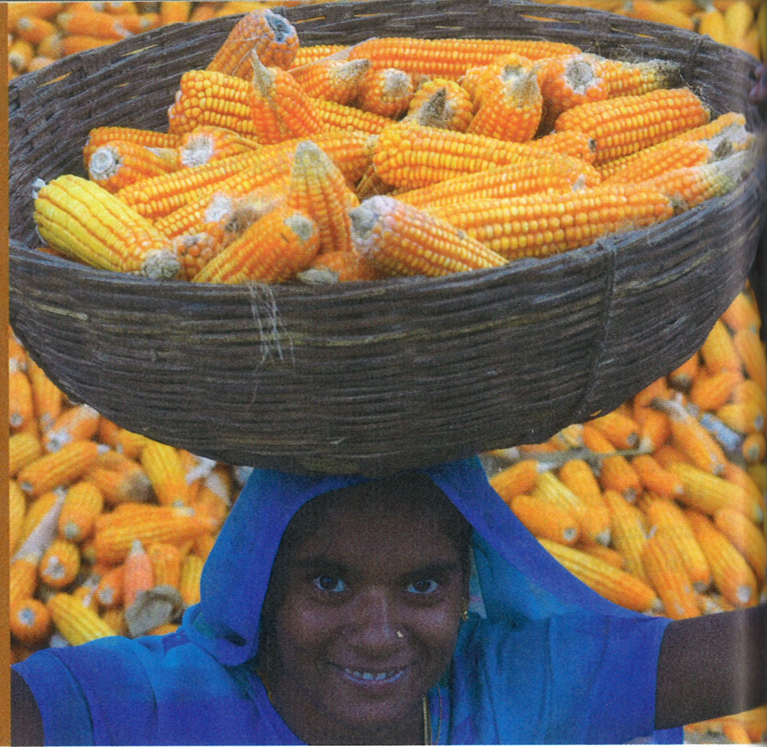
2·7–2·10 Carbohydrates are fuel for living machines.



Worldwide, more corn is produced (by weight) than any other grain.

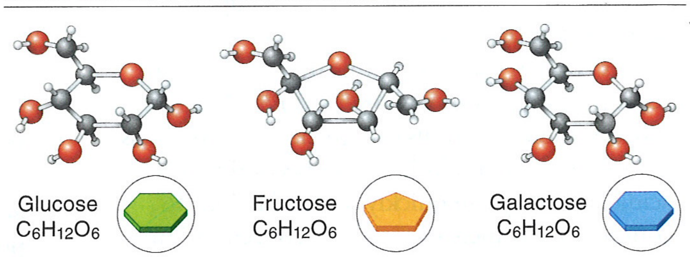
2·7 Carbohydrates include macromolecules that function as fuel.

Hardly a day goes by without an item in a magazine or newspaper or on TV talking about whether carbohydrates are good or bad for us. Sports drinks such as Gatorade are filled with carbs, and in the days before a big game or race, athletes often "carbo-load" by eating bowls of pasta. Yet other dietary supplements and "power" bars tout that they are low-carb and effective in weight loss by causing the body to resort to using fat for energy. Meanwhile, nutritionists, doctors, and many diet programs exhort people to increase the amount of fiber—another type of carbohydrate—in their diet. What exactly are they all talking about?

Four types of **macromolecules**—large molecules made up from smaller building blocks or subunits—are essential to the building and functioning of living organisms: carbohydrates, lipids, proteins, and nucleic acids. **Carbohydrates** are molecules that contain mostly carbon, hydrogen, and oxygen: they are the primary fuel for running all of the cellular machinery and also form much of the structure of cells in all life forms. Sometimes they contain atoms of other elements, but they must have carbon, hydrogen, and oxygen to be considered a carbohydrate (**FIGURE 2-20**). Additionally, a carbohydrate generally has approximately the same number of carbon atoms as it does H_2O units. For instance, the best-known carbohydrate, glucose, has the composition $C_6H_{12}O_6$ (6 carbons and, as a little math will show us, 6 H_2O units; notice that $6 \times H_2 = H_{12}$ and $6 \times O = O_6$). A carbohydrate called maltose has the composition $C_{12}H_{22}O_{11}$.

