydrogen bonds described for standard secondary structures. For example, R groups with like charges are repelled by each other and those with unlike charges are attracted to each other (ionic bonds). When protein folding takes place, the hydrophobic R groups of nonpolar amino acids lie in the interior of the protein, whereas the hydrophilic R groups lie on the outside. The former types of interactions are also known as hydrophobic interactions. Interaction between cysteine side chains forms disulfide linkages in the presence of oxygen, the only covalent bond forming during protein folding.

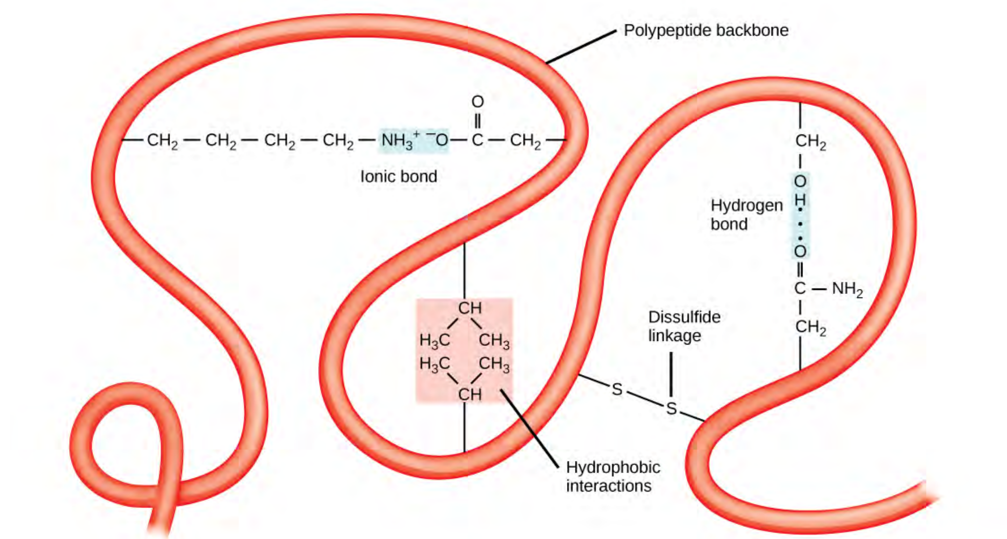


Figure 3.31 The tertiary structure of proteins is determined by a variety of chemical interactions. These include hydrophobic interactions, ionic bonding, hydrogen bonding and disulfide linkages.

All of these interactions, weak and strong, determine the final three-dimensional shape of the protein. When a protein loses its three-dimensional shape, it may no longer be functional.

Quaternary Structure

In nature, some proteins are formed from several polypeptides, also known as subunits, and the interaction of these subunits forms the **quaternary structure**. Weak interactions between the subunits help to stabilize the overall structure. For example, insulin (a globular protein) has a combination of hydrogen bonds and disulfide bonds that cause it to be mostly clumped into a ball shape. Insulin starts out as a single polypeptide and loses some internal sequences in the presence of post-translational modification after the formation of the disulfide linkages that hold the remaining chains together. Silk (a fibrous protein), however, has a β-pleated sheet structure that is the result of hydrogen bonding between different chains.

The four levels of protein structure (primary, secondary, tertiary, and quaternary) are illustrated in **Figure 3.32**.

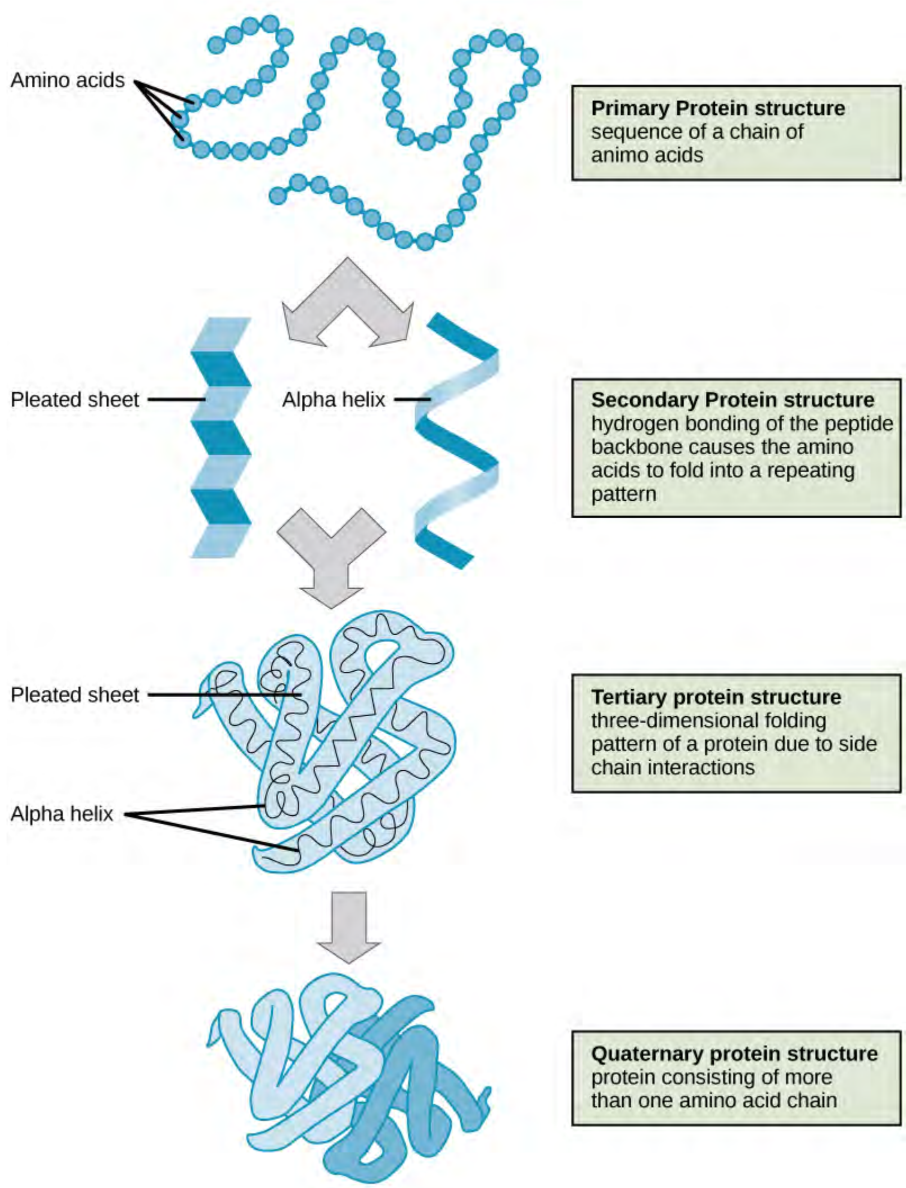


Figure 3.32 The four levels of protein structure can be observed in these illustrations. (credit: modification of work by National Human Genome Research Institute)

Denaturation and Protein Folding

Each protein has its own unique sequence and shape that are held together by chemical interactions. If the protein is subject to changes in temperature, changes in pH, or exposure to chemicals, the protein structure may change, losing its shape without losing its primary sequence in what is known as denaturation. Denaturation is often reversible because the primary structure of the polypeptide is conserved in the process if the denaturing agent is removed, allowing the protein to resume its function. Sometimes denaturation is irreversible, leading to loss of function. One example of irreversible protein denaturation is when an egg is fried. The albumin protein in the liquid egg white is denatured when placed in a hot pan. Not all proteins are denatured at high temperatures; for instance, bacteria that survive in hot springs have proteins that function at temperatures close to boiling. The stomach is also very acidic, has a low pH, and denatures proteins as part of the digestion process; however, the digestive enzymes of the stomach retain their activity under these conditions.

Protein folding is critical to its function. It was originally thought that the proteins themselves were responsible for the folding process. Only recently was it found that often they receive assistance in the folding process from protein helpers known as **chaperones** (or chaperonins) that associate with the target protein during the folding process. They act by preventing aggregation of polypeptides that make up the complete protein structure, and they disassociate from the protein once the target protein is folded.

LINK TO LEARNING

For an additional perspective on proteins, view **this animation (http://openstaxcollege.org/l/proteins)** called "Biomolecules: The Proteins."

Vegans are people who do not consume any animal products in their diet. Why do vegans need to pay special attention to the protein they eat?

a. Plant proteins contain all of the essential as well as non-essential amino acids.

b. It is more difficult to obtain all essential amino acids from single plant sources.

c. Plant proteins contain only non-essential amino acids.

d. Plants proteins do not have all of the non-essential amino acids, but do contain the essential amino acids.

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Think About It

- Predict what happens if even one amino acid is substituted for another in a polypeptide and provide a specific example.
- What categories of amino acids would you expect to find on the surface of a soluble protein, and which would you expect to find in the interior? What distribution of amino acids would you expect to find in a protein embedded in a lipid bilayer of a plasma cell membrane?

Activity

Folding is an important property of proteins, especially enzymes. Proteins have a narrow range of conditions in which they fold properly; outside that range, proteins can unfold (denature) and often cannot refold and become functional again. Investigate one disease that results from improper folding of a protein. Describe causes of the unfolding and consequences to the molecular structure of the polypeptide that result in the disease.

3.5 | Nucleic Acids

In this section, you will investigate the following questions:

- What are the two types of nucleic acid?
- What is the structure and role of DNA?
- What is the structure and roles of RNA?

Connection for AP® Courses

Nucleic acids (DNA and RNA) comprise the fourth group of biological macromolecules and contain phosphorus (P) in addition to carbon, hydrogen, oxygen, and nitrogen. Conserved through evolution in all organisms, nucleic acids store and transmit hereditary information. As will be explored in more detail in Chapters 14-17, DNA contains the instructions for the synthesis of proteins by dictating the sequences of amino acids in polypeptides through processes known as transcription and translation. Nucleic acids are made up of nucleotides; in turn, each nucleotide consists of a pentose sugar (deoxyribose in DNA and ribose in RNA), a nitrogenous base (adenine, cytosine, guanine, and thymine or uracil), and a phosphate group. DNA carries the genetic blueprint of the cell that is passed from parent to offspring via cell division. DNA has a double-helical structure with the two strands running in opposite directions (antiparallel), connected by hydrogen bonds and complementary to each other. In DNA, purines pair with pyrimidines: adenine pairs with thymine (A-T), and cytosine pairs with guanine (C-G). In RNA, uracil replaces thymine to pair with adenine (U-A). RNA also differs from DNA in that it is single-stranded and has many forms, such as messenger RNA (mRNA), ribosomal RNA (rRNA), and transfer RNA (tRNA) that all participate in the synthesis of proteins. MicroRNAs (miRNAs) regulate the use of mRNA. The flow of genetic information is usually DNA → RNA → protein, also known as the Central Dogma of Life.

