

Molecules of the Cell: The Building Blocks of Life

3

Looking Ahead

Having examined the basic structure of microbial cells, it is important to consider the molecules building cells and understand the roles these molecules play in cell function.

On completing this chapter, you should be capable of:

- Describing the structure of an atom and explaining how atoms form molecules.
- Distinguishing between monosaccharides, disaccharides, and polysaccharides, and describing their roles in cells.
- Sketching the structure of a fat and assessing the role of phospholipids in separating an aqueous cytoplasm from an aqueous environment.
- Sketching the structure of an amino acid and explaining how amino acids form proteins.
- Distinguishing DNA from RNA and identifying their roles in cells.

Many ideas have been put forward to explain how life began on planet Earth. Here Dr. Stanley Miller is shown recreating his famous experiment performed in 1953. A spark was sent through a flask containing gases believed present in the atmosphere of the Earth billions of years ago, resulting in the eventual formation of amino acids, one of the building blocks of life.

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Stanley Miller was intrigued. As a young graduate student at the University of Chicago, he became fascinated with the ideas presented in a lecture presented by Professor Harold Urey. Urey told the audience he believed the atmosphere of primitive Earth was very different from today's atmosphere and likely consisted of several gases, including methane, ammonia, hydrogen sulfide, and hydrogen. Urey further suggested that within such an atmosphere it might be possible to synthesize some of the chemical building blocks needed to form the raw materials for the emergence of life.

Life on Earth began around 3.8 billion years ago, evolving from some form of “primordial soup” into the incredible diversity of microbes and life we see today. So, where did the very first molecules of life on Earth come from?

■ **primordial soup** A pond or body of water rich in substances that could provide favorable conditions for the emergence of life.

In 1952, Miller took a research position in Urey's lab and asked to test Urey's hypothesis that a primitive gas mixture could form some of the building blocks of life. After much argument and Miller's persistence, Urey gave his approval to the experiment. After three months of planning, Miller's experiment would attempt to simulate the primitive Earth atmosphere by putting methane, ammonia, hydrogen gas, and water vapor together in a closed reaction vessel (FIGURE 3.1). But how would he get these gases to interact with one another. There needed to be a spark.

Because lightning storms would have been very common in the atmosphere of early Earth, Miller had the brilliant idea of putting an electric charge through the gas mixture to simulate lightning going through the atmosphere. So, using electrical sparks in the reaction vessel, Miller allowed the reaction to continue for several days. As the days passed, he noticed the accumulation of a brown slime on the reaction vessel and a yellow-brown color in the water. When analyzed, Miller detected five amino acids, which are some of the building blocks of proteins.

The Miller-Urey experiment showed for the first time that some of the building blocks of life, like amino acids, could be made under conditions simulating early Earth. Today, we know Earth's primitive atmosphere did not have the exact composition Urey

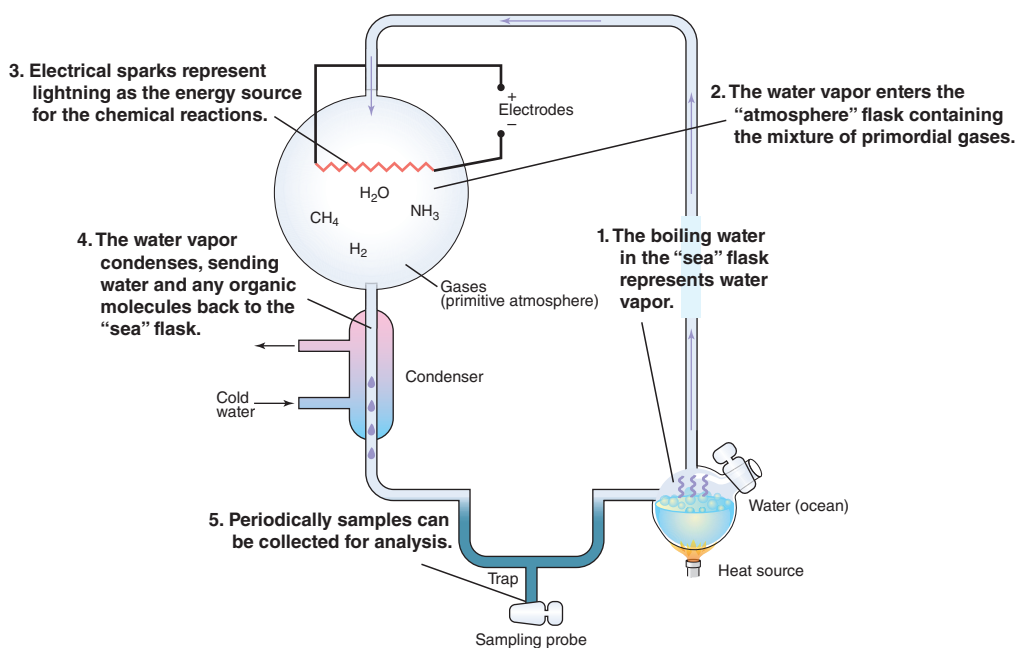


FIGURE 3.1 The Miller-Urey Experiment. The experiment consisted of a reaction vessel containing Earth's primordial gases in which an electrical spark provided the catalyst for the chemical reactions.

proposed. Still, Miller's work represents a landmark experiment. In fact, in 2008, a year after Miller died, more modern techniques of analysis turned up more amino acids and other substances of interest from the original reaction vessels Miller used.

Today, we cannot answer for certain how life began, but we can study the building blocks and other large molecules forming the structure and function of microbes, viruses, and all life. These are the carbohydrates, lipids, proteins, and nucleic acids—and they are the topic in the coming pages.

3.1 Chemistry Basics: Atoms, Bonds, and Molecules

In the primordial soup, the capture of organic molecules, the building blocks of life, into a concentrated area, within a membrane bound compartment, permitted the chemical reactions of life (metabolism) to take place at a reasonable rate, something that would not have happened with the molecules floating freely and randomly in the environment. Of course, when the membrane of the cell formed, water was also captured within the cell and would be the substance in which metabolism evolved.

Atoms and Bonding

The basic units of matter, called **atoms**, have three basic components: negatively charged **electrons**, positively charged **protons**, and uncharged **neutrons**. Protons and neutrons possess most of the mass of an atom and form the core or atomic nucleus, while the electrons orbit the nucleus in regions called “shells” (FIGURE 3.2a). There are some 92 different naturally occurring **elements**, all of which differ from one another based on the number of protons and neutrons in the atomic nucleus and the number of electrons orbiting the atomic nucleus (FIGURE 3.2b). Of these, about 25 are commonly found in microbes and other organisms. The four most abundant are hydrogen (H), carbon (C), nitrogen (N), and oxygen (O).

In a very real way, the atoms are like a box of Legos® in that atoms of different sizes and configurations can “snap together,” provided the atoms fit, to form different structures. When this happens, the electrons of the interacting atoms are held together by **chemical bonds** formed between electrons in the interacting atoms. So, **molecules** are simply two or more atoms bonded together by their electrons. For example, the gases used in the Miller-Urey experiment included methane and ammonia. Methane

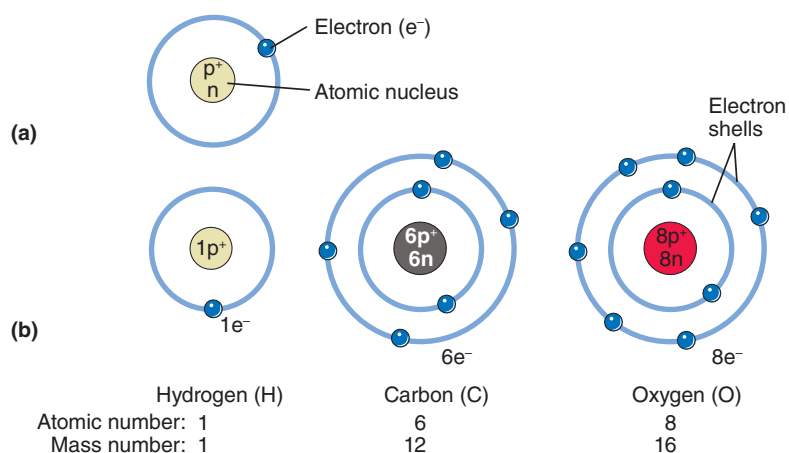
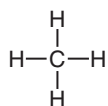


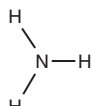
FIGURE 3.2 The Structure of Atoms. (a) An atom consists of protons and neutrons in the atomic nucleus and surrounding shells of electrons. (b) Different atoms have different numbers of protons, neutrons, and electrons.

