Chapter 3: Molecules of Life Chapter Contents
Book Title: Biology
Printed By: Dina DiSantis (ddisantis@dasd.org)

Chapter 3

Molecules of Life

Chapter 3: Molecules of Life Chapter Introduction

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Chapter Introduction

Rice has been cultivated for thousands of years. Carbohydrate-packed seeds make this grain the most important food source for humans worldwide.

Photograph by Alex Treadway, National Geographic Creative.

Links to Earlier Concepts

Having learned about atomic interactions (Section 2.3), you are now in a position to understand the structure of the molecules of life. Keep the big picture in mind by reviewing Section 1.1. You will be building on your knowledge of covalent bonding (2.3), acids and bases (2.5), and the effects of hydrogen bonds (2.4).

Key Concepts

Structure Dictates Function

Complex carbohydrates and lipids, proteins, and nucleic acids are assembled from simpler molecules. Functional groups add chemical character to a backbone of carbon atoms.

Carbohydrates

Cells use carbohydrates as structural materials, for fuel, and to store and transport energy. They can build different complex carbohydrates from the same simple sugars.

Lipids

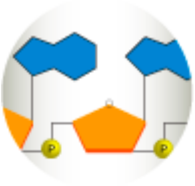
Lipids are the main structural component of all cell membranes. Cells use them to make other compounds, to store energy, and as waterproofing or lubricating substances.

Proteins

Proteins are the most diverse molecules of life. They include enzymes and structural materials. A protein's function arises from and depends on its structure.

Nucleic Acids

Nucleotides are building blocks of nucleic acids; some have additional roles in metabolism. DNA stores a cell's heritable information. RNA helps put that information to use.



Chapter 3: Molecules of Life: 3.1 What are the Molecules of Life?
Book Title: Biology
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3.1 What are the Molecules of Life?

The Stuff of Life: Carbon

The same elements that make up a living body also occur in nonliving things, but their proportions differ. For example, compared to sand or seawater, a human body contains a much larger proportion of carbon atoms. Why? Unlike sand or seawater, a body consists of a very high proportion of the molecules of life—complex carbohydrates and lipids, proteins, and nucleic acids—which in turn consist of a high proportion of carbon atoms. Molecules that have primarily hydrogen and carbon atoms are said to be **organic** (Describes a molecule that consists mainly of carbon and hydrogen atoms.) . The term is a holdover from a time when these molecules were thought to be made only by living things, as opposed to the "inorganic" molecules that formed by nonliving processes.

Carbon's importance to life arises from its versatile bonding behavior. Carbon has four vacancies (Section 2.2), so it can form four covalent bonds with other atoms, including other carbon atoms. Many organic molecules have a backbone—a chain of carbon atoms—to which other atoms attach. The ends of a backbone may join to form a carbon ring structure (Figure 3.1). Carbon's ability to form chains and rings, and also to bond with many other elements, means that atoms of this element can be assembled into a wide variety of organic compounds.

Figure 3.1

Carbon rings.

A Carbon's versatile bond-

B Carbon rings form the

ing behavior allows it to form a variety of structures, including rings.

framework of many sugars, starches, and fats (such as those found in doughnuts).

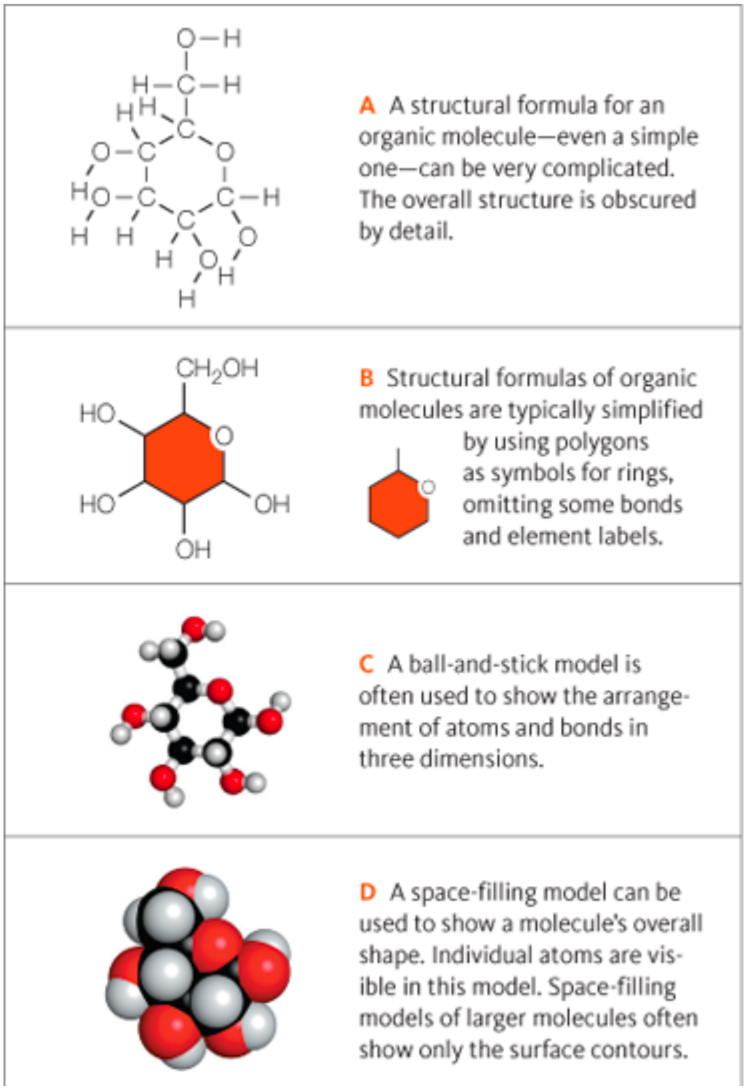
(1A) From Starr/Evers/Starr, Biology Today and Tomorrow with Physiology, 4E. © 2013 Cengage Learning; (1B) © JupiterImages/Getty Images

We represent organic molecules in several ways. The structure of many organic molecules is quite complex (Figure 3.2A). For clarity, we may omit some of the bonds in a structural formula. Hydrogen atoms bonded to a carbon backbone may also be omitted. Carbon rings are often represented as polygons (Figure 3.2B). If no atom is shown at a corner or at the end of a bond, a carbon is implied there. Ball-and-stick models are useful for representing smaller organic compounds (Figure 3.2C). Space-filling models show a molecule's overall shape (Figure 3.2D). Proteins and nucleic acids are often represented as ribbon structures, which, as you will see in Section 3.4, show how the backbone folds and twists.

Figure 3.2

Modeling an organic molecule.

All of these models represent the same molecule: glucose.



A A structural formula for an organic molecule—even a simple one—can be very complicated. The overall structure is obscured by detail.

B Structural formulas of organic molecules are typically simplified by using polygons as symbols for rings, omitting some bonds and element labels.

C A ball-and-stick model is often used to show the arrangement of atoms and bonds in three dimensions.

D A space-filling model can be used to show a molecule's overall shape. Individual atoms are visible in this model. Space-filling models of larger molecules often show only the surface contours.

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Chapter 3: Molecules of Life From Structure to Function
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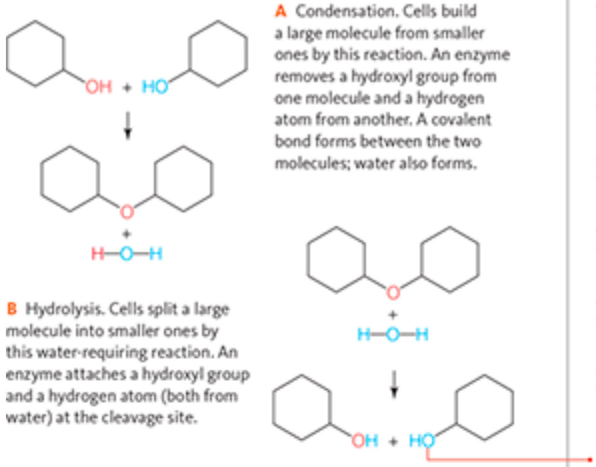
From Structure to Function

An organic molecule that consists only of hydrogen and carbon atoms is called a **hydrocarbon** (Compound or region of one that consists only of carbon and hydrogen atoms.) . Hydrocarbons are generally nonpolar. Methane, the simplest kind, is one carbon atom bonded to four hydrogen atoms. Other organic molecules, including the molecules of life, have at least one functional group. A **functional group** (An atom (other than hydrogen) or a small molecular group bonded to a carbon of an organic compound; imparts a specific chemical property.) is an atom (other than hydrogen) or small molecular group covalently bonded to a carbon atom of an organic compound. These groups impart chemical properties such as acidity or polarity (Table 3.1). The chemical behavior of the molecules of life arises mainly from the number, kind, and arrangement of their functional groups.