Information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in Big Idea 3 and Big Idea 4 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® Exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

Big Idea 3	Living systems store, retrieve, transmit and respond to information essential to life processes.
Enduring Understanding 3.A	Heritable information provides for continuity of life.
Essential Knowledge	**3.A.1** DNA, and in some cases RNA, is the primary source of heritable information.
Science Practice	**6.5** The student can evaluate alternative scientific explanations.
Learning Objective	**3.1** The student is able to construct scientific explanations that use the structures and mechanisms of DNA and RNA to support the claim that DNA and, in some cases, that RNA are the primary sources of heritable information.
Essential Knowledge	**3.A.1** DNA, and in some cases RNA, is the primary source of heritable information.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**3.6** The student can predict how a change in a specific DNA or RNA sequence can result in changes in gene expression.
Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**7.1** The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	**4.1** The student is able to explain the connection between the sequence and the subcomponents of a biological polymer and its properties.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.

Science Practice	**1.3** The student can refine representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	**4.2** The student is able to refine representations and models to explain how the subcomponents of a biological polymer and their sequence determine the properties of that polymer.
Essential Knowledge	**4.A.1** The subcomponents of biological molecules and their sequence determine the properties of that molecule.
Science Practice	**6.1** The student can justify claims with evidence.
	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.3** The student is able to use models to predict and justify that changes in the subcomponents of a biological polymer affect the functionality of the molecules.

The Science Practice Challenge Questions contain additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 3.1] [APLO 4.17]

DNA and RNA

Nucleic acids are the most important macromolecules for the continuity of life. They carry the genetic blueprint of a cell and carry instructions for the functioning of the cell.

The two main types of nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. DNA is the genetic material found in all living organisms, ranging from single-celled bacteria to multicellular mammals. It is found in the nucleus of eukaryotes and in the organelles, chloroplasts, and mitochondria. In prokaryotes, the DNA is not enclosed in a membranous envelope.

The entire genetic content of a cell is known as its genome, and the study of genomes is genomics. In eukaryotic cells but not in prokaryotes, DNA forms a complex with histone proteins to form chromatin, the substance of eukaryotic chromosomes. A chromosome may contain tens of thousands of genes. Many genes contain the information to make protein products; other genes code for RNA products. DNA controls all of the cellular activities by turning the genes “on” or “off.”

The other type of nucleic acid, RNA, is mostly involved in protein synthesis. The DNA molecules never leave the nucleus but instead use an intermediary to communicate with the rest of the cell. This intermediary is the **messenger RNA (mRNA)**. Other types of RNA—like rRNA, tRNA, and microRNA—are involved in protein synthesis and its regulation.

DNA and RNA are made up of monomers known as **nucleotides**. The nucleotides combine with each other to form a **polynucleotide**, DNA or RNA. Each nucleotide is made up of three components: a nitrogenous base, a pentose (five-carbon) sugar, and a phosphate group (**Figure 3.33**). Each nitrogenous base in a nucleotide is attached to a sugar molecule, which is attached to one or more phosphate groups.

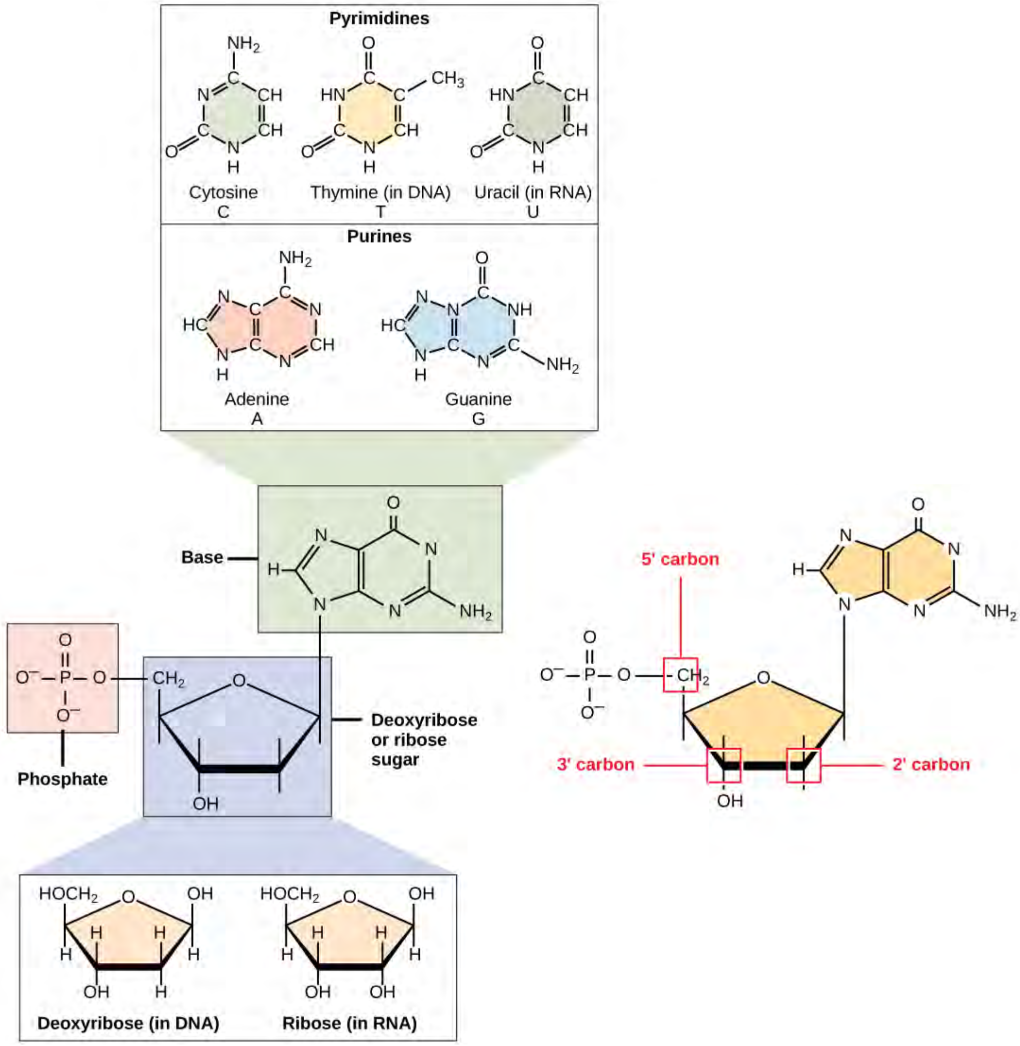

Figure 3.33 A nucleotide is made up of three components: a nitrogenous base, a pentose sugar, and one or more phosphate groups. Carbon residues in the pentose are numbered 1′ through 5′ (the prime distinguishes these residues from those in the base, which are numbered without using a prime notation). The base is attached to the 1′ position of the ribose, and the phosphate is attached to the 5′ position. When a polynucleotide is formed, the 5′ phosphate of the incoming nucleotide attaches to the 3′ hydroxyl group at the end of the growing chain. Two types of pentose are found in nucleotides, deoxyribose (found in DNA) and ribose (found in RNA). Deoxyribose is similar in structure to ribose, but it has an H instead of an OH at the 2′ position. Bases can be divided into two categories: purines and pyrimidines. Purines have a double ring structure, and pyrimidines have a single ring.

The nitrogenous bases, important components of nucleotides, are organic molecules and are so named because they contain carbon and nitrogen. They are bases because they contain an amino group that has the potential of binding an extra hydrogen, thus decreasing the hydrogen ion concentration in its environment, making it more basic. Each nucleotide in DNA contains one of four possible nitrogenous bases: adenine (A), guanine (G) cytosine (C), and thymine (T).

Adenine and guanine are classified as **purines**. The primary structure of a purine is two carbon-nitrogen rings. Cytosine, thymine, and uracil are classified as **pyrimidines** which have a single carbon-nitrogen ring as their primary structure (Figure 3.33). Each of these basic carbon-nitrogen rings has different functional groups attached to it. In molecular biology shorthand, the nitrogenous bases are simply known by their symbols A, T, G, C, and U. DNA contains A, T, G, and C whereas RNA contains A, U, G, and C.

The pentose sugar in DNA is deoxyribose, and in RNA, the sugar is ribose (Figure 3.33). The difference between the sugars is the presence of the hydroxyl group on the second carbon of the ribose and hydrogen on the second carbon of the deoxyribose. The carbon atoms of the sugar molecule are numbered as 1′, 2′, 3′, 4′, and 5′ (1′ is read as “one prime”). The phosphate residue is attached to the hydroxyl group of the 5′ carbon of one sugar and the hydroxyl group of the 3′ carbon of the sugar of the next nucleotide, which forms a 5′–3′ **phosphodiester** linkage. The phosphodiester linkage is not formed by simple dehydration reaction like the other linkages connecting monomers in macromolecules: its formation involves the removal of two phosphate groups. A polynucleotide may have thousands of such phosphodiester linkages.

DNA Double-Helix Structure

DNA has a double-helix structure (Figure 3.34). The sugar and phosphate lie on the outside of the helix, forming the backbone of the DNA. The nitrogenous bases are stacked in the interior, like the steps of a staircase, in pairs; the pairs are bound to each other by hydrogen bonds. Every base pair in the double helix is separated from the next base pair by 0.34 nm. The two strands of the helix run in opposite directions, meaning that the 5′ carbon end of one strand will face the 3′ carbon end of its matching strand. (This is referred to as antiparallel orientation and is important to DNA replication and in many nucleic acid interactions.)