■ **MM01:**
methane molecule

■ **MM02:**
ammonia molecule



Methane



Ammonia

■ **MM03:**
water molecule



Water

■ **solvent** The substance doing the dissolving in a solution.

■ **solute** The substance dissolved in a solution.

consists of one carbon atom bonded to four hydrogen atoms and is written as CH_4 (Note: if there is just one atom in a molecule, there is no subscript number used); ammonia is written as NH_3 . In addition, many of the molecules contain carbon and one refers to such carbon-containing chemicals as **organic** molecules.

Water

Another very important molecule for life is water, a molecule consisting of three atoms—two hydrogen (H) and one oxygen (O) and is written as H_2O . Approximately 70% of the mass of a cell is water, demonstrating that no organism can survive and grow without water, and many organisms, including microbes, live in water.

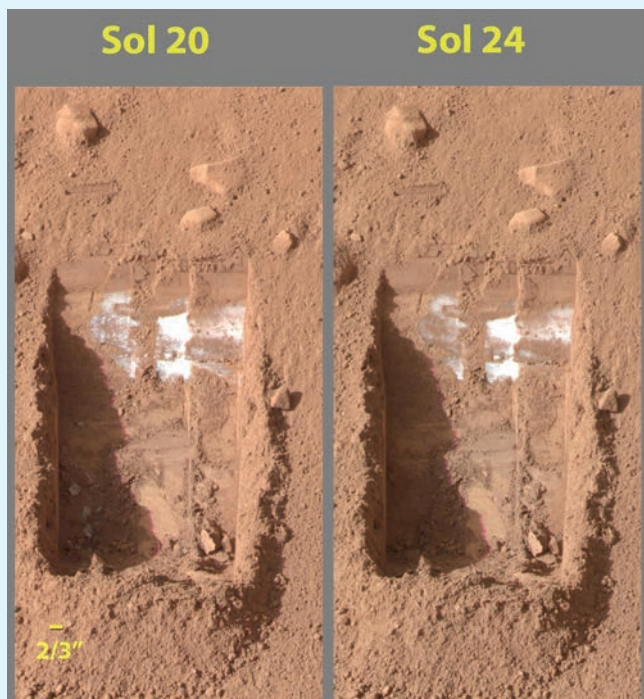
Liquid water is the medium in which all cellular chemical reactions occur because water acts as the universal **solvent** in cells. Take for example what happens when you put a **solute** like salt or sugar in water. The salt and sugar dissolve, forming an **aqueous solution**; that is, one or more solutes dissolved in water. Water molecules also are part of many chemical reactions, as we will see later in this chapter.

Besides its solvent properties, water also has other characteristics that make it an ideal molecule for life, as pointed out in **A Closer Look 3.1**.

A CLOSER LOOK 3.1

Water and Life

Life on Earth certainly evolved in a watery primordial soup some 3.8 billion years ago and remained in a water environment for some 3 billion years before spreading to land where survival still depended on water. Without water, the human body would be unable to survive for more than one week. In fact, water is such a necessity for life as we know it, that when scientists send spacecraft and rovers in search for traces of microbial life on other worlds, such as Mars, water is one of the most important molecules they look for (see figure).



The white bits in this photo are Martian water ice.

Courtesy of JPL-Caltech/University of Arizona/Texas A&M University/NASA.

Besides its property as the solvent for life, what are water's other life-supporting properties? We can identify three.

- **Cohesion.** Water molecules will stick together due to weak bonding. The sticking together is called cohesion. For example, it is the cohesion between water molecules that allows water to be transported up trees from the roots to the leaves. Also, by sticking together, water has a high surface tension; it is hard to break water molecules apart. That means small insects can “walk on water” as if there was a film on the water surface.
- **Temperature moderation.** It takes a lot of energy (heat) to raise the temperature of water. For instance, if you have ever accidentally touched a metal pot full of water being heated, the metal heats up much faster than the water as a misdirected finger will attest. The bonding between water molecules gives water a stronger resistance to temperature changes than occurs with most other substances. Likewise, coastal areas, bordering an ocean, such as San Diego, in the summertime tend to have more moderate air temperatures than deserts, such as around Phoenix, because of the higher humidity (water content) in the atmosphere. There is more water to absorb the heat along the ocean coast. In the human body, water also moderates body temperature by evaporative cooling. When water evaporates, the water left behind cools down because the water molecules with the greatest energy (the

A CLOSER LOOK 3.1

Water and Life . . .

“hottest” ones) vaporize first. That’s why sweating is important—it helps prevent an individual from overheating.

- **Insulation.** As you know, frozen water (ice) floats, unlike most substances that will sink on freezing. These substances sink because the atoms move closer together and become denser than the surrounding liquid when frozen. Due to bonding between water molecules, these molecules move farther apart, making the ice less dense than the surrounding liquid water and the ice therefore floats.

By ice floating it acts as insulation. If frozen water was denser than liquid water, it would sink and in the winter all ponds and lakes (and perhaps oceans too) would eventually freeze solid, freezing any living creatures (including microbes). However, because ice floats, it forms an insulating “blanket” over the body of water in winter, allowing the water underneath to remain liquid—and life to survive.

So drink up and stay hydrated. And that goes for microbes too!!

The Molecules of Microbes

Most of the molecules in a cell involved in structure and cell function—including metabolism, cell movement, and cell growth—are significantly larger than simple molecules like methane and water. Indeed, the molecules of life often are hundreds to billions of atoms in size. For this reason, they are called “macromolecules” (*macro* = “large”) and form the carbohydrates, lipids, proteins, and nucleic acids. Their structural differences will be in the way the atoms in each macromolecule are bonded together.

3.2 Carbohydrates: Simple Sugars and Polysaccharides

Carbohydrates are organic molecules containing carbon, hydrogen, and oxygen, generally in a ratio of one atom of carbon to two atoms of hydrogen to one atom of oxygen. Thus, the basic formula unit for a carbohydrate is CH_2O .

Carbohydrates vary from relatively small, simple molecules to extremely large, complex macromolecules. The smallest carbohydrates are the simple sugars, which include the **monosaccharides** (“single sugars”) and **disaccharides** (“double sugars”), both names derived from the Latin word *saccharo* meaning “sugar.” Slightly larger molecules are referred to as “oligosaccharides” (*oligo* = “few”), while those composed of thousands of monosaccharides are called **polysaccharides** (*poly* = “many”).

Some carbohydrates, such as the sugars, serve as energy sources in cells while others, specifically the polysaccharides, either store energy (starches) or build the cell walls of most all prokaryotes, and those of the eukaryotic algae and fungi (and plants of course).