Carbohydrates are classified into several categories, based on their size and their composition. The simplest carbohydrates are the **monosaccharides,** or **simple sugars.** The simple sugars contain anywhere from three to six carbon atoms and, when they are broken down, the products usually are not carbohydrates. Two common monosaccharides are glucose, found in the sap and fruit of many plants, and fructose, found primarily in fruits and vegetables, as well as in honey. Fructose is the sweetest of all naturally occurring sugars. The suffix *-ose* tells us that a substance is a carbohydrate.

SOME COMMON MONOSACCHARIDES



Carbohydrates function well as fuels because of their many carbon-hydrogen bonds; as those bonds are broken down and other, more stable bonds (primarily between carbon and oxygen) are formed, a great deal of energy is released that organisms can utilize.

In the next section we investigate glucose, the chief carbohydrate used by organisms to fuel their activities.

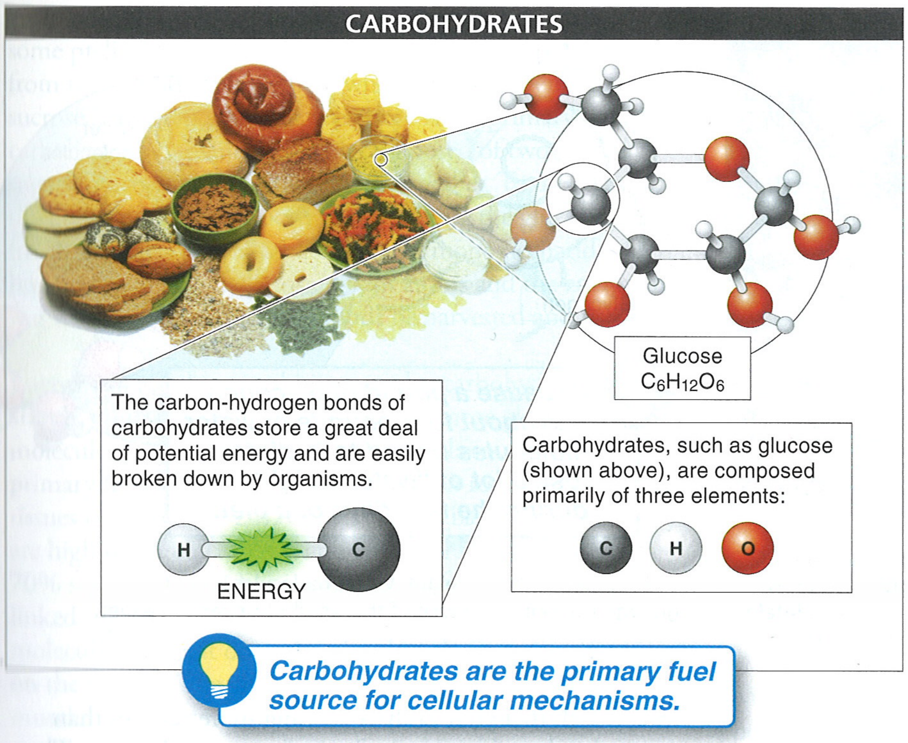


FIGURE 2-20 All carbohydrates have a similar structure and function.

TAKE-HOME MESSAGE 2·7

Carbohydrates are the primary fuel for running all cellular machinery and also form much of the structure of cells in all life forms. Carbohydrates contain carbon, hydrogen, and oxygen, and generally have the same number of carbon atoms as they do H_2O units. The simplest carbohydrates, including glucose, are monosaccharides or simple sugars. They contain from three to six carbon atoms. As the chemical bonds of carbohydrates are broken down and other more stable bonds are formed, a great deal of energy is released that can be used by organisms.

2·8 Glucose provides energy for the body's cells.

The carbohydrate of most importance to living organisms is glucose. This simple sugar is found naturally in most fruits, but most of the carbohydrates that you eat, including table sugar (called sucrose) and the starchy carbohydrates found in bread and potatoes, are converted into glucose in your digestive system. The glucose then circulates in your blood at a concentration of about 0.1%. Circulating glucose, also called "blood sugar," has one of three fates (**FIGURE 2-21**).

1. Fuel for cellular activity. Once it arrives at and enters a cell, glucose can be used as an energy source. Through a series of chemical reactions, the glucose molecule is converted into other molecules with stronger bonds (a process explained in detail in Chapter 4). The change from weaker bonds to stronger bonds releases energy, and organisms use the released energy to fuel cellular activity, including the muscle contractions that enable you to move and the nerve activities that enable you to think.

