Introduction to Organic Compounds

2.1 Life's molecular diversity is based on the properties of carbon

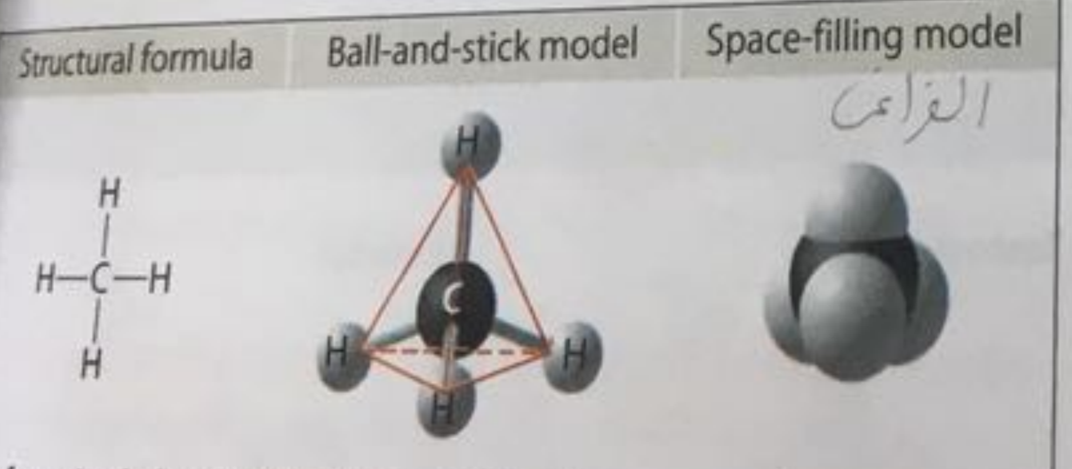
When it comes to making molecules, carbon usually takes center stage. Almost all the molecules a cell makes are composed of carbon atoms bonded to one another and to atoms of other elements. Carbon is unparalleled in its ability to form large and complex molecules, which build the structures and carry out the functions required for life. Carbon-based molecules are called **organic compounds.**

Why are carbon atoms the lead players in the chemistry of life? The number of electrons in the outermost shell of its atoms determines an element's chemical properties. A carbon atom has 4 electrons in a valence shell that holds 8. Carbon completes its outer shell by sharing electrons with other atoms in four covalent bonds. Thus, each carbon atom is a connecting point from which a molecule can branch in up to four directions.

Figure 2.1A illustrates three representations of methane (CH_4), one of the simplest organic molecules. The structural formula shows that covalent bonds link four hydrogen atoms to the carbon atom. Each of the four lines in the formula represents a pair of shared electrons. The two models help you see that methane is three-dimensional, with the space-filling model on the right better portraying its overall shape. The ball-and-stick model shows that carbon's four bonds (the gray "sticks") angle out toward the corners of an imaginary tetrahedron (an object with four triangular sides). The red lines trace this shape, which occurs wherever a carbon atom participates in four single bonds. Different bond angles and shapes occur when carbon atoms form double bonds. Large organic molecules can have very elaborate shapes. And as we will see many times, a molecule's shape often determines its function.

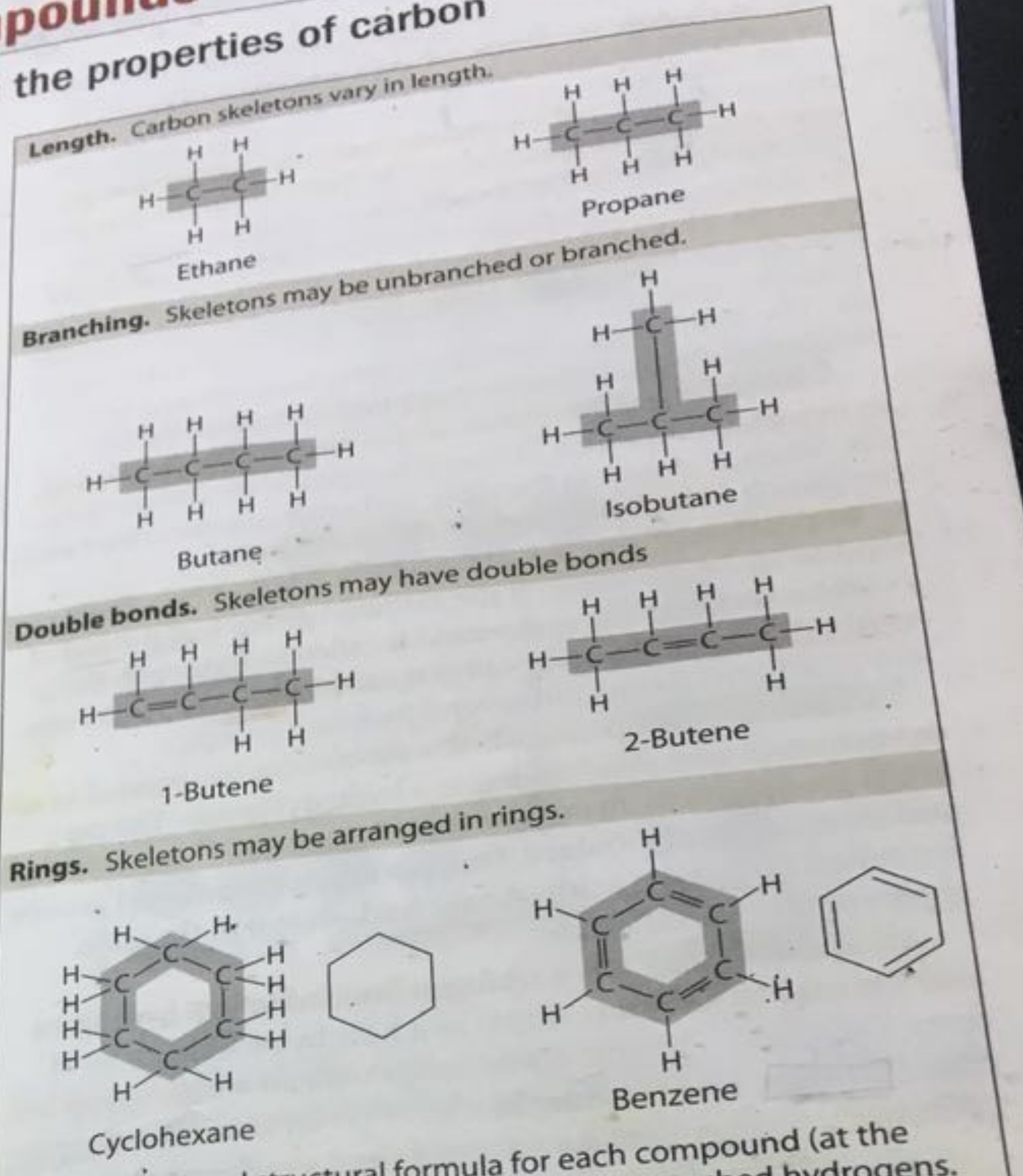
Compounds composed of only carbon and hydrogen are called **hydrocarbons**. Methane and propane are examples of hydrocarbon fuels. As components of fats, longer hydrocarbons provide fuel to your body cells. **Figure 2.1B** illustrates some of the variety of hydrocarbon structures. The chain of carbon atoms in an organic molecule is called a **carbon skeleton** (shaded in gray in the figure). Carbon skeletons can vary in length and can be unbranched or branched. Carbon skeletons may also include double bonds, which can vary in number and location. Some carbon skeletons are arranged in rings.

The two compounds in the second row of Figure 2.1B, butane and isobutane, have the same molecular formula, C_4H_{10}, but differ in the bonding pattern of their carbon skeleton. The two molecules in the third row also have the same numbers of atoms, but they have different three-dimensional shapes because of the location of the double bond. Compounds with the same formula but different structural arrangements are called **isomers**. Isomers can also result from different spatial arrangements of the four partners bonded to a carbon atom. This type of isomer is important in the pharmaceutical industry, because the two isomers of a drug may not be equa effective or may have different (and sometimes harmful) effects. The different shapes of isomers result in unique pro ties and add greatly to the diversity of organic molecules.



The four single bonds of carbon point to the corners of a tetrahedron.

Figure 2.1A Three representations of methane (CH_4)



In the abbreviated structural formula for each compound (at the right), each corner represents a carbon and its attached hydrogens.

▲ Figure 2.1B Four ways that carbon skeletons can vary

? One isomer of methamphetamine is the addictive illegal d known as "crank." The other is a medicine for sinus conge How can you explain the differing effects of the two isome

ers have different structures, or shapes, and the shape of a molecule helps determine the way it functions in the body.

2.2 A few chemical groups are key to the functioning of biological molecules

The unique properties of an organic compound depend not only on the size and shape of its carbon skeleton but also on the groups of atoms that are attached to that skeleton. **Table 2.2** illustrates six chemical groups important in the chemistry of life. The first five are called **functional groups.** They affect a molecule's function by participating in chemical reactions in characteristic ways. These groups are polar, because oxygen or nitrogen atoms exert a strong pull on shared electrons. This polarity tends to make compounds containing these groups **hydrophilic** (water-loving) and therefore soluble in water—a necessary condition for their roles in water-based life. The sixth group, a methyl group, is nonpolar and not reactive, but it affects molecular shape and thus function.

??

A **hydroxyl group** consists of a hydrogen atom bonded to an oxygen atom, which in turn is bonded to the carbon skeleton. Ethanol, shown in the table, and other organic compounds containing hydroxyl groups are called alcohols.

In a **carbonyl group,** a carbon atom is linked by a double bond to an oxygen atom. If the carbonyl group is at the end of a carbon skeleton, the compound is called an aldehyde; if it is within the chain, the compound is called a ketone. Sugars contain a carbonyl group and several hydroxyl groups.

A **carboxyl group** consists of a carbon double-bonded to an oxygen atom and also bonded to a hydroxyl group. The carboxyl group acts as an acid by contributing an H^+ to a solution and thus becoming ionized. Compounds with carboxyl groups are called carboxylic acids. Acetic acid, shown in the table, gives vinegar its sour taste.

An **amino group** has a nitrogen bonded to two hydrogens and the carbon skeleton. It acts as a base by picking up an H^+ from a solution. Organic compounds with an amino group are called amines. The building blocks of proteins are called amino acids because they contain an amino and a carboxyl group.

A **phosphate group** consists of a phophorus atom bonded to four oxygen atoms. It is usually ionized and attached to the carbon skeleton by one of its oxygen atoms. This structure is abbreviated as Ⓟ in this text. Compounds with phosphate groups are called organic phosphates and are often involved in energy transfers, as is the energy-rich compound ATP, shown in the table.

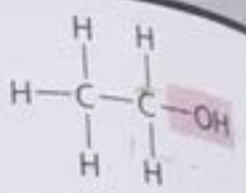
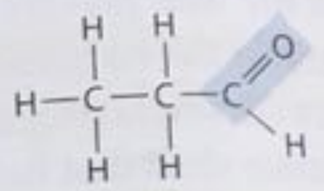
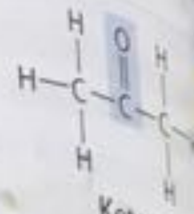
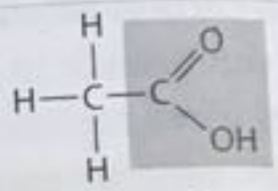
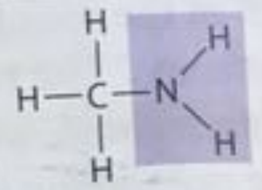
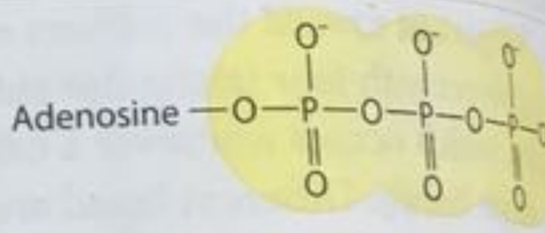
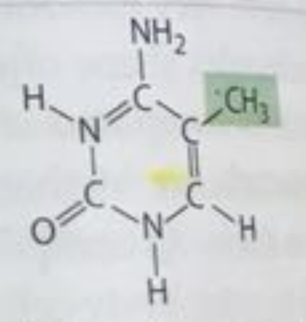
A **methyl group** consists of a carbon bonded to three hydrogens. Compounds with methyl groups are called methylated compounds. The addition of a methyl group to the component of DNA shown in the table affects the expression of genes.

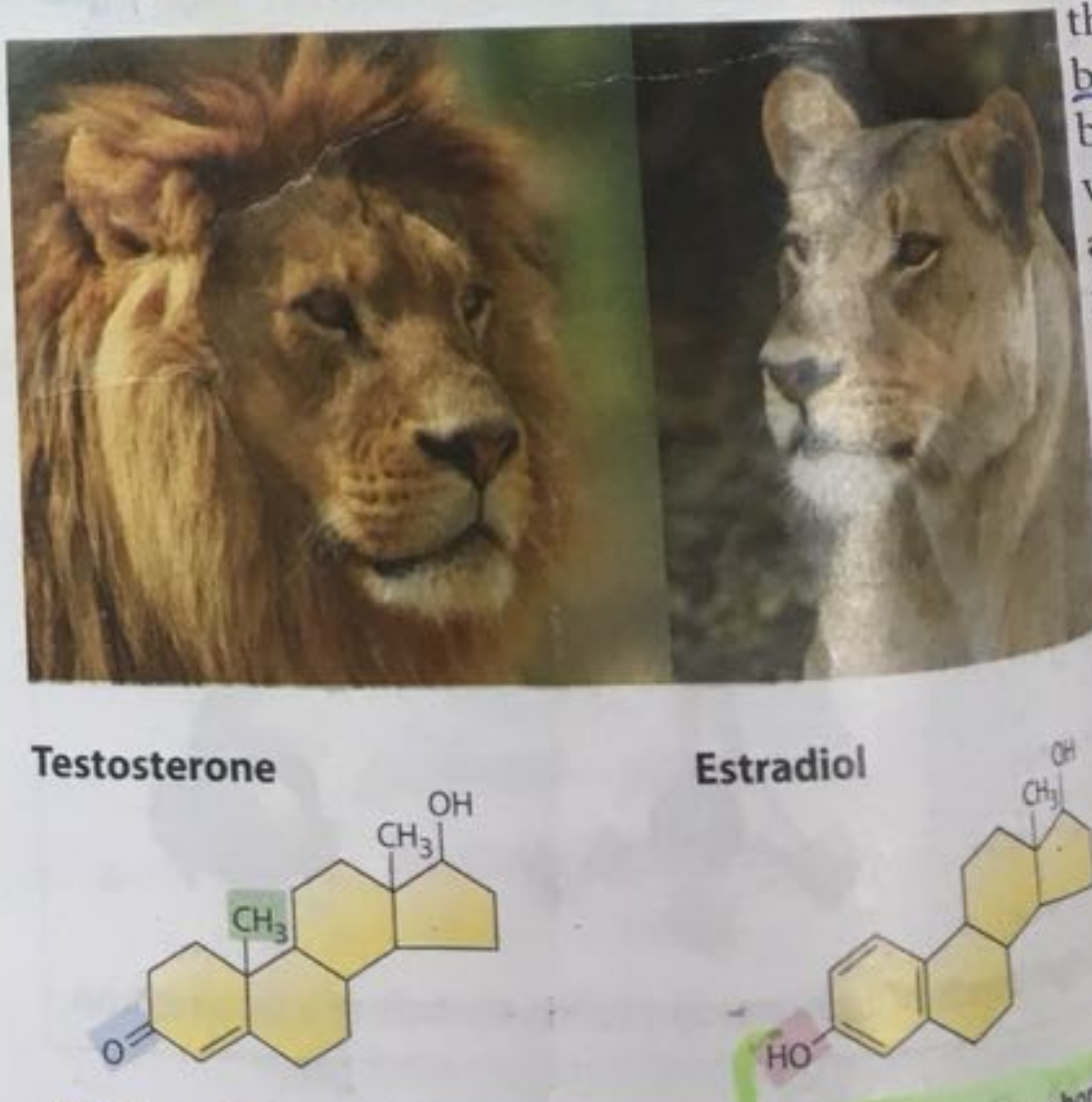
Figure 2.2 shows how a small difference in chemical groups can lead to a big difference in body form and behavior. The male and female sex hormones shown here differ only in the groups highlighted with colored boxes. These subtle differences result in the different actions of these molecules, which help produce the contrasting features of males and females in lions and other vertebrates. Keeping in mind this basic scheme—carbon skeletons with chemical groups—we are now ready to see how our cells make large molecules out of smaller ones.

? **Identify the chemical groups that do *not* contain carbon.**

The hydroxyl, amino, and phosphate groups.

TABLE 2.2 IMPORTANT CHEMICAL GROUPS OF ORGANIC COMPOUNDS

Chemical Group	Examples
Hydroxyl group —OH	 Alcohol
Carbonyl group +δ $C=O$ -δ -NH2	 Aldehyde  Ketone
Carboxyl group —COOH	 Carboxylic acid  Ionized
Amino group $—NH_2$	 Amine  Ionized
Phosphate group $—OPO_3^{2-}$	 Organic phosphate
Methyl group $—CH_3$	 Methylated compound



▲ **Figure 2.2** Differences in the chemical groups of sex hormones

2.3 Cells ma
of smal

Given the rich comp
to be an enormous
however, the impor
bacteria to elephan
drates, lipids, prote
molecules of three
and nucleic acids–
macromolecules.
of atoms. How do
Cells make m
molecules into c
many, and *mero*
ing of many ide
gether, much as
blocks of polym

Making Polym
polymers by a
molecule of w
monomer has
hydroxyl grou
added to a ch
Figure 2.3A t
short polyme
other monor
occurs, a nev
Dehydration
monomers

Breaking P
but also ha
organic m
that are m
these poly
cells. This
the revers
break (*ly*
bond bet
water m
attachin
the adja
The l
chapter
the sug
dehydr
enzym
macro

The D
in the
thous
ingre
other

بنجر ← beet

Carbohydrates

2.4 Monosaccharides are the simplest carbohydrates

The name **carbohydrate** refers to a class of molecules ranging from the small sugar molecules dissolved in soft drinks to large polysaccharides, such as the starch molecules we consume in pasta and potatoes.