Figure 3.3

Two common metabolic processes by which cells build and break down organic molecules.



A Condensation. Cells build a large molecule from smaller ones by this reaction. An enzyme removes a hydroxyl group from one molecule and a hydrogen atom from another. A covalent bond forms between the two molecules; water also forms.

B Hydrolysis. Cells split a large molecule into smaller ones by this water-requiring reaction. An enzyme attaches a hydroxyl group and a hydrogen atom (both from water) at the cleavage site.

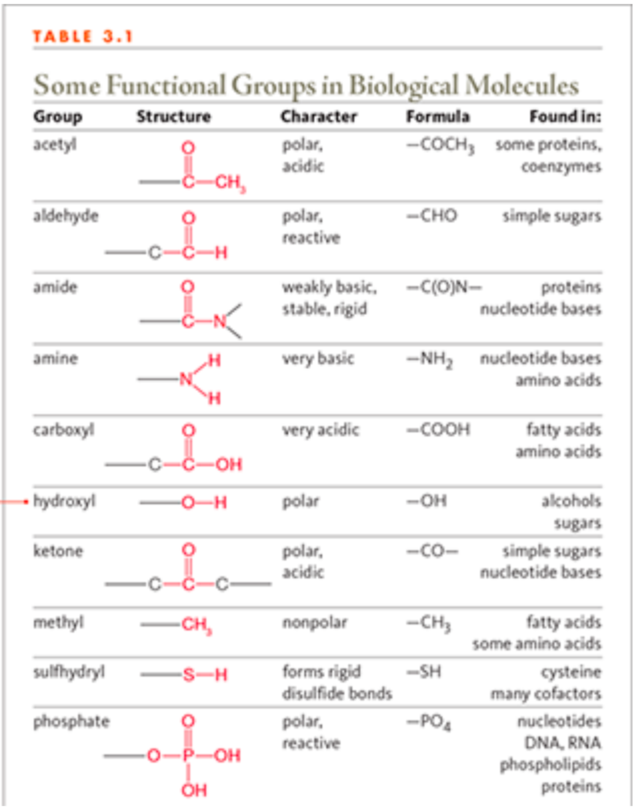


TABLE 3.1

Some Functional Groups in Biological Molecules

Group	Structure	Character	Formula	Found in:
acetyl	$-\overset{O}{\overset{\|}{C}}-CH_3$	polar, acidic	$-COCH_3$	some proteins, coenzymes
aldehyde	$-C-\overset{O}{\overset{\|}{C}}-H$	polar, reactive	$-CHO$	simple sugars
amide	$-\overset{O}{\overset{\|}{C}}-N<$	weakly basic, stable, rigid	$-C(O)N-$	proteins nucleotide bases
amine	$-N\begin{smallmatrix}H\\H\end{smallmatrix}$	very basic	$-NH_2$	nucleotide bases amino acids
carboxyl	$-C-\overset{O}{\overset{\|}{C}}-OH$	very acidic	$-COOH$	fatty acids amino acids
hydroxyl	$-O-H$	polar	$-OH$	alcohols sugars
ketone	$-C-\overset{O}{\overset{\|}{C}}-C-$	polar, acidic	$-CO-$	simple sugars nucleotide bases
methyl	$-CH_3$	nonpolar	$-CH_3$	fatty acids some amino acids
sulfhydryl	$-S-H$	forms rigid disulfide bonds	$-SH$	cysteine many cofactors
phosphate	$-O-\underset{OH}{\underset{\|}{\overset{O}{\overset{\|}{P}}}}-OH$	polar, reactive	$-PO_4$	nucleotides DNA, RNA phospholipids proteins

(3) From Starr/Taggart/Evers/Starr, Biology, 12E. © 2009 Cengage Learning. (Table 3.1) © Cengage Learning.

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All biological systems are based on the same organic molecules, a similarity that is one of many legacies of life's common origin. However, the details of those molecules differ among organisms. Just as atoms bonded in different numbers and arrangements form different molecules, simple organic building blocks bonded in different numbers and arrangements form different versions of the molecules of life. These small organic molecules—simple sugars, fatty acids, amino acids, and nucleotides—are called **monomers** (Molecules that are subunits of polymers.) when they are used as subunits of larger molecules. Molecules that consist of multiple monomers are called **polymers** (Molecule that consists of multiple monomers.) .

Cells build polymers from monomers, and break down polymers to release monomers. These and any other processes of molecular change are called chemical **reactions** (Process of molecular change.) . Cells constantly run reactions as they acquire and use energy to stay alive, grow, and reproduce—activities that are collectively called **metabolism** (All of the enzyme-mediated chemical reactions by which cells acquire and use energy as they build and break down organic molecules.) . Metabolism requires **enzymes** (Organic molecule that speeds up a reaction without being changed by it.) , which are organic molecules (usually proteins) that speed up reactions without being changed by them.

In many metabolic reactions, large organic molecules are assembled from smaller ones. With **condensation** (Chemical reaction in which an enzyme builds a large molecule from smaller subunits; water also forms.) , an enzyme covalently bonds two molecules together. Water (H—O—H) usually forms as a product of condensation when a hydroxyl group (—OH) from one of the molecules combines with a hydrogen atom (—H) from the other molecule (Figure 3.3A). With **hydrolysis** (Water-requiring chemical reaction in which an enzyme breaks a molecule into smaller subunits.) , the reverse of condensation, an enzyme breaks apart a large organic molecule into smaller ones. During hydrolysis, a bond between two atoms breaks when a hydroxyl group gets attached to one of the atoms, and a hydrogen atom gets attached to the other (Figure 3.3B). The hydroxyl group and hydrogen atom come from a water molecule, so this reaction requires water.

We will revisit enzymes and metabolic reactions in Chapter 5. The remainder of this chapter introduces the different types of biological molecules and the monomers from which they are built.

Take-Home Message 3.1

- The molecules of life are organic, which means they consist mainly of carbon and hydrogen atoms. Functional groups bonded to their carbon backbone impart chemical characteristics to these molecules.
- Cells assemble large polymers from smaller monomer molecules.

They also break apart polymers into monomers.

Chapter 3: Molecules of Life: 3.2 What is a Carbohydrate?
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3.2 What is a Carbohydrate?

Carbohydrates (Molecule that consists primarily of carbon, hydrogen, and oxygen atoms in a 1:2:1 ratio.) are organic compounds that consist of carbon, hydrogen, and oxygen in a 1:2:1 ratio. Cells use different kinds as structural materials, for fuel, and for storing and transporting energy. The three main types of carbohydrates in living systems are monosaccharides, oligosaccharides, and polysaccharides.

Chapter 3: Molecules of Life Simple Sugars
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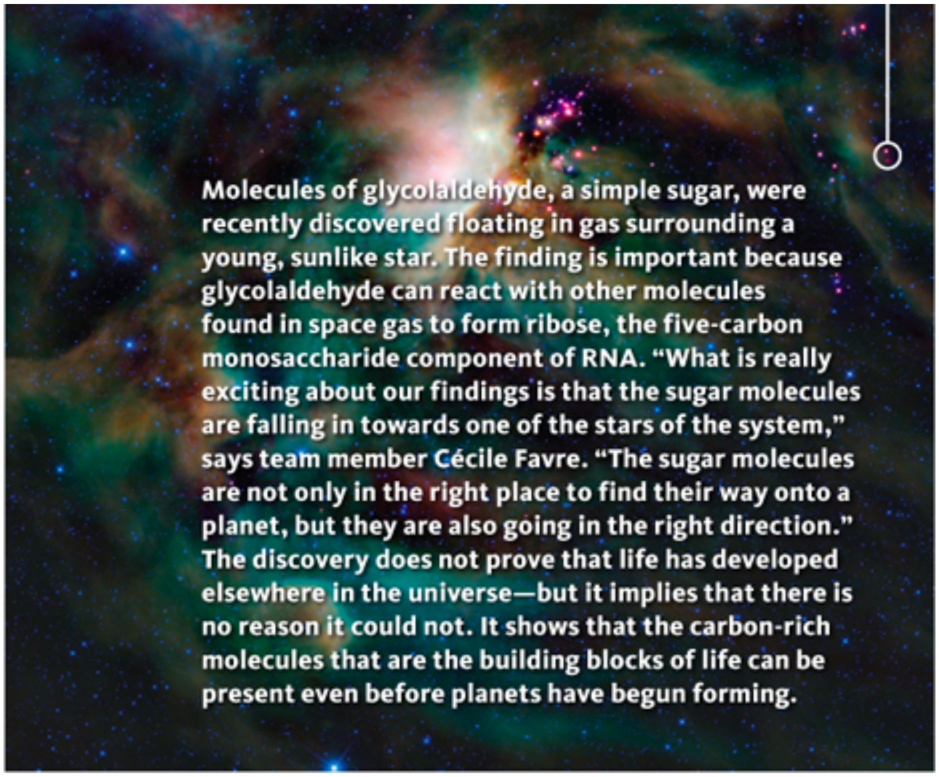
Simple Sugars