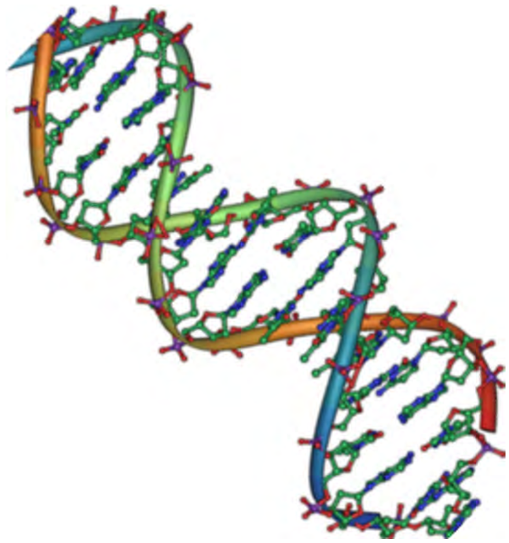

Figure 3.34 Native DNA is an antiparallel double helix. The phosphate backbone (indicated by the curvy lines) is on the outside, and the bases are on the inside. Each base from one strand interacts via hydrogen bonding with a base from the opposing strand. (credit: Jerome Walker/Dennis Myts)

Only certain types of base pairing are allowed. For example, a certain purine can only pair with a certain pyrimidine. This means A can pair with T, and G can pair with C, as shown in Figure 3.35. This is known as the base complementary rule. In other words, the DNA strands are complementary to each other. If the sequence of one strand is AATTGGCC, the complementary strand would have the sequence TTAACCGG. During DNA replication, each strand is copied, resulting in a daughter DNA double helix containing one parental DNA strand and a newly synthesized strand.

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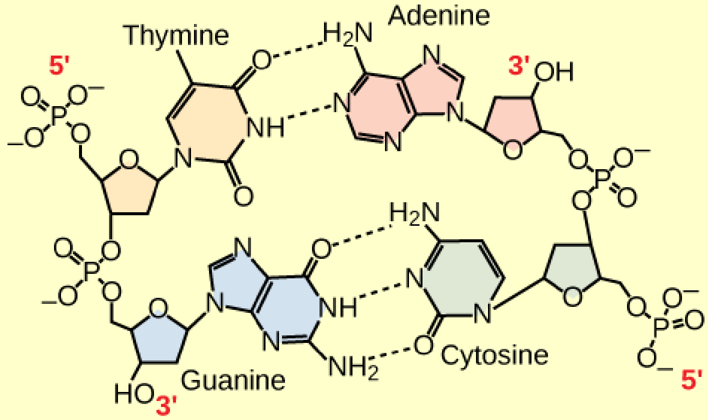

Figure 3.35 In a double stranded DNA molecule, the two strands run antiparallel to one another so that one strand runs 5′ to 3′ and the other 3′ to 5′. The phosphate backbone is located on the outside, and the bases are in the middle. Adenine forms hydrogen bonds (or base pairs) with thymine, and guanine base pairs with cytosine.

A mutation occurs, and cytosine is replaced with adenine. What impact do you think this will have on the DNA structure?

a. The DNA will normally pair its adenine with thymine, causing no change in the DNA structure.
b. The DNA will bulge in the places where cytosine is replaced by adenine.
c. The adenine substituted in the place of cytosine will get methylated and will not be transcribed further.
d. The DNA will cause another mutation to replace this incorrect DNA base.

RNA

Ribonucleic acid, or RNA, is mainly involved in the process of protein synthesis under the direction of DNA. RNA is usually single-stranded and is made of ribonucleotides that are linked by phosphodiester bonds. A ribonucleotide in the RNA chain contains ribose (the pentose sugar), one of the four nitrogenous bases (A, U, G, and C), and the phosphate group.

There are four major types of RNA: messenger RNA (mRNA), ribosomal RNA (rRNA), transfer RNA (tRNA), and microRNA (miRNA). The first, mRNA, carries the message from DNA, which controls all of the cellular activities in a cell. If a cell requires a certain protein to be synthesized, the gene for this product is turned "on" and the messenger RNA is synthesized in the nucleus. The RNA base sequence is complementary to the coding sequence of the DNA from which it has been copied. However, in RNA, the base T is absent and U is present instead. If the DNA strand has a sequence AATTGCGC, the sequence of the complementary RNA is UUAACGCG. In the cytoplasm, the mRNA interacts with ribosomes and other cellular machinery (**Figure 3.36**).

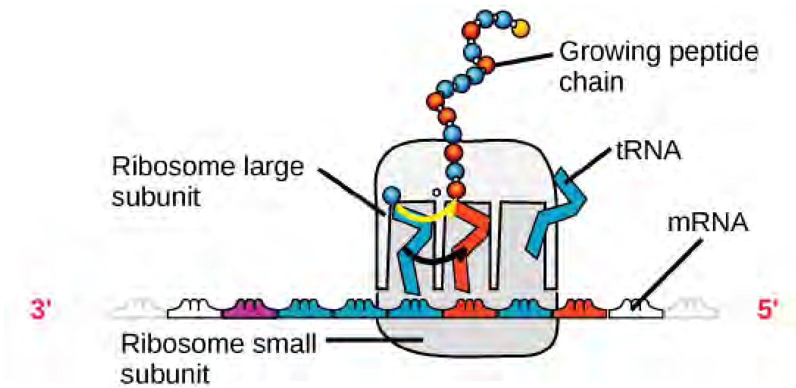

Figure 3.36 A ribosome has two parts: a large subunit and a small subunit. The mRNA sits in between the two subunits. A tRNA molecule recognizes a codon on the mRNA, binds to it by complementary base pairing, and adds the correct amino acid to the growing peptide chain.

The mRNA is read in sets of three bases known as codons. Each codon codes for a single amino acid. In this way, the mRNA is read and the protein product is made. **Ribosomal RNA (rRNA)** is a major constituent of ribosomes on which the mRNA binds. The rRNA ensures the proper alignment of the mRNA and the ribosomes; the rRNA of the ribosome also has an enzymatic activity (peptidyl transferase) and catalyzes the formation of the peptide bonds between two aligned amino acids. **Transfer RNA (tRNA)** is one of the smallest of the four types of RNA, usually 70–90 nucleotides long. It carries the correct amino acid to the site of protein synthesis. It is the base pairing between the tRNA and mRNA that allows for the correct amino acid to be inserted in the polypeptide chain. microRNAs are the smallest RNA molecules and their role involves the regulation of gene expression by interfering with the expression of certain mRNA messages. Table 3.2 summarizes features of DNA and RNA.

Features of DNA and RNA

	DNA	RNA
Function	Carries genetic information	Involved in protein synthesis
Location	Remains in the nucleus	Leaves the nucleus
Structure	Double helix	Usually single-stranded
Sugar	Deoxyribose	Ribose
Pyrimidines	Cytosine, thymine	Cytosine, uracil
Purines	Adenine, guanine	Adenine, guanine

Table 3.2

Even though the RNA is single stranded, most RNA types show extensive intramolecular base pairing between complementary sequences, creating a predictable three-dimensional structure essential for their function.

As you have learned, information flow in an organism takes place from DNA to RNA to protein. DNA dictates the structure of mRNA in a process known as **transcription**, and RNA dictates the structure of protein in a process known as **translation**. This is known as the Central Dogma of Life, which holds true for all organisms; however, exceptions to the rule occur in connection with viral infections.

LINK TO LEARNING

To learn more about DNA, explore the **Howard Hughes Medical Institute BioInteractive animations (http://openstaxcollege.org/l/DNA)** on the topic of DNA.

Why is DNA replication like an assembly line?

a. It consists of many biochemical machines that functions specifically in order to drive a specific action like an assembly line.

b. It consists of many biochemical machines that have the same function in order to drive a specific action like an assembly line.

c. It consists of many biochemical machines where each functions randomly in order to drive a specific action like an assembly line.

d. It consists of many biochemical machines that functions in order to drive a non-specific action like an assembly line.

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Activity

Using construction paper, markers, and scissors, construct a model of DNA with at least 8 nucleotides. Then, use the model to distinguish between DNA and RNA and hypothesize how the DNA molecule is replicated during cell division. (Keep your molecule to model the processes of transcription and translation that you will explore in Chapter 15.)

Think About It

A mutation occurs, and cytosine is replaced with adenine. Explain how this affects how the changed strand will base pair with its complimentary strand of DNA.

KEY TERMS

alpha-helix structure (α-helix) type of secondary structure of proteins formed by folding of the polypeptide into a helix shape with hydrogen bonds stabilizing the structure

amino acid monomer of a protein; has a central carbon or alpha carbon to which an amino group, a carboxyl group, a hydrogen, and an R group or side chain is attached; the R group is different for the most common 20 amino acids

beta-pleated sheet (β-pleated) secondary structure found in proteins in which “pleats” are formed by hydrogen bonding between atoms on the backbone of the polypeptide chain

biological macromolecule large molecule necessary for life that is built from smaller organic molecules

carbohydrate biological macromolecule in which the ratio of carbon to hydrogen and to oxygen is 1:2:1; carbohydrates serve as energy sources and structural support in cells and form the a cellular exoskeleton of arthropods

cellulose polysaccharide that makes up the cell wall of plants; provides structural support to the cell

chaperone (also, chaperonin) protein that helps nascent protein in the folding process

chitin type of carbohydrate that forms the outer skeleton of all arthropods that include crustaceans and insects; it also forms the cell walls of fungi

dehydration synthesis (also, condensation) reaction that links monomer molecules together, releasing a molecule of water for each bond formed

denaturation loss of shape in a protein as a result of changes in temperature, pH, or exposure to chemicals

deoxyribonucleic acid (DNA) double-helical molecule that carries the hereditary information of the cell

disaccharide two sugar monomers that are linked together by a glycosidic bond

enzyme catalyst in a biochemical reaction that is usually a complex or conjugated protein

glycogen storage carbohydrate in animals

glycosidic bond bond formed by a dehydration reaction between two monosaccharides with the elimination of a water molecule

hormone chemical signaling molecule, usually protein or steroid, secreted by endocrine cells that act to control or regulate specific physiological processes

hydrolysis reaction that causes breakdown of larger molecules into smaller molecules with the utilization of water

lipid macromolecule that is nonpolar and insoluble in water

messenger RNA (mRNA) RNA that carries information from DNA to ribosomes during protein synthesis

monomer smallest unit of larger molecules called polymers

monosaccharide single unit or monomer of carbohydrates

nucleic acid biological macromolecule that carries the genetic blueprint of a cell and carries instructions for the functioning of the cell

nucleotide monomer of nucleic acids; contains a pentose sugar, one or more phosphate groups, and a nitrogenous base