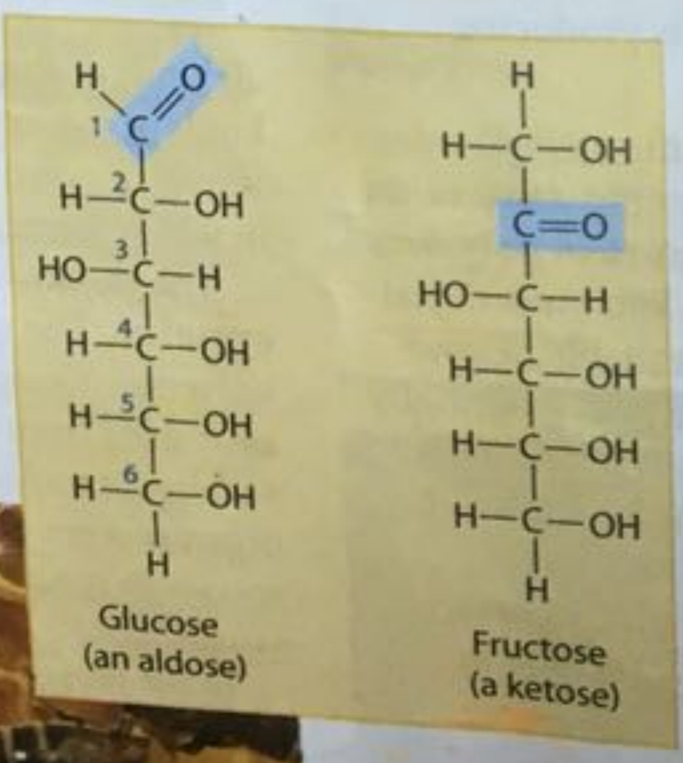
The carbohydrate monomers (single-unit sugars) are **monosaccharides** (from the Greek *monos*, single, and *sacchar*, sugar). The honey shown in **Figure 2.4A** consists mainly of monosaccharides called glucose and fructose. These and other single-unit sugars can be hooked together by dehydration reactions to form more complex sugars and polysaccharides.

Monosaccharides generally have molecular formulas that are some multiple of CH_2O. For example, the formula for glucose, a common monosaccharide of central importance in the chemistry of life, is $C_6H_{12}O_6$. **Figure 2.4B** illustrates the molecular structure of glucose, with its carbons numbered 1 to 6. This structure also shows the two trademarks of a sugar: a number of hydroxyl groups (—OH) and a carbonyl group ($>C=O$, highlighted in blue). The hydroxyl groups make a sugar an alcohol, and the carbonyl group, depending on its location, makes it either an aldose (an aldehyde sugar) or a ketose (a ketone sugar). As you see in Figure 2.4B, glucose is an aldose and fructose is a ketose. (Note that most names for sugars end in *-ose*. Also, as you saw with the enzyme lactase that digests lactose, the names for most enzymes end in *-ase*.)

محلول

[illegible]

If you count the numbers of different atoms in the fructose molecule in Figure 2.4B, you will find that its molecular formula is $C_6H_{12}O_6$, identical to that of glucose. Thus, glucose and fructose are isomers; they differ only in the arrangement of their atoms (in this case, the positions of the carbonyl groups). Seemingly minor differences like this give isomers different properties, such as how they react with other molecules. These differences also make fructose taste considerably sweeter than glucose.



◀ **Figure 2.4B** Structures of glucose and fructose

The carbon skeletons of both glucose and fructose are six carbon atoms long. Other monosaccharides may have three seven carbons. Five-carbon sugars, called pentoses, and six-carbon sugars, called hexoses, are among the most common.

It is convenient to draw sugars as if their carbon skeleto were linear, but in aqueous solutions, many monosaccharid form rings, as shown for glucose in **Figure 2.4C**. To form th glucose ring, carbon 1 bonds to the oxygen attached to carb 5. As shown in the middle representation, the ring diagram glucose and other sugars may be abbreviated by not showin the carbon atoms at the corners of the ring. Also, the bonds in the ring are often drawn with varied thickness, indicatin that the ring is a relatively flat structure with attached atoms extending above and below it. The simplified ring symbol o the right is often used in this book to represent glucose.

Monosaccharides, particularly glucose, are the main fuel molecules for cellular work. Because cells release energy from glucose when they break it down, an aqueous solution of glucose (often called dextrose) may be injected into the bloodstream of sick or injured patients; the glucose provides an immediate energy source to tissues in need of repair. Cel also use the carbon skeletons of monosaccharides as raw material for making other kinds of organic molecules, such amino acids and fatty acids. Sugars not used in these ways may be incorporated into disaccharides and polysaccharides, as we see next.

? **Write the formula for a monosaccharide that has three carbons.**

$C_3H_6O_3$

2.5 Two mo

Cells construct a d
monomers by a de
maltose, also calle
monomers. One n
other gives up a h
is released, an oxy
Maltose, which is
making beer, mal

The most com
a glucose monom
in plant sap, sucr
rials to all the par
sugarcane or the

? **Lactose, as**
charide sug
The formul
What is the

2.6 Polys

Polysaccharid
thousands of n
reactions. Poly
or as structura
mon types of

Starch, a st
glucose mono
and may be u
Starch granul
cells can with
mans and mo
plant starch t
and rice, are

Animals s
called **glycog**
starch, as sh
as granules i
glycogen to

Cellulos
is a

2.3 Cells make a huge number of large molecules from a limited set of small molecules

Given the rich complexity of life on Earth, we might expect there to be an enormous diversity of types of molecules. Remarkably, however, the important molecules of all living things—from bacteria to elephants—fall into just four main classes: carbohydrates, lipids, proteins, and nucleic acids. On a molecular scale, molecules of three of these classes—carbohydrates, proteins, and nucleic acids—may be gigantic; in fact, biologists call them **macromolecules**. For example, a protein may consist of thousands of atoms. How does a cell make such a huge molecule?

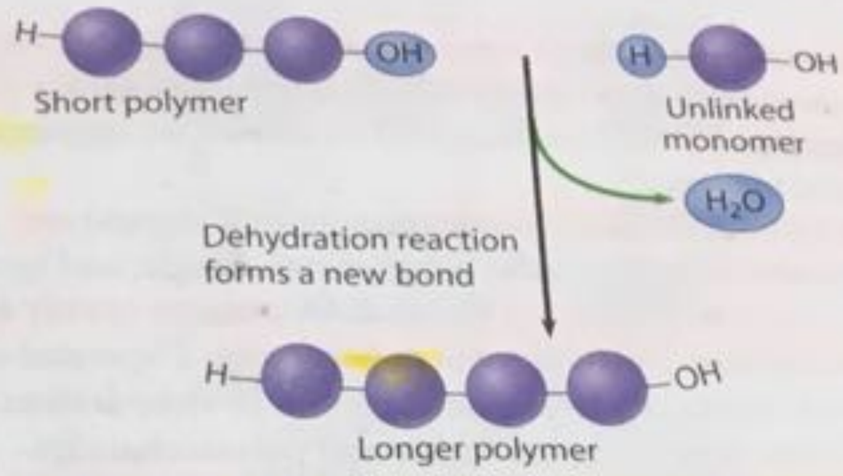
Cells make most of their macromolecules by joining smaller molecules into chains called **polymers** (from the Greek *polys*, many, and *meros*, part). A polymer is a large molecule consisting of many identical or similar building blocks strung together, much as a train consists of a chain of cars. The building blocks of polymers are called **monomers**.

Making Polymers Cells link monomers together to form polymers by a **dehydration reaction**, a reaction that removes a molecule of water. As you can see in **Figure 2.3A**, an unlinked monomer has a hydrogen atom (—H) at one end and a hydroxyl group (—OH) at the other. For each monomer added to a chain, a water molecule (H_2O) is released. Notice in Figure 2.3A that one monomer (the one at the right end of the short polymer in this example) loses a hydroxyl group and the other monomer loses a hydrogen atom to form H_2O. As this occurs, a new covalent bond forms, linking the two monomers. Dehydration reactions are the same regardless of the specific monomers and the type of polymer the cell is producing.

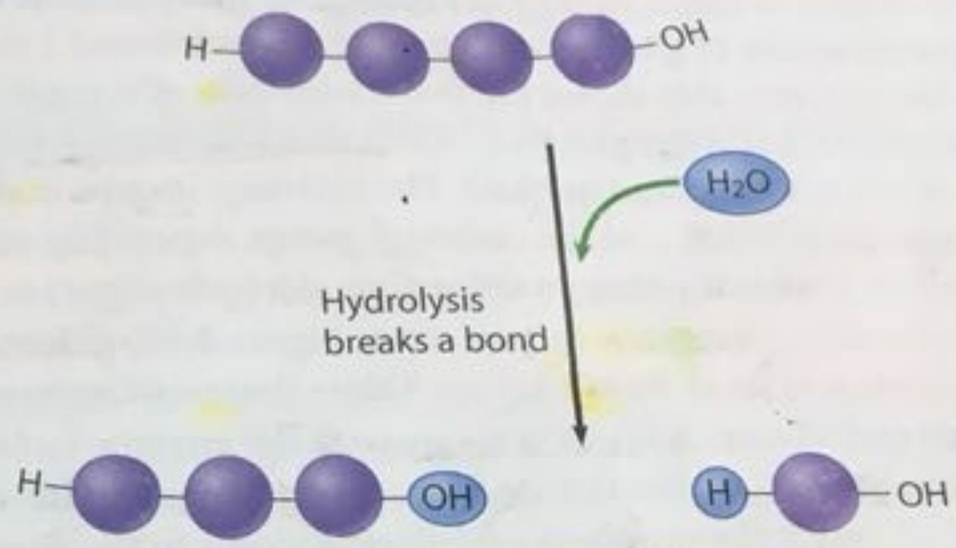
Breaking Polymers Cells not only make macromolecules ut also have to break them down. For example, most of the rganic molecules in your food are in the form of polymers hat are much too large to enter your cells. You must digest ese polymers to make their monomers available to your lls. This digestion process is called **hydrolysis**. Essentially e reverse of a dehydration reaction, hydrolysis means to eak (*lyse*) with water (*hydro*-). As **Figure 2.3B** shows, the nd between monomers is broken by the addition of a ter molecule, with the hydroxyl group from the water ching to one monomer and a hydrogen attaching to adjacent monomer.

The lactose-intolerant individuals you learned about in the ter introduction are unable to hydrolyze such a bond in ugar lactose because they lack the enzyme lactase. Both dration reactions and hydrolysis require the help of mes to make and break bonds. **Enzymes** are specialized omolecules that speed up chemical reactions in cells.

iversity of Polymers The diversity of macromolecules living world is vast. Remarkably, a cell makes all its nds of different macromolecules from a small list of ients—about 40 to 50 common components and a few that are rare. Proteins, for example, are built from only 20 kinds of amino acids. Your DNA is built from just four kinds of monomers called nucleotides. The key to the great diversity of polymers is arrangement—variation in the sequence in which monomers are strung together.



▲ **Figure 2.3A** Dehydration reaction building a polymer chain



▲ **Figure 2.3B** Hydrolysis breaking down a polymer

The variety in polymers accounts for the uniqueness of each organism. The monomers themselves, however, are essentially universal. Your proteins and those of a tree or an ant are assembled from the same 20 amino acids. Life has a simple yet elegant molecular logic: Small molecules common to all organisms are ordered into large molecules, which vary from species to species and even from individual to individual in the same species.

In the remainder of the chapter, we explore each of the four classes of large biological molecules. Like water and simple organic molecules, large biological molecules have unique emergent properties arising from the orderly arrangement of their atoms. As you will see, for these molecules of life, structure and function are inseparable.

? **Suppose you eat some cheese. What reactions must occur for the protein of the cheese to be broken down into its amino acid monomers and then for these monomers to be converte to proteins in your body?**

n digestion, the proteins are broken down into amino acids by hydrolysis. proteins are formed in your body cells from these monomers in ydration reactions.

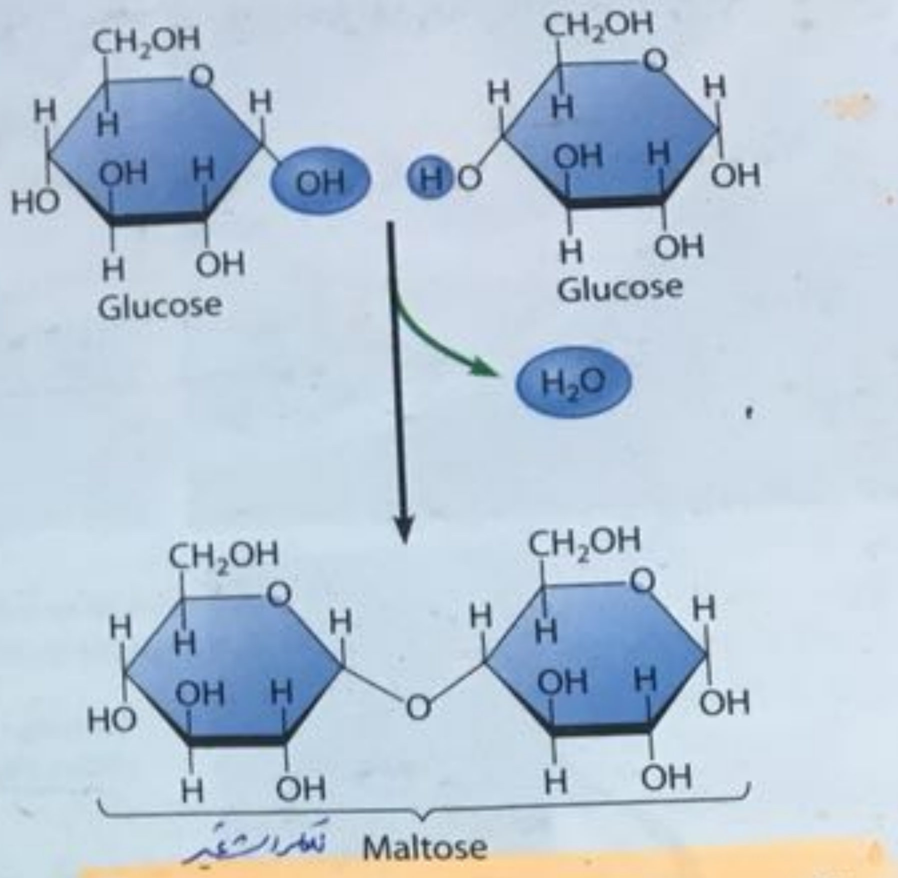
2.5 Two monosaccharides are linked to form a disaccharide

Cells construct a **disaccharide** from two monosaccharide monomers by a dehydration reaction. **Figure 2.5** shows how maltose, also called malt sugar, is formed from two glucose monomers. One monomer gives up a hydroxyl group and the other gives up a hydrogen atom from a hydroxyl group. As H_2O is released, an oxygen atom is left, linking the two monomers. Maltose, which is common in germinating seeds, is used in making beer, malted milk shakes, and malted milk candy.

The most common disaccharide is sucrose, which is made of a glucose monomer linked to a fructose monomer. Transported in plant sap, sucrose provides a source of energy and raw materials to all the parts of the plant. We extract it from the stems of sugarcane or the roots of sugar beets to use as table sugar.

? Lactose, as you read in the chapter introduction, is the disaccharide sugar in milk. It is formed from glucose and galactose. The formula for both these monosaccharides is $C_6H_{12}O_6$. What is the formula for lactose?

● $C_{12}H_{22}O_{11}$



▲ **Figure 2.5** Disaccharide formation by a dehydration reaction

2.6 Polysaccharides are long chains of sugar units

Polysaccharides are macromolecules, polymers of hundreds to thousands of monosaccharides linked together by dehydration reactions. Polysaccharides may function as storage molecules or as structural compounds. **Figure 2.6** illustrates three common types of polysaccharides: starch, glycogen, and cellulose.

Starch, a storage polysaccharide in plants, consists entirely of glucose monomers. Starch molecules coil into a helical shape and may be unbranched (as shown in the figure) or branched. Starch granules serve as carbohydrate "banks" from which plant cells can withdraw glucose for energy or building materials. Humans and most other animals have enzymes that can hydrolyze plant starch to glucose. Potatoes and grains, such as wheat, corn, and rice, are the major sources of starch in the human diet.

Animals store glucose in a different form of polysaccharide, called **glycogen**. Glycogen is more highly branched than starch, as shown in the figure. Most of your glycogen is stored as granules in your liver and muscle cells, which hydrolyze the glycogen to release glucose when it is needed.

Cellulose, the most abundant organic compound on Earth, is a major component of the tough walls that enclose plant cells. Cellulose is also a polymer of glucose, but its monomers are linked together in a different orientation. (Carefully compare the oxygen "bridges" highlighted in yellow between glucose monomers in starch, glycogen, and cellulose in the figure.) Arranged parallel to each other, cellulose molecules are joined by hydrogen bonds, forming cable-like microfibrils. Layers of microfibrils combine with other polymers, producing strong support for trees and structures we build with lumber.

Animals do not have enzymes that can hydrolyze the glucose linkages in cellulose. Therefore, cellulose is not a nutrient for humans, although it does contribute to digestive system health. The cellulose that passes unchanged through your digestive tract is referred to as "insoluble fiber." Fresh fruits, vegetables, and grains are rich in fiber.