“Saccharide” is from *sacchar*, a Greek word that means sugar. Monosaccharides (one sugar) are the simplest type of carbohydrate. These molecules have extremely important biological roles. Common monosaccharides have a backbone of five or six carbon atoms (carbon atoms of sugars are numbered in a standard way: 1′, 2′, 3′, and so on, as illustrated in the model of glucose). Glucose has six carbon atoms. Five-carbon monosaccharides are components of the nucleotide monomers of DNA and RNA (Figure 3.4). Two or more hydroxyl (–OH) groups impart solubility to a sugar molecule, which means that monosaccharides move easily through the water-based internal environments of all organisms.

Figure 3.4

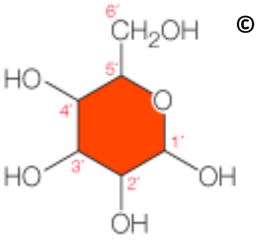
Astronomers made a sweet discovery in 2012.



Molecules of glycolaldehyde, a simple sugar, were recently discovered floating in gas surrounding a young, sunlike star. The finding is important because glycolaldehyde can react with other molecules found in space gas to form ribose, the five-carbon monosaccharide component of RNA. "What is really exciting about our findings is that the sugar molecules are falling in towards one of the stars of the system," says team member Cécile Favre. "The sugar molecules are not only in the right place to find their way onto a planet, but they are also going in the right direction." The discovery does not prove that life has developed elsewhere in the universe—but it implies that there is no reason it could not. It shows that the carbon-rich molecules that are the building blocks of life can be present even before planets have begun forming.

photo, NASA/JPL-Caltech/UCLA; inset, © Cengage Learning 2015;

Cells use monosaccharides for cellular fuel, because breaking the bonds of sugars releases energy that can be harnessed to power other cellular processes (we return to this important metabolic process in Chapter 7). Monosaccharides are also used as precursors, or parent molecules, that are remodeled into other molecules; and as structural materials to build larger molecules.



glucose

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Chapter 3: Molecules of Life Polymers of Simple Sugars
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Polymers of Simple Sugars

Oligosaccharides are short chains of covalently bonded monosaccharides (*oligo-* means a few). Disaccharides consist of two monosaccharide monomers. The lactose in milk, with one glucose and one galactose, is a disaccharide. Sucrose, the most plentiful sugar in nature, has a glucose and a fructose unit (sucrose extracted from sugarcane or sugar beets is our table sugar). Oligosaccharides attached to lipids or proteins have important functions in immunity.

Foods that we call "complex" carbohydrates consist mainly of polysaccharides: chains of hundreds or thousands of monosaccharide monomers. The chains may be straight or branched, and can consist of one or many types of monosaccharides. The most common polysaccharides are cellulose, starch, and glycogen. All consist only of glucose monomers, but as substances their properties are very different. Why? The answer begins with differences in patterns of covalent bonding that link their monomers.

Cellulose (Tough, insoluble carbohydrate that is the major structural material in plants.) , the major structural material of plants, is the most abundant biological molecule on Earth. Its long, straight chains are locked into tight, sturdy bundles by hydrogen bonds (Figure 3.5A). The bundles form tough fibers that act like reinforcing rods inside stems and other plant parts, helping these structures resist wind and other forms of mechanical stress. Cellulose does not dissolve in water, and it is not easily broken down. Some bacteria and fungi make enzymes that can break it apart into its component sugars, but humans and other mammals do not. Dietary fiber, or "roughage," usually refers to the cellulose in our vegetable foods. Bacteria that live in the guts of termites and grazers such as cattle and sheep help these animals digest the cellulose in plants.

Figure 3.5

Three of the most common complex carbohydrates and their locations in a few organisms. Each polysaccharide consists only of glucose subunits, but different bonding patterns result in substances with very different properties.

A Cellulose
Cellulose is the main structural component of plants. Above, in cellulose, chains of glucose monomers stretch side by side and hydrogen-bond at many —OH groups. The hydrogen bonds stabilize the chains in tight bundles that form long fibers. Very few types of organisms can digest this tough, insoluble material.

B Starch
Starch is the main energy reserve in plants, which store it in their roots, stems, leaves, seeds, and fruits. Below, in starch, a series of glucose monomers form a chain that coils up.

C Glycogen
Glycogen functions as an energy reservoir in animals, including people. It is especially abundant in the liver and muscles. Above, glycogen consists of highly branched chains of glucose monomers.

(5A–C), © Cengage Learning 2015; middle, © JupiterImages Corporation

In starch, a different covalent bonding pattern between glucose monomers makes a chain that coils up into a spiral (Figure 3.5B). Like cellulose, starch does not dissolve easily in water, but it is more easily broken down than cellulose. These properties make starch ideal for storing sugars in the watery, enzymefilled interior of plant cells. Most plant leaves make glucose during the day, and their cells store it by building starch. At night, hydrolysis enzymes break the bonds between starch's glucose monomers. The released glucose can be broken down immediately for energy, or converted to sucrose that is transported to other parts of the plant. Humans also have hydrolysis enzymes that break down starch, so this carbohydrate is an important component of our food.

Animals store their sugars in the form of glycogen. The covalent bonding pattern between glucose monomers in glycogen forms highly branched chains (Figure 3.5C). Muscle and liver cells contain most of the body's stored glycogen. When the sugar level in blood falls, liver cells break down stored glycogen, and the released glucose subunits enter the blood.

David Liittschwager/National Geographic Creative.

In chitin, a polysaccharide similar to cellulose, long, unbranching chains of nitrogen-containing monomers are linked by hydrogen bonds. As a structural material, chitin is durable, translucent, and flexible. It strengthens hard parts of many animals, including the outer cuticle of lobsters, and it reinforces the cell wall of many fungi.

Take-Home Message 3.2

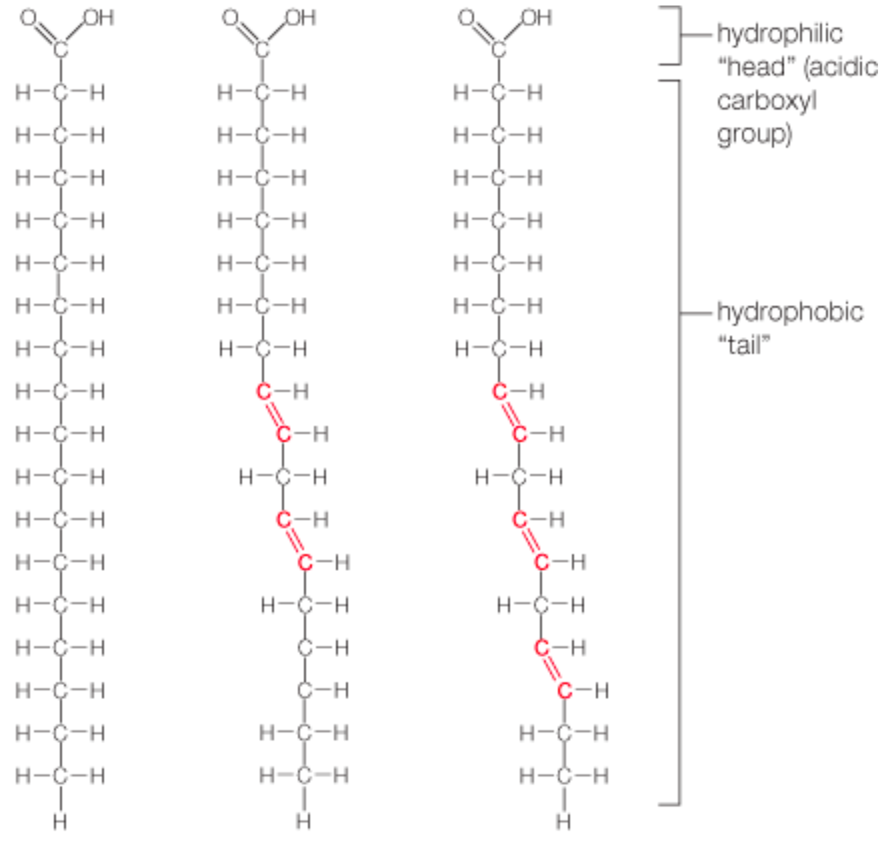
- Cells use simple carbohydrates (sugars) for energy and to build other molecules.
- Glucose monomers, bonded in different ways, form complex carbohydrates, including cellulose, starch, and glycogen.