omega fat type of polyunsaturated fat that is required by the body; the numbering of the carbon omega starts from the methyl end or the end that is farthest from the carboxylic end

peptide bond bond formed between two amino acids by a dehydration reaction

phosphodiester linkage covalent chemical bond that holds together the polynucleotide chains, with a phosphate group linking two pentose sugars of neighboring nucleotides

phospholipid major constituent of the membranes; composed of two fatty acids and a phosphate-containing group attached to a glycerol backbone

polymer chain of monomer residues that is linked by covalent bonds; polymerization is the process of polymer formation from monomers by condensation

polynucleotide long chain of nucleotides

polypeptide long chain of amino acids linked by peptide bonds

polysaccharide long chain of monosaccharides; may be branched or unbranched

primary structure linear sequence of amino acids in a protein

protein biological macromolecule composed of one or more chains of amino acids

purine type of nitrogenous base in DNA and RNA; adenine and guanine are purines

pyrimidine type of nitrogenous base in DNA and RNA; cytosine, thymine, and uracil are pyrimidines

quaternary structure association of discrete polypeptide subunits in a protein

ribonucleic acid (RNA) single-stranded, often internally base paired, molecule that is involved in protein synthesis

ribosomal RNA (rRNA) RNA that ensures the proper alignment of the mRNA and the ribosomes during protein synthesis and catalyzes the formation of the peptide linkage

saturated fatty acid long-chain of hydrocarbon with single covalent bonds in the carbon chain; the number of hydrogen atoms attached to the carbon skeleton is maximized

secondary structure regular structure formed by proteins by intramolecular hydrogen bonding between the oxygen atom of one amino acid residue and the hydrogen attached to the nitrogen atom of another amino acid residue

starch storage carbohydrate in plants

steroid type of lipid composed of four fused hydrocarbon rings forming a planar structure

tertiary structure three-dimensional conformation of a protein, including interactions between secondary structural elements; formed from interactions between amino acid side chains

trans fat fat formed artificially by hydrogenating oils, leading to a different arrangement of double bond(s) than those found in naturally occurring lipids

transcription process through which messenger RNA forms on a template of DNA

transfer RNA (tRNA) RNA that carries activated amino acids to the site of protein synthesis on the ribosome

translation process through which RNA directs the formation of protein

triacylglycerol (also, triglyceride) fat molecule; consists of three fatty acids linked to a glycerol molecule

unsaturated fatty acid long-chain hydrocarbon that has one or more double bonds in the hydrocarbon chain

wax lipid made of a long-chain fatty acid that is esterified to a long-chain alcohol; serves as a protective coating on some feathers, aquatic mammal fur, and leaves

CHAPTER SUMMARY

3.1 Synthesis of Biological Macromolecules

Proteins, carbohydrates, nucleic acids, and lipids are the four major classes of biological macromolecules—large molecules necessary for life that are built from smaller organic molecules. Macromolecules are made up of single units known as monomers that are joined by covalent bonds to form larger polymers. The polymer is more than the sum of its parts: it acquires new characteristics, and leads to an osmotic pressure that is much lower than that formed by its ingredients; this is an important advantage in the maintenance of cellular osmotic conditions. A monomer joins with another monomer with the release of a water molecule, leading to the formation of a covalent bond. These types of reactions are known as dehydration or condensation reactions. When polymers are broken down into smaller units (monomers), a molecule of water is used for each bond broken by these reactions; such reactions are known as hydrolysis reactions. Dehydration and hydrolysis reactions are similar for all macromolecules, but each monomer and polymer reaction is specific to its class. Dehydration reactions typically require an investment of energy for new bond formation, while hydrolysis reactions typically release energy by breaking bonds.

3.2 Carbohydrates

Carbohydrates are a group of macromolecules that are a vital energy source for the cell and provide structural support to plant cells, fungi, and all of the arthropods that include lobsters, crabs, shrimp, insects, and spiders. Carbohydrates are classified as monosaccharides, disaccharides, and polysaccharides depending on the number of monomers in the molecule. Monosaccharides are linked by glycosidic bonds that are formed as a result of dehydration reactions, forming disaccharides and polysaccharides with the elimination of a water molecule for each bond formed. Glucose, galactose, and fructose are common monosaccharides, whereas common disaccharides include lactose, maltose, and sucrose. Starch and glycogen, examples of polysaccharides, are the storage forms of glucose in plants and animals, respectively. The long polysaccharide chains may be branched or unbranched. Cellulose is an example of an unbranched polysaccharide, whereas amylopectin, a constituent of starch, is a highly branched molecule. Storage of glucose, in the form of polymers like starch of glycogen, makes it slightly less accessible for metabolism; however, this prevents it from leaking out of the cell or creating a high osmotic pressure that could cause excessive water uptake by the cell.

3.3 Lipids

Lipids are a class of macromolecules that are nonpolar and hydrophobic in nature. Major types include fats and oils, waxes, phospholipids, and steroids. Fats are a stored form of energy and are also known as triacylglycerols or triglycerides. Fats are made up of fatty acids and either glycerol or sphingosine. Fatty acids may be unsaturated or saturated, depending on the presence or absence of double bonds in the hydrocarbon chain. If only single bonds are present, they are known as saturated fatty acids. Unsaturated fatty acids may have one or more double bonds in the hydrocarbon chain. Phospholipids make up the matrix of membranes. They have a glycerol or sphingosine backbone to which two fatty acid chains and a phosphate-containing group are attached. Steroids are another class of lipids. Their basic structure has four fused carbon rings. Cholesterol is a type of steroid and is an important constituent of the plasma membrane, where it helps to maintain the fluid nature of the membrane. It is also the precursor of steroid hormones such as testosterone.

3.4 Proteins

Proteins are a class of macromolecules that perform a diverse range of functions for the cell. They help in metabolism by providing structural support and by acting as enzymes, carriers, or hormones. The building blocks of proteins (monomers) are amino acids. Each amino acid has a central carbon that is linked to an amino group, a carboxyl group, a hydrogen atom, and an R group or side chain. There are 20 commonly occurring amino acids, each of which differs in the R group. Each amino acid is linked to its neighbors by a peptide bond. A long chain of amino acids is known as a polypeptide.

Proteins are organized at four levels: primary, secondary, tertiary, and (optional) quaternary. The primary structure is the unique sequence of amino acids. The local folding of the polypeptide to form structures such as the α helix and β-pleated sheet constitutes the secondary structure. The overall three-dimensional structure is the tertiary structure. When two or more polypeptides combine to form the complete protein structure, the configuration is known as the quaternary structure of a protein. Protein shape and function are intricately linked; any change in shape caused by changes in temperature or pH may lead to protein denaturation and a loss in function.

3.5 Nucleic Acids

Nucleic acids are molecules made up of nucleotides that direct cellular activities such as cell division and protein synthesis. Each nucleotide is made up of a pentose sugar, a nitrogenous base, and a phosphate group. There are two types of nucleic acids: DNA and RNA. DNA carries the genetic blueprint of the cell and is passed on from parents to offspring (in the form of chromosomes). It has a double-helical structure with the two strands running in opposite directions, connected by hydrogen bonds, and complementary to each other. RNA is single-stranded and is made of a pentose sugar (ribose), a nitrogenous base, and a phosphate group. RNA is involved in protein synthesis and its regulation. Messenger

RNA (mRNA) is copied from the DNA, is exported from the nucleus to the cytoplasm, and contains information for the construction of proteins. Ribosomal RNA (rRNA) is a part of the ribosomes at the site of protein synthesis, whereas transfer RNA (tRNA) carries the amino acid to the site of protein synthesis. MicroRNA regulates the use of mRNA for protein synthesis.

REVIEW QUESTIONS

1. Dehydration synthesis leads to the formation of what?

a. monomers
b. polymers
c. carbohydrates only
d. water only

2. What is removed during the formation of nucleic acid polymers?

a. carbon
b. hydroxyl groups
c. phosphates
d. amino acids

3. During the breakdown of polymers, which of the following reactions takes place?

a. condensation
b. covalent bond
c. dehydration
d. hydrolysis

4. Energy is released as a result of which of the following chemical reactions?

a. condensation
b. dehydration synthesis
c. hydrolysis
d. dissolution

5. In the metabolism of cell, why is hydrolysis used?

a. Hydrolysis breaks down polymers.
b. Hydrolysis is used to form linkages in DNA.
c. Hydrolysis is used to produce proteins.
d. Hydrolysis synthesizes new macromolecules.

6. Plant cell walls contain which of the following in abundance?

a. cellulose
b. glycogen
c. lactose
d. starch

7. What makes up the outer layer of some insects?

a. carbohydrate
b. protein
c. RNA
d. triglyceride

8. What is an example of a monosaccharide?

a. cellulose
b. fructose
c. lactose
d. sucrose

9. Cellulose and starch are examples of _________.

a. disaccharides
b. lipids
c. monosaccharides
d. polysaccharides

10. What type of bond joins the molecules in the disaccharide lactose? What molecule is joined with glucose to form lactose?

a. a glycosidic bond between glucose and lactose
b. a glycosidic bond between glucose and galactose
c. a hydrogen bond between glucose and sucrose
d. a hydrogen bond between glucose and fructose

11. What is structurally different about cellulose when compared to starch?

a. an extra hydrogen atom is left on the monomer
b. β-1,4 glycosidic linkages are used
c. α-1,6 glycosidic linkages are used
d. an extra hydroxyl group is removed during synthesis

12. Which of the following are classified as lipids?

a. disaccharides and cellulose
b. essential amino acids
c. mRNA and DNA
d. oils and waxes

13. What is cholesterol specifically classified as?

a. a lipid
b. a phospholipid
c. a steroid
d. a wax

14. Which fat serves as an animal’s major form of energy storage?

a. cholesterol
b. glycerol
c. phospholipid
d. triglycerides

15. Which hormones are made from cholesterol?

a. estradiol and testosterone
b. insulin and growth hormone
c. progesterone and glucagon
d. prolactin and thyroid hormone

16. Which of the following characteristics is not true for saturated fats?

a. They are solid at room temperature.
b. They have single bonds within the carbon chain.
c. They tend to dissolve in water easily.