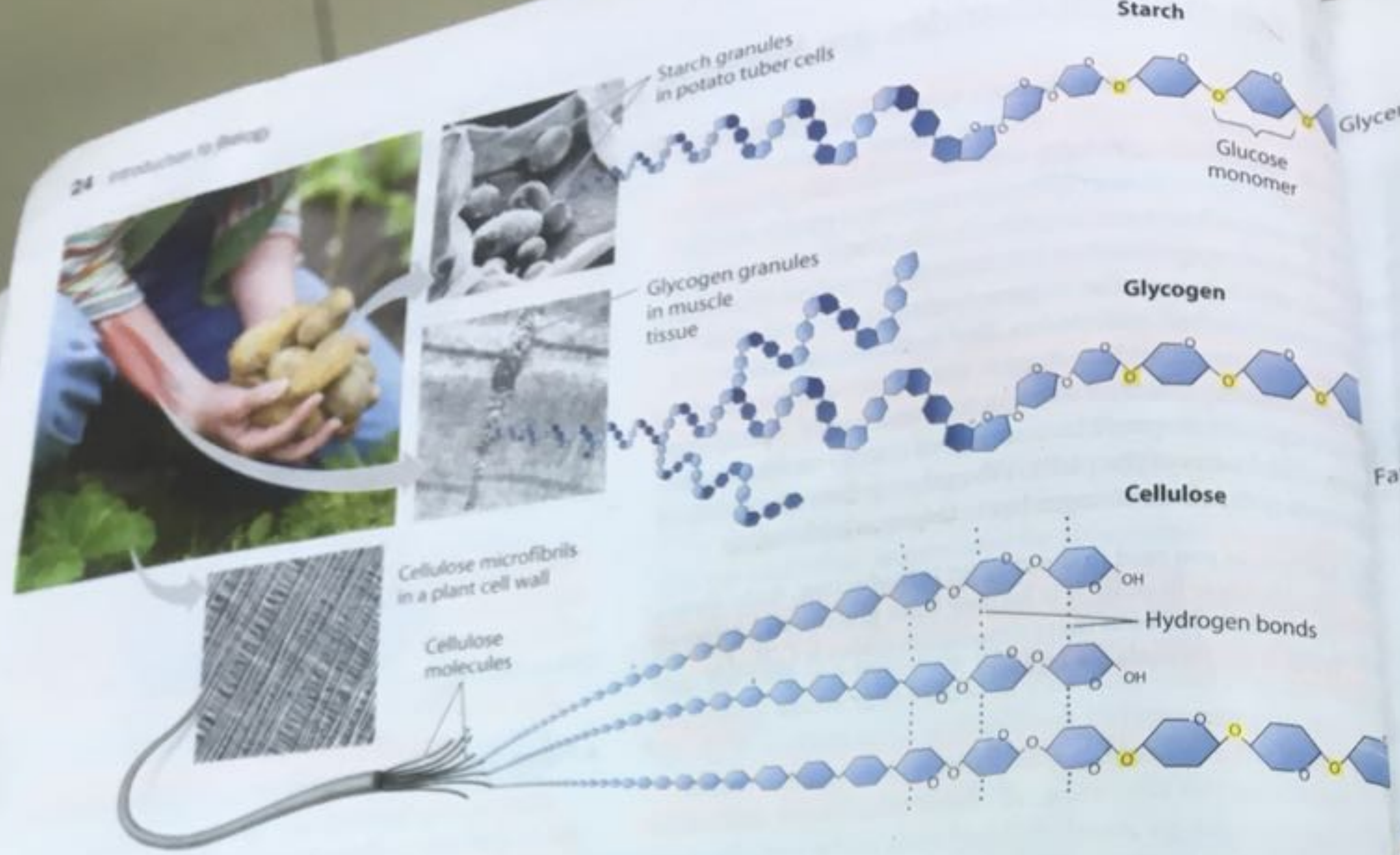
Some microorganisms do have enzymes that can hydrolyz cellulose. Cows and termites house such microorganisms in their digestive tracts and are thus able to derive energy from cellulose. Decomposing fungi also digest cellulose, helping t recycle its chemical elements within ecosystems.

Another structural polysaccharide, **chitin**, is used by ins and crustaceans to build their exoskeleton, the hard case en closing the animal. Chitin is also found in the cell walls of fungi. Humans use chitin to make a strong and flexible sur thread that decomposes after a wound or incision heals.

Almost all carbohydrates are hydrophilic owing to the many hydroxyl groups attached to their sugar monomers (see Figure 2.4B). Thus, cotton bath towels, which are mo cellulose, are quite water absorbent due to the water-lovin nature of cellulose. Next we look at a class of macromolec that are not hydrophilic.

? Compare and contrast starch and cellulose, two plant polysaccharides.

a polymers of glucose, but the bonds between glucose monomers
ent shapes. Starch functions mainly for sugar storage. Cellulose is a
polysaccharide that is the main material of plant cell walls.



▲ Figure 2.6 Polysaccharides

Lipids

2.7 Fats are lipids that are mostly energy-storage molecules

Lipids are diverse compounds that are grouped together because they share one trait: They do not mix well with water. Lipids consist mainly of carbon and hydrogen atoms linked by nonpolar covalent bonds. In contrast to carbohydrates and most other biological molecules, lipids are **hydrophobic** (water fearing). You can see this chemical behavior in an unshaken bottle of salad dressing: The oil (a type of lipid) separates from the vinegar (which is mostly water). The oils that ducks spread on their feathers make the feathers repel water (**Figure 2.7A**), which helps such waterfowl stay afloat.

Lipids also differ from carbohydrates, proteins, and nucleic acids in that they are neither huge macromolecules nor polymers built from similar monomers. You will see that lipids vary a great deal in structure and function. In this and the next two modules, we will consider three types of lipids: fats, phospholipids, and steroids.

A **fat** is a large lipid made from two kinds of smaller molecules: glycerol and fatty acids. Shown at the top in **Figure 2.7B**, glycerol is an alcohol with three carbons, each bearing a hydroxyl group (—OH). A fatty acid consists of a carboxyl group (the functional group that gives these molecules the name fatty *acid*, —COOH) and a hydrocarbon chain, usually 16 or 18 carbon atoms in length. The nonpolar hydrocarbon chains are the reason fats are hydrophobic.

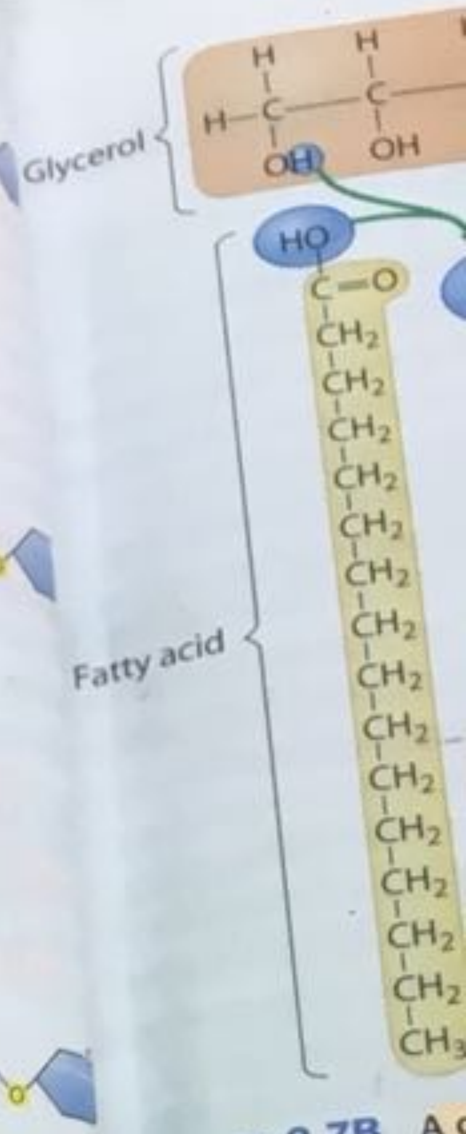
Figure 2.7B shows how one fatty acid molecule can link to a glycerol molecule by a dehydration reaction. Linking three fatty acids to glycerol produces a fat, as illustrated in **Figure 2.7C**. A synonym for fat is *triglyceride*, a term you may see on food labels or on medical tests for fat in the blood.

Some fatty acids contain one or more double bonds, which cause kinks (or bends) in the carbon chain. See the third fatty acid in Figure 2.7C. Such an **unsaturated fatty acid** has one fewer hydrogen atom on each carbon of the double bond. Fatty acids with no double bonds in their hydrocarbon chain have th maximum number of hydrogen atoms (are "saturated" with hydrogens) and are called **saturated fatty acids**. The kinks in unsaturated fatty acids prevent fats containing them from packing tightly together and solidifying at room temperature. Corn oil, olive oil, and other vegetable oils are called unsaturated fats.

⇒ [illegible]

Most animal fats are saturated. Their unkinked fatty acid chains pack closely together, making butter and beef fat solid at room temperature. When you see "hydrogenated vegetable oils" on a margarine

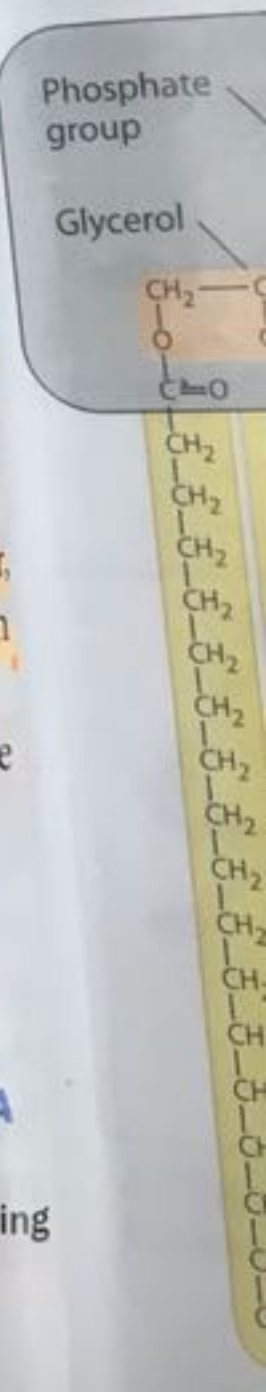
◀ **Figure 2.7A** Water beading on the oily coating of feathers

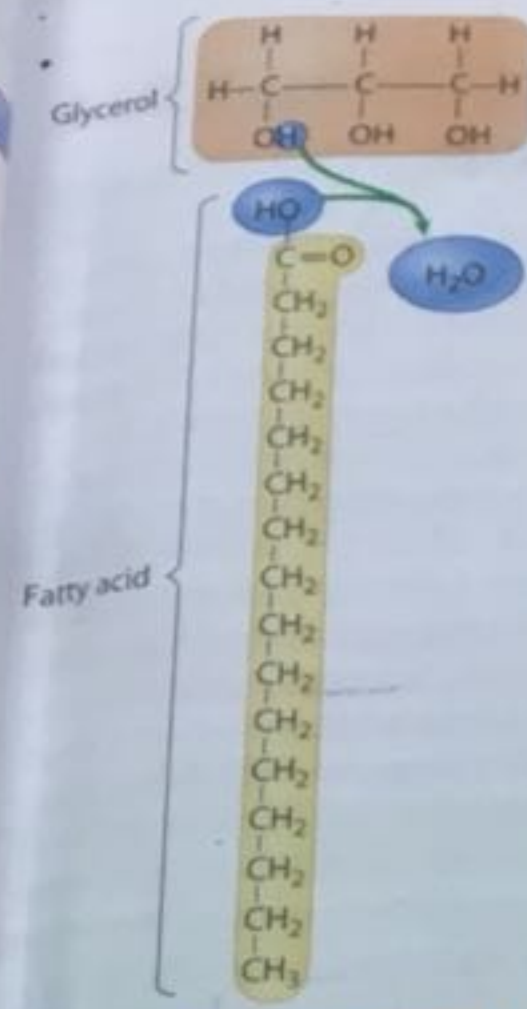


▲ **Figure 2.7B** A c
reaction linking a fat
molecule to a glycer

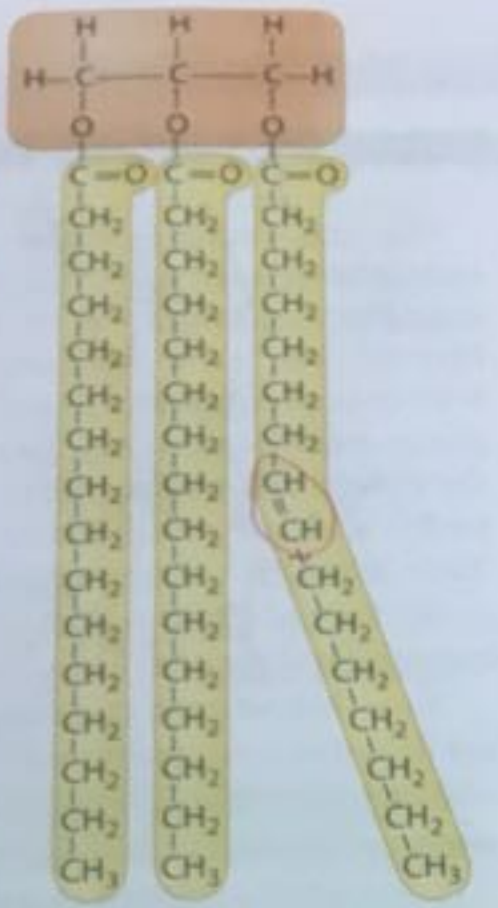
2.8 Phosp

Cells could not e
nent of cell mem
to fats, but they
instead of three
phosphate grou
linked to anoth
carbon. (Note t
of phospholipi





▲ **Figure 2.7B** A dehydration reaction linking a fatty acid molecule to a glycerol molecule



▲ **Figure 2.7C** A fat molecule (triglyceride) consisting of three fatty acids linked to glycerol

label, it means that unsaturated fats have been converted to saturated fats by adding hydrogen. Unfortunately, hydrogenation also creates **trans fats**, a form of fat that recent research associates with health risks. Diets rich in saturated fats and trans fats may contribute to cardiovascular disease by promoting atherosclerosis. In this condition, lipid-containing deposits called plaques build up within the walls of blood vessels, reducing blood flow. Unsaturated fatty acids called omega-3 fatty acids are found in certain nuts, plant oils, and fatty fish and appear to protect against cardiovascular disease.

The main function of fats is long-term energy storage. A gram of fat stores more than twice as much energy as a gram of polysaccharide. For immobile plants, the bulky energy storage form of starch is not a problem. (Vegetable oils are generally obtained from seeds, where more compact energy storage is a benefit.) A mobile animal, such as a duck or a human, can get around much more easily carrying its energy stores in the form of fat. Of course, the downside of this energy-packed storage form is that it takes more effort for a person to "burn off" excess fat. In addition to storing energy, fatty tissue cushions vital organs and insulates the body.

? **How do you think the structure of a monounsaturated fat differs from a polyunsaturated fat?**

A monounsaturated fat has a fatty acid with a single double bond in its carbon chain. A polyunsaturated fat has a fatty acid with several double bonds.

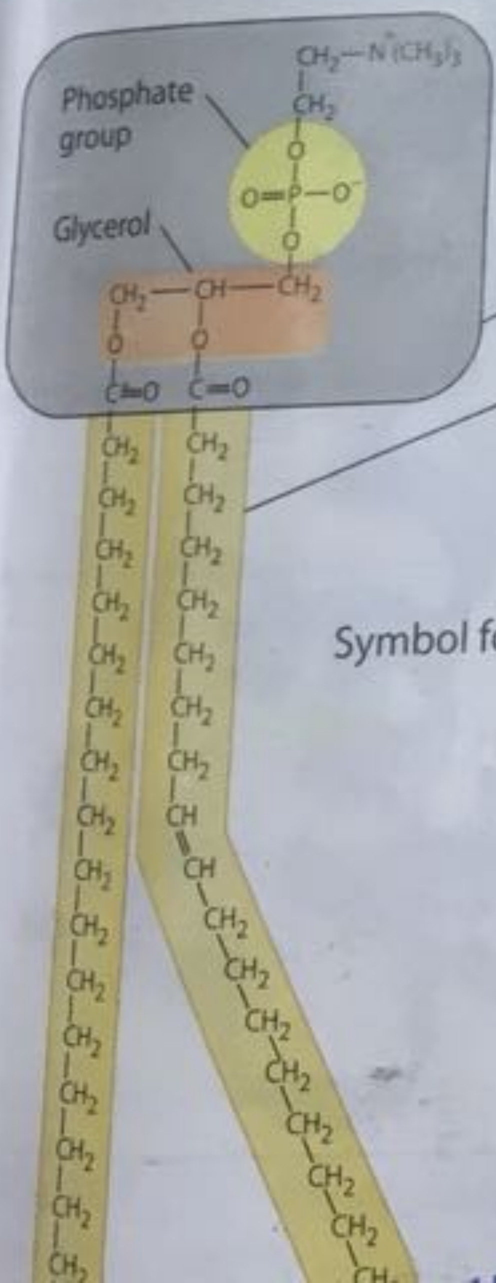
2.8 Phospholipids and steroids are important lipids with a variety of functions

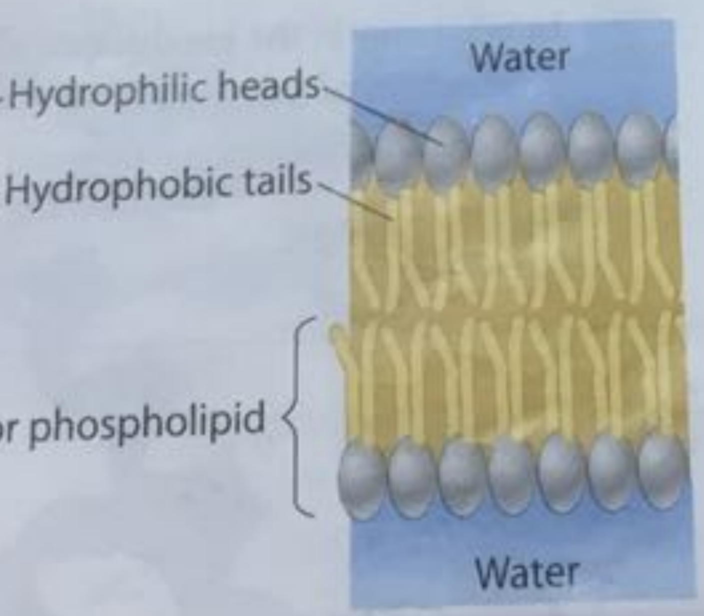
Cells could not exist without **phospholipids**, the major component of cell membranes. Phospholipids are structurally similar to fats, but they contain only two fatty acids attached to glycerol instead of three. As shown in **Figure 2.8A**, a negatively charged phosphate group (shown as a yellow circle in the figure and linked to another small molecule) is attached to glycerol's third carbon. (Note that glycerol is shown in orange.) The structure of phospholipids provides a classic example of how form fits function. The hydrophilic and hydrophobic ends of multiple molecules assemble in a bilayer of phospholipids to form a membrane (**Figure 2.8B**). The hydrophobic tails of the fatty acids cluster in the center, and the hydrophilic phosphate heads face the watery environment on either side of the membrane. Each gray-headed, yellow-tailed structure in the membrane shown here represents a phospholipid; this symbol is used throughout this book. We will explore the structure and function of biological membranes further in Chapter 3.