3.3 What are Lipids?

Lipids (Fatty, oily, or waxy organic compound.) are fatty, oily, or waxy organic compounds. Many lipids incorporate **fatty acids** (Organic compound that consists of a chain of carbon atoms with an acidic carboxyl group at one end.) , which are small organic molecules that consist of a long hydrocarbon "tail" with a carboxyl group "head" (Figure 3.6). The tail is hydrophobic; the carboxyl group makes the head hydrophilic (and acidic). You are already familiar with the properties of fatty acids because these molecules are the main component of soap. The hydrophobic tails of fatty acids in soap attract oily dirt, and the hydrophilic heads dissolve the dirt in water.

Figure 3.6

Fatty acids. **A** The tail of stearic acid is fully saturated with hydrogen atoms. **B** Linoleic acid, with two double bonds, is unsaturated. The first double bond occurs at the sixth carbon from the end, so linoleic acid is called an omega-6 fatty acid. Omega-6 and **C** omega-3 fatty acids are "essential fatty acids." Your body does not make them, so they must come from food.



A stearic acid (saturated)

B linoleic acid (omega-6)

C linolenic acid (omega-3)

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Saturated fatty acids have only single bonds linking the carbons in their tails. In other words, their carbon chains are fully saturated with hydrogen atoms (Figure 3.6A). Saturated fatty acid tails are flexible and they wiggle freely. Double bonds between carbons of unsaturated fatty acid tails limit their flexibility (Figure 3.6B, C).

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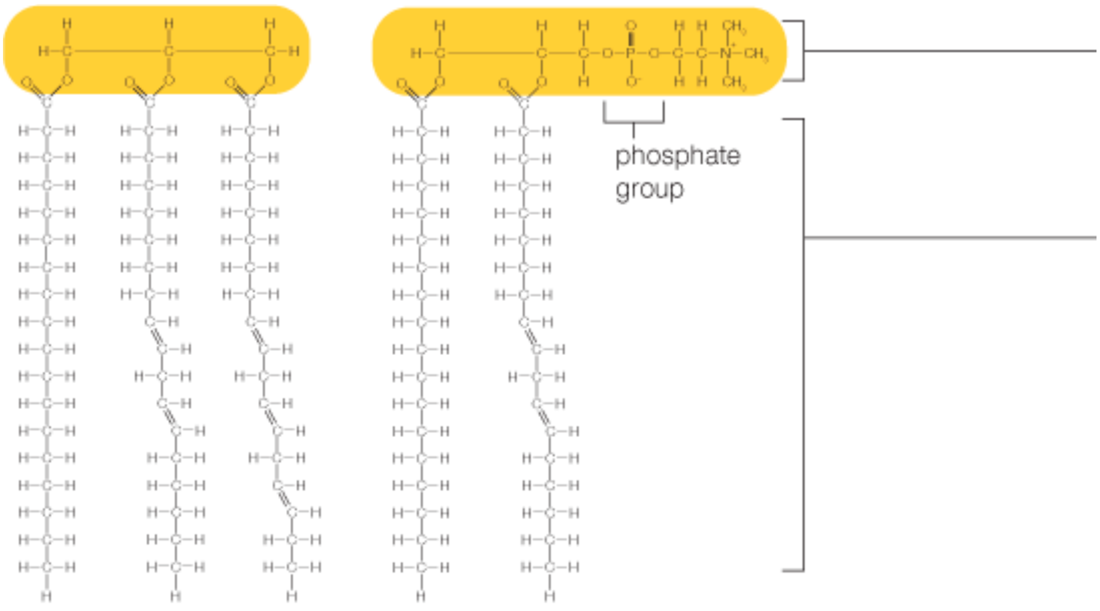
Fats

The carboxyl group head of a fatty acid can easily form a covalent bond with another molecule. When it bonds to a glycerol, a type of alcohol, it loses its hydrophilic character and becomes part of a fat. **Fats** (Lipid that consists of a glycerol molecule with one, two, or three fatty acid tails.) are lipids with one, two, or three fatty acids bonded to the same glycerol. A fat with three fatty acid tails is called a **triglyceride** (A fat with three fatty acid tails.) (Figure 3.7A). Triglycerides are entirely hydrophobic, so they do not dissolve in water. Most "neutral" fats, such as butter and vegetable oils, are examples. Triglycerides are the most abundant and richest energy source in vertebrate bodies. Gram for gram, fats store more energy than carbohydrates.

Figure 3.7

Lipids with fatty acid tails.



A The three fatty acid tails of a triglyceride are attached to a glycerol head.

B The two fatty acid tails of this phospholipid are attached to a phosphate-containing head.

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Butter, cream, and other high-fat animal products have a high proportion of **saturated fats**

(Triglyceride that has three saturated fatty acid tails.) , which means they consist mainly of triglycerides with three saturated fatty acid tails. Saturated fats tend to be solid at room temperature because their floppy saturated tails can pack tightly. Most vegetable oils are **unsaturated fats** (Triglyceride that has one or more unsaturated fatty acid tails.) , which means they consist mainly of triglycerides with one or more unsaturated fatty acid tails. Each double bond in a fatty acid tail makes a rigid kink. Kinky tails do not pack tightly, so unsaturated fats are typically liquid at room temperature.

Chapter 3: Molecules of Life Phospholipids
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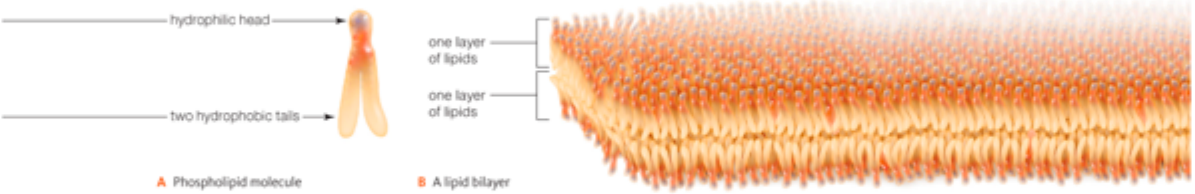
Phospholipids

A **phospholipid** (A lipid with a phosphate group in its hydrophilic head, and two nonpolar tails typically derived from fatty acids.) consists of a phosphate-containing head with two long hydrocarbon tails that are typically derived from fatty acids (Figure 3.7B). The tails are hydrophobic, but the highly polar phosphate group makes the head hydrophilic. These opposing properties give rise to the basic structure of cell membranes, which consist mainly of phospholipids. In a cell membrane, phospholipids are arranged in two layers—a **lipid bilayer** (Double layer of lipids arranged tail-to-tail; structural foundation of cell membranes.) (Figure 3.8). The heads of one layer are dissolved in the cell's watery interior, and the heads of the other layer are dissolved in the cell's fluid surroundings. All of the hydrophobic tails are sandwiched between the hydrophilic heads.

Figure 3.8

Phospholipids as components of cell membranes. A double layer of phospholipids—the lipid bilayer—is the structural foundation of all cell membranes. You will read more about the structure of cell membranes in Chapter 4.



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Waxes

A **wax** (Water-repellent mixture of lipids with long fatty acid tails bonded to long-chain alcohols or carbon rings.) is a complex, varying mixture of lipids with long fatty acid tails bonded to alcohols or carbon rings. The molecules pack tightly, so waxes are firm and water-repellent. Plants secrete waxes onto their exposed surfaces to restrict water loss and keep out parasites and other pests. Other types of waxes protect, lubricate, and soften skin and hair. Waxes, together with fats and fatty acids, make feathers waterproof. Bees store honey and raise new generations of bees inside a honeycomb of secreted beeswax.