Simple Sugars

A monosaccharide may contain three to seven carbon atoms. Among the most significant monosaccharides are the five-carbon sugars (pentoses), such as ribose and deoxyribose and the six-carbon sugars (hexoses), including glucose, fructose, and galactose. These three hexoses have the same numbers of carbon, hydrogen, and oxygen atoms, and they all have the same chemical formula: $\text{C}_6\text{H}_{12}\text{O}_6$. However, their atoms are snapped together in a different order and are called **isomers** of one another.

Monosaccharides, especially glucose, act as the fundamental building blocks for larger carbohydrate molecules and as sources of energy for cellular processes. These monosaccharides can be bonded together in a chemical reaction that involves

■ **isomer** A substance that has the same number and types of atoms as another substance but where the atoms are arranged differently.

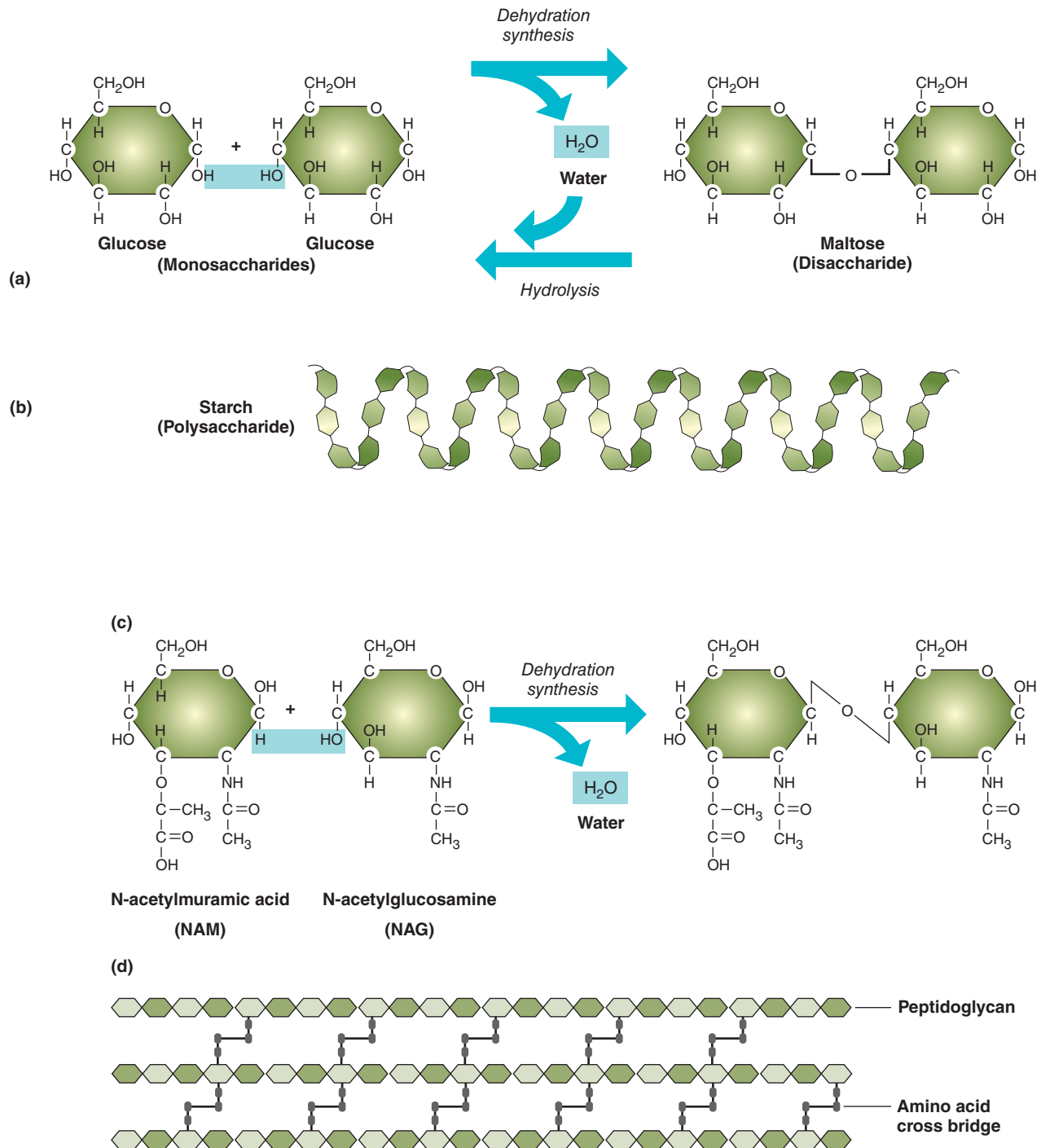


FIGURE 3.3 Carbohydrates Consist of the Monosaccharides, Disaccharides, and Polysaccharides. (a) Glucose is a monosaccharide that can bond with another glucose in a dehydration synthesis reaction to form maltose, a disaccharide. (b) The bonding of additional glucose molecules leads to the formation of a polysaccharide, such as starch. Note that each little hexagon is glucose. (c) N-acetylmuramic acid (NAM) and N-acetylglucosamine (NAG) are modified simple sugars that can bond together to form the bacterial cell wall peptidoglycan. (d) Peptidoglycans can be held together by side chains of amino acids.

the removal of H_2O from the sugars. When water is lost during the synthesis of a molecule, it is known as a **dehydration synthesis reaction** (FIGURE 3.3a). These reactions involve the action of cellular **enzymes**, protein molecules capable of rearranging the components of organic substances while themselves remaining unchanged.

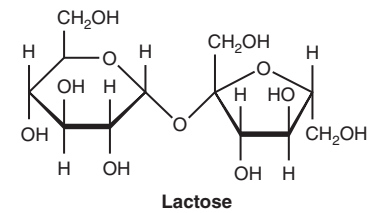
The linking together of two monosaccharide molecules through a dehydration synthesis reaction forms a disaccharide (see **FIGURE 3.3a**). Among the commonly encountered disaccharides is maltose, also known as malt sugar. This disaccharide is found in cereal grains such as barley, where the sugar is fermented by yeast cells in the absence of oxygen to produce the alcohol in beer. Another well-known disaccharide is lactose, the principal carbohydrate in milk. This carbohydrate is a combination of a glucose molecule and a galactose molecule. Lactose can be chemically changed to lactic acid by certain species of bacteria. The acid causes milk to become sour. However, the reaction can be controlled and used in the dairy industry to produce yogurt, buttermilk, and sour cream (depending on the starting material). A third disaccharide, sucrose, is a combination of a glucose molecule and a fructose molecule. It is commonly known as table sugar.

Polysaccharides

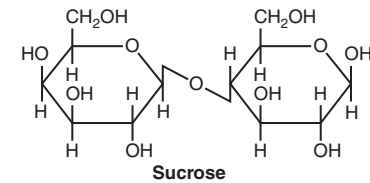
The polysaccharides are extremely large and complex carbohydrate molecules. A single polysaccharide molecule may contain hundreds or thousands of monosaccharide subunits bonded together through dehydration synthesis reactions. One example of an “energy polysaccharide” is **starch**, which is composed exclusively of glucose molecules (**FIGURE 3.3b**). Starch is typically found in many plants like potatoes and corn. Organisms from microbes to humans can break down starch to obtain the constituent glucose monosaccharides that are then used for energy production. This tearing apart of a molecule is known as a **hydrolysis reaction** and it involves enzymes along with the addition of water molecules.

Other large carbohydrate polymers are “structural polysaccharides.” For example, **cellulose**, a major part of plant cell walls, is also composed of long fibers made of glucose. However, the glucose molecules in cellulose are linked together differently than in starch and humans lack the necessary enzyme to break these linkages. Therefore, we cannot digest the cellulose present in the plant foods we eat—and we therefore excrete the cellulose as roughage or so-called “dietary fiber.” Unlike humans, termites and herbivores primarily ingest cellulose (e.g., wood, grasses, and hay) for energy. How can they break down cellulose but we can't? **A Closer Look 3.2** provides the microbial solution.