Steroids are lipids in which the carbon skeleton contains four fused rings, as shown in the structural formula of cholesterol in **Figure 2.8C**. (The diagram omits the carbons making up the rings and most of the chain and also their attached hydrogens.) **Cholesterol** is a common component in animal cell membranes, and animal cells also use it as a starting material for making other steroids, including sex hormones. Different steroids vary in the chemical groups attached to the rings, as you saw in Figure 2.2. Too much cholesterol in the blood m contribute to atherosclerosis.

? **Compare the structure of a phospholipid with that of a fat (triglyceride).**

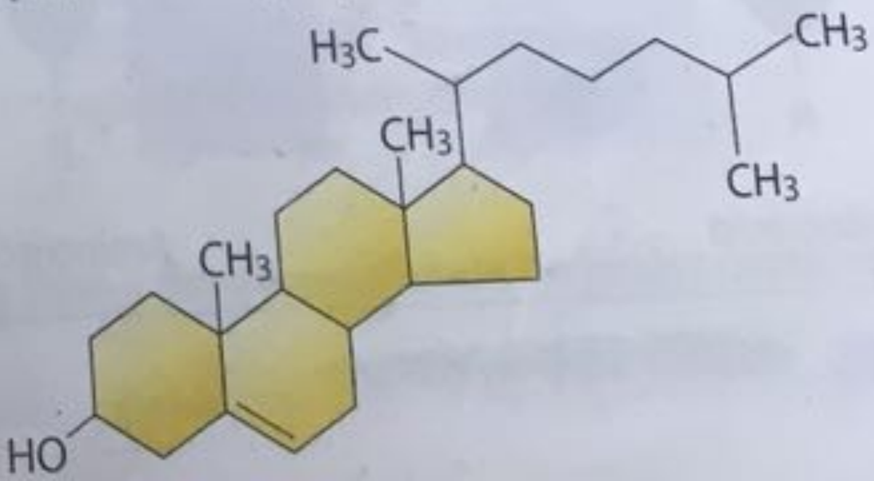
hospholipid has two fatty acids and a phosphate group attached to glycerol
fatty acids are attached to the glycerol of a fat molecule.





▲ **Figure 2.8B** Section of a phospholipid membrane

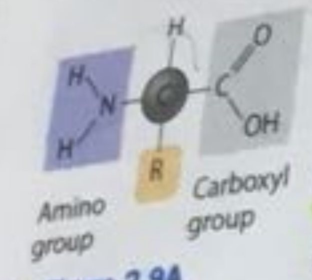
▲ **Figure 2.8A** Chemical structure



Proteins

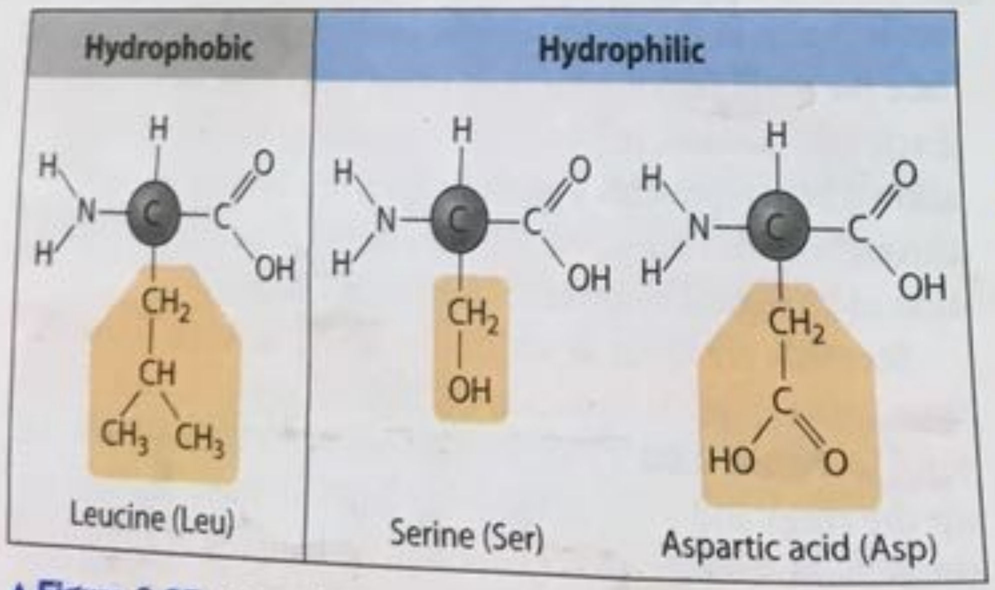
2.9 Proteins are made from amino acids linked by peptide bonds

Nearly every dynamic function in your body depends on proteins. You have tens of thousands of different proteins, each with a specific structure and function. Of all of life's molecules, proteins are structurally the most elaborate and diverse. A **protein** is a polymer of amino acids. Protein diversity is based on differing arrangements of a common set of just 20 amino acid monomers.



▲ Figure 2.9A General structure of an amino acid

Amino acids all have an amino group and a carboxyl group (which makes it an acid, hence the name amino *acid*). As you can see in the general structure shown in Figure 2.9A, both of these functional groups are covalently bonded to a central carbon atom, called the alpha carbon. Also bonded to the alpha carbon is a hydrogen atom and a chemical group symbolized by the letter R. The R group, also called the side chain, differs with each amino acid. In the simplest amino acid (glycine), the R group is just a hydrogen atom. In all others, such as those shown in Figure 2.9B, the R group consists of one or more carbon atoms with various chemical groups attached. The composition and structure of the R group determines the specific properties of each of the 20 amino acids that are found in proteins.



▲ Figure 2.9B Examples of amino acids with hydrophobic and hydrophilic R groups

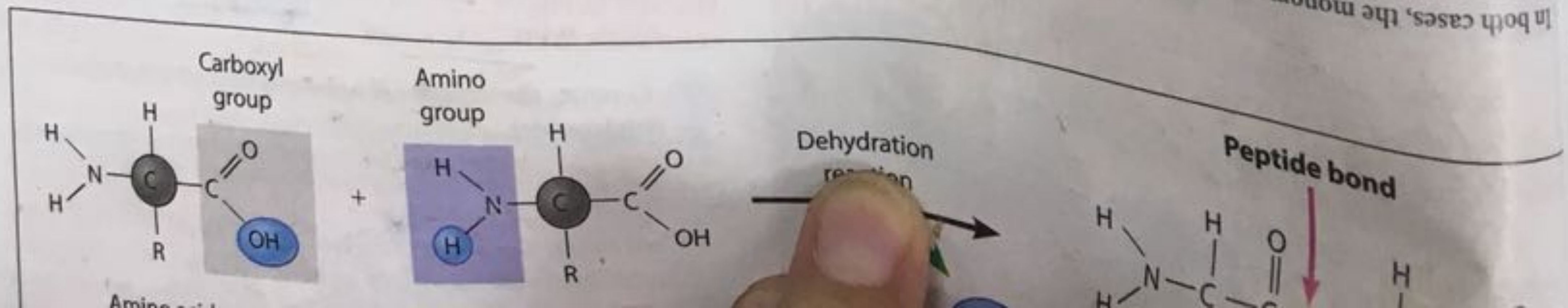
The amino acids in Figure 2.9B represent two main types, hydrophobic and hydrophilic. Leucine (abbreviated Leu) is a example of an amino acid in which the R group is nonpolar a hydrophobic. Serine (Ser), with a hydroxyl group in its R gro is an example of an amino acid with a polar, hydrophilic R group. Aspartic acid (Asp) is acidic and negatively charged at the pH of a cell. (Indeed, all the amino and carboxyl groups o amino acids are usually ionized at cellular pH, as shown in Table 2.2.) Other amino acids have basic R groups and are po tively charged. Amino acids with polar and charged R groups help proteins dissolve in the aqueous solutions inside cells.

Now that we have examined amino acids, let's see how they are linked to form polymers. Can you guess? Cells join amino acids together in a dehydration reaction that links the carboxy group of one amino acid to the amino group of the next amin acid as a water molecule is removed (Figure 2.9C). The resulti covalent linkage is called a **peptide bond**. The product of the reaction shown in the figure is called a *dipeptide*, because it w made from *two* amino acids. Additional amino acids can be added by the same process to form a chain of amino acids, a **polypeptide**. To release amino acids from the polypeptide by hydrolysis, a molecule of H_2O must be added back to break each peptide bond.

How is it possible to make thousands of different kinds of proteins from just 20 amino acids? The answer has to do with sequence. You know that thousands of English words can be made by varying the sequence of letters and word length. Although the protein "alphabet" is slightly smaller (just 20 "letter rather than 26), the "words" are much longer. Most polypeptid are at least 100 amino acids in length; some are 1,000 or more. Each polypeptide has a unique sequence of amino acids. But a long polypeptide chain of specific sequence is not the same as a protein, any more than a long strand of yarn is the same as a sweater that can be knit from that yarn. A functioning protein one or more polypeptide chains precisely coiled, twisted, and folded into a unique three-dimensional shape.

? **In what way is the production of a dipeptide similar to the production of a disaccharide?**

In both cases, the monomers are joined by a dehydration reaction.



2.10 A protein's

What do the tens of thou
body do? Probably their
the chemical catalysts th
chemical reactions in ce
the chapter introductio
enzymes that may be pr
Structural proteins a
fibers that make up co
and ligaments. Muscle
proteins.

Other types of prot
such as the antibodies
proteins, such as many
messengers that help
facilitating communic
may be built into cell
cells. Hemoglobin in
that delivers O_2 to w
the body. Other tran
into cells for energy.
such as ovalbumin, t
as a source of amino
proteins provide am
seeds contain stora
plant embryos.

The functions of
depend on their sp
ribbon model of ly
tears, and saliva. L
represented by the
is called globular
Figure 2.10B, a sp
model, the colors
oxygen, nitrogen,
balls are sulfur at
as yellow lines in
proteins are glob

f a protein. As shown in
ptide has a globular shap
ngement of its alpha hel
.

ids making up the
protein's shape. Tertiar
tween these R groups. F
eins found in aqueous
phobic R groups are on
drophilic R groups on
ion to the clustering of
ng between polar side
he charged (ionized) R
cture. A protein's shape
bonds called disulfide
he yellow lines in the
10A.

s consist of two or mor
functional macromol
structure, resulting
des, which are known
lete
ntical
ua-
he
three
arger
ong
tion
,
c-
ly.
at
ple,
glo-

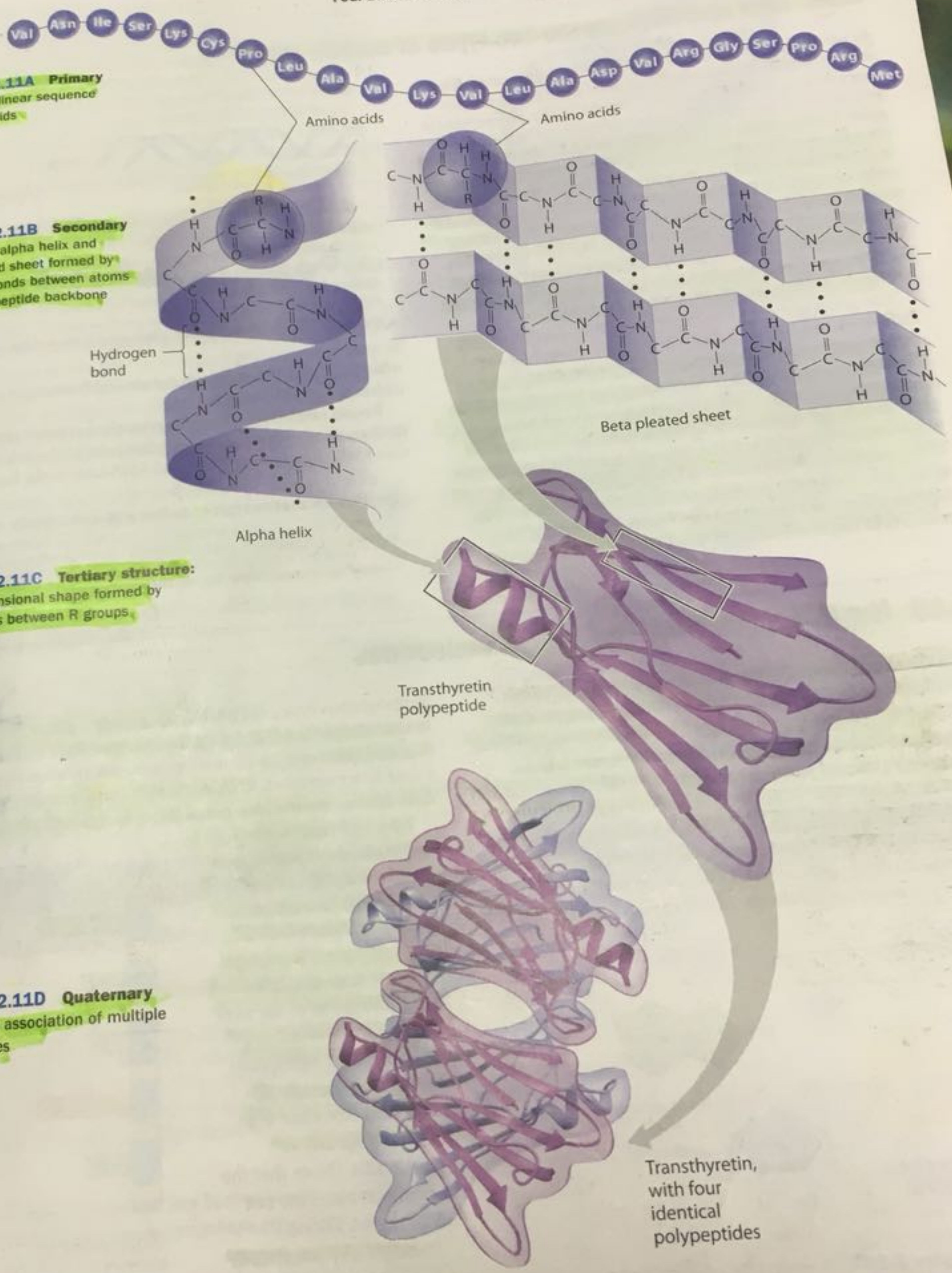
Collagen

rectly? Many
son's, involve an
ons are infectious
ith serious
cow disease.
ructure fits function:
pe determines its

ry structure of a pro-
's function?

● Primary structure, the
which affects the tertiary s
ary). Thus, primary structur
of a protein depends on its

Four Levels of Protein Structure



▶ **Figure 2.11A Primary structure:** linear sequence of amino acids

▶ **Figure 2.11B Secondary structure:** alpha helix and beta pleated sheet formed by hydrogen bonds between atoms of the polypeptide backbone

▶ **Figure 2.11C Tertiary structure:** three-dimensional shape formed by interactions between R groups

▶ **Figure 2.11D Quaternary structure:** association of multiple polypeptides

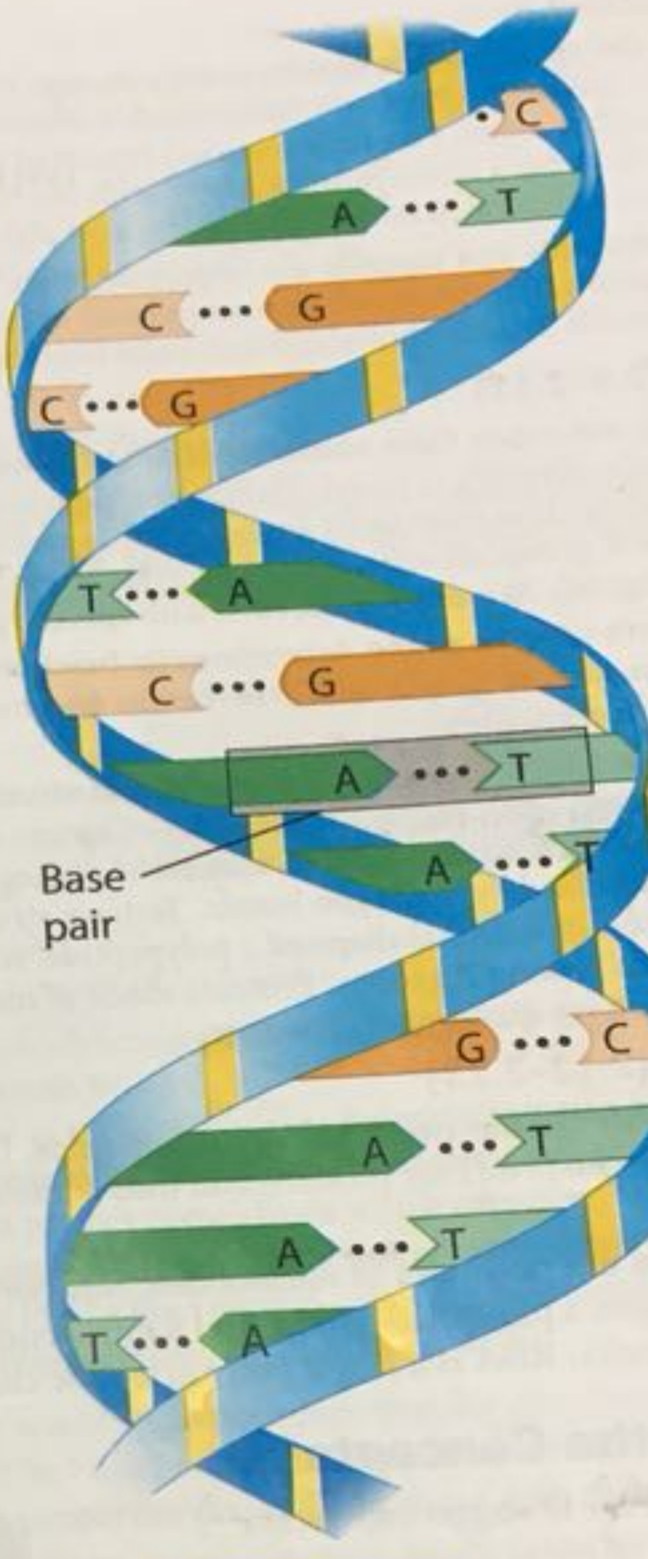
double helix, in which two polynucleotides wrap around each other (**Figure 2.13C**). The nitrogenous bases protrude from the two sugar-phosphate backbones and pair in the center of the helix. As shown by their diagrammatic shapes in the figure, A always pairs with T, and C always pairs with G. The two DNA chains are held together by hydrogen bonds (indicated by the dotted lines) between their paired bases. These bonds are individually weak, but collectively they zip the two strands together into a very stable double helix. Most DNA molecules have thousands or even millions of base pairs.