17. Which fat has the least number of hydrogen atoms?

a. trans fat
b. saturated fat
c. unsaturated fat
d. wax

18. Of what are phospholipids important components?

a. the double bond in hydrocarbon chains
b. the plasma membrane of animal cells
c. the ring structure of steroids
d. the waxy covering on leaves

19. What is a diacylglycerol 3-phosphate?

a. phospholipid
b. phosphatidylcholine
c. phosphatidylserine
d. phosphatidate

20. What is the basic structure of a steroid?

a. four fused hydrocarbon rings
b. glycerol with three fatty acid chains
c. two fatty acid chains and a phosphate group
d. two six carbon rings

21. Besides its use in hormone production, for what does the body use cholesterol?

a. mRNA transport
b. production of bile salts
c. water reabsorption in the kidney
d. wax production

22. Where is cholesterol found in cell membranes?

a. attached to the inner side of the membrane
b. attached to the outer side of the membrane
c. floating in the phospholipid tail layer
d. penetrating both lipid layers

23. Which type of body cell would have a higher amount of cholesterol in its membrane?

a. a cartilage cell
b. a liver cell
c. a red blood cell
d. a spleen cell

24. Which of the following is a function of proteins in cells?

a. energy storage
b. gene storage and access
c. membrane fluidity
d. structure

25. What type of protein facilitates or accelerates chemical reactions?

a. an enzyme
b. a hormone
c. a membrane transport protein
d. a tRNA molecule

26. What type of amino acids would you expect to find on the surface of proteins that must interact closely with water?

27. What are the monomers that make up proteins called?

a. amino acids
b. chaperones
c. disaccharides
d. nucleotides

28. Where is the linkage made that combines two amino acids?

a. between the R group of one amino acid and the R group of the second
b. between the carboxyl group of one amino acid and the amino group of the other
c. between the 6 carbon of both amino acids
d. between the nitrogen atoms of the amino groups in the amino acids

29. The α-helix and the β-pleated sheet are part of which protein structure?

a. the primary structure
b. the secondary structure
c. the tertiary structure
d. the quaternary structure

30. Which structural level of proteins is most often associated with their biological function?

a. the primary structure
b. the secondary structure
c. the tertiary structure
d. the quaternary structure

31. Which of the following may cause a protein to denature?

a. changes in pH
b. high temperatures
c. the addition of some chemicals
d. all of the above

32. What is a protein's chaperone?

a. a chemical that assists the protein in its enzymatic functions
b. a second protein that completes the quaternary structure
c. a chemical that helps the protein fold properly
d. a chemical that functions as a cofactor for the protein

33. What are the building blocks of nucleic acids?

a. nitrogenous bases
b. nucleotides
c. peptides
d. sugars

34. What may a nucleotide of DNA contain?

a. ribose, uracil, and a phosphate group
b. deoxyribose, uracil, and a phosphate group
c. deoxyribose, thymine, and a phosphate group
d. ribose, thymine, and a phosphate group

35. What is DNA's structure described as?

a. a step ladder
b. a double helix
c. a tertiary protein-like structure
d. barber pole

36. What is found in RNA that is not in DNA?

a. deoxyribose and adenine
b. fructose and thymine
c. glucose and quinine
d. ribose and uracil

37. What is the smallest type of RNA?

a. mRNA
b. microRNA
c. rRNA
d. tRNA

38. Where is the largest amount of DNA found in a eukaryotic cell?

a. attached to the inner layer of the cell membrane
b. in the nucleus
c. in the cytoplasm
d. on ribosomes

CRITICAL THINKING QUESTIONS

39. The word hydrolysis is defined as the lysis of water. How does this apply to polymers?

a. Polymers break by separating water into hydrogen and hydroxyl group that are added to the monomers.
b. Polymers are synthesized by using the energy released by the breaking of water molecules into hydrogen and hydroxyl group.
c. Polymers are separated into monomers producing energy and water molecules.
d. Polymers are hydrolyzed into monomers using water in the process and are called as dehydration synthesis.

40. What role do electrons play in dehydration synthesis and hydrolysis?

a. Electrons are added to OH and H ion in the dehydration synthesis. They are removed from OH and H in hydrolysis.
b. Electrons are transferred from OH and H ions to the monomers in dehydration synthesis. They are taken up by the H and OH ions from the monomers in hydrolysis.
c. Electrons are removed from OH and H in the dehydration synthesis. They are added to OH and H in hydrolysis.
d. Electrons are transferred from monomers to H and OH ions in hydrolysis and from OH and H to monomers in dehydration synthesis.

41. Which of the following bodily process would most likely be hindered by a lack of water in the body?

a. digestion
b. protein synthesis
c. copying DNA
d. breathing

42. Why is it impossible for humans to digest food that contains cellulose?

a. There is no energy available in fiber.
b. An inactive form of cellulase in human digestive tract renders it undigested and removes it as waste.
c. The acidic environment in the human stomach makes it impossible to break the bonds in cellulose.
d. Human digestive enzymes cannot break down the β-1,4 glycosidic linkage in cellulose, which requires a special enzyme that is absent in humans.

43. Which of these describe some of the similarities and differences between glycogen and starch?

a. Glycogen is less branched than starch and is found in animals.
b. Glycogen is more highly branched than starch and is found in plants.
c. Starch is less branched than glycogen and is found in plants.
d. Starch is more branched than glycogen and is found in animals.

44. Which of these best describes the production of sucrose, maltose, and lactose?

a. Glucose and fructose combine to form sucrose. Glucose and galactose combine to form lactose. Two glucose monomers combine to form maltose.
b. Glucose and fructose combine to form sucrose. Glucose and galactose combine to form maltose. Two glucose combine to form lactose.
c. Two glucose combine to form lactose. Glucose and galactose combine to form sucrose. Glucose and fructose combine to form maltose.
d. Two galactose combine to form sucrose. Fructose and glucose combine to form lactose. Two glucose combine to form maltose.

45. What are the four classes of lipids and what is an example of each?

a. 1. lipids like margarine
   2. wax like the coating on feathers
   3. phospholipids like cell membrane constituents
   4. steroid like cholesterol
b. 1. lipids like phosphatidylserine
   2. wax like phosphatidic acid
   3. phospholipids like oleic acid
   4. steroid like epinephrine
c. 1. lipids like phosphatidic acid
   2. waxes like margarine
   3. phospholipids like phosphatidylcholine
   4. steroids like testosterone
d. 1. lipids like cholesterol
   2. waxes like the coating on feathers
   3. phospholipids like phosphatidylserine
   4. steroids like margarine

46. What are three functions that lipids serve in plants and/ or animals?

a. Lipids serve in the storage of energy, as a structural component of hormones, and also as signaling molecules.
b. Lipids serve in the storage of energy, as carriers for the transport of proteins across the membrane, and as signaling molecules.
c. Lipids serve in the breakdown of stored energy molecules, as signaling molecules, and as structural components of hormones.
d. Lipids serve in the breakdown of stored energy molecules, as signaling molecules, and as channels for protein transport.

47. Why have trans fats been banned from some restaurants? How are they created?

a. Trans fat is produced by the hydrogenation of oil that makes it more saturated and isomerized. It increases LDL amounts.
b. The dehydrogenation of oil forms the trans fat, which contains single bonds in its structure. This increases HDL in the body and has been banned.
c. Trans fat is produced by dehydrogenation of oils, which makes it unsaturated. It increases LDL in body.
d. The hydrogenation of oil makes the trans fat, which contains double bonds in its structure. It decreases HDL in the body.

48. How do phospholipids contribute to cell membrane structure?

a. Phospholipids orient their heads towards the polar molecules and tails in the interior of the membrane, thus forming a bilayer.
b. Phospholipids orient their tails towards the polar molecules of water solutions, and heads in the interior of the membrane, thus forming a bilayer.
c. Phospholipids orient their heads towards the non-polar molecules and tails in the interior of the membrane, forming a bilayer.
d. Phospholipids orient their tails towards the polar molecules and heads in the non-polar side of the membrane, forming a bilayer.

49. What type of compound functions in hormone production, contributes to membrane flexibility, and is the starting molecule for bile salts?

a. All steroid molecules help in the mentioned functions.
b. Cholesterol, which is a lipid and also a steroid, functions here.
c. Glycogen, which is a multi-branched polysaccharide of glucose, is the compound.
d. Phosphatidylcholine that is a phospholipid with a choline head group, which serves the functions.

50. What part of cell membranes gives flexibility to the structure?

a. carbohydrates
b. cytoskeleton filaments
c. lipids
d. proteins

51. How do the differences in amino acid sequences lead to different protein functions?

a. Different amino acids produce different proteins based on the bonds formed between them.
b. Differences in amino acids lead to the recycling of proteins, which produces other functional proteins.
c. Different amino acids cause rearrangements of amino acids to produce a functional protein.
d. Differences in the amino acids cause post-translational modification of the protein, which reassembles to produce a functional protein.

52. What causes the changes in protein structure through the three or four levels of structure?

a. The primary chain forms secondary α-helix and β-pleated sheets which fold onto each other forming the tertiary structure.
b. The primary structure undergoes alternative splicing to form secondary structures, which fold on other protein chains to form tertiary structures.
c. The primary structure forms secondary α-helix and β-pleated sheets. This further undergoes phosphorylation and acetylation to form the tertiary structure.
d. The primary structure undergoes alternative splicing to form a secondary structure, and then disulfide bonds give way to tertiary structures.

53. What structural level of proteins is functional? Why?

a. The secondary structure is functional as it attains its 2-dimensional shape which has the necessary bonds.
b. The tertiary structure is functional as it possesses the geometric shape showing the necessary loops and bends.
c. The tertiary structure is functional as it has the non-covalent and covalent bonds along with the subunits attached at the right places, which help it function properly.
d. Quaternary structure is functional as it has the essential set of subunits.

54. How does a chaperone work with proteins?

a. Chaperones assist proteins in folding.
b. Chaperones cause the aggregation of polypeptides.
c. Chaperones associate with proteins once the target protein is folded.
d. Chaperones escort proteins during translation.

55. What are some differences between DNA and RNA?

a. DNA is made from nucleotides; RNA is not.
b. DNA contains deoxyribose and thymine, while RNA contains ribose and uracil.
c. DNA contains adenine, while RNA contains guanine.
d. DNA is double stranded, while RNA may be double stranded in animals.