■ **MM04:**
lactose molecule



■ **MM05:**
sucrose molecule



A CLOSER LOOK 3.2

What's in Your Gut?

Due to their wood-eating habits, termites cause more damage to American homes than do tornadoes, fires, and earthquakes combined. The cost is estimated to be over \$5 billion annually. On the positive side, around the world, more than 2,600 species of termites are busily breaking down tons of fallen, dead trees and other woody plants, digesting the wood (primarily cellulose) that is the main component of plant cell walls. Ecologically, termites are critical to the recycling of the forests nutrients. But without microbes, the digestion of these polysaccharides (for good or bad) by termites would be impossible.

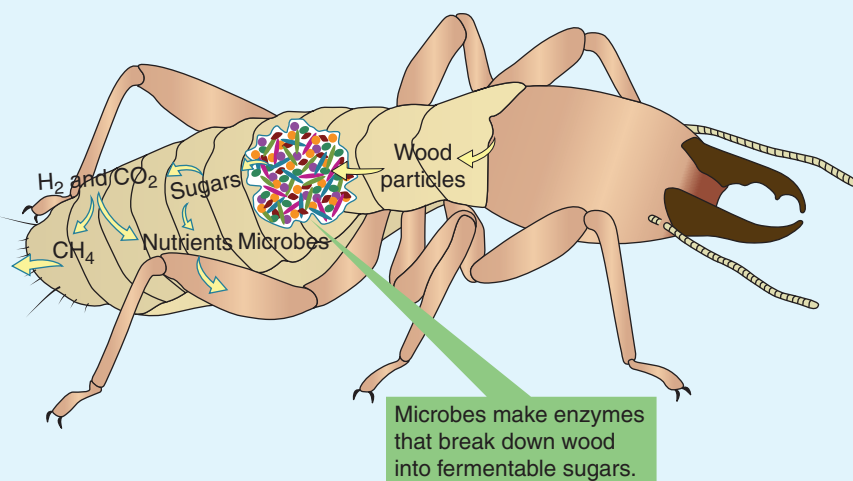
Within a termite's gut is one of nature's most efficient bioreactors—a microbial community capable of converting

95% of cellulose into simple sugars within 24 hours. This microbial community consists of more than 200 bacterial, archaeal, and protist species—many species not found anywhere else on Earth—that produce a variety of wood-digesting enzymes. So, without the wood-eating microbes, a termite could not extract needed nutrients and energy from the wood and without the termite to initially grind the wood into tiny pieces, the microbes could not survive in the termite's gut. This “living together,” called a symbiosis, between termite and gut microbes creates the energy-producing end-products both the termite and microbes need (see figure).

(continued)

A CLOSER LOOK 3.2

What's in Your Gut? (continued)



A drawing illustrating the microbial products of cellulose digestion in the termite gut.

A similar symbiotic scenario plays out between cows (and other ruminants) and their home-dwelling microbes. For example, cows re-chew their food [primarily grass in summer and silage (preserved grass or corn) in winter] to increase the surface area for digestion. However, that

digestion is not primarily done by cow enzymes. Of the cow's four so-called "stomachs," the rumen is especially important because it contains billions of microbes (bacterial, archaeal, protist, and fungal species) that help the bovines digest cellulose and other similar polysaccharides. And like those in the termite gut, the bovine microorganisms all depend on each other for survival, the by-products from one species being used by another.

So why can't we digest cellulose and most other plant polysaccharides? After all, we also have billions of microbes in our gut. Unfortunately we do not have the microbes capable of producing the massive numbers of cellulose-busting enzymes. Here's a science fiction thought for discussion: Suppose an "experiment" was carried out that supplied our gut with a resident population of microbes capable of digesting cellulose. How would this change affect our food consumption, both personally and on a global scale?

The bacterial cell wall also is a structural polysaccharide made from sugars that have been modified to contain nitrogen (FIGURE 3.3c). These sugars, N-acetylmuramic acid (NAM) and N-acetylglucosamine (NAG), form through dehydration synthesis reactions into long fibers called **peptidoglycan**. In many cases, multiple layers of peptidoglycan build the cell wall and the adjacent chains are stabilized and held together by cross bridges made of amino acids.

3.3 Lipids: Fats, Phospholipids, and Sterols

We are all familiar with some types of **lipids**, such as the animal fats and plant oils in our diet. Like the carbohydrates, these lipids are used by some microbes and many other organisms for energy and energy storage. Lipids are built from carbon, hydrogen, and oxygen atoms, but there are more carbon-hydrogen bonds in a lipid than in a carbohydrate. As a result, there is more energy that can be harvested from a fat or oil than from a similar weight carbohydrate.

As you know, if you shake a mixture of water and oil, the two liquids will separate from one another because lipids do not dissolve in water. We therefore say lipids are **hydrophobic** (*hydro* = "water;" *phobic* = "fearing") whereas simple sugars like glucose and sucrose are **hydrophilic** (*philic* = "loving") and dissolve in water. Because lipids do not dissolve in water, environmental cleanup of major oil spills is a challenging task to which microbes can be of great assistance, as revealed in A Closer Look 3.3.

A CLOSER LOOK 3.3

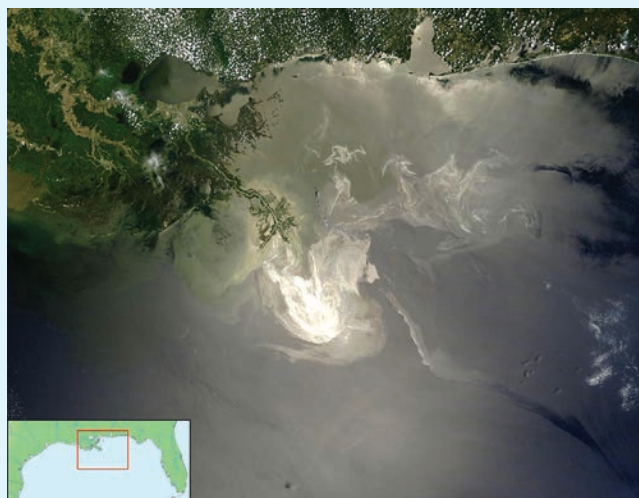
Microbes to the Rescue!

On April 20, 2010, the *Deepwater Horizon* drilling rig that was working on a well for the British Petroleum oil company blew up in the Gulf of Mexico. Four days later, engineers discovered the wellhead was damaged and was leaking oil and methane gas into the Gulf. For 3 months, oil spilled into the Gulf and contaminated nearby shores and wetlands (see figure), making it the largest accidental oil spill in history. According to federal government estimates, some 5 million barrels, or 780 million liters, were spilled, and it was not until September that the well was declared sealed. Then, within weeks, many parts of the Gulf were almost oil free. Where did all the spilled oil go?

An oil well, such as the *Deepwater Horizon*, produced primarily crude oil (petroleum), which is "unprocessed" oil. For decades, scientists have tried to use bioremediation—the breakdown (biodegradation) of contaminating compounds using microorganisms—as a natural method for cleaning up some of the environment's worst chemical hazards, including oil spills.

But what about all the crude oil released and dispersed from the ruptured *Deepwater Horizon* well? Could local bacterial species present in the Gulf act as natural bioremediation agents? It appears they did!