Because of the base-pairing rules, the two strands of the double helix are said to be *complementary*, each a predictable counterpart of the other. Thus, if a stretch of nucleotides on one strand has the base sequence –AGCACT–, then the same stretch on the other strand must be –TCGTGA–. Complementary base pairing is the key to how a cell makes two identical copies of each of its DNA molecules every time it divides. Thus, the structure of DNA accounts for its function of transmitting genetic information whenever a cell reproduces. The same base-pairing rules (with the exception that U nucleotides of RNA pair with A nucleotides of DNA) also account for the precise transcription of information from DNA to RNA.

An organism's genes determine the proteins and thus the structures and functions of its body. Let's return to the subject of the chapter introduction—lactose intolerance—to conclude our study of biological molecules. In the next chapter, we move up in the biological hierarchy to the level of the cell.

? What roles do complementary base pairing play in the functioning of nucleic acids?

● Complementary base pairing makes possible the precise replication of DNA, ensuring that genetic information is faithfully transmitted every time a cell divides. It also ensures that RNA molecules carry accurate instructions for the synthesis of proteins.



▲ **Figure 2.13C** **DNA double helix**

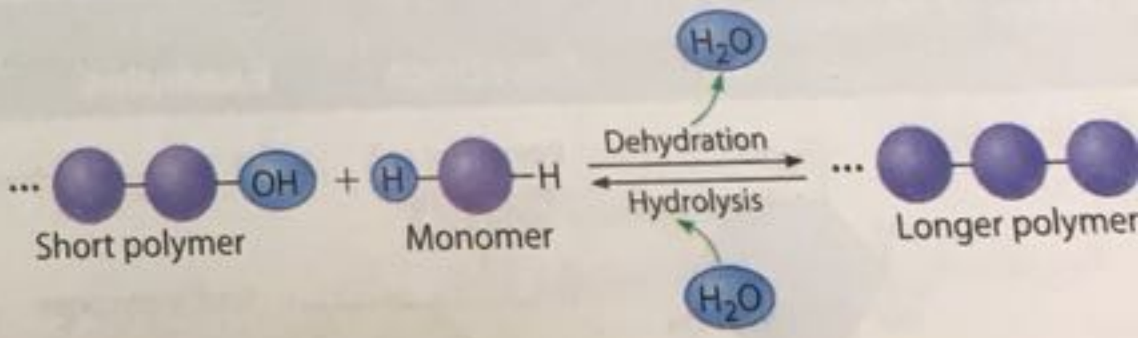
CHAPTER 2 REVIEW

Reviewing the Concepts

Introduction to Organic Compounds (2.1–2.3)

2.1 Life's molecular diversity is based on the properties of carbon. Carbon's ability to bond with four other atoms is the basis for building large and diverse organic compounds. Hydrocarbons are composed of only carbon and hydrogen. Isomers have the same molecular formula but different structures.

2.2 A few chemical groups are key to the functioning of biological molecules. Hydrophilic functional groups give organic molecules specific chemical properties.



Carbohydrates (2.4–2.6)

2.4 Monosaccharides are the simplest carbohydrates. A monosaccharide has a formula that is a multiple of CH_2O and contains hydroxyl groups and a carbonyl group.

2.5 Two monosaccharides are linked to form a disaccharide.

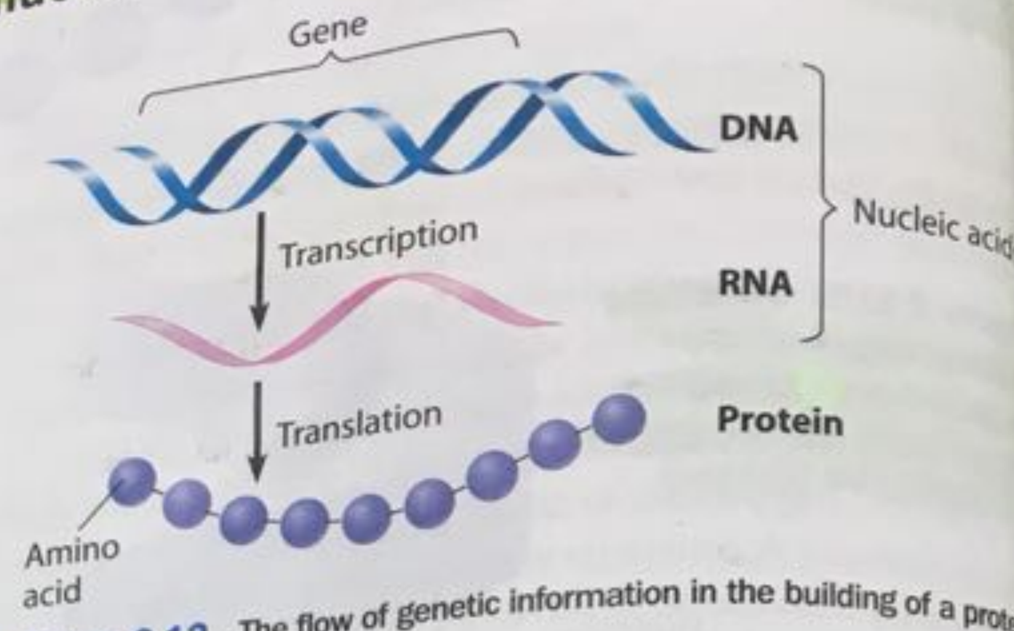
2.6 Polysaccharides are long chains of sugar units. Starch a glycogen are storage polysaccharides; cellulose is structural, in plant cell walls. Chitin is a component of insect exoskelet

Nucleic Acids

2.12 DNA and RNA are the two types of nucleic acids

As we just saw, the primary structure of a polypeptide determines the shape of a protein. But what determines the primary structure? The amino acid sequence of a polypeptide is programmed by a discrete unit of inheritance known as a **gene**. Genes consist of **DNA (deoxyribonucleic acid)**, one of the two types of polymers called **nucleic acids**. The name nucleic comes from their location in the nuclei of eukaryotic cells. The genetic material that humans and other organisms inherit from their parents consists of DNA. Unique among molecules, DNA provides directions for its own replication. Thus, as a cell divides, its genetic instructions are passed to each daughter cell. These instructions program all of a cell's activities by directing the synthesis of proteins.

The genes present in DNA do not build proteins directly. They work through an intermediary—the second type of nucleic acid, known as **ribonucleic acid (RNA)**. **Figure 2.12** illustrates the main roles of these two types of nucleic acids in the production of proteins. In the nucleus of a eukaryotic cell, a gene directs the synthesis of an RNA molecule. We say that DNA is transcribed into RNA. The RNA molecule moves out of the nucleus and interacts with the protein-building machinery of the cell. There, the gene's instructions, written in "nucleic acid language," are translated into "protein language," the amino acid sequence of a polypeptide. (In prokaryotic cells, which lack nuclei, both transcription and translation take place within the cytoplasm of the cell.)



▲ **Figure 2.12** The flow of genetic information in the building of a protein

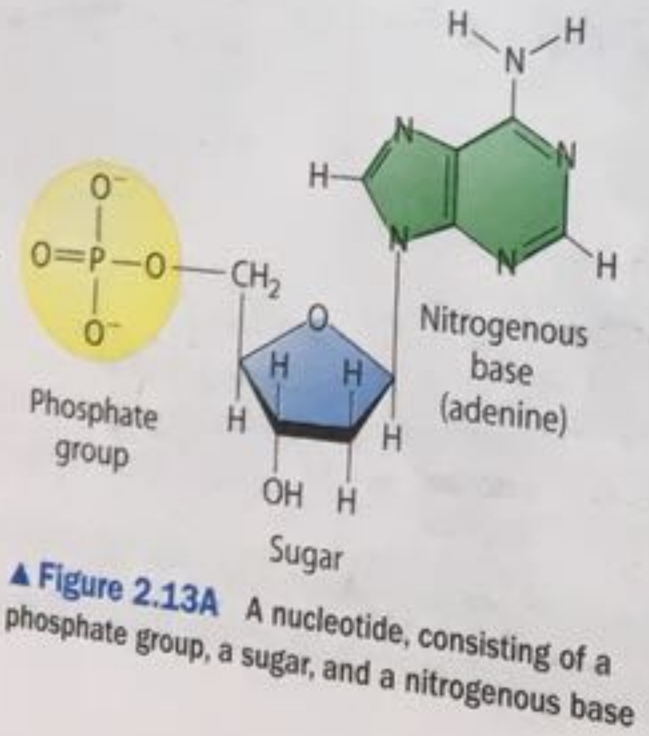
Recent research has found previously unknown types of RNA molecules that play many other roles in the cell. We return to the functions of DNA and RNA later in the book.

? How are the two types of nucleic acids functionally related?

The hereditary material of DNA contains the instructions for the primary ucture of polypeptides. RNA is the intermediary that conveys those tructions to the protein-making machinery that assembles amino acids in designated order.

2.13 Nucleic acids are polymers of nucleotides

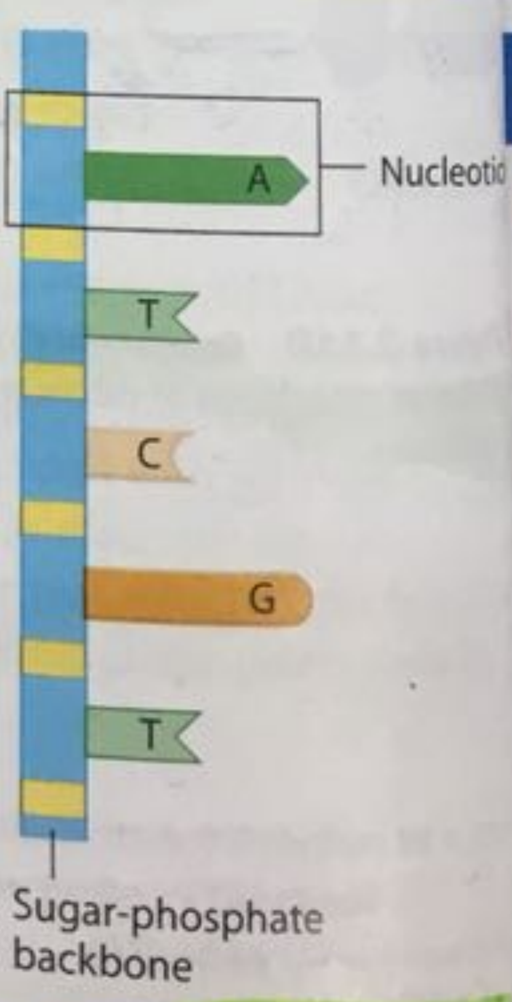
The monomers that make up nucleic acids are **nucleotides**. As indicated in **Figure 2.13A**, each nucleotide contains three parts. At the center of a nucleotide is a five-carbon sugar (blue); the sugar in DNA is deoxyribose (shown in Figure 2.13A), whereas RNA has a slightly different sugar called ribose. Linked to one side of the sugar in both types of nucleotides is a negatively charged phosphate group (yellow). Linked to the sugar's other side is a nitrogenous base (green), a molecular structure containing nitrogen and carbon. (The nitrogen atoms tend to take up H^+ in aqueous solutions, which explains why it is called a nitrogenous *base*.) Each DNA nucleotide has one of four different nitrogenous bases: adenine (A), thymine (T), cytosine (C), and guanine (G). Thus, all genetic information is written in a four-letter alphabet. RNA nucleotides also contain the bases A, C, and G; but the base uracil (U) is found instead of thymine.



▲ **Figure 2.13A** A nucleotide, consisting of a phosphate group, a sugar, and a nitrogenous base

Like polysaccharides and polypeptides, a nucleic acid polymer—a polynucleotide—is built from its monomers by dehydration reactions. In this process, the sugar of one nucleotide bonds to the phosphate group of the next monomer. The result is a repeating sugar-phosphate backbone in the polymer, as represented by the blue and yellow ribbon in **Figure 2.13B**. (Note that the nitrogenous bases are not part of the backbone.)

RNA usually consists of a single polynucleotide strand, but DNA is a



▲ **Figure 2.13B** Part of a polynucleotide

double helix, in which t
each other (**Figure 2.13C**
from the two sugar-phos
ter of the helix. As show
the figure, A always pair
The two DNA chains ar
(indicated by the dotted
These bonds are indivic
the two strands togethe
DNA molecules have th
pairs.

Because of the base-
double helix are said to
counterpart of the othe
one strand has the base
stretch on the other str
Complementary base p
two identical copies of
divides. Thus, the struc
transmitting genetic in
The same base-pairing
nucleotides of RNA pa
account for the precise
to RNA.

An organism's gene
structures and functio
of the chapter introdu
our study of biologica
up in the biological hi

**? What roles do co
tioning of nuclei**

recise replication of DNA.
itted every time a cell
urate instructions for the

C H A P

Reviewing the

Introduction to Org

2.1 Life's molecular carbon. Carbon's abi
basis for building la
Hydrocarbons are c
Isomers have the sa
structures.

2.2 A few chemical
molecules. Hydroph
specific chemical pr

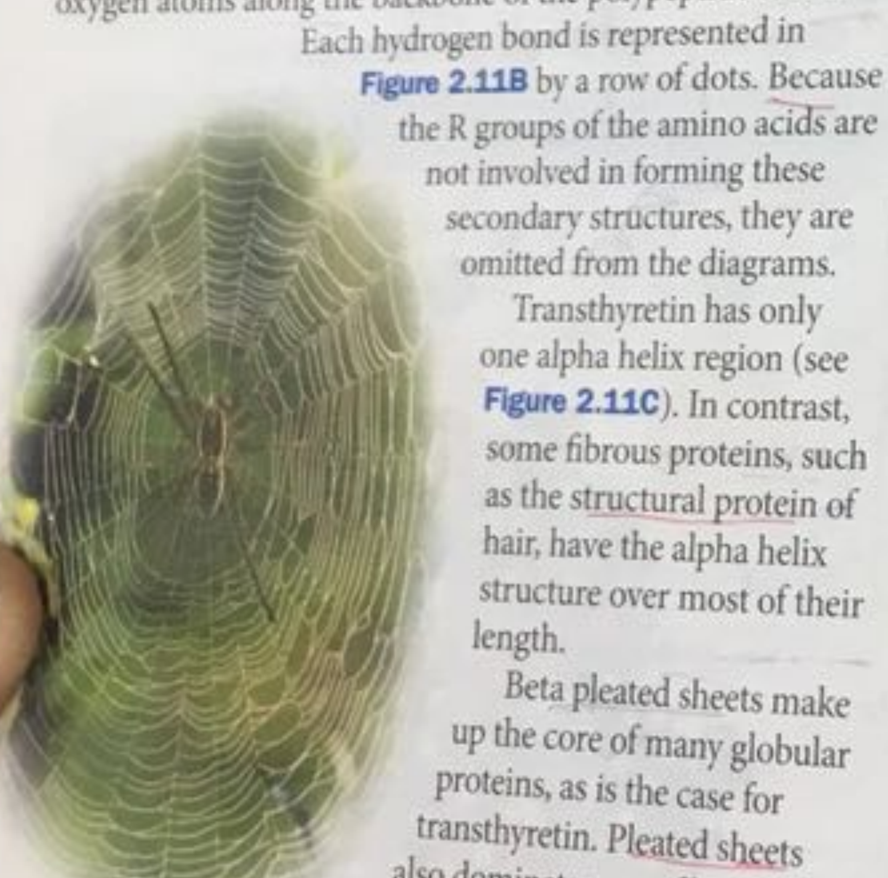
2.3 Cells make a hu
set of small molecu

2.11 A protein's shape depends on four levels of structure

Primary Structure The **primary structure** of a protein is its unique sequence of amino acids. As an example, let's consider transthyretin, an important transport protein found in your blood. Its specific shape enables it to transport vitamin A and one of the thyroid hormones throughout your body. A complete molecule of transthyretin has four identical polypeptide chains, each made up of 127 amino acids. **Figure 2.11A**, on the next page, shows part of one of these chains unraveled for a closer look at its primary structure. The three-letter abbreviations represent the specific amino acids that make up the chain.

In order for transthyretin or any other protein to perform its specific function, it must have the correct amino acids arranged in a precise order. The primary structure of a protein is determined by inherited genetic information. Even a slight change in primary structure may affect a protein's overall shape and thus its ability to function. For instance, a single amino-acid change in hemoglobin, the oxygen-carrying blood protein, causes sickle-cell disease, a serious blood disorder.

Secondary Structure In the second level of protein structure, parts of the polypeptide coil or fold into local patterns called **secondary structure**. Coiling of a polypeptide chain results in a secondary structure called an alpha helix; a certain kind of folding leads to a secondary structure called a beta pleated sheet. Both of these patterns are maintained by regularly spaced hydrogen bonds between hydrogen atoms and oxygen atoms along the backbone of the polypeptide chain. Each hydrogen bond is represented in **Figure 2.11B** by a row of dots. Because the R groups of the amino acids are not involved in forming these secondary structures, they are omitted from the diagrams.



Transthyretin has only one alpha helix region (see **Figure 2.11C**). In contrast, some fibrous proteins, such as the structural protein of hair, have the alpha helix structure over most of their length.

Beta pleated sheets make up the core of many globular proteins, as is the case for transthyretin. Pleated sheets also dominate some fibrous proteins, including the silk protein of a spider's web, shown to the left. The combined strength of so many hydrogen bonds makes each silk fiber stronger than a steel strand of the same weight. Potential uses of spider silk proteins include surgical thread, fishing line, and bulletproof vests.

Tertiary Structure The term **tertiary structure** refers to the overall three-dimensional shape of a polypeptide, which, as we've said, determines the function of a protein. As shown i Figure 2.11C, a transthyretin polypeptide has a globular sha which results from the compact arrangement of its alpha hel region and beta pleated sheet regions.