2. Stored temporarily as glycogen. If there is more glucose circulating in your bloodstream than is necessary to meet your body's current energy needs, the excess glucose can be temporarily stored in various tissues, primarily your muscles and liver. The stored glucose molecules are linked together to form a large web of molecules called **glycogen.** When you need energy later, the glycogen can easily be broken down to release glucose molecules back into your bloodstream. Glycogen is the primary form of short-term energy storage in animals.

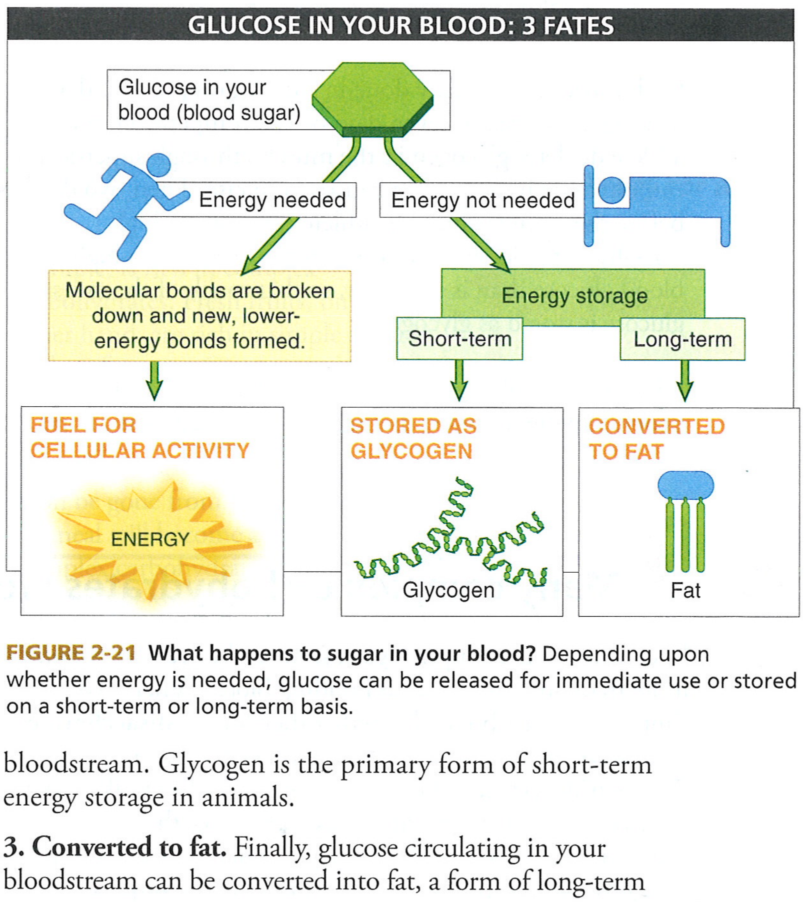


FIGURE 2-21 What happens to sugar in your blood? Depending upon whether energy is needed, glucose can be released for immediate use or stored on a short-term or long-term basis.

3. Converted to fat. Finally, glucose circulating in your bloodstream can be converted into fat, a form of long-term energy storage.

FIGURE 2-22 **Some competitive athletes carbo-load to maintain high energy levels.**

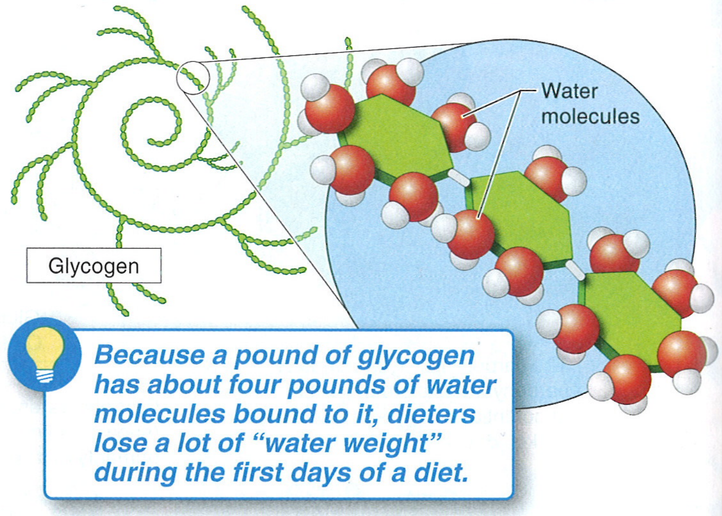


FIGURE 2-23 **Water weight.** Water molecules bound to glycogen account for much of the weight lost early in a diet.