The Gulf has many natural oil seeps and resident bacterial species have evolved the metabolism needed to break down the oil. So, when the *Deepwater Horizon* spill occurred, oil-hungry bacterial cells were ready to multiply and able to consume much of the oil. It remains to be determined just how efficient these oil



Sunlight is reflected off the *Deepwater Horizon* oil spill in the Gulf of Mexico on May 24, 2010. The image was taken by NASA's Terra satellite.

Courtesy of NASA/GSFC, MODIS Rapid Response.

denizens were in mopping up the oil, but it is clear they were intimately involved in the cleanup. The spill might have been even worse if it was not for the bacterial species present in the Gulf waters. Still, microbes cannot eliminate or digest all the oil and it may be several years before the Gulf and the wetlands are completely recovered.

Based on their chemical composition, lipids may be subdivided into three different groups: fats and oils, phospholipids, and sterols.

Fats and Oils

Fats and oils contain two components, a three-carbon molecule called glycerol and three long chains of carbon atoms called fatty acid molecules (FIGURE 3.4). The synthesis of a fat or oil is the result of each fatty acid being joined to the glycerol through a dehydration synthesis reaction. A fatty acid is considered to be **saturated** if it contains the maximum number of hydrogen atoms extending from the carbon backbone, whereas a fatty acid is **unsaturated** if it contains less than the maximum hydrogen atoms. Notice in FIGURE 3.4 that two of the chains are saturated and straight while the third is unsaturated and bent. Importantly, saturated fatty acids tend to make the fat solid at room temperature (e.g., butter) while unsaturated fatty acids tend to make the fat liquid at room temperature and would be then be called an oil (e.g., vegetable and fish oils).

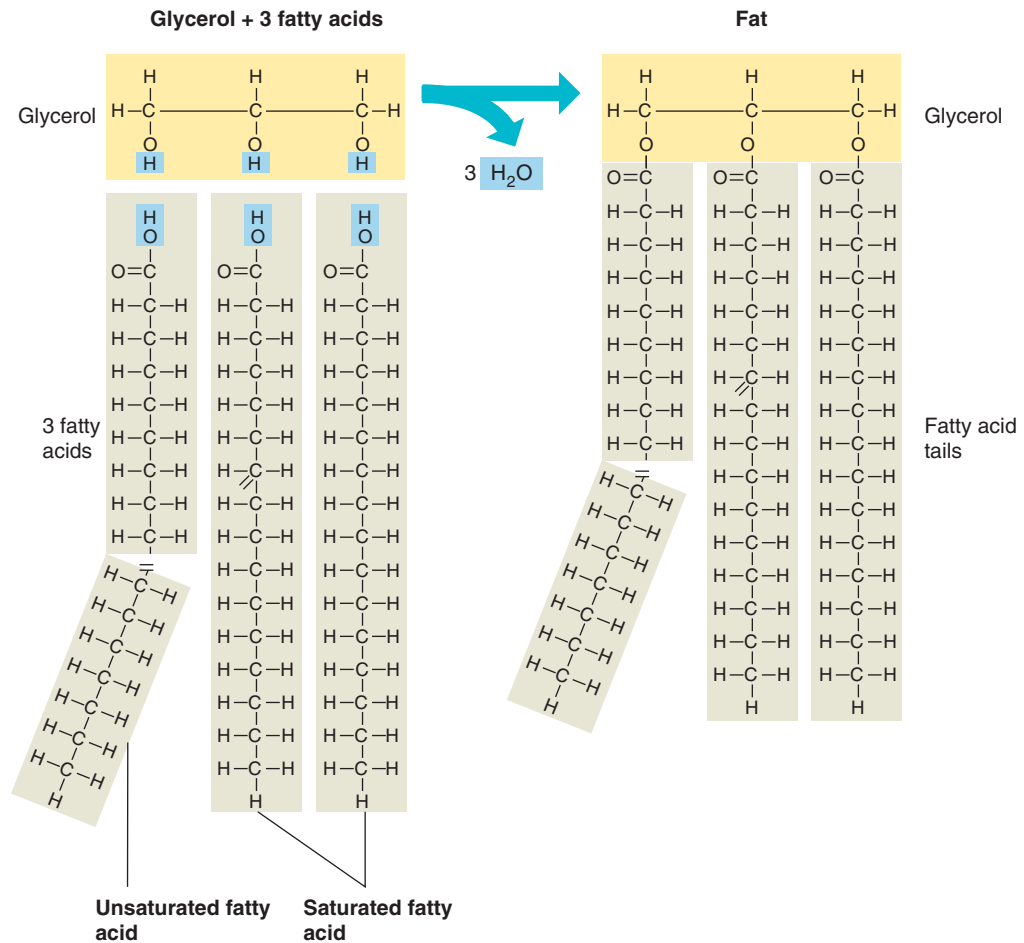


FIGURE 3.4 Glycerol and Fatty Acids Combine to Form a Fat. Glycerol is a three-carbon molecule and fatty acids are long carbon–hydrogen chains that can be saturated or unsaturated. Three fatty acid chains can combine with each glycerol through dehydration synthesis reactions to form fat.

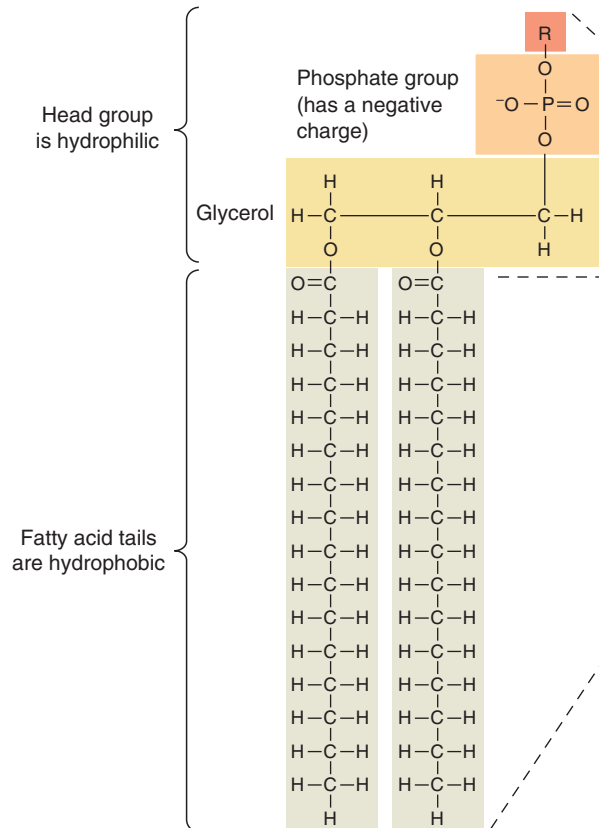
Phospholipids

Phospholipids are phosphorus-containing lipids that possess a phosphate group (PO_4) in the place of one fatty acid chain (**FIGURE 3.5a**). The phosphate group makes the “head” end of the phospholipid hydrophilic, while the fatty acid tails are hydrophobic. This gives the phospholipid the property of being “amphipathic,” meaning one portion is hydrophobic (the tails) and another portion is hydrophilic (the head) (**FIGURE 3.5b**). The amphipathic property of the phospholipid is the basis on which the cell forms a membrane in a watery environment. By organizing as a double-layer (or bilayer), phospholipids can accommodate a watery exterior with hydrophilic head groups toward the cell environment, and accommodate the watery interior of the cell with hydrophilic head groups toward the cytoplasm (**FIGURE 3.5c**). Such a configuration also allows the hydrophobic fatty acid tails to associate with one another and not be exposed to water.

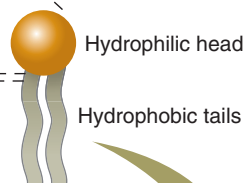
Sterols

Other types of lipids include the **sterols**, which are very different from fats and phospholipids, and are included with lipids solely because they too are hydrophobic molecules. Sterols play structural roles in microbes by stabilizing cell membranes of a few bacterial species as well as the membranes of protists and fungi. The sterol cholesterol is found in the plasma membranes of human cells.