Here the R groups of the amino acids making up the polypeptide get involved in creating a protein's shape. Tertiar structure results from interactions between these R groups. F example, transthyretin and other proteins found in aqueous solutions are folded so that the hydrophobic R groups are on the inside of the molecule and the hydrophilic R groups on the outside, exposed to water. In addition to the clustering of hydrophobic groups, hydrogen bonding between polar side chains and ionic bonding of some of the charged (ionized) R groups help maintain the tertiary structure. A protein's shape may be reinforced further by covalent bonds called disulfide bridges. You saw disulfide bridges as the yellow lines in the ribbon model of lysozyme in Figure 2.10A.

Quaternary Structure Many proteins consist of two or mo polypeptide chains aggregated into one functional macromol ecule. Such proteins have a **quaternary structure**, resulting from the association of these polypeptides, which are known "subunits." **Figure 2.11D** shows a complete transthyretin molecule with its four identical globular subunits.

Another example of a protein with quaternary structure is collagen, shown to the right. Collagen is a fibrous protein with three helical polypeptides intertwined into a larger triple helix. This arrangement gives the long fibers great strength, suited to their function as the girders of connective tissue in skin, bone, tendons, and ligaments. Collagen accounts for 40% of the protein in your body.

Collagen

Many other proteins have subunits that are different from one another. For example, the oxygen-transporting molecule hemoglobin has four polypeptides of two distinct types. Each polypeptide has a nonprotein attachment, called a heme, with an iron atom that binds oxygen.

What happens if a protein folds incorrectly? Many diseases, such as Alzheimer's and Parkinson's, involve an accumulation of misfolded proteins. Prions are infectious misshapen proteins that are associated with serious degenerative brain diseases such as mad cow disease. Such diseases reinforce the theme that structure fits functio A protein's unique three-dimensional shape determines its proper functioning.

? **If a genetic mutation changes the primary structure of a protein, how might this destroy the protein's function?**

Primary structure, the amino acid sequence, affects the secondary structure, ich affects the tertiary structure, which affects the quaternary structure (if y). Thus, primary structure determines the shape of a protein, and the function protein depends on its shape. A shape change could eliminate function.

▶ **Figure 2.11A Primary structure:** linear sequence of amino acids

▶ **Figure 2.11B Secondary structure:** alpha helix and beta pleated sheet formed by hydrogen bonds between atoms of the polypeptide backbone

Hydroge
bond

▶ **Figure 2.11C Tertiary stru** three-dimensional shape formed interactions between R groups

▶ **Figure 2.11D Quaternar structure:** association of multi polypeptides

Themes in the Study of Biology

1.1 All forms of life share common properties

Defining **biology** as the scientific study of life raises the obvious question: What is *life*? How would you describe what distinguishes living things from nonliving things? Even a small child realizes that a bug or a flower is alive, while a rock or water is not. They, like all of us, recognize life mainly by what living things do. **Figure 1.1** highlights seven of the properties and processes that we associate with life.

(1) *Order*. This close-up of a sunflower illustrates the highly ordered structure that typifies life. Living cells are the basis of this complex organization.

(2) *Reproduction*. Organisms reproduce their own kind. Here an emperor penguin protects its baby.

(3) *Growth and development*. Inherited information in the form of DNA controls the pattern of growth and development of all organisms, including this hatching crocodile.

(4) *Energy processing*. When this bear eats its catch, it will use the chemical energy stored in the fish to power its own activities and chemical reactions.

(5) *Response to the environment*. All organisms respond to environmental stimuli. This Venus flytrap closed its trap rapidly in response to the stimulus of a damselfly landing on it.

معرنات الارضية

(6) *Regulation*. Many types of mechanisms regulate an organism's internal environment, keeping it within limits that sustain life. Pictured here is a typical lemur behavior with a regulatory function—"sunbathing"—which helps raise the animal's body temperature on cold mornings.

الحفاظ ع الوسط الداخلي

اكيزن

(7) *Biological adaptation*. The leaflike appearance of this katydid camouflages it in its environment. Such adaptations appear over many generations as individuals with traits best suited to their environment have greater reproductive success and pass their traits to offspring.

Figure 1.1 reminds us that the living world is wondrously varied. How do biologists make sense of this diversity and complexity, and how can you? Indeed, biology is a subject of enormous scope that gets bigger every year. One of the ways to help you organize all this information is to connect what you learn to a set of themes that you will encounter throughout your study of life. The next few modules introduce several of these themes: novel properties emerging at each level of biological organization, the cell as the fundamental unit of life, the correlation of structure and function, and the exchange of matter and energy as organisms interact with the environment. We then focus on the core theme of biology—adaption, the theme that makes sense of both the unity and diversity of life. And in the final two sections of the chapter, we look at the process of science and the relationship of biology to our everyday lives.

Let's begin our journey with a tour through the levels of the biological hierarchy.

? **How would you define life?**

Life can be defined by a set of common properties such as those described in this module.

▲ **Figure 1.1** Some important properties of life

2.10 A protein's specific shape determines its function

What do the tens of thousands of different proteins in your body do? Probably their most important role is as *enzymes*, ① the chemical catalysts that speed and regulate virtually all chemical reactions in cells. Lactase, which you read about in the chapter introduction, is just one of thousands of different enzymes that may be produced by cells.

② *Structural proteins* are found in hair and the fibers that make up connective tissues such as tendons and ligaments. Muscle cells are packed with *contractile* ③ *proteins*.

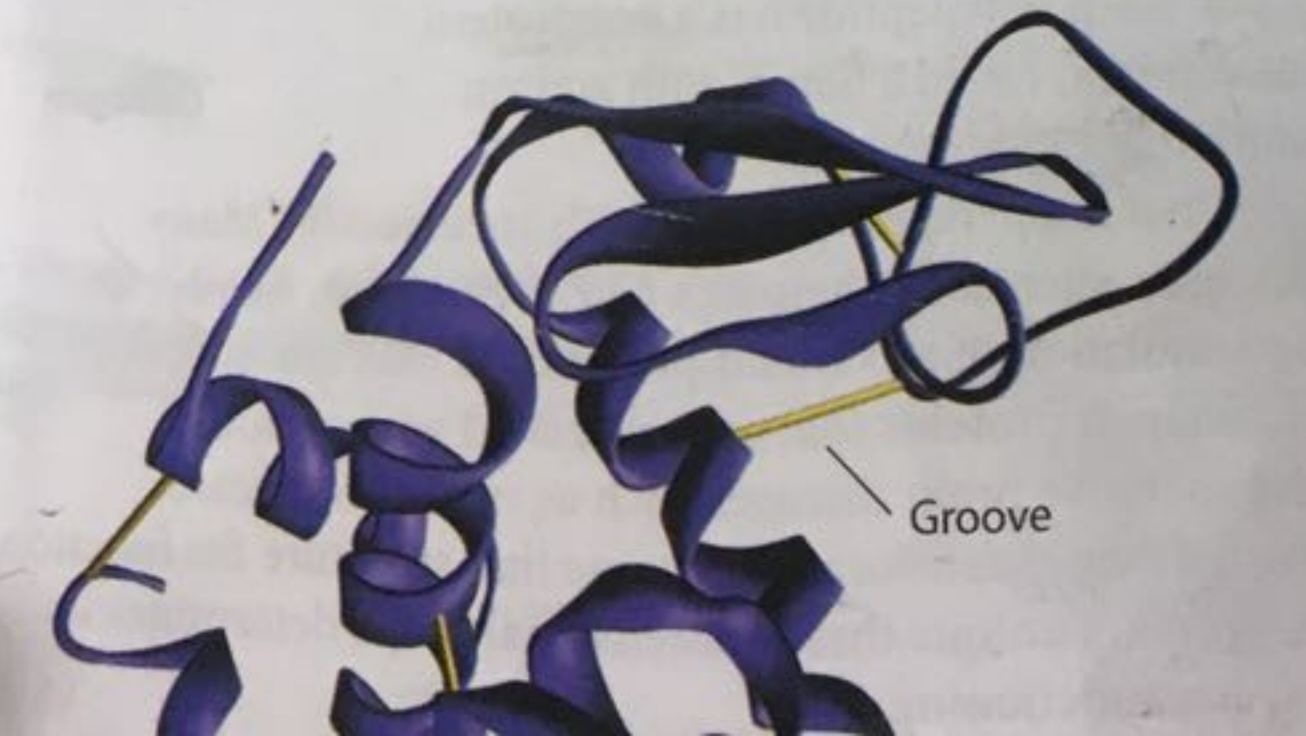
Other types of proteins include *defensive proteins*, 4 such as the antibodies of the immune system, and *signal* ⑤ *proteins*, such as many of the hormones and other chemical messengers that help coordinate body activities by facilitating communication between cells. *Receptor proteins* ⑥ may be built into cell membranes and transmit signals into cells. Hemoglobin in red blood cells is a *transport protein* ⑦ that delivers O_2 to working muscles and tissues throughout the body. Other transport proteins move sugar molecules into cells for energy. Some proteins are *storage proteins*, 8) such as ovalbumin, the protein of egg white, which serves as a source of amino acids for developing embryos. Milk proteins provide amino acids for baby mammals, and plant seeds contain storage proteins that nourish developing plant embryos.

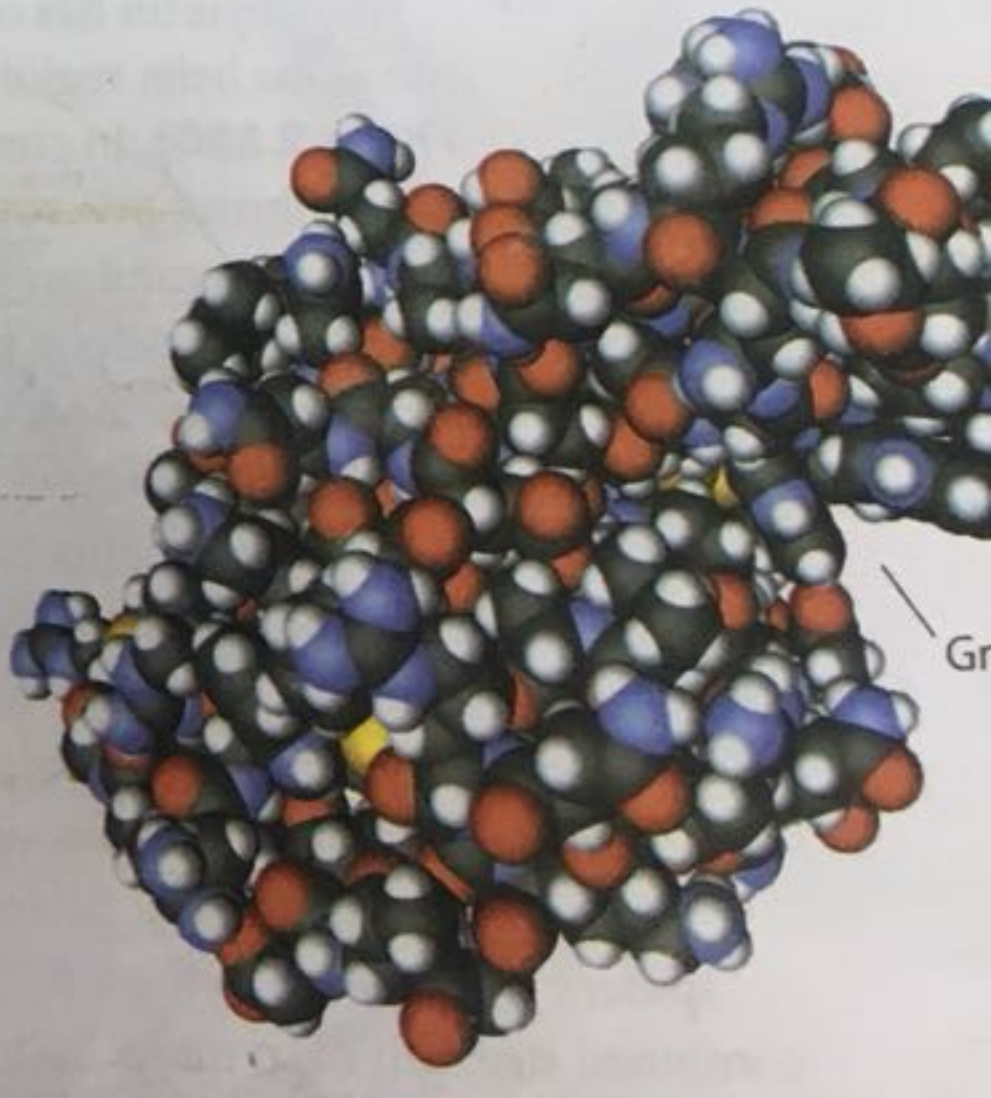
The functions of all these different types of proteins depend on their specific shape. **Figure 2.10A** shows a ribbon model of lysozyme, an enzyme found in your sweat, tears, and saliva. Lysozyme consists of one long polypeptide, represented by the purple ribbon. Lysozyme's general shape is called globular. This overall shape is more apparent in **Figure 2.10B**, a space-filling model of lysozyme. In that model, the colors represent the different atoms of carbon, oxygen, nitrogen, and hydrogen. The barely visible yellow balls are sulfur atoms that form the stabilizing bonds shown as yellow lines in the ribbon model. Most enzymes and other proteins are globular. Structural proteins, such as those making up hair, tendons, and ligaments, are typically long and thin and are called fibrous proteins.

Descriptions such as globular and fibrous refer to a protein's general shape. Each protein also has a much more specific shape. The coils and twists of lysozyme's polypeptide ribbon appear haphazard, but they represen the molecule's specific, three-dimensional shape, and thi shape is what determines its specific function. Nearly all proteins must recognize and bind to some other molecu to function. Lysozyme, for example, can destroy bacteri cells, but first it must bind to specific molecules on the bacterial cell surface. Lysozyme's specific shape enables it to recognize and attach to its molecular target, which fits into the groove you see on the right in the figures.

The dependence of protein function on a protein's specific shape becomes clear when proteins are altered In a process called **denaturation**, polypeptide chains unravel, losing their specific shape and, as a result, the function. Changes in salt concentration and pH can denature many proteins, as can excessive heat. For exa visualize what happens when you fry an egg. Heat qui denatures the clear proteins surrounding the yolk, ma them solid, white, and opaque. One of the reasons wh extremely high fevers are so dangerous is that some proteins in the body become denatured and cannot function.

Given the proper cellular environment, a newly synthesized polypeptide chain spontaneously folds i functional shape. We examine the four levels of a pr structure next.





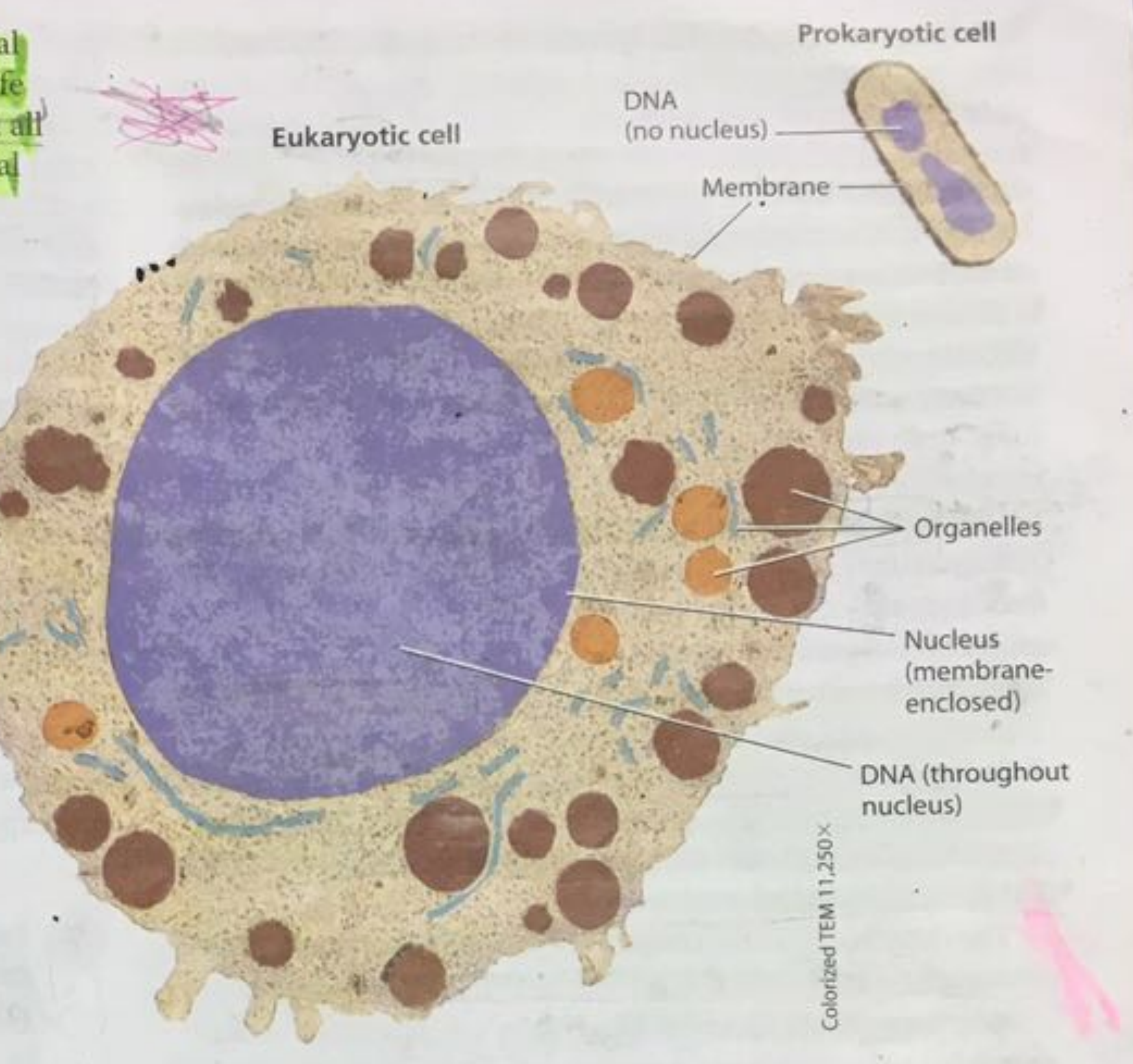
1.3 Cells are the structural and functional units of life

تسلسل هرمي [illegible]

The cell has a special place in the hierarchy of biological organization. It is the level at which the properties of life emerge—the lowest level of structure that can perform all activities required for life. A cell can regulate its internal environment, take in and use energy, respond to its environment, and develop and maintain its complex organization. The ability of cells to give rise to new cells is the basis for all reproduction and for the growth and repair of multicellular organisms.