"Carbo-loading" is a method by which athletes can, for a short time, double or triple the usual amount of glycogen stored in their muscles and liver, increasing the store of fuel available for extended exertion and delaying the onset of fatigue during an endurance event (**FIGURE 2-22**).

Q What is "carbo-loading"?

Carbo-loading is usually done in a depletion phase and a loading phase. Six or seven days before competition, the athlete depletes glycogen in the muscles through super-low carbohydrate intake and exhaustive exercise. Then two days before the competition, the athlete eats a super-high carbohydrate diet and reduces exercise to achieve a higher blood glucose than is necessary, so that much of the excess glucose is stored as glycogen.

Glycogen also plays a role in the initial rapid weight loss people experience when dieting. If you reduce your caloric intake such that your body is burning more calories than you are consuming, your body must use stored energy. The first, most accessible molecules that can be broken down for energy in the absence of sufficient sugar in your bloodstream are glycogen molecules in your muscles and liver. Large amounts of water are bound to glycogen. As that glycogen is removed from your tissue, so, too, is the water. This leads to the initial dramatic weight loss that occurs before your body resorts to using stored fat, and the rate of weight loss slows considerably (**FIGURE 2-23**).

TAKE-HOME MESSAGE 2·8

Glucose is the most important carbohydrate to living organisms. Glucose in the bloodstream can be used as an energy source, can be stored as glycogen in the muscles and liver for later use, or can be converted to fat.

2·9 Many complex carbohydrates are time-release packets of energy.

In contrast to the simple sugars, some carbohydrates contain more than one sugar unit or building block. When two simple sugars are bonded together they form a **disaccharide;** the joining of glucose and galactose, for example, makes the disaccharide lactose, which is the sugar found in milk. When large numbers of simple sugars are joined together—sometimes as many as 10,000 may be linked—the resulting carbohydrate is called a **polysaccharide,** or a **complex carbohydrate** (**FIGURE 2-24**). Depending on how the simple sugars are bonded together, polysaccharides may function as "time-release" stores of energy or as structural materials that may be completely indigestible by most animals. An example of such a structural material is the polysaccharide cellulose—the primary component of plant cell walls.

Like simple sugars, many disaccharides and polysaccharides are important sources of fuel for cells. Unlike simple sugars, however, disaccharides and polysaccharides must undergo some preliminary processing before the energy can be released from their bonds. Let's look at what happens when we eat sucrose, common table sugar. Sucrose is the primary carbohydrate in plant sap and is composed of two simple sugars, glucose and fructose, linked together. To use sucrose, the body must first break the bond linking the glucose and fructose. Only then can the individual monosaccharides be broken down into their component atoms and the energy that was stored in their chemical bonds be harvested and used.

Energy can also be stored in a complex carbohydrate called **starch,** which consists of a hundred or more glucose molecules joined together in a line. In plants, starch is the primary form of energy storage, found in roots and other tissues (see Figure 2-24). Grains such as barley, wheat, and rye are high in starch content, and corn and rice are more than 70% starch. Although it is composed of glucose molecules linked together, starch does not taste sweet. Because of its molecular shape, it does not stimulate the sweetness receptors on the tongue. The glycogen that stores energy in your muscles and liver is also a complex carbohydrate, so it is sometimes referred to as "animal starch" (although it has a more branched structure than starch and carries more glucose units linked together).