56. Which molecule carries information in a form that is inherited from one generation to another?

a. Hereditary information is stored in DNA.
b. Hereditary information is stored in mRNA.
c. Hereditary information is stored in proteins.
d. Hereditary information is stored in tRNA.

57. What are the four types and functions of RNA?

a. mRNA is a single stranded transcript of DNA. rRNA is found in ribosomes. tRNA transfers specific amino acids to a developing protein strand. miRNA regulates the expression of mRNA strands.
b. mRNA is a single stranded transcript of rRNA. rRNA is translated in ribosomes to make proteins. tRNA transfers specific amino acids to a developing protein strand. microRNA (miRNA) regulates the expression of the mRNA strand.
c. mRNA regulates the expression of the miRNA strand. rRNA are found in ribosomes. tRNA transfers specific amino acids to a developing protein strand. miRNA is a single stranded transcript of DNA.
d. mRNA is a single stranded transcript of DNA. rRNA transfers specific amino acids to a developing protein strand. tRNA is found in ribosomes. miRNA regulates the expression of the mRNA strand.

TEST PREP FOR AP® COURSES

58. Urey and Miller constructed an experiment to illustrate the early atmosphere of the Earth and possible development of organic molecules in the absence of living cells. Which assumption did Urey and Miller make regarding conditions on Earth?

a. electric sparks occurred to catalyze the reaction
b. the composition of the gases in the atmosphere
c. there was sufficient oxygen for creating life
d. it produced water-soluble organic molecules

59. Urey and Miller proposed that a series of reactions occurred, which ultimately resulted in amino acid formation. Which of the following is true based upon their theory?

a. Hydrogen and nitrogen combined to create amino acids.
b. Hydrogen and oxygen combined to create macromolecules.
c. Nitrogenous bases combined to form monomers then RNA.
d. Periodic elements combined to create molecules then DNA.

60. How does Stanley Miller and Harold Urey’s model support the claim that simple precursors present on early Earth could have assembled into complex molecules necessary for life?

a. The simple molecules assembled to form amino acids and nucleic acids.
b. The organic molecules assembled to form the large complexes such as water and methane.
c. The inorganic molecules assembled to form the amino acids and nucleic acids.
d. The inorganic molecules assembled to form the large complexes such as water and methane.

61. Which statement most accurately describes the importance of the condensation stage during Urey and Miller’s experiment?

a. Condensed water enabled the formation of monomers.
b. Condensation and evaporation simulated lightning storms.
c. Condensation and evaporation simulated the water cycle.
d. Condensed water enabled the formation of polymers.

62. According to the findings of the Urey and Miller experiment, the primitive atmosphere consisted of water in the form of steam, methane, ammonia, and hydrogen gases. If there was so much hydrogen gas in the early atmosphere, why is there so little now?

a. Hydrogen gas is so light with a molecular weight of 1 that the excess diffused into space over time and is now absent from the atmosphere.

b. Hydrogen combined with ammonia to make ammonium.

c. It was all used up in the production of organic molecules.

d. The excess hydrogen gas was dissolved in the early oceans.

63. Could the primitive atmosphere illustrated by the Urey and Miller experiment be reproduced on today's Earth? Why or why not?

a. The primitive atmosphere cannot be created due to the oxidizing atmosphere and lack of hydrogen.

b. The primitive atmosphere can be created as the atmosphere is reducing and the Earth has sufficient hydrogen to reproduce the conditions.

c. The primitive atmosphere cannot be created due to the presence of abundant water and hydrogen in the atmosphere.

d. The primitive atmosphere can be created as the atmosphere is oxidizing and has less of hydrogen.

64. What is structurally different between starch and cellulose that gives them different physical properties?

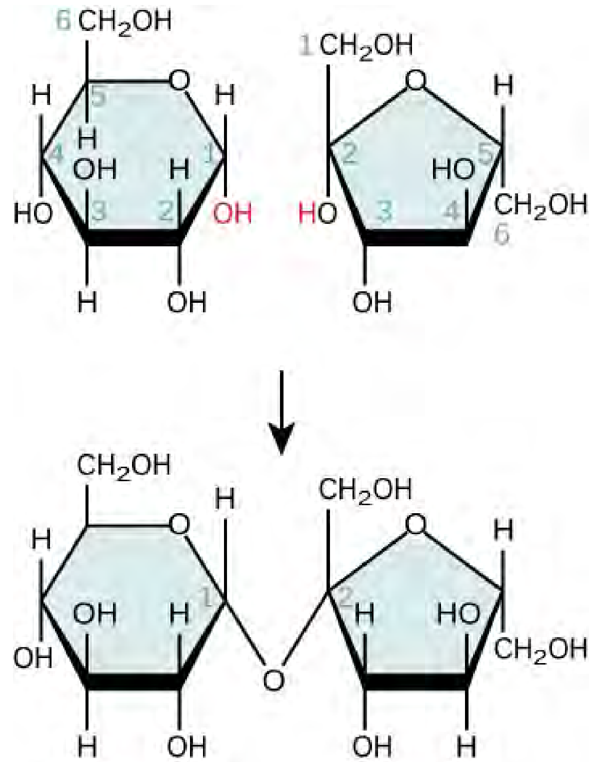
a. Cellulose is formed by β-1,4 glycosidic linkages and crosslinks, making it rigid. Starch has α-1.4 and α-1.6 glycosidic linkages without the tight crosslinks of cellulose.

b. Cellulose has rigid α-1,4 glycosidic linkages while starch has less rigid β-1,4 glycosidic linkages

c. Cellulose has amylose and amylopectin, making it more rigid than starch.

d. Starch has amylose and amylopectin that make it more rigid than cellulose.

65.



Complex polymers are built from combinations of smaller monomers. What type of reaction is shown, and what is a product of the following reaction? Assume water is also produced.

a. a synthesis reaction producing glucose and water

b. a hydrolysis reaction producing fructose and water

c. a condensation reaction producing lactose and water

d. a dehydration reaction producing sucrose and water

66. The fatty acids of triglycerides are classified as saturated, unsaturated, or trans fats. What is it about the structure of these compounds that gives them their physical characteristics?

a. Saturated fats and trans fats contain the greatest possible number of hydrogen atoms, while unsaturated fats do not.

b. Saturated and unsaturated fats have stable configurations, while trans fats are transient.

c. Unsaturated fats and trans fats have some double bonded carbon atoms, while saturated fats do not.

d. Unsaturated and trans fats are the same; the fatty acids are just found on opposite sides of a trans fat.

67. Carbohydrates serve various functions in different animals. Arthropods like insects, crustaceans, and others, have an outer layer, called the exoskeleton, which protects their internal body parts. This exoskeleton is made mostly of chitin. Chitin is also a major component of the cell walls of fungi, the kingdom that includes molds and mushrooms. Chitin is a polysaccharide. What is the major difference between chitin and other types of polysaccharides?

a. Chitin is a nitrogen-containing polysaccharide, with repeating units of N-acetyl- β -D-glucosamine, a modified sugar.

b. Chitin is similar to amylase, but with sulfur linkages between the monomers.

c. Chitin is similar to inulin, a polysaccharide with fructose, but with additional glucose monomers.

d. Chitin contains phosphate groups that give it a stiffness not found in other polysaccharides.

68. What categories of amino acids would you expect to find on the surface of a soluble protein and which would you expect to find in the interior? Which of these are some examples for each part of the answer?

a. Non-polar and charged amino acids will be present on the surface and polar in the interior of the membrane whereas non-polar will be found in the membrane embedded proteins.

b. Non-polar and uncharged proteins will be found on the surface with non-polar in the interior, while only non-polar will be found in the embedded proteins.

c. Polar and charged amino acids will be found on the surface whereas non-polar in the interior.

d. Polar and charged amino acids will be found on the surface of a membrane protein whereas non-polar in the interior. The membrane protein will be polar and hydrophobic.

69. You have been identifying the sequence of a segment of a protein. The sequence to date is: leucine-methionine-tyrosine-alanine-glutamine-lysine-glutamate. You insert arginine between the leucine and methionine. What effect would this have on the segment?

a. Arginine is a negatively charged amino acid and could attach to the glutamate at the end of the segment

b. Inserting arginine places a positively charged amino acid in a portion that is non-polar, creating the possibility of a hydrogen bond in this area.

c. There would be no effect other than an additional amino acid.

d. The arginine could attach to the lysine and bend the protein chain at this point.

70. What would happen if even one amino acid is substituted for another in a polypeptide? What would be an example?

a. The change will definitely not be sufficient to have any effect on the function and structure of the protein.

b. The amino acid may not show any significant effect the protein structure and function or it may have a significant effect, as in the case of hemoglobin in individuals with sickle cell trait.

c. These changes would increase the possibility of having extra bends and loops in the proteins as in Leber congenital disease.

d. These changes would modify the structures of proteins making them nonfunctional.

71. HIV is an RNA virus that affects CD4 cells, also known as T cells, in the human body. Which mechanism is most likely responsible for the fast rate at which HIV can spread?

a. recombination

b. mutation

c. reassortment

d. formation errors

72. For many years, scientist believed that proteins were the source of heritable information. There are many thousands of different proteins in a cell, and they mediate the cell's metabolism, producing the traits and characteristics of a species. Researchers working with DNA viruses proved that it is DNA that stores and passes on genes. They worked with viruses with an outer coat of protein and a DNA strand inside. How did they prove that it was DNA, not protein, which is the primary source of heritable information?

a. The DNA and protein of the virus were tagged with different isotopes and exposed to host cell where only the DNA was transferred to the host.

b. The DNA was tagged with an isotope, which was retained in the virus, proving it to be the genetic material.

c. The viral protein was tagged with an isotope, and the host cell was infected by it. This protein was transferred to the host.

d. The viral DNA, when sequenced, was found to be present in the host cell proving it to be the hereditary material instead of protein.