All organisms are composed of cells. They occur singly as a great variety of unicellular (single-celled) organisms, such as amoebas and most bacteria. And cells are the subunits that make up multicellular organisms, such as lemurs and trees. Your body consists of trillions of cells of many different kinds.

All cells share many characteristics. For example, every cell is enclosed by a membrane that regulates the passage of materials between the cell and its surroundings. And every cell uses DNA as its genetic information. There are two basic types of cells. **Prokaryotic cells** were the first to develop and were Earth's sole inhabitants for about the first 1.5 billion years of life on Earth. Fossil evidence indicates that **eukaryotic cells** developed about 2.1 billion years ago.



▲ **Figure 1.3** Contrasting the size and complexity of prokaryotic and eukaryotic cells (shown here approximately 11,250 times their real size)

Figure 1.3 shows these two types of cells as artificially colored photographs taken with an electron microscope. A prokaryotic cell is much simpler and usually much smaller than a eukaryotic cell. The cells of the microorganisms we call bacteria are prokaryotic. Plants, animals, fungi, and protists are all composed of eukaryotic cells. As you can see in Figure 1.3, a eukaryotic cell is subdivided by membranes into many functional compartments, called organelles. These include a nucleus, which houses the cell's DNA.

The properties of life emerge from the ordered arrangement and interactions of the structures of a cell. Such a combination of components forms a more complex organization that we can call a *system*. Cells are examples of biological systems, as are organisms and ecosystems. Systems and their emergent properties are not unique to life. Consider a box of bicycle parts. When all of the individual parts are properly assembled, the result is a mechanical system you can use for exercise or transportation.

The emergent properties of life, however, are particularly challenging to study because of the unrivaled complexity of biological systems. At the cutting edge of large-scale research today is an approach called **systems biology**. The goal of systems biology is to construct models for the dynamic behavior of whole systems based on studying the interactions among the parts. Biological systems can range from the functioning of the biosphere to the molecular machinery of an organelle.

Cells illustrate another theme of biology: the correlation of structure and function. Experience shows you that form generally fits function. A screwdriver tightens or loosens screws, a hammer pounds nails. Because of their form, these tools can't do each other's jobs. Applied to biology, this theme of form fitting function is a guide to the structure of life at all its organizational levels. For example, the long extension of the nerve cell shown in Figure 1.2 enables it to transmit impulses across long distances in the body. Often, analyzing a biological structure gives us clues about what it does and how it works.

The activities of organisms are all based on cells. For example, your every thought is based on the actions of nerve cells, and your movements depend on muscle cells. Even a global process such as the cycling of carbon is the result of cellular activities, including the photosynthesis of plant cells and the cellular respiration of nearly all cells, a process that uses oxygen to break down sugar for energy and releases carbon dioxide. In the next module, we explore these processes and how they relate to the theme of organisms interacting with their environments.

? **Why are cells considered the basic units of life?**

● They are the lowest level in the hierarchy of biological organization at which the properties of life emerge.

1.2 In life's hierarchy of organization, new properties emerge at each level

As **Figure 1.2** illustrates, the study of life extends from the global scale of the biosphere to the microscopic scale of molecules. At the upper left we take a distant view of the **biosphere**, all of the environments on Earth that support life. These include most regions of land, bodies of water, and the lower atmosphere.

A closer look at one of these environments brings us to the level of an **ecosystem**, which consists of all the organisms living in a particular area, as well as the physical components with which the organisms interact, such as air, soil, water, and sunlight.

The entire array of organisms in an ecosystem is called a **community**. The community in this forest ecosystem in Madagascar includes the lemurs and the agave plant they are eating, as well as birds, snakes, and catlike carnivores called civets; a huge diversity of insects; many kinds of trees and other plants; fungi; and enormous numbers of microscopic protists and bacteria. Each unique form of life is called a species.

A **population** includes all the individuals of a particular species living in an area, such as all the ring-tailed lemurs in the forest community. Next in the hierarchy is the **organism**, an individual living thing.

Within a complex organism such as a lemur, life's hierarchy continues to unfold. An **organ system**, such as the circulatory system or nervous system, consists of several organs that cooperate in a specific function. For instance, the organs of the nervous system are the brain, the spinal cord, and the nerves. A lemur's nervous system controls its actions, such as climbing trees.

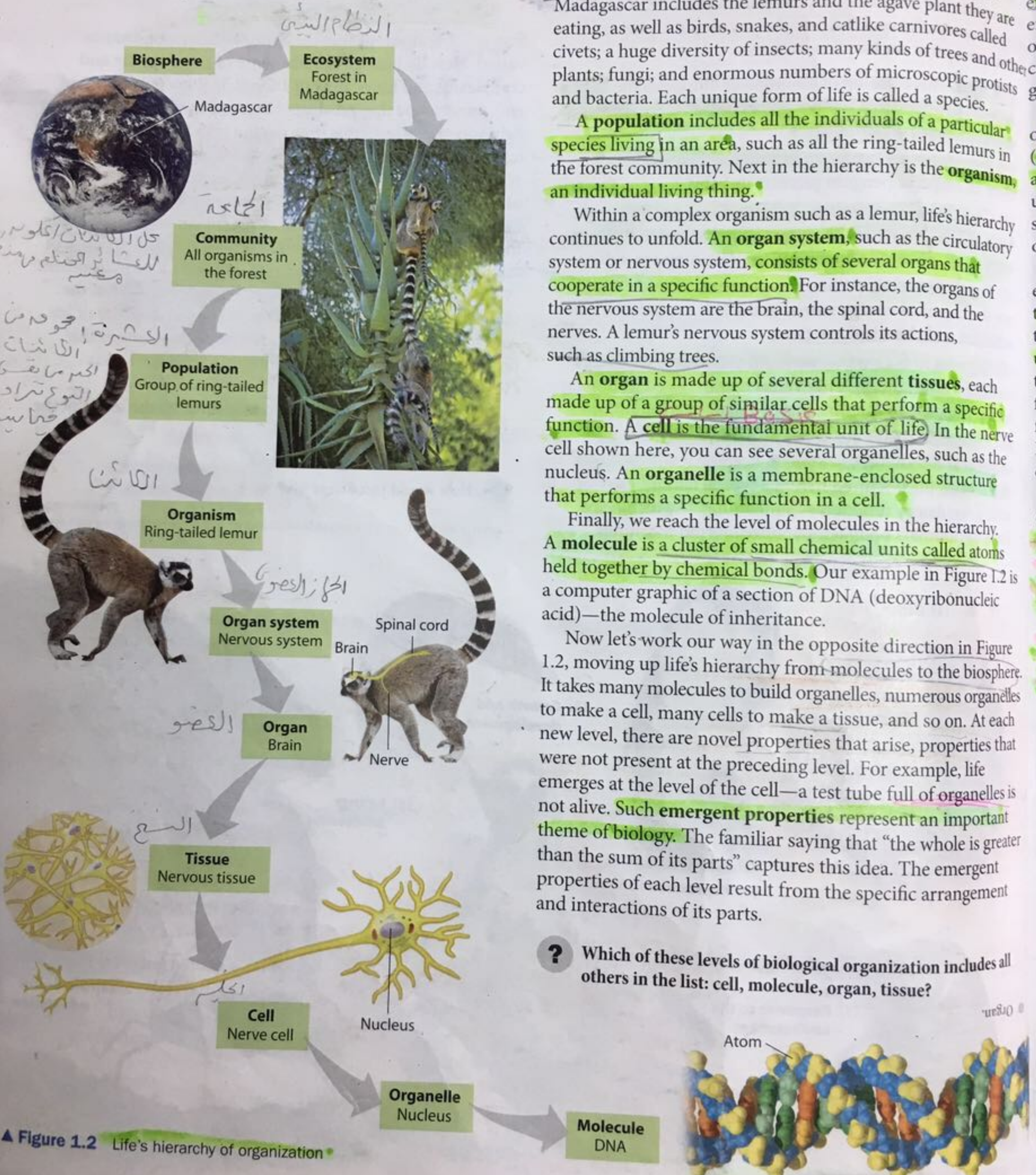
An **organ** is made up of several different **tissues**, each made up of a group of similar cells that perform a specific function. A **cell** is the fundamental unit of life. In the nerve cell shown here, you can see several organelles, such as the nucleus. An **organelle** is a membrane-enclosed structure that performs a specific function in a cell.

Finally, we reach the level of molecules in the hierarchy. A **molecule** is a cluster of small chemical units called atoms held together by chemical bonds. Our example in Figure 1.2 is a computer graphic of a section of DNA (deoxyribonucleic acid)—the molecule of inheritance.

Now let's work our way in the opposite direction in Figure 1.2, moving up life's hierarchy from molecules to the biosphere. It takes many molecules to build organelles, numerous organelles to make a cell, many cells to make a tissue, and so on. At each new level, there are novel properties that arise, properties that were not present at the preceding level. For example, life emerges at the level of the cell—a test tube full of organelles is not alive. Such **emergent properties** represent an important theme of biology. The familiar saying that "the whole is greater than the sum of its parts" captures this idea. The emergent properties of each level result from the specific arrangement and interactions of its parts.

? **Which of these levels of biological organization includes all others in the list: cell, molecule, organ, tissue?**

● Organ.

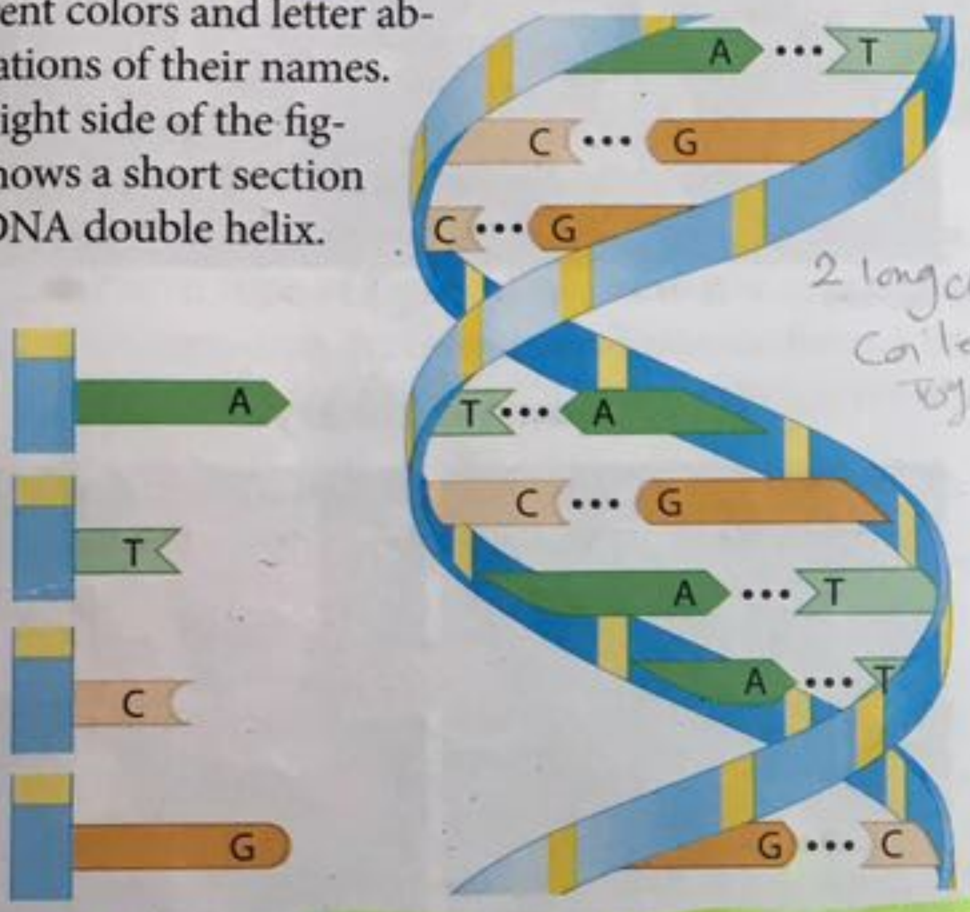


▲ **Figure 1.2** Life's hierarchy of organization

Unity of Life, the Core Theme of Biology

1.5 The unity of life is based on DNA and a common genetic code

All cells have DNA, and the continuity of life depends on this universal genetic material. DNA is the chemical substance of **genes**, the units of inheritance that transmit information from parents to offspring. Genes, which are grouped into very long DNA molecules called chromosomes, also control all the activities of a cell. The molecular structure of DNA accounts for these functions. Let us explain: Each DNA molecule is made up of two long chains coiled together into what is called a double helix. The chains are made up of four kinds of chemical building blocks. **Figure 1.5** illustrates these four building blocks, called nucleotides, with different colors and letter abbreviations of their names. The right side of the figure shows a short section of a DNA double helix.



2 long chains coiled together

▲ **Figure 1.5** The four building blocks of DNA (left); part of a DNA double helix (right)

double helix

The way DNA encodes a cell's information is analogous to the way we arrange letters of the alphabet into precise sequences with specific meanings. The word *rat*, for example, conjures up an image of a rodent; *tar* and *art*, which contain the same letters, mean very different things. We can think of the four building blocks as the alphabet of inheritance. Specific sequential arrangements of these four chemical letters encode precise information in genes, which are typically hundreds or thousands of "letters" long.

The DNA of genes provides the blueprints for making proteins, and proteins serve as the tools that actually build and maintain the cell and carry out its activities. A bacterial gene may direct the cell to "Make a yellow pigment." A particular human gene may mean "Make the hormone insulin." All forms of life use essentially the same genetic code to translate the information stored in DNA into proteins. This makes it possible to engineer cells to produce proteins normally found only in some other organism. Thus, bacteria can be used to produce insulin for the treatment of diabetes by inserting a gene for human insulin into bacterial cells.

The diversity of life arises from differences in DNA sequences—in other words, from variations on the common theme of storing genetic information in DNA. Bacteria and humans are different because they have different genes. But both sets of instructions are written in the same language.

In the next module, we see how biologists attempt to organize the diversity of life.

? **What is the chemical basis for all of life's kinship?**

● DNA as the genetic material.

1.6 The diversity of life can be arranged into three domains

We can think of biology's enormous scope as having two dimensions. The "vertical" dimension, which we examined in Module 1.2, is the size scale that stretches from molecules to the biosphere. But biology also has a "horizontal" dimension, spanning across the great diversity of organisms existing now and over the long history of life on Earth.

Grouping Species Diversity is a hallmark of life. Biologists have so far identified and named about 1.8 million species, and thousands more are identified each year. Estimates of the total number of species range from 10 million to over 100 million. Whatever the actual number, biologists face a major challenge in attempting to make sense of this enormous variety of life.

There seems to be a human tendency to group diverse items according to similarities. We may speak of bears or butterflies, though we recognize that each group includes many different species. We may even sort groups into broader categories, such as mammals and insects. Taxonomy, the branch of biology that names and classifies species, arranges species into a hierarchy of broader and broader groups, from genus, family, order, class, and phylum, to kingdom.

The Three Domains of Life Until the 1990s, most biologists used a taxonomic scheme that divided all of life into five kingdoms. But new methods for assessing phylogenetic relationships, such as comparison of DNA sequences, have led to an ongoing reevaluation of the number and boundaries of kingdoms. As that debate continues, however, there is consensus that life can be organized into three higher levels called **domains**. **Figure 1.6**, on the facing page, shows representatives of the three domains: Bacteria, Archaea, and Eukarya.

Domains **Bacteria** and **Archaea** both consist of prokaryotes, organisms with prokaryotic cells. Most prokaryotes are single-celled and microscopic. The photos of the prokaryotes in Figure 1.6 were made with an electron microscope, and the number along the side indicates the magnification of the image. Bacteria and archaea were once combined in a single kingdom. But much evidence indicates that they represent two very distinct branches of life, each of which includes multiple kingdoms.

Bacteria are the most diverse and widespread prokaryotes. In the photo of bacteria in Figure 1.6, each of the rod-shaped structures is a bacterial cell.

Many of the prokaryotes known as archaea live in Earth's extreme environments, such as salty lakes and boiling hot springs. Each round structure in the photo of archaea in Figure 1.6 is an archaeal cell.

All the eukaryotes, organisms with eukaryotic cells, are grouped in domain **Eukarya**. As you learned in Module 1.3, eukaryotic cells have a nucleus and other internal structures called organelles.

Protists are a diverse collection of mostly single-celled organisms and some relatively simple multicellular relatives. Pictured in Figure 1.6 is an assortment of protists in a drop of pond water. Although protists were once placed in a single kingdom, it is now clear that they do not form a single natural group of species. Biologists are currently debating how to split the protists into groups that accurately reflect their phylogenetic relationships.

The three remaining groups within Eukarya contain multicellular eukaryotes. These kingdoms are distinguished partly by their modes of nutrition. Kingdom Plantae consists of plants, which produce their own food by photosynthesis. The representative of kingdom Plantae in Figure 1.6 is a tropical bromeliad, a plant native to the Americas.

Kingdom Fungi, represented by the mushrooms in Figure 1.6, is a diverse group, whose members mostly decompose the remains of dead organisms and organic wastes and absorb the nutrients into their cells.

Animals obtain food by ingestion, which means they eat other organisms. Representing kingdom Animalia, the sloth in Figure 1.6 resides in the trees of Central and South American rain forests. There are actually members of two other groups in the sloth photo. The sloth is clinging to a tree (kingdom Plantae), and the greenish tinge in the animal's hair is a luxuriant growth of photosynthetic prokaryotes (domain Bacteria). This photograph exemplifies a theme reflected in our book's title: connections between living things. The sloth depends on trees for food and shelter; the tree uses nutrients from the decomposition of the sloth's feces; the prokaryotes gain access to the sunlight necessary for photosynthesis by living on the sloth; and the sloth is camouflaged from predators by its green coat.

The diversity of life and its interconnectedness are evident almost everywhere. Earlier we looked at life's unity in its shared properties, two basic types of cell structure, and common genetic code.