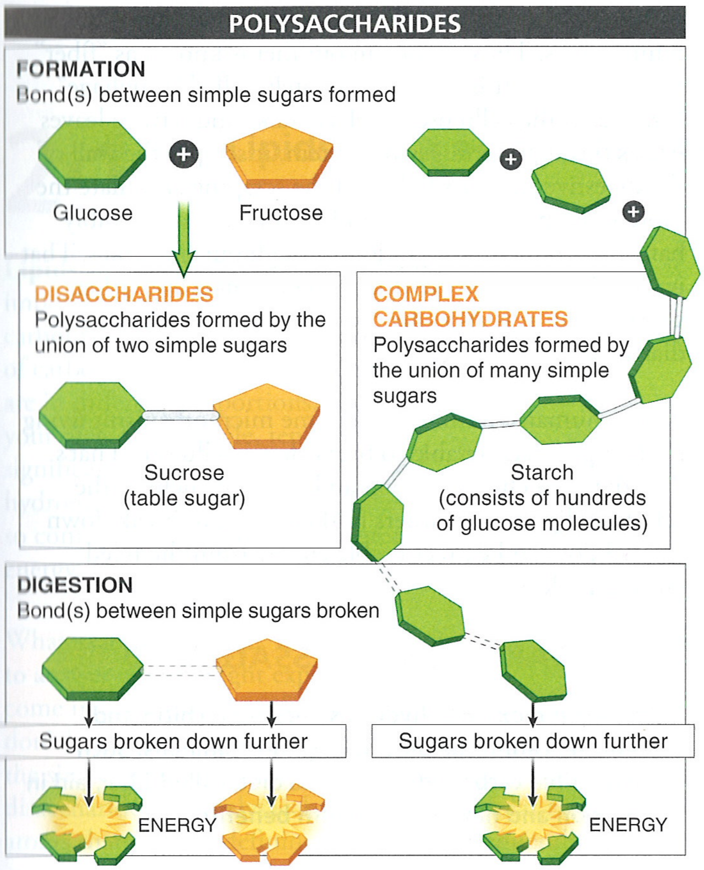


FIGURE 2-24 Chains of sugars. Polysaccharides are made from simple sugars bonded together.

Depending on their structure, dietary carbohydrates can lead to quick-but-brief or slow-but-persistent increases in blood sugar.

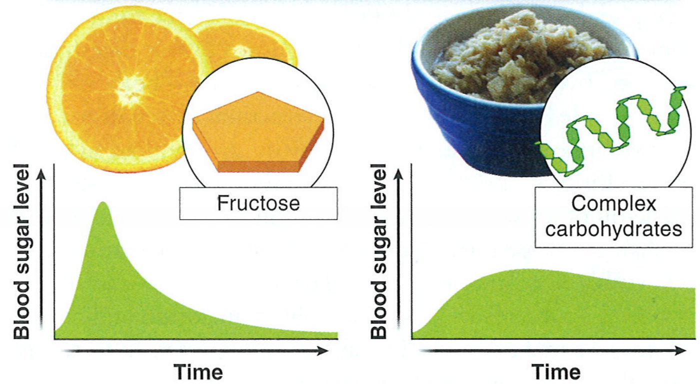


FIGURE 2-25 Short-term versus long-term energy. Simple sugars and complex carbohydrates differ in the way they make energy available to you.

Many complex carbohydrates are like "time-release" fuel pellets. The glucose molecules become available slowly, as the bonds between glucose units are broken. As a demonstration, put a piece of potato or bread into your mouth and let it rest on your tongue. Initially, it does not taste sweet. After a few minutes, you will begin to taste some sweetness as the chemicals in your saliva break the starch down into glucose.

The relative amounts of complex carbohydrates and simple sugars in foods cause them to have different effects when you eat them. Oatmeal (along with rice and pasta), for example, is rich in complex carbohydrates. Fresh fruits, on the other hand, are rich in simple sugars, such as fructose. Consequently, although fruit will give a quick burst of energy as the sugars are almost immediately available, the fuel will soon be gone from the bloodstream. Simple sugars in the oatmeal will become available only gradually, as the complex carbohydrates of the oats are broken down into their simple sugar components (**FIGURE 2-25**).

Q Before heading to the library for a long study session, students would be wise to consume oatmeal rather than fresh fruits. Why?

TAKE-HOME MESSAGE 2·9

Multiple simple carbohydrates are sometimes linked together into more complex carbohydrates. Types of complex carbohydrates include starch, which is the primary form of energy storage in plants, and glycogen, which is a primary form of energy storage in animals.

2·10 Not all carbohydrates are digestible.

Despite their general importance as a fuel source for humans, not all carbohydrates can be broken down by our digestive system. Two different complex carbohydrates—both indigestible by humans—serve as structural materials for invertebrate animals and plants: **chitin** (pronounced KITE-in) and **cellulose** (**FIGURE 2-26**). Chitin forms the rigid outer skeleton of most insects and crustaceans (such as lobsters and crabs). Cellulose forms a huge variety of plant structures that are visible all around us. We find cellulose in trees and the wooden structures we build from them, in cotton and the clothes we make from it, in leaves and in grasses. In fact, it is the single most prevalent compound on earth.

Surprisingly, cellulose is almost identical in composition to starch. Nonetheless, because of one small difference in the chemical bond between the simple sugar units, cellulose has a slightly different three-dimensional structure. Even tiny differences in the shape of a molecule can have a huge effect on its behavior. In this case, the difference in shape makes it impossible for humans to digest cellulose as they can starch. Consequently, the cellulose we eat passes right through our digestive system unused.