(a) Molecular model of a phospholipid



(b) Schematic model of a phospholipid



(c) The cell membrane is a phospholipid bilayer

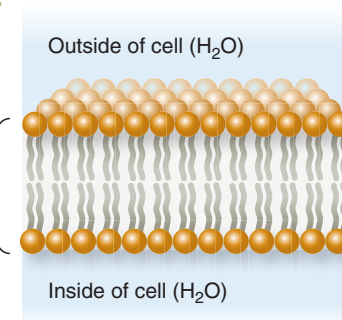


FIGURE 3.5 Phospholipid, the Lipid of Cell Membranes. (a) Phospholipids are composed of glycerol and two fatty acid tails and a charged phosphate group. The charge makes this region of the phospholipid hydrophilic. (b) A schematic drawing of a phospholipid with the glycerol and head group shown as a circle with the fatty acid tails drawn by two lines. (c) The membrane of the cell is a phospholipid bilayer. This allows the hydrophilic head groups to associate with the watery exterior and interior of the cell.

3.4 Proteins: Amino Acids and Polypeptides

Proteins are the most abundant large molecules in all living organisms, including microorganisms. Composed of carbon, hydrogen, oxygen, nitrogen, and, usually, sulfur atoms, proteins make up about 60% of a microbial cell's **dry weight**, this high percentage indicating the essential and diverse roles of proteins. Many proteins function as structural components of cells and cell walls, and as transport agents in membranes. A large number of proteins also serve as enzymes that catalyze all the chemical reactions of metabolism, although sometimes we need to help metabolism. A **Closer Look 3.4** describes one embarrassing situation where microbial enzymes come to the rescue. In addition, viruses are composed of genetic information enclosed in a covering of protein.

■ **dry weight** The weight of the materials in a cell after all the water is removed.

A CLOSER LOOK 3.4

"Not Without My Beano®!"

Some people would not dare sit down to a meal of corned beef and cabbage without a knife, fork, soda bread—and, of course, their Beano®. Nor would they have Brussels sprouts with their steak or broccoli with their fried chicken

unless they were sure their Beano was nearby. Eating pasta e fagioli ("pasta and beans") without Beano? Some say—"No thanks!"

(continued)

A CLOSER LOOK 3.4

"Not Without My Beano®!" (continued)



Beans are one source of raffinose carbohydrate.

Courtesy of Debora Cartagena/CDC.

So what's the problem? Cabbage, broccoli, Brussels sprouts, and other "strong tasting" vegetables, and high-fiber foods like beans, contain a family of

oligosaccharides (3–5 monosaccharides in length) called raffinose. Unfortunately, humans lack the ability to produce the enzyme needed to break down raffinose. That means the oligosaccharides pass undigested into the large intestine where resident bacteria of our human microbiome have the enzyme to digest raffinose, but in the process also produces gas (methane, carbon dioxide, and hydrogen). Now unfortunate individuals pay a heavy price: gas (flatulence), bloating, embarrassment—and an unwillingness to go back for seconds.

Enter Beano, the trade name for an enzyme preparation produced from the mold *Aspergillus niger*. The enzyme breaks down raffinose into the simple sugars galactose, fructose, and glucose, and leaves nothing for the intestinal bacteria to work on. So, all it takes is a couple of Beano tablets just before eating the first bites of food (it tastes somewhat like soy sauce) and the fungal enzyme breaks down the raffinose, leaving a happy memory of the meal (or so says the manufacturer).

■ **Pronunciation1:**
Aspergillus niger

Amino Acids

All proteins are built from subunits called **amino acids**, whose fundamental structure is shown in **FIGURE 3.6a**. This structure includes one amino group (NH_2) and one carboxyl group (COOH) bonded together through a central carbon atom. The amino acids vary from one another on the basis of what atoms are attached as a side group to this central carbon. This side-group of atoms, known as the "R-group," can be as simple as a hydrogen in the case of glycine, or involve other combinations of atoms, some of which are shown in **FIGURE 3.5b** for the amino acids alanine, valine, and lysine. Notice cysteine is one of the sulfur-containing amino acids. In all, up to 20 different combinations of atoms form the R-groups, which means there are 20 different amino acids available to build proteins.

Similar to the way polysaccharides are built from monosaccharide subunits, proteins are built from amino acids by means of dehydration synthesis reactions (**FIGURE 3.7**). The bond linking two amino acids is referred to as a **peptide bond**. By forming successive peptide bonds, more and more amino acids can be added to the growing chain. The final number of amino acids in a chain may vary from a very few (in which case, the small protein is called a "peptide") to thousands making a **polypeptide**. A protein then is composed of one or more polypeptides and an extraordinary variety of proteins can be formed from the 20 available amino acids.

Protein Shape

Because proteins play diverse roles and carry out most of the metabolic activities of the cell, they have tremendous differences in shape. Protein shape can be defined on three or four levels of structure.

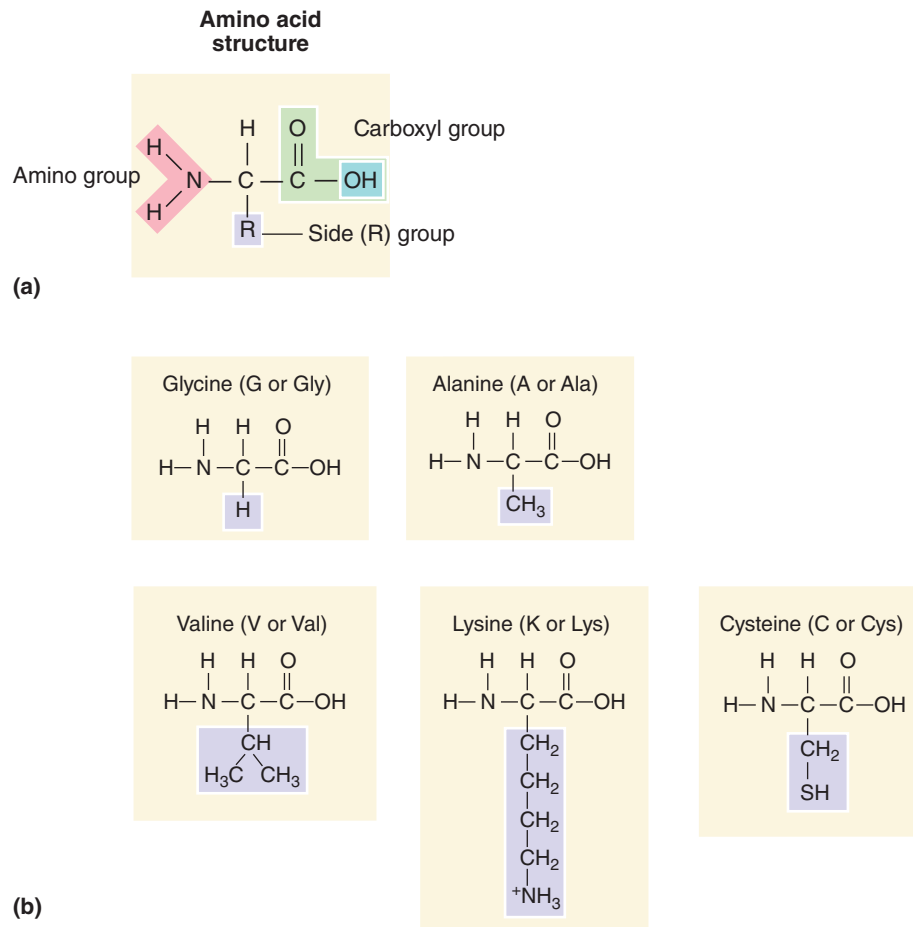


FIGURE 3.6 The Structure of Amino Acids. (a) All amino acids have the same basic structure, but each varies by the R-group, which is a set of atoms attached to the central carbon. (b) Five of the 20 amino acids are shown with their unique R-group.