73. The genetic code is based on each amino acid being coded for by a distinctive series of three nucleic acid bases called a codon. The following is a short segment of DNA using the slash symbol (/) to separate the codons for easy viewing: ATC/GTT/GAA/CTG/TAG/GAT/AAA

A change has occurred in the segment resulting in the following:

ATC/GTT/GTA/CTG/TAG/GAT/AAA

What kind of change has occurred?

a. A substitution of T for A , changing the coding for the third codon
b. An addition of C for G , lengthening the strand and changing every codon past the addition
c. A deletion of an A , resulting in a shortening and changing every codon past the deletion
d. No change has occurred; the same one base was replaced with the same one

74. A change in DNA on a chromosome affects all proteins made from that gene for the life of the cell. A change in the RNA involved in protein production is short lived. What is the difference between the effects of the changes in the two types of nucleic acids?

a. DNA is the genetic material that is passed from parent cells to daughter cells and to future generations.
b. DNA would not affect the individuals as the proteins made are finally altered and modified. RNA would cause harm to the person as the RNA is encoded by the DNA and is not altered.
c. DNA is the genetic material and is transferred from one generation to another making use of repair mechanisms for every mutation. The RNA does not use a repair mechanism.
d. DNA, when mutated, makes use of the repair mechanisms and can be repaired whereas RNA is not repaired and is transferred in generations.

SCIENCE PRACTICE CHALLENGE QUESTIONS

75. The capture of radiant energy through the conversion of carbon dioxide and water into carbohydrates is the engine that drives life on Earth. Ribose, $C_5H_{10}O_5$, and hexose, $C_6H_{12}O_6$, form stable five- and six-carbon rings.

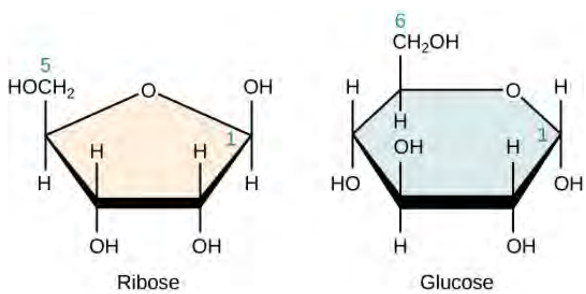


Figure 3.37

The numbering of the carbons on these rings is important in organizing our description of the role these molecules play in biological energy transfer and information storage and retrieval. Glycolysis is a sequence of chemical reactions that convert glucose to two three-carbon compounds called pyruvic acid.

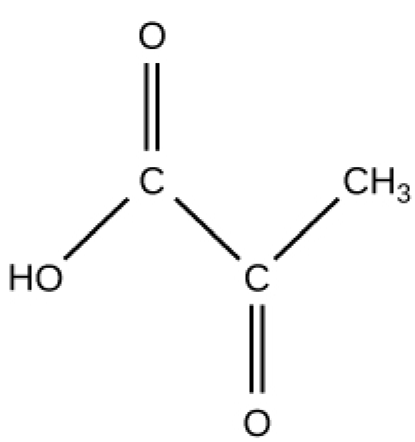


Figure 3.38

A. **Create visual representations** to show how when bonds in the glucose molecules are broken between carbon number 1 and the oxygen atom and between carbons 3 and 4, two molecules of pyruvic acid are produced.

Several enzymes in the cell are involved in converting glucose to pyruvic acid. These enzymes are proteins whose amino acid sequences provide these functions. This protein structure is information that was inherited from the cell's parent, and is stored in deoxyribonucleic acid (DNA). The "deoxyribo" component of that name is a shorthand for 2-deoxyribose.

B. **Create a visual representation** of 2-deoxyribose, 5-phosphate by replacing the OH at carbon 2 with a hydrogen atom and replacing the OH at carbon 5 with a hydrogen phosphate ion, HPO_3^{-2}, whose structure is shown in problem AP3.2. Use your representation to show that both phosphorylation (the addition of a phosphate ion) at carbon 5 and removal of the hydroxide at carbon 2 produce water molecules in an aqueous solution where hydrogen ions are abundant.

DNA is a polymer formed from a chain with repeated 2-deoxyribose, 5-phosphate molecules.

C. **Create a visual representation** of three 2-deoxyribose, 5-phosphate molecules forming a chain in which an oxygen atom in the phosphate that is attached to the 5-carbon replaces the OH on the 3-carbon of the next ribose sugar.

76. Cells are bounded by membranes composed of phospholipids. A phospholipid consists of a pair of fatty acids that may or may not have carbon-carbon double bonds, fused at the carboxylic acid with a three-carbon glycerol that is terminated by a phosphate, as shown in the figure below. Most cell membranes comprise two phospholipid layers with the hydrophilic phosphate ends of each molecule in the outer and inner surfaces. The hydrophobic chains of carbon atoms extend into the space between these two surfaces.

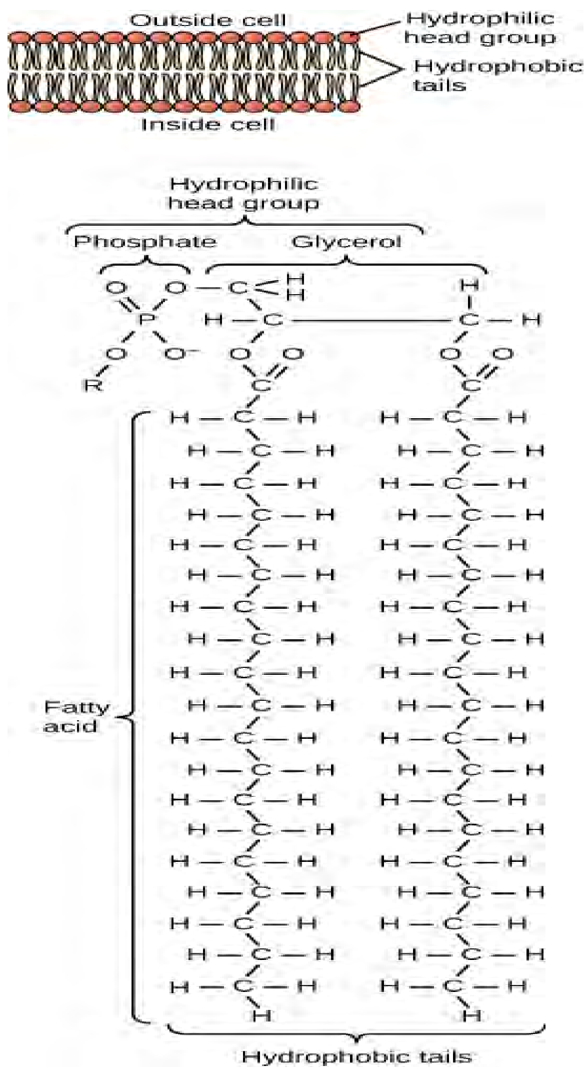


Figure 3.39

The exchange of matter between the interior of the cell and the environment is mediated by this membrane with selective permeability.

A. **Pose questions** that identify

- the important characteristics of this lipid bilayer structure
- the molecules that must be acquired from the environment and eliminated from the cell
- relationships between the structures of these molecules and the structure of the bilayer

Because the plasma cell membrane has both hydrophilic and hydrophobic properties, few types of molecules possess structures that allow them to pass between the interior of the cell and the environment through passive diffusion. The fluidity of the membrane affects passive transport, and the incorporation of other molecules in the membrane, in particular cholesterols, has a strong effect on its fluidity. Fluidity is also affected by temperature.

Measurements of the speed of movement of oxygen molecules, O_2, through three types of membranes were made (Widomska et al., *Biochimica et Biophysica Acta*, 1,768, 2007) and compared with the speed of movement of O_2 through water. These measurements were carried out at four different temperatures. One type of membrane was obtained from the cells in the eyeball of a calf (lens lipid). Synthetic membranes composed of palmitic acid with cholesterol (POPC/CHOL) and without cholesterol (POPC) were also used. The results from these experiments are shown in the table below.

	Temperature (°C)			
	15	25	35	45
Material	Speed (cm/s)			
Lens lipids	15	30	65	110
POPC/CHOL	15	30	60	95
POPC	55	100	155	280
Water	45	55	65	75

Table 3.3

B. **Represent** these **data graphically**. The axes should be labeled, and different symbols should be used to plot data for each material.

C. **Analyze** the data by comparing transport of oxygen through the biological membrane, water, and the synthetic membranes. Consider both membrane composition and temperature in your analysis.

The plasma membrane separates the interior and the exterior of the cell. A potential to do work is established by defining regions inside and outside the cell with different concentrations of key molecules and net charge. In addition to the membrane defining the cell boundary, eukaryotic cells have internal membranes.

D. **Explain** how internal membranes significantly increase the functional capacity of the cells of eukaryotes relative to those of prokaryotes.

77. Proteins are polymers whose sub-components are amino acids connected by peptide bonds. The carboxylic acid carbon, O = C – OH, of one amino acid can form a bond with the amine, NH_2, of another amino acid. In the formation of this peptide bond, the amine replaces the OH to form O = C – NH_2. The other product of this reaction is water, H_2O.

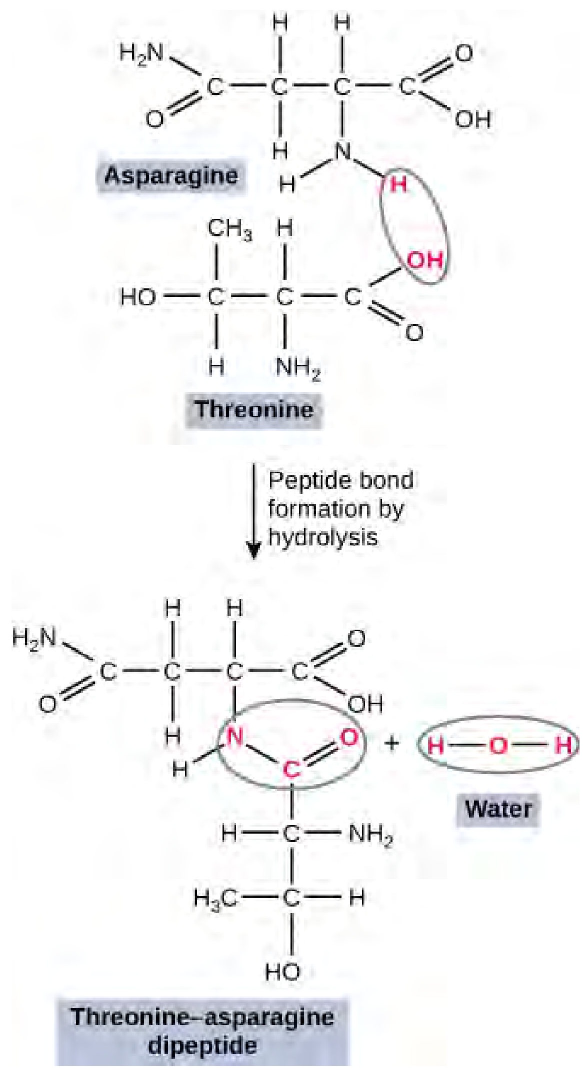


Figure 3.40

Amino acids can be synthesized in the laboratory from simpler molecules of ammonia (NH_3), water (H_2O), methane (CH_4), and hydrogen (H_2) if energy is provided by processes that simulate lightning strikes or volcanic eruptions (Miller, *Science*, 117, 1953; Johnson et al., *Science*, 322, 2008).