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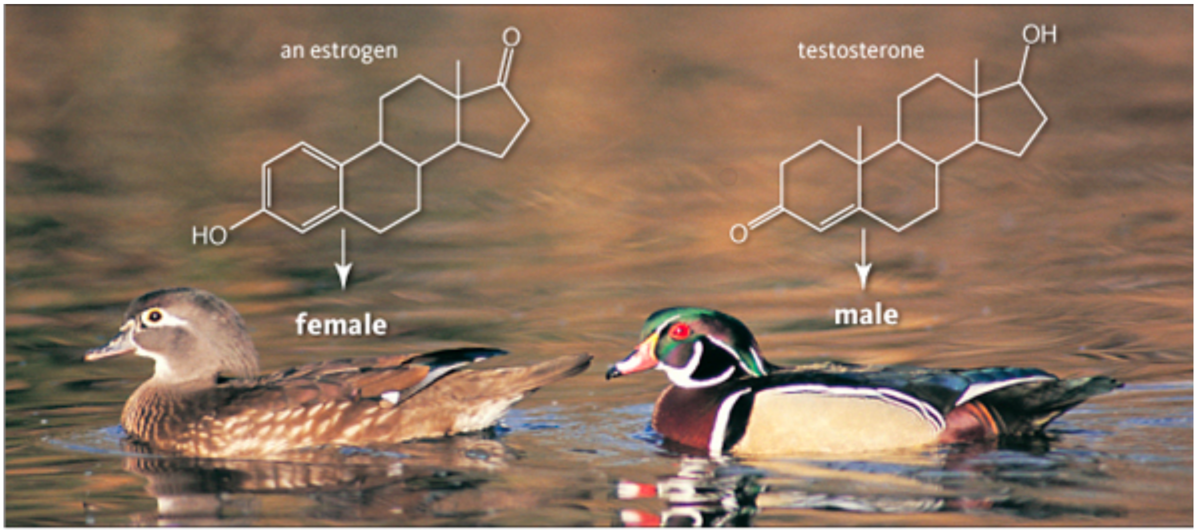
Steroids

Steroids (Type of lipid with four carbon rings and no tails.) are lipids with no fatty acid tails; they have a rigid backbone that consists of twenty carbon atoms arranged in a characteristic pattern of four rings (Figure 3.9). Functional groups attached to the rings define the type of steroid. These molecules serve varied and important physiological functions in plants, fungi, and animals. Cells remodel cholesterol, the most common steroid in animal tissue, to produce many other molecules, including bile salts (which help digest fats), vitamin D (required to keep teeth and bones strong), and steroid hormones.

Figure 3.9

Steroids.

Estrogen and testosterone are steroid hormones that govern reproduction and secondary sexual traits. The two hormones are the source of gender-specific traits in many species, including wood ducks.



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Take-Home Message 3.3

- Lipids are fatty, waxy, or oily organic compounds.
- Fats have one, two, or three fatty acid tails; triglyceride fats are an important energy reservoir in vertebrate animals.
- Phospholipids arranged in a lipid bilayer are the main component of cell membranes.
- Waxes have complex, varying structures. They are components of water-repelling and lubricating secretions.
- Steroids serve varied and important physiological roles in plants, fungi, and animals.

Chapter 3: Molecules of Life: 3.4 What are Proteins?
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3.4 What are Proteins?

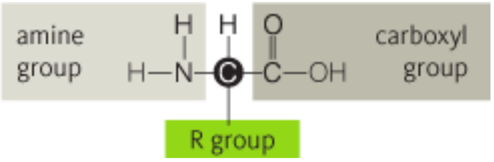
Amino Acid Subunits

With a few exceptions, cells can make all of the thousands of different proteins they need from only twenty kinds of monomers called amino acids. An **amino acid** (Small organic compound that is a subunit of proteins. Consists of a carboxyl group, an amine group, and a characteristic side group (R), all typically bonded to the same carbon atom.) is a small organic compound with an amine group (–NH_2), a carboxyl group (–COOH, the acid), and a side chain called an "R group" that defines the kind of amino acid. In most amino acids, all three groups are attached to the same carbon atom (Figure 3.10).

Figure 3.10

Generalized structure of an amino acid.

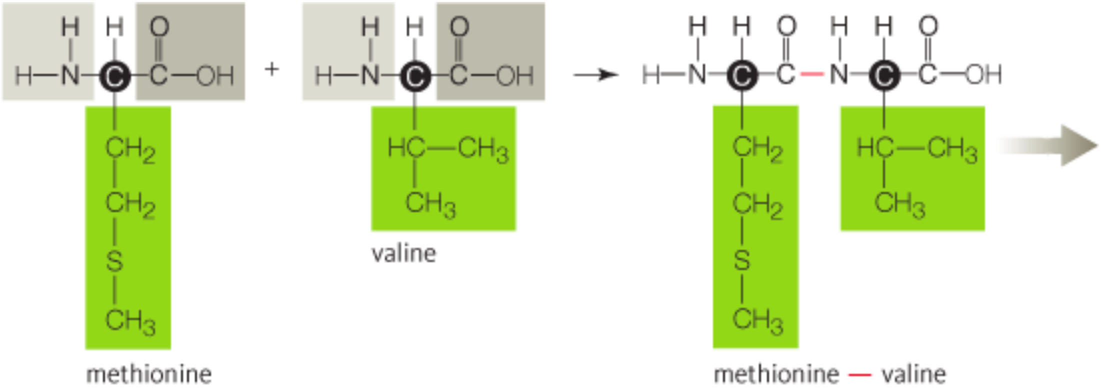
See Appendix V for the complete structures of the twenty most common amino acids found in eukaryotic proteins.



The covalent bond that links amino acids in a protein is called a **peptide bond** (A bond between the amine group of one amino acid and the carboxyl group of another. Joins amino acids in proteins.) . During protein synthesis, a peptide bond forms between the carboxyl group of the first amino acid and the amine group of the second (Figure 3.11). Another peptide bond links a third amino acid to the second, and so on (you will learn more about the details of protein synthesis in Chapter 9). A short chain of amino acids is called a **peptide** (Short chain of amino acids linked by peptide bonds.) ; as the chain lengthens, it becomes a **polypeptide** (Long chain of amino acids linked by peptide bonds.) . **Proteins** (Organic molecule that consists of one or more polypeptides.) consist of polypeptides that are hundreds or even thousands of amino acids long.

Figure 3.11

Peptide bond formation. A condensation reaction joins the carboxyl group of one amino acid and the amine group of another to form a peptide bond. In this example, a peptide bond forms between methionine and valine.



Chapter 3: Molecules of Life Structure Dictates Function
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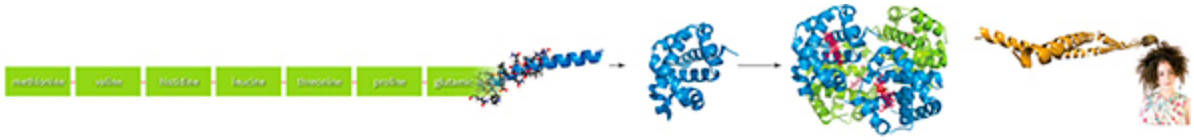
Structure Dictates Function

Of all biological molecules, proteins are the most diverse. Structural proteins support cell parts and, as part of tissues, multicelled bodies. Feathers, hooves, and hair, as well as tendons and other body parts, consist mainly of structural proteins. A tremendous number of different proteins, including some structural types, participate in all processes that sustain life. Most enzymes that help cells carry out metabolic reactions are proteins. Proteins also function in movement, defense, and cellular communication.

One of the fundamental ideas in biology is that structure dictates function. This idea is particularly appropriate for proteins, because a protein's biological activity arises from and depends on its structure (Figure 3.12).

Figure 3.12

Protein structure.



① A protein's primary structure consists of a linear sequence of amino acids (a polypeptide chain). Each type of protein has a unique primary structure.

② Secondary structure arises as a polypeptide chain twists into a helix (coil), loop, or sheet held in place by hydrogen bonds.

③ Tertiary structure occurs when loops, helices, and sheets fold up into a domain. In this example, the helices of a globin chain form a pocket.

④ Many proteins have two or more polypeptide chains (quaternary structure). Hemoglobin, shown here, consists of four globin chains (green and blue). Each globin pocket now holds a heme group (red).

⑤ Some types of proteins aggregate into much larger structures. As an example, organized arrays of keratin, a fibrous protein, compose filaments that make up your hair.