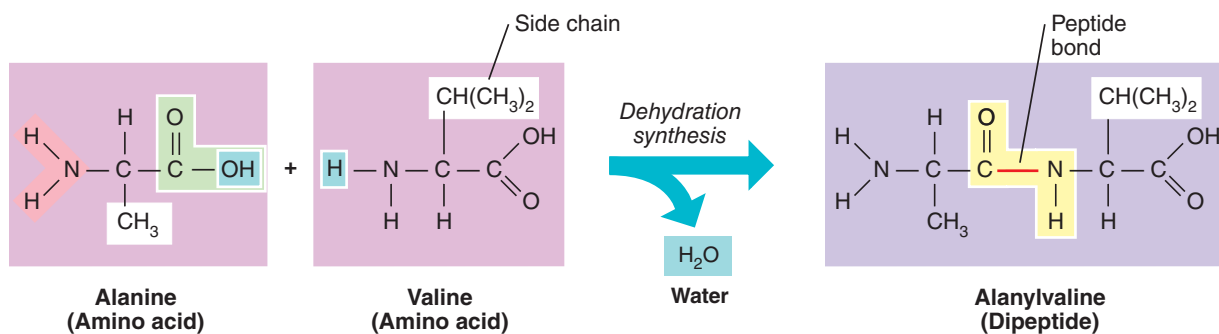


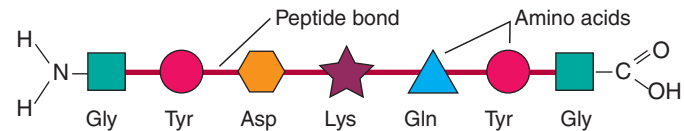
FIGURE 3.7 Formation of a Dipeptide. The amino acids alanine and valine are shown. The OH group from the acid group of alanine combines with the H from the amino group of valine to form water. The carbon atom of alanine and the nitrogen atom of valine then link together, yielding a peptide bond. Continued dehydration synthesis reactions will form a polypeptide.

Primary Structure. The specific sequence of amino acids in a polypeptide is referred to as the **primary structure** (FIGURE 3.8a). This sequence is unique to each polypeptide and is determined by the genetic information in each gene coding for a unique sequence of amino acids. However, a long chain of amino acids does not, in itself, form the final shape of the protein.

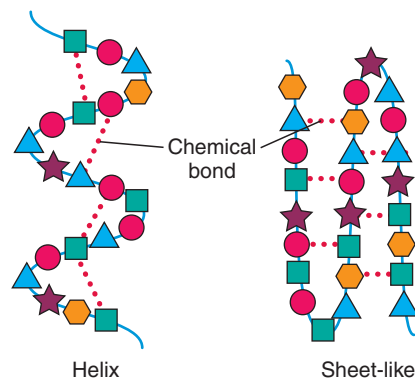
Secondary Structure. The amino acids in the primary sequence can interact with one another, forming the polypeptide's **secondary structure** (FIGURE 3.8b). Often this secondary structure takes on the form of a helix (coil) or a folded sheet-like structure.

Tertiary and Quaternary Structure. Most polypeptides can further fold to form the **tertiary structure** (FIGURE 3.8c). This three-dimensional shape depends on the interactions between R-groups of various amino acids in different regions of the polypeptide, giving the polypeptide a globular or fibrous structure.

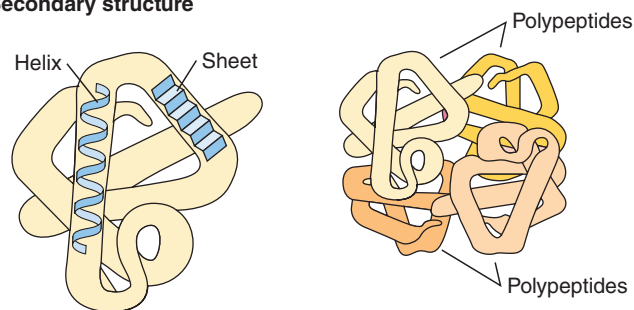
In some cases, two or more polypeptides bond together to form the final functional protein and this represents the **quaternary structure**. Examples include the red blood cell protein hemoglobin and antibodies, both of which consist of four polypeptides.



(a) Primary structure: polypeptide chain



(b) Secondary structure



(c) Tertiary and quaternary structure

FIGURE 3.8 Protein Structure. (a) The primary structure refers to the sequence of amino acids. (b) Interactions between amino acids can cause changes in shape of the polypeptide. Called the secondary structure, the shape is usually a helix or sheet-like structure. (c) A polypeptide can further fold back on itself through interactions between R-groups, forming the so-called tertiary structure. In addition, some proteins require more than one polypeptide to function, and the polypeptide configuration of these proteins is known as the quaternary structure.

The bonds between R-groups are relatively weak and can be easily disrupted, causing the protein to unravel and lose its shape. This process, referred to as **denaturation**, is brought about by heat, antiseptics, disinfectants, or other agents that alter the protein's surrounding environment. Loss of protein function may kill microbes or inhibit their growth. Also, a high fever (104°C or higher) can be fatal to an individual because blood proteins and enzymes are subject to denaturation and loss of function at high body temperatures.

3.5 Nucleic Acids: DNA and RNA

Nucleic acids are the fourth major group of large molecules found in all organisms and they are composed of carbon, hydrogen, oxygen, and nitrogen atoms. The two important nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. DNA is the nucleic acid of which chromosomes are composed and RNA is the nucleic acid involved in converting the information in a gene into a polypeptide.

Nucleic acids are built from subunits called **nucleotides** (FIGURE 3.9a). Each nucleotide is composed of three parts: a pentose sugar, a phosphate group (PO₄), and a nitrogen-containing molecule called a nitrogenous base, or simply, a **nucleobase**. The pentose sugar in DNA is deoxyribose, while in RNA it is ribose.

The four nucleobases in DNA are adenine, guanine, cytosine, and thymine; in RNA, they are adenine, guanine, cytosine, and uracil. (Note that DNA has thymine but no uracil, and RNA has uracil but no thymine.) Adenine and guanine are double-ring molecules called “purines,” while cytosine, thymine, and uracil are single-ring molecules called “pyrimidines.”

The phosphate group found in nucleic acids links the sugars to one another in both DNA and RNA (FIGURE 3.9b). The chain of alternating sugar and phosphate subunits forms the so-called sugar-phosphate “backbone.”

To visualize a DNA molecule, picture a ladder. In the molecule, two sugar-phosphate backbones make up the sides of the ladder, and the rungs (the steps) of the ladder are composed of the nucleobases (FIGURE 3.9c). On one side of each rung is a purine molecule, and on the other side is a pyrimidine molecule. Thus, an adenine molecule always bonds with a thymine molecule (and vice versa), and a guanine molecule with a cytosine molecule (and vice versa). The ladder is then twisted into a spiral staircase-like structure called a **double helix**. Microbes and all other living organisms have their DNA in this form.

RNA is a single-stranded molecule with a single sugar-phosphate backbone from which protrudes the nucleobases. TABLE 3.1 summarizes the differences between DNA and RNA.