A. The synthesis of amino acids in solutions under laboratory conditions consistent with early Earth was a step toward an explanation of how life began. **Pose a question** that should have been asked but was not until 2014 (Parker et al., *Angewandte Chemie*, 53, 2014), when these solutions that had been stored in a refrigerator were analyzed.

The diversity and complexity of life begins in the variety of sequences of the 20 common amino acids.

B. Apply mathematical reasoning to **explain** the source of biocomplexity by calculating the possible variations in a polymer composed of just three amino acids.

Polarity in a bond between atoms occurs when electrons are distributed unequally. Polarity in a molecule also is caused by charge asymmetry. Life on Earth has evolved within a framework of water, H_2O, one of the most polar molecules. The polarities of the amino acids that compose a protein determine the properties of the polymer.

The electric polarity of an amino acid in an aqueous solution depends on the pH of the solution. Here are three forms of the general structure of an amino acid.

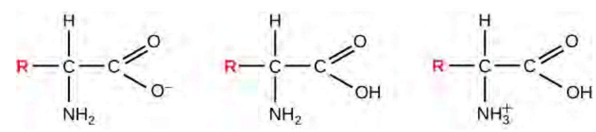


Figure 3.41

C. Qualitatively **predict** the relationship between solution pH and the form of the amino acid for three solutions of pH: pH < 7, pH = 7, and pH > 7.

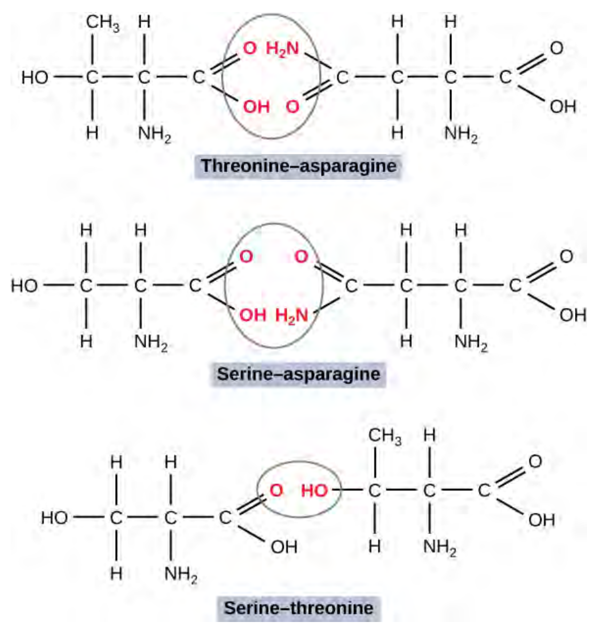


Figure 3.42

The properties of proteins are determined by interactions among the amino acids in the peptide-bonded chain. The protein subcomponents, especially amino R (variable) groups, can interact with very strong charge-charge forces, with attractive forces between groups of atoms with opposite polarities and with repulsive forces between groups of atoms with the same or no polarity. Attractive polar forces often arise between molecules through interactions between oxygen and hydrogen atoms or between nitrogen and hydrogen atoms.

D. Consider particular orientations of pairs of three different amino acids. **Predict** the relative strength of attractive interaction of all pairs; rank them and provide your reasoning.

In an amino acid, the atoms attached to the α carbon are called the R group.

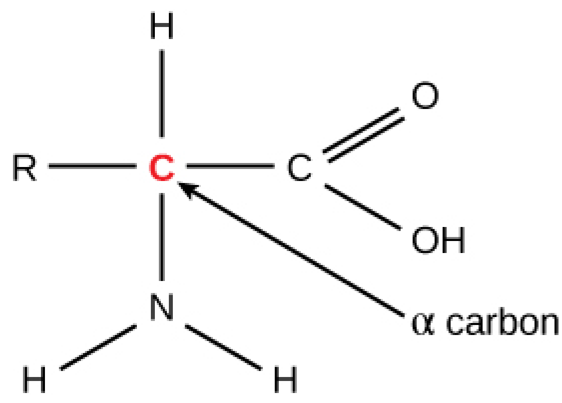


Figure 3.43

Interactions between R groups of a polypeptide give three-dimensional structure to the one-dimensional, linear sequence of amino acids in a polypeptide.

E. **Construct an explanation** for the effect of R-group interactions on the properties of a polymer with drawings showing molecular orientations with stronger and weaker polar forces between R groups on asparagine and threonine and between asparagine and alanine.

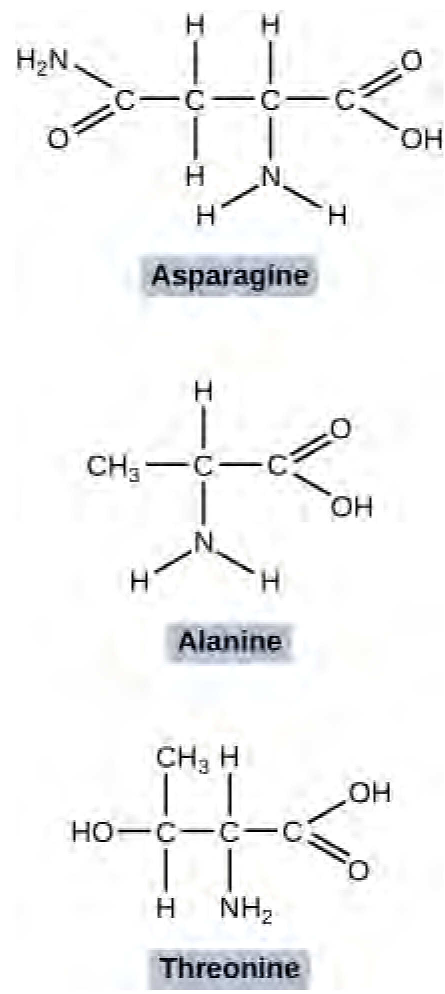


Figure 3.44

78. The nucleobase part of deoxyribonucleic acid encodes information in each component in the sequence making up the polymer. There are five nucleobases that are commonly represented by only a single letter: A (adenine), C (cytosine), G (guanine), T (thymine), and U (uracil). These molecules form a bond with the 1-carbon of deoxyribose. In this problem, we need to look at the molecules in slightly more detail so that you can development the ability to explain why DNA, and sometimes RNA, is the primary source of heritable information.

Edwin Chargaff and his team isolated nucleobases from salmon sperm and determined the fraction of each (Chargaff et al., *Journal of Biological Chemistry*, 192, 1951). Experiments in which the fraction of all four nucleobases was determined are shown. Also shown are averages as two standard deviations and the sum of total fractions for each experiment. Precision is calculated with each average.

Shown below are the chemical structures of these four nucleobases. In these structures, the nitrogen that attaches to the 2-deoxyribose, 5-phosphate polymer is indicated as N*. The partial charges of particular atoms are indicated with δ^+ and δ^-.

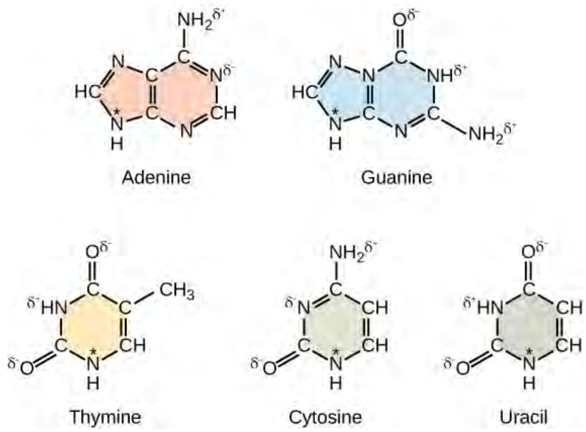


Figure 3.45

A. **Analyze** Chargaff's data in terms of the partial charges on these molecules to show how molecular interactions affect the function of these molecules in the storage and retrieval of biological information.

Experiment	Adenine	Guanine	Cytosine	Thymine	Total
5	0.28	0.20	0.21	0.27	0.96
6	0.30	0.22	0.20	0.29	1.01
7	0.27	0.18	0.19	0.25	0.89
8	0.28	0.21	0.20	0.27	0.96
11	0.29	0.18	0.20	0.27	0.94
12	0.28	0.21	0.19	0.26	0.94
13	0.30	0.21	0.20	0.30	1.01
	0.29±0.02	0.20±0.03	0.20±0.01	0.27±0.02	0.96±0.08

Figure 3.46

The interactions between nucleobase molecules are strong enough to produce the association of pairs observed in Chargaff's data. However, these pairs are bonded by much weaker hydrogen bonds, chemical bonds within the molecules.

Demonstrating an understanding of the replication of DNA requires the ability to explain how the two polymer strands of the double helix interact and grow. To retrieve information from DNA, the strands must be separated. The proteins that perform that task interact with the polymer without forming new chemical bonds. In their paper (Watson and Crick, *Nature*, 3, 1953) announcing the structure of the polymer that we consider in this problem, Watson and Crick stated, "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material."

Eschenmoser and Lowenthal (*Chemical Society Reviews*, 21, 1992) asked why the 5-carbon sugar ribose is used in DNA when the 6-carbon sugar glucose is so common in biological systems. To answer the question, they synthesized polymeric chains with this alternative form of sugar. They discovered that the strength of the interaction between pairs of nucleobases increased in the new material. Paired strands of hexose-based polymers were more stable.

The AP Biology Curriculum Framework (College Board, 2012) states, "The double-stranded structure of DNA provides a simple and elegant solution for the transmission of heritable information to the next generation; by using each strand as a template, existing information can be preserved and duplicated with high fidelity within the replication process. However, the process of replication is imperfect…."

B. **Explain** why the weaker interaction observed by Eschenmoser and Lowenthal, and the acknowledgement in the Framework that "replication is imperfect," support the claim implied by Watson and Crick that DNA is the source of heritable information.