2–4: 1BBB, A third quaternary structure of human hemoglobin A at 1.7-A resolution. Silva, M.M., Rogers, P.H., Arnone, A., Journal: (1992) J.Biol.Chem. 267: 17248–17256; 1, 5 left: © Cengage Learning; 5 right: © JupiterImages Corporation.

The linear series of amino acids in a polypeptide chain is called primary structure ①, which defines the type of protein. The protein's three-dimensional shape begins to arise during synthesis, when hydrogen bonds that form among amino acids cause the lengthening polypeptide chain to twist and fold. Parts of the polypeptide form loops, helixes (coils), or flat sheets, and these patterns constitute secondary structure ②. The primary structure of each type of protein is unique, but most proteins have similar patterns of secondary structure.

Much as an overly twisted rubber band coils back upon itself, hydrogen bonding between nonadjacent regions of a protein makes its loops, helices, and sheets fold up into even more compact domains (Figure 3.13A). These domains are called tertiary structure ③. Tertiary structure makes a protein a working molecule. For example, the helices and loops in a globin chain fold up together to form a pocket that can hold a heme, which is a small compound essential to the finished protein's function. Sheets, loops, and helices of other proteins roll up into complex structures that resemble barrels, propellers, sandwiches, and so on. Large proteins typically have several domains, each contributing a particular structural or functional property to the molecule. For example, some barrel domains rotate like motors in small molecular machines (Figure 3.13B). Other barrels function as tunnels for small molecules, allowing them to pass, for example, through a cell membrane.

Figure 3.13

Examples of protein domains.

A In this protein, loops (green), coils (red), and a sheet (yellow) fold up together into a chemically active pocket. The pocket gives this protein the ability to transfer electrons from one molecule to another. Many other proteins have the same pocket structure.

B This barrel domain is part of a rotary mechanism in a larger protein. The protein functions as a molecular motor that pumps hydrogen ions through cell membranes.

(13A) Castrignanò T, De Meo PD, Cozzetto D, Talamo IG, Tramontano A. (2006). The PMDB Protein Model Database. Nucleic Acids Research, 34: D306-D309. (13B) pdb ID2W5J, Vollmar, M., Shlieper, D., Winn M., Buechner, C., Groth, G. "Structure of the C14 rotor ring of the proton translocating chloroplast ATP synthase." (2009) *J. Biol. Chem.* 284:18228.

Many proteins also have quaternary structure, which means they consist of two or more polypeptide chains that are closely associated or covalently bonded together ④. Most enzymes are like this, with multiple polypeptide chains that collectively form a roughly spherical shape.

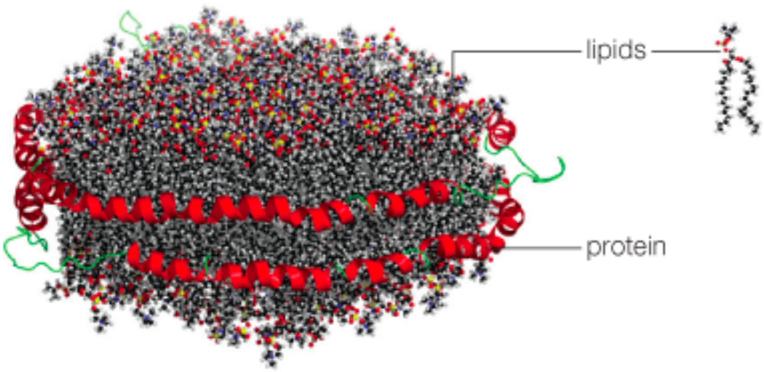
Fibrous proteins aggregate by many thousands into much larger structures, with their polypeptide chains organized into strands or sheets. The keratin in your hair is an example ⑤. Some fibrous proteins contribute to the structure and organization of cells and tissues. Others help cells, cell parts, and multicelled bodies move.

Enzymes often attach sugars or lipids to proteins. A glycoprotein forms when oligosaccharides are attached to a polypeptide. The molecules that allow a tissue or a body to recognize its own cells are glycoproteins, as are other molecules that help cells interact in immunity.

Some lipoproteins form when enzymes covalently bond lipids to a protein. Other lipoproteins are aggregate structures that consist of variable amounts and types of proteins and lipids (Figure 3.14).

Figure 3.14

A lipoprotein particle. The one depicted here (HDL, often called "good" cholesterol) consists of thousands of lipids lassoed into a clump by two protein chains.



Castrignanò T, De Meo PD, Cozzetto D, Talamo IG, Tramontano A. (2006). The PMDB Protein Model Database. Nucleic Acids Research, 34: D306-D309.

Take-Home Message 3.4

- Proteins are chains of amino acids. The order of amino acids in a polypeptide chain dictates the type of protein.
- Polypeptide chains twist and fold into coils, sheets, and loops, which fold and pack further into functional domains.
- A protein's function arises from its three-dimensional shape.

Chapter 3: Molecules of Life: 3.5 Why is Protein Structure Important?
Book Title: Biology
Printed By: Dina DiSantis (ddisantis@dasd.org)

3.5 Why is Protein Structure Important?

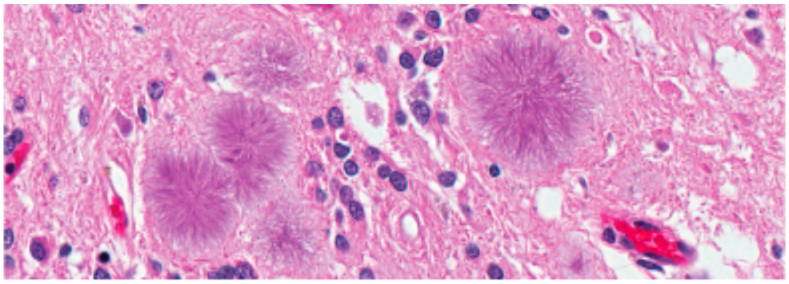
Protein shape depends on hydrogen bonding, which can be disrupted by heat, some salts, shifts in pH, or detergents. Such disruption causes proteins to **denature** (To unravel the shape of a protein or other large biological molecule.) , which means they lose their three-dimensional shape. Once a protein's shape unravels, so does its function.

Consider three fatal diseases: scrapie in sheep, mad cow disease (BSE, bovine spongiform encephalopathy), and variant Creutzfeldt—Jakob disease (vCJD) in humans. All begin with a glycoprotein called PrPC that occurs normally in cell membranes of the mammalian body. Sometimes, a PrPC protein spontaneously misfolds. A single misfolded protein molecule should not pose much of a threat, but when this particular protein misfolds it becomes a **prion** (Infectious protein.) , or infectious protein. The altered shape of a misfolded PrPC protein causes normally folded PrPC proteins to misfold too. Because each protein that misfolds becomes infectious, the number of prions increases exponentially.

The shape of misfolded PrPC proteins allows them to align tightly into long fibers. In the brain, these fibers accumulate in water-repellent patches that disrupt brain cell function, resulting in relentlessly worsening symptoms of confusion, memory loss, and lack of coordination. Holes form in the brain as its cells die (Figure 3.15).

Figure 3.15

Variant Creutzfeldt-Jakob disease (vCJD). Characteristic holes and prion protein fibers radiating from several deposits are visible in this slice of brain tissue from a person with vCJD.



Sherif Zaki, MD PhD, Wun-Ju Shieh, MD PhD; MPH/CDC

In the mid-1980s, an epidemic of mad cow disease in Britain was followed by an outbreak of vCJD in humans. The cattle became infected by the prion after eating feed prepared from the remains of scrapie-infected sheep, and people became infected by eating beef from infected cattle. The use of animal parts in livestock feed is now banned in many countries, and the number of cases of BSE and vCJD has since declined.

Take-Home Message 3.5

- Protein shape can unravel if hydrogen bonds are disrupted.
- A protein’s function depends on its structure, so conditions that alter a protein’s structure also alter its function.