Like proteins, nucleic acids cannot be denatured without injuring the microbe or killing it. For example, ultraviolet (UV) and gamma ray radiations damage or break DNA and can be used to lower the microbial population on an environmental surface or sterilize food products. Chemicals such as formaldehyde alter the nucleic acids of viruses and can be used to produce some viral vaccines. Moreover, certain antibiotics interfere with nucleic acid activity, thereby killing bacteria. We shall encounter many other instances where tampering with nucleic acids or with the other key organic molecules of a microbe leads to its destruction.

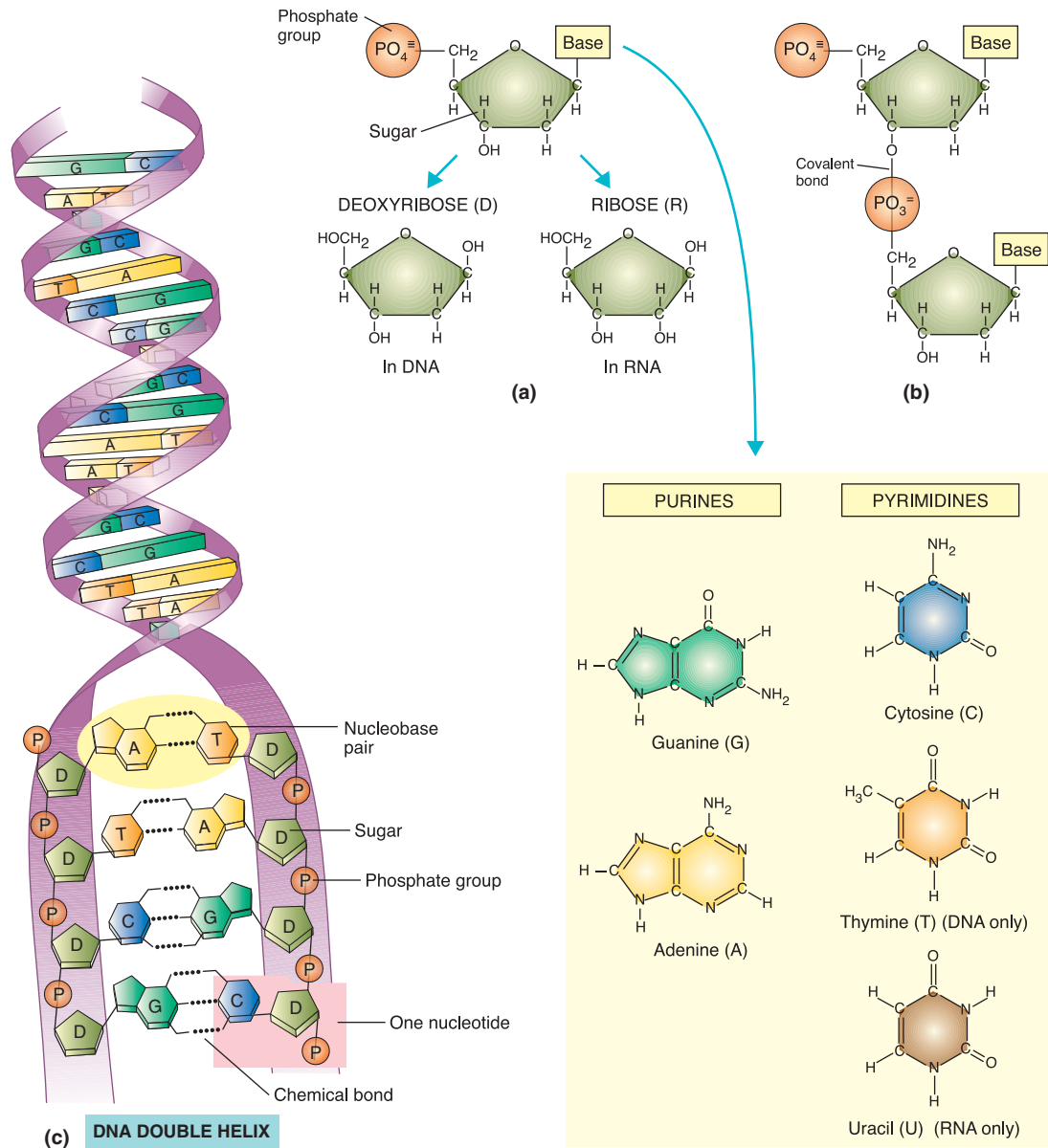


FIGURE 3.9 The Molecular Structures of Nucleotide Components and the Construction of DNA.

(a) The sugars in nucleotides are ribose and deoxyribose, which are identical except for one additional oxygen atom in RNA. The nucleobases include the purines adenine and guanine and the pyrimidines thymine, cytosine, and uracil. (b) Nucleotides are bonded together by dehydration synthesis reactions. (c) The two polynucleotides of DNA are held together by chemical bonds between adenine (A) and thymine (T) or guanine (G) and cytosine (C) to form a double helix.

TABLE

3.1 A Comparison of DNA and RNA

Property	DNA	RNA
Pentose sugar	Deoxyribose	Ribose
Nucleobases	Adenine (A), guanine (G), cytosine (C), thymine (T)	Adenine (A), guanine (G), cytosine (C), uracil (U)
Number of polynucleotides	2 (double helix)	1

A Final Thought

We could probably talk about microbes without talking about their chemistry, but it would be like trying to describe a Big Mac[®] without knowing what is in the hamburger. We realize that to some people, the word “chemistry” is equivalent to “root canal,” but we also know chemical molecules are the nuts and bolts of all living organisms—and viruses, too.

In other chapters, we shall discuss milk products containing “carbohydrates,” membranes composed of “lipids,” antibodies consisting of “proteins,” genes composed of “nucleic acids,” and a host of other concepts that include a smattering of chemistry. To understand how yeasts cause bread to rise, we must understand the chemistry of the process; and to explain genetic engineering to our friends, we must know a bit of the chemistry behind the process. Viral replication is centered in chemistry; the production of yogurt is a chemical process; and the process of disinfection is based in chemistry.

We recommend you give this chapter on chemistry a careful reading. In succeeding chapters, you will find that your investment of time was worthwhile.

Questions to Consider

1. Polysaccharides are important sources of sugar for energy; however, polysaccharides are also important structural components of the cell. Give an example of at least two structural polysaccharides. Which sugars are linked together to form these polysaccharides?
2. The cell membrane is made of phospholipids. What unique properties of phospholipids make this molecule uniquely adept at forming cell membranes?
3. Suppose you had the option of destroying one type of organic molecule in a bacterial species as a way of eliminating the microbe. Which type of molecule would you choose and why?
4. If proteins are all long chains of amino acids, then how can different proteins have different shapes and take on different functions?
5. Oxygen comprises about 65% of the weight of a living organism. This means a 120-pound person contains 78 pounds of oxygen. How can this be?
6. The toxin associated with the foodborne disease botulism is a protein. To avoid botulism, home canners are advised to heat preserved foods to boiling for at least 12 minutes. How does the heat help?

Key Terms

Informative facts are necessary for the expression of every concept, and the information for a concept is founded in a set of key terms. The following terms form the basis for the concepts of this chapter. On completing the chapter, you should be able to explain and/or define each one.

amino acid	denaturation
aqueous solution	deoxyribonucleic acid (DNA)
atom	disaccharide
carbohydrate	double helix
cellulose	electron
chemical bond	element
dehydration synthesis reaction	enzyme

fat	phospholipid
hydrolysis reaction	polypeptide
hydrophilic	polysaccharide
hydrophobic	primary structure
lipid	protein
molecule	proton
monosaccharide	quaternary structure
neutron	ribonucleic acid (RNA)
nucleic acid	saturated
nucleobase	secondary structure
nucleotide	starch
oil	sterol
organic	tertiary structure
peptide bond	unsaturated
peptidoglycan	