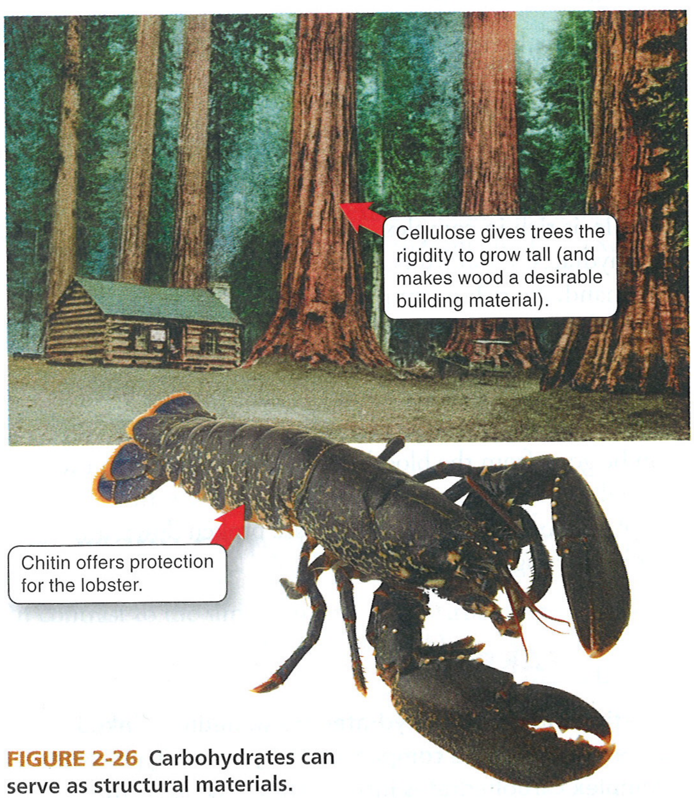


FIGURE 2-26 Carbohydrates can serve as structural materials.

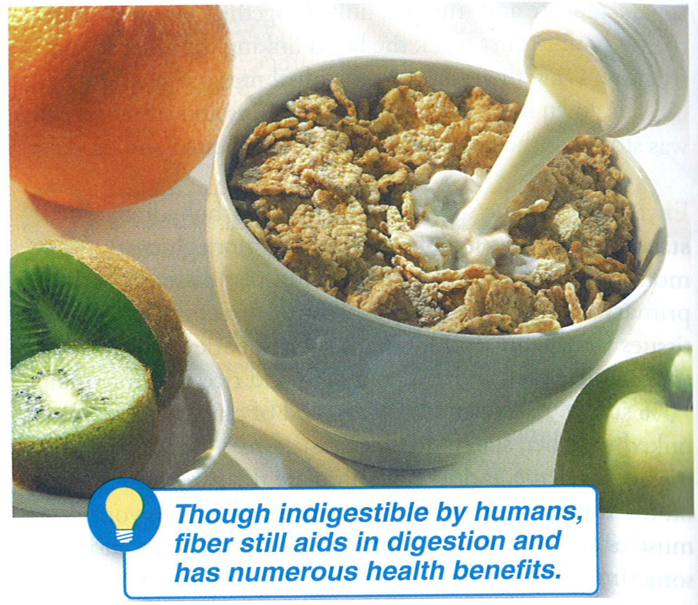


FIGURE 2-27 Fiber. It's not digestible, but it's still important for our diet.

Although it is not digestible, cellulose is still important to human diets. The cellulose in our diet is known as "fiber" (**FIGURE 2-27**). It is also appropriately called "roughage" because, as the cellulose of celery stalks and lettuce leaves passes through our digestive system, it scrapes the wall of the digestive tract. Its bulk and the scraping stimulate the more rapid passage of food and the unwanted, possibly harmful products of digestion through our intestines. That is why fiber reduces the risk of colon cancer and other diseases (but it is also why too much fiber can lead to diarrhea).

Unlike humans, termites have some microorganisms living in their gut that are able to break down cellulose. That's why they can chew on wood and, with the help of the cellulose-digesting boarders in their gut, can break down the cellulose and extract usable energy from the freed glucose molecules.

TAKE-HOME MESSAGE 2·10

Some complex carbohydrates, including chitin and cellulose, cannot be digested by most animals. Such indigestible carbohydrates in the diet, called fiber, aid in digestion and have many health benefits.