Chapter 3: Molecules of Life: 3.6 What are Nucleic Acids?
Book Title: Biology
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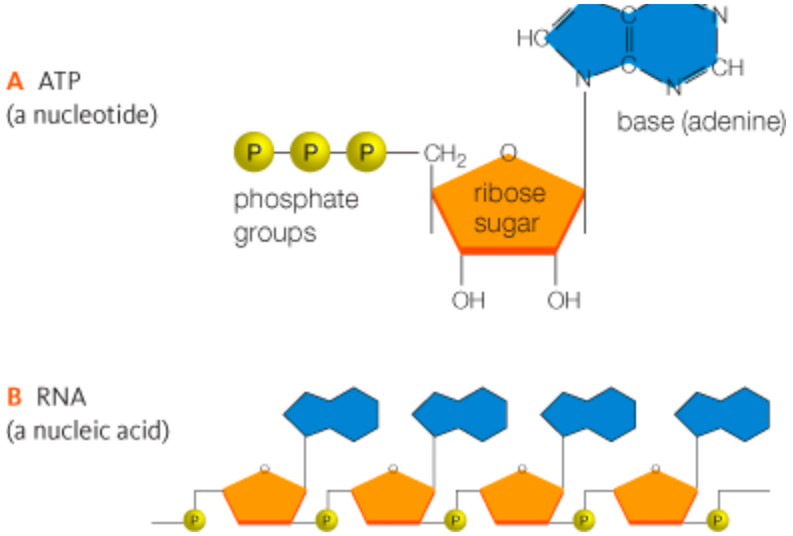
3.6 What are Nucleic Acids?

A **nucleotide** (Monomer of nucleic acids; has a five-carbon sugar, a nitrogen-containing base, and one, two, or three phosphate groups.) is a small organic molecule that consists of a sugar with a five-carbon ring bonded to a nitrogen-containing base and one, two, or three phosphate groups (Figure 3.16A). When the third phosphate group of a nucleotide is transferred to another molecule, energy is transferred along with it. The nucleotide **ATP** (Adenosine triphosphate. Nucleotide that serves an important role as an energy carrier in cells.) (adenosine triphosphate) serves an especially important role as an energy carrier in cells.

Figure 3.16

Nucleic acids.



(16A) From Starr/Evers/Starr, Biology Today and Tomorrow with Physiology, 4E. © 2013 Cengage Learning; (16B) © Cengage Learning 2015.

Nucleic acids (Polymer of nucleotides; DNA or RNA.) are polymers, chains of nucleotides in which the sugar of one nucleotide is bonded to the phosphate group of the next (Figure 3.16B). An example is ribonucleic acid, or **RNA** (Ribonucleic acid. Single-stranded chain of nucleotides.) , named after the ribose sugar of its component nucleotides. An RNA molecule is a chain of four kinds of nucleotide monomers, one of which is ATP. RNA molecules carry out protein synthesis. Deoxyribonucleic acid, or **DNA** (Deoxyribonucleic acid. Consists of two chains of nucleotides twisted into a double helix.) , is a nucleic acid named after the deoxyribose sugar of its component nucleotides. A DNA molecule consists of two chains of nucleotides twisted into a double helix. Hydrogen bonds between the nucleotides hold the chains together. Each cell's DNA holds all information necessary to build a new cell and, in the case of multicelled organisms, a new individual.

Take-Home Message 3.6

- Nucleotides are monomers of nucleic acids. ATP has an important metabolic role as an energy carrier.
- RNA carries out protein synthesis. DNA holds information necessary to build cells and multicelled individuals.

Chapter 3: Molecules of Life: 3.7 Application: Fear of Frying
Book Title: Biology
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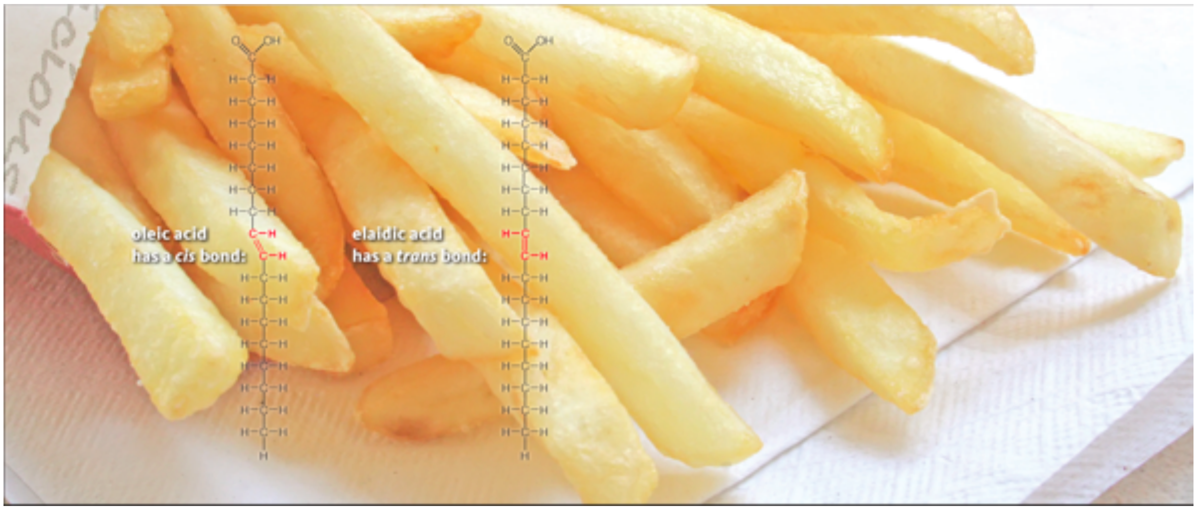
3.7 Application: Fear of Frying

Fats are Not Inert Molecules That Simply Accumulate in Strategic Areas of Our Bodies. They are major constituents of cell membranes, and as such they have powerful effects on cell function. As you learned in Section 3.3, the long carbon backbone of fatty acid tails can vary a bit in structure. *Trans* fats have unsaturated fatty acid tails with a particular arrangement of hydrogen atoms around the double bonds (Figure 3.17). Small amounts of *trans* fats occur naturally, but the main source of these fats in the American diet is an artificial food product called partially hydrogenated vegetable oil. Hydrogenation is a manufacturing process that adds hydrogen atoms to oils in order to change them into solid fats. In 1908, Procter & Gamble Co. developed partially hydrogenated soybean oil as a substitute for the more expensive solid animal fats they had been using to make candles. However, the demand for candles began to wane as more households in the United States became wired for electricity, and P&G looked for another way to sell its proprietary fat. Partially hydrogenated vegetable oil looks like lard, so the company began aggressively marketing it as a revolutionary new food: a solid cooking fat with a long shelf life, mild flavor, and lower cost than lard or butter. By the mid-1950s, hydrogenated vegetable oil had become a major part of the American diet, and it is still found in many manufactured and fast foods. For decades, it was considered healthier than animal fats, but we now know otherwise. *Trans* fats raise the level of cholesterol in our blood more than any other fat, and they directly alter the function of our arteries and veins. The effects of such changes are quite serious. Eating as little as 2 grams a day (about 0.4 teaspoon) of hydrogenated vegetable oil measurably increases a person's risk of atherosclerosis (hardening of the arteries), heart attack, and diabetes. A small serving of french fries made with hydrogenated vegetable oil contains about 5 grams of *trans* fat.

Figure 3.17

Exploration

Trans fats, an unhealthy food. Double bonds in the tail of most naturally occurring fatty acids are *cis*, which means that the two hydrogen atoms flanking the bond are on the same side of the carbon backbone. Hydrogenation creates abundant *trans* bonds, with hydrogen atoms on opposite sides of the tail.



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Chapter 3: Molecules of Life Chapter Review
Book Title: Biology
Printed By: Dina DiSantis (ddisantis@dasd.org)

Chapter Review

Summary

Section 3.1 Complex carbohydrates and lipids, proteins, and nucleic acids are **organic**, which means they consist mainly of carbon and hydrogen atoms. **Hydrocarbons** have only carbon and hydrogen atoms.

Carbon chains or rings form the backbone of the molecules of life. **Functional groups** attached to the backbone influence the chemical character of these compounds, and thus their function.

Metabolism includes chemical **reactions** and all other processes by which cells acquire and use energy as they make and break the bonds of organic compounds. In reactions such as **condensation**, **enzymes** build **polymers** from **monomers** of simple sugars, fatty acids, amino acids, and nucleotides. Reactions such as **hydrolysis** release the monomers by breaking apart the polymers.

Section 3.2 Enzymes build complex **carbohydrates** such as **cellulose**, glycogen, and starch from simple carbohydrate (sugar) subunits. Cells use carbohydrates for energy, and as structural materials.

Section 3.3 **Lipids** are fatty, oily, or waxy compounds. All are nonpolar. **Fats** have **fatty acid** tails; **triglycerides** have three. **Saturated fats** are mainly triglycerides with three saturated fatty acid tails (only single bonds link their carbons). **Unsaturated fats** are mainly triglycerides with one or more unsaturated fatty acids.

A **lipid bilayer** (that consists primarily of **phospholipids**) is the basic structure of all cell membranes. **Waxes** are part of water-repellent and lubricating secretions. **Steroids** occur in cell membranes, and some are remodeled into other molecules such as hormones.

Section 3.4 Structurally and functionally, **proteins** are the most diverse molecules of life. The shape of a protein is the source of its function. Protein structure begins as a series of **amino acids** (primary structure) linked by **peptide bonds** into a **peptide**, then a **polypeptide**. Polypeptides twist into helices, sheets, and coils (secondary structure) that can pack further into functional domains (tertiary structure). Many proteins, including most enzymes, consist of two or more polypeptides (quaternary structure). Fibrous proteins aggregate into much larger structures.

Section 3.5 A protein's structure dictates its function, so changes in a protein's structure may also alter its function. A protein's shape may be disrupted by shifts in pH or temperature, or exposure to detergent or some salts. If that happens, the protein unravels, or **denatures**, and so loses its function. **Prion** diseases are a fatal consequence of misfolded proteins.

Section 3.6 **Nucleotides** are small organic molecules that consist of a five-carbon sugar, a nitrogen-containing base, and one, two, or three phosphate groups. Nucleotides are monomers of **DNA** and **RNA**, which are **nucleic acids**. Some, especially **ATP**, have additional functions such as carrying energy. DNA encodes information necessary to build cells and multicelled individuals. RNA molecules carry out protein synthesis.

Section 3.7 All organisms consist of the same kinds of molecules. Seemingly small differences in the way those molecules are put together can have big effects inside a living organism.

Chapter 3: Molecules of Life Self-Quiz
Book Title: Biology
Printed By: Dina DiSantis (ddisantis@dasd.org)

Chapter Review

Self-Quiz

1. Organic molecules consist mainly of ____ atoms.
   a. carbon
   b. carbon and oxygen
   c. carbon and hydrogen
   d. carbon and nitrogen

2. Each carbon atom can bond with as many as ____ other atom(s).

3. ____ groups are the "acid" part of amino acids and fatty acids.
   a. Hydroxyl (—OH)
   b. Carboxyl (—COOH)
   c. Methyl (—CH_3)

d. Phosphate ($-PO_4$)

4. ____ is a simple sugar (a monosaccharide).

a. Glucose

b. Sucrose

c. Ribose

d. Starch

e. both a and c

f. a, b, and c

5. Unlike saturated fats, the fatty acid tails of unsaturated fats incorporate one or more ____ .

a. phosphate groups

b. glycerols

c. double bonds

d. single bonds

6. Is this statement true or false? Unlike saturated fats, all unsaturated fats are beneficial to health because their fatty acid tails kink and do not pack together.

T F

7. Steroids are among the lipids with no ____ .

a. double bonds

b. fatty acid tails

c. hydrogens

d. carbons

8. Name three kinds of carbohydrates that can be built using only glucose monomers.

9. Which of the following is a class of molecules that encompasses all of the other molecules listed?

   a. triglycerides

   b. fatty acids

   c. waxes

   d. steroids

   e. lipids

   f. phospholipids

10. ____ are to proteins as ____ are to nucleic acids.

   a. Sugars; lipids

   b. Sugars; proteins

   c. Amino acids; hydrogen bonds

   d. Amino acids; nucleotides

11. A denatured protein has lost its ____ .

   a. hydrogen bonds

   b. shape

   c. function

   d. all of the above

12. ____ consist(s) of nucleotides.

   a. Sugars

   b. DNA

   c. RNA

   d. b and c

13. In the following list, identify the carbohydrate, the fatty acid, the amino acid,

and the polypeptide:

a. $NH_2 - CH_2 - COOH$

b. $C_6H_{12}O_6$

c. $(\text{methionine})_{20}$

d. $CH_3(CH_2)_{16}COOH$

14. Match the molecules with the best description.

wax

starch

triglyceride

a. sugar storage in plants

b. richest energy source

c. water-repellent secretions

15. Match each polymer with the appropriate monomer(s).

protein

phospholipids

glycoprotein

fat

nucleic acid

wax

nucleotide

lipoprotein

sucrose

glycogen

a. phosphate, fatty acids

b. amino acids, sugars

c. glycerol, fatty acids

d. nucleotides

e. glucose only

f. sugar, phosphate, base

g. amino acids

h. glucose, fructose

i. lipids, amino acids

j. fatty acids, carbon rings

Chapter Review

Data Analysis Activities

Effects of Dietary Fats on Lipoprotein Levels Cholesterol that is made by the liver or that enters the body from food cannot dissolve in blood, so it is carried through the bloodstream by lipoproteins. Low-density lipoprotein (LDL) carries cholesterol to body tissues such as artery walls, where it can form deposits associated with cardiovascular disease. Thus, LDL is often called "bad" cholesterol. High-density lipoprotein (HDL) carries cholesterol away from tissues to the liver for disposal, so HDL is often called "good" cholesterol.

In 1990, Ronald Mensink and Martijn Katan published a study that tested the effects of different dietary fats on blood lipoprotein levels. Their results are shown in Figure 3.18.

Figure 3.18

Effect of diet on lipoprotein levels. Researchers placed 59 men and women on a diet in which 10 percent of their daily energy intake consisted of *cis* fatty acids, *trans* fatty acids, or saturated fats.

Blood LDL and HDL levels were measured after three weeks on the diet; averaged results are shown in mg/dL (milligrams per deciliter of blood). All subjects were tested on each of the diets. The ratio of LDL to HDL is also shown.

	Main Dietary Fats			
	cis fatty acids	*trans* fatty acids	saturated fats	optimal level
LDL	103	117	121	<100
HDL	55	48	55	>40
ratio	1.87	2.44	2.2	<2

Source, Mensink R P, Katan MB., "Effect of dietary trans fatty acids on high-density and low-density lipoprotein cholesterol levels in healthy subjects." NEJM 323(7):439–45, 1990 From Starr/Taggart/Evers/Starr, Biology, 13E. © Cengage Learning

1. In which group was the level of LDL ("bad" cholesterol) highest?
2. In which group was the level of HDL ("good" cholesterol) lowest?
3. An elevated risk of heart disease has been correlated with increasing LDL-to-HDL ratios. Which group had the highest LDL-to-HDL ratio?
4. Rank the three diets from best to worst according to their potential effect on heart disease.

Chapter 3: Molecules of Life Critical Thinking
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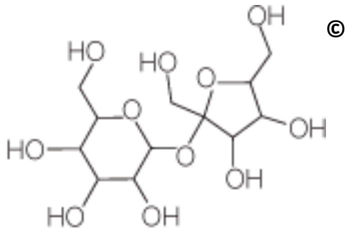
Chapter Review

Critical Thinking

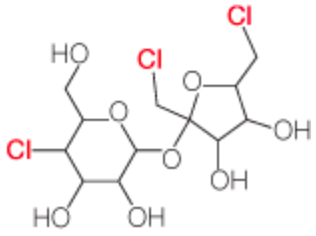
1. Lipoproteins are relatively large, spherical clumps of protein and lipid molecules (see Figure 3.14) that circulate in the blood of mammals. They are like suitcases that move cholesterol, fatty acid remnants, triglycerides, and phospholipids from one place to another in the body. Given what you know about the insolubility of lipids in water, which of the four kinds of lipids would you predict to be on the outside of a lipoprotein clump, bathed in the water-based fluid portion of blood?
2. In 1976, a team of chemists in the United Kingdom was developing new insecticides by modifying sugars with chlorine (Cl_2), phosgene (Cl_2CO), and other toxic gases. One young member of the team misunderstood his verbal instructions to "test" a new molecule. He thought he had been told to "taste" it. Luckily for him, the molecule was not toxic, but it was very sweet. It became the food additive sucralose.

   Sucralose has three chlorine atoms substituted for three hydroxyl groups of sucrose (table sugar). It binds so strongly to the sweet-taste receptors on the tongue that the human brain perceives it as 600 times sweeter than sucrose. Sucralose was originally marketed as an artificial sweetener called Splenda®, but it is now available under several other brand names.

Researchers investigated whether the body recognizes sucralose as a carbohydrate by feeding sucralose labeled with ^{14}C to volunteers. Analysis of the radioactive molecules in the volunteers' urine and feces showed that 92.8 percent of the sucralose passed through the body without being altered. Many people are worried that the chlorine atoms impart toxicity to sucralose. How would you respond to that concern?



sucrose



sucralose

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