Domain Bacteria

Bacteria

Domain Archaea

Archaea

Domain Eukarya

Protists (multiple kingdoms)

Kingdom Plantae

Kingdom Fungi

Kingdom Animalia

▲ **Figure 1.6** The three domains of life

? **To which of the three domains of life do we belong?**

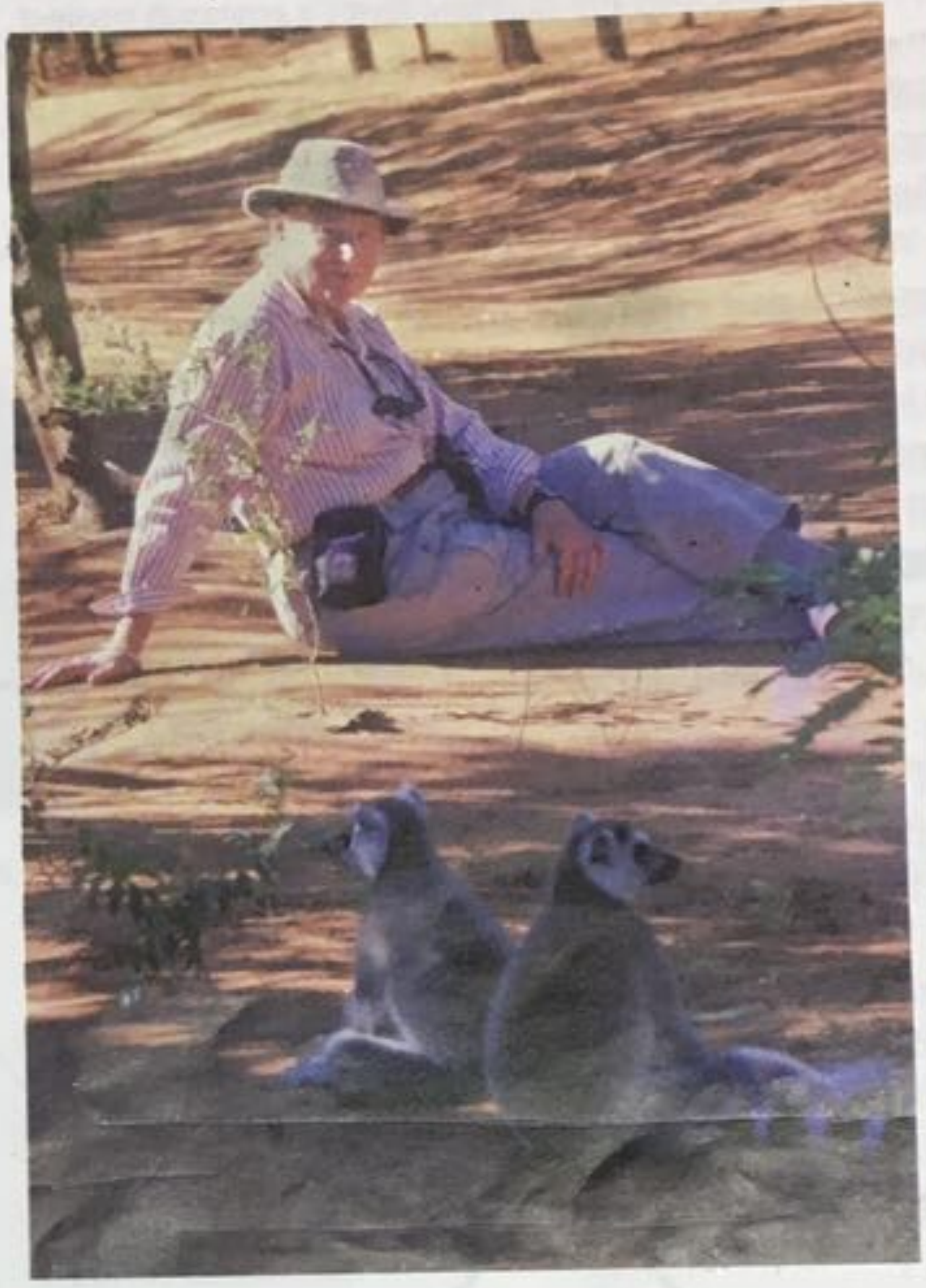
Eukarya.

The Process of Science

1.7 Scientific inquiry is used to ask and answer questions about nature

The word *science* is derived from a Latin verb meaning "to know." Science is a way of knowing—an approach to understanding the natural world. It stems from our curiosity about ourselves and the world around us. And it involves the process of inquiry—a search for information, explanations, and answers to specific questions. Scientific inquiry involves making observations, forming hypotheses, and testing predictions.

Recorded observations and measurements are the data of science. Some data are *quantitative*, such as numerical measurements. Other data may be descriptive, or *qualitative*. For example, primatologist Alison Jolly has spent over 40 years making observations of lemur نوع من القرود behavior during field research in Madagascar, amassing data that is mostly qualitative **(Figure 1.7)**.



▲ **Figure 1.7** Alison Jolly with her research subjects, ring-tailed lemurs

Collecting and analyzing observations can lead to conclusions based on a type of logic called **inductive reasoning**. This kind of reasoning derives generalizations from a large number of specific observations. "All organisms are made of cells" is an inductive conclusion based on the discovery of cells in every biological specimen observed over two centuries of time. Careful observations and the inductive conclusions they lead to are fundamental to understanding nature.

Observations often stimulate us to seek natural causes and explanations. Such inquiry usually involves the forming and testing of hypotheses. A **hypothesis** is a proposed explanation for a set of observations. A good hypothesis leads to predictions that scientists can test by recording additional observations or by designing experiments.

Deduction is the type of logic used to come up with ways to test hypotheses. In **deductive reasoning**, the logic flows from general premises to the specific results we should expect if the premises are true. If all organisms are made of cells (premise 1), and humans are organisms (premise 2), then humans are composed of cells (deduction). This deduction is a prediction that can be tested by examining human tissues.

Theories in Science

How is a theory different from a hypothesis? A scientific **theory** is much broader in scope than a hypothesis. It is usually general enough to generate many new, specific hypotheses that can then be tested. And a theory is supported by a large and usually growing body of evidence. Theories that become widely adopted explain a great diversity of observations and are supported by a vast accumulation of evidence.

? **Contrast inductive reasoning with deductive reasoning.**

● Inductive reasoning derives a generalization from many observations; deductive reasoning predicts specific outcomes from a general premise.

Introduction to the Cell

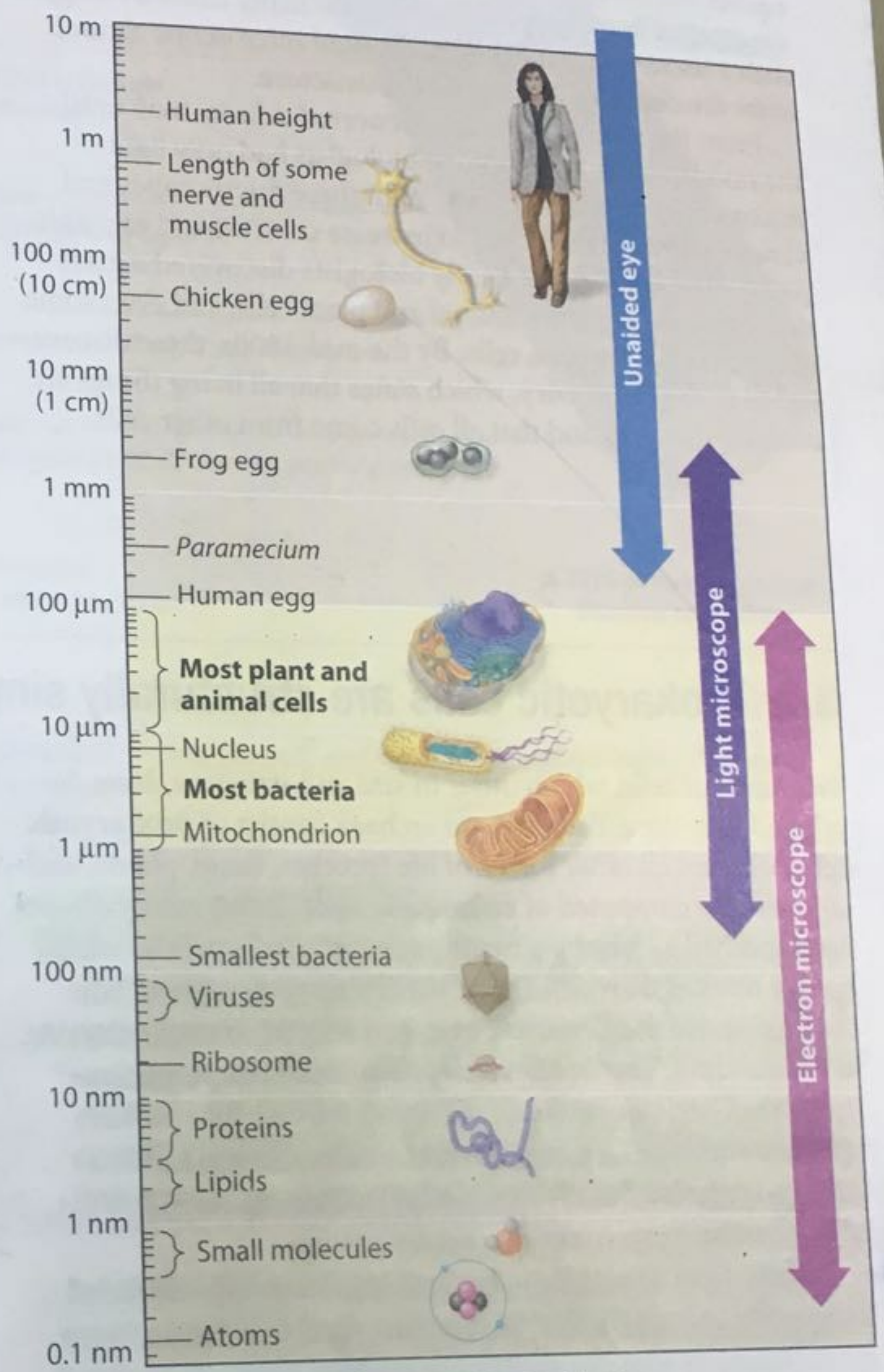
3.1 Microscopes reveal the world of the cell

Our understanding of nature often goes hand in hand with the nvention and refinement of instruments that extend human senses. Before microscopes were first used in the 17th century, no one knew that living organisms were composed of cells. The irst microscopes were light microscopes, like the ones you may use in a biology laboratory. In a **light microscope (LM)**, visible light is passed through a specimen, such as a microorganism or a thin slice of animal or plant tissue, and then through glass lenses. The lenses bend the light in such a way that the image of the specimen is magnified as it is projected nto your eye or a camera.

Magnification is the increase in the apparent size of an object. **Figure 3.1A** shows a single-celled protist called *Paramecium*. The notation "LM230×" printed along the right edge of this **micrograph** tells you that the photograph was taken through a light microscope and that this image is 230 times the actual size of the organism.

The actual size of this *Paramecium* is about 0.33 millimeter (mm) in length. **Figure 3.1B** shows the size range of cells compared with objects both larger and smaller. The most common units of length that biologists use are listed at the bottom of the figure. Notice that the scale along the left side of the figure is logarithmic to accommodate the range of sizes shown. Starting at the top of the scale with 10 meters (m) and going down, each reference measurement marks a 10-fold decrease in length. Most cells are between 1 and 100 micrometers (µm) in diameter (yellow region of the figure) and are therefore visible only with a microscope. Certain bacteria are as small as 0.2 µm in diameter and can barely be seen with a light microscope, whereas bird eggs are large enough to be seen with the unaided eye. A single nerve cell running from the base of your spinal cord to your big toe may be 1 m in length, although it is so thin you would still need a microscope to see it.

Figure 3.1A Light micrograph of a protist, *Paramecium*



1 meter (m) = 10^0 meter (m) = 39.4 inches
1 centimeter (cm) = 10^{-2} m = 0.4 inch
1 millimeter (mm) = 10^{-3} m
1 micrometer (µm) = 10^{-3} mm = 10^{-6} m
1 nanometer (nm) = 10^{-3} µm = 10^{-9} m

▲ **Figure 3.1B** The size range of cells and related objects

Light microscopes can effectively magnify objects about 1,000 times. Greater magnification does not show more details clearly; indeed, the image becomes blurry. Thus, another important factor in microscopy is resolution, a measure of the clarity of an image. Resolution is the ability of an optical instrument to show two nearby objects as separate.

For example, what looks to your unaided eye like a single star in the sky may be resolved as twin stars with a telescope. Just as the resolution of the human eye is limited, the light microscope cannot resolve detail finer than about 0.2 μm, about the size of the smallest bacterium. No matter how many times its image of such a bacterium is magnified, the light microscope cannot show the details of this small cell's structure.

From the time that Hooke discovered cells in 1665 until the middle of the 20th century, biologists had only light microscopes for viewing cells. With these microscopes and various staining techniques to increase contrast and highlight parts of the sample, these early biologists discovered a great deal—microorganisms, animal and plant cells, and even some of the structures within cells. By the mid-1800s, these discoveries led to the **cell theory**, which states that all living things are composed of cells and that all cells come from other cells.

Our knowledge of cell structure took a giant leap forw as biologists began using the electron microscope in the 1950s. Instead of using light, an **electron microscope (EM** focuses a beam of electrons through a specimen or onto it surface. Electron microscopes can distinguish biological structures as small as about 2 nanometers (nm), a 100-fol improvement over the light microscope. This high resoluti has enabled biologists to explore cell ultrastructure, the co plex internal anatomy of a cell.

? Which type of microscope would you use to study (a) the changes in shape of a living human white blood cell; (b) t finest details of surface texture of a human hair; (c) the detailed structure of an organelle in a liver cell?

Light microscope; (b) scanning electron microscope; (c) transmission electron microscope.

3.2 Prokaryotic cells are structurally simpler than eukaryotic cells

Two kinds of cells, which differ in size and structure, have developed over time. Bacteria and archaea consist of **prokaryotic cells**, whereas all other forms of life (protists, fungi, plants, and animals) are composed of **eukaryotic cells**. Eukaryotic cells are distinguished by having a membrane-enclosed nucleus, which houses most of their DNA. The word *eukaryote* means "true nucleus" (from the Greek *eu*, true, and *karyon*, kernel, referring to the nucleus). The word *prokaryote* means "before nucleus" (from the Greek *pro*, before), reflecting the fact that prokaryotic cells developed before eukaryotic cells. They are also, as you shall see, structurally much simpler than eukaryotic cells while sharing some common characteristics.

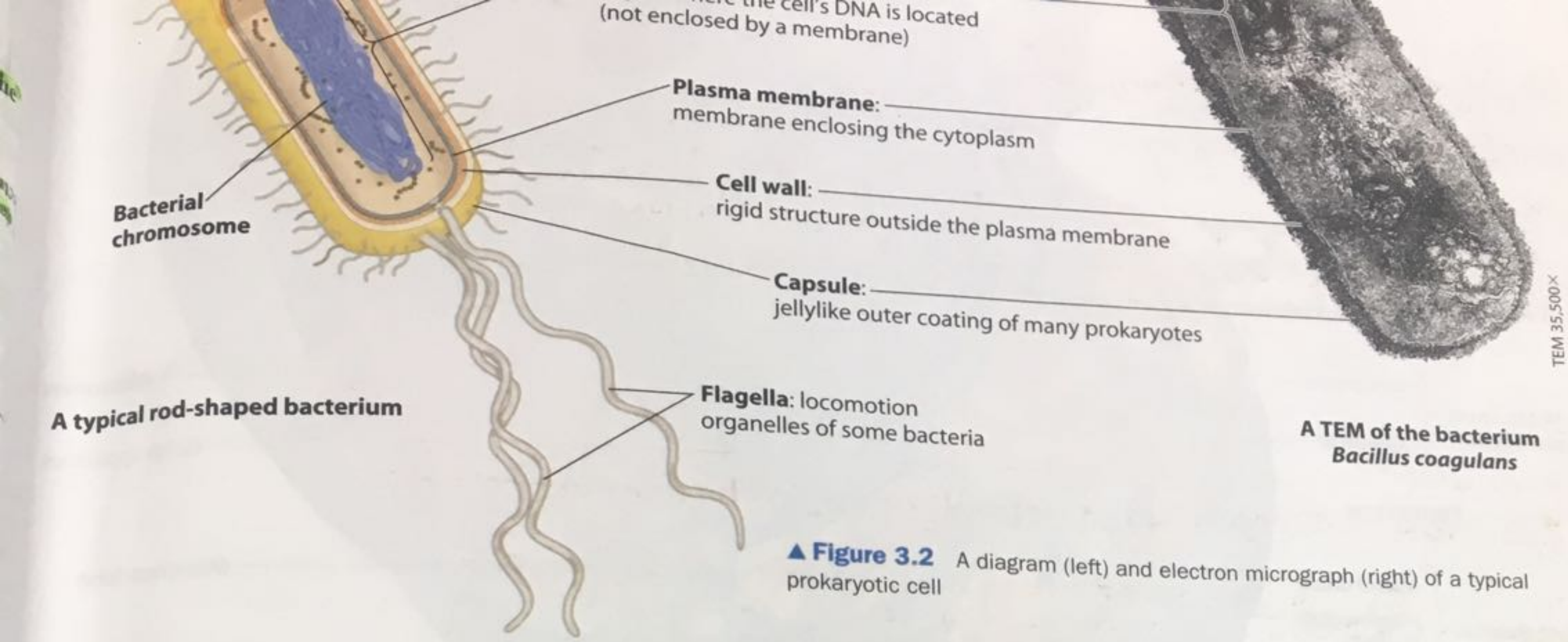
All cells have several basic features in common. In addition to being bounded by a plasma membrane, all cells have one or more **chromosomes** carrying genes made of DNA. And all cells contain **ribosomes**, tiny structures that make proteins according to instructions from the genes. The interior of both types of cell is called the **cytoplasm**. However, in eukaryotic cells, this term refers only to the region between the nucleus and the plasma membrane. The cytoplasm of a eukaryotic cell contains many membrane-enclosed organelles that perform specific functions.

The cutaway diagram in **Figure 3.2** reveals the structure of a generalized prokaryotic cell. Notice that the DNA is coiled into a region called the **nucleoid** (nucleus-like), but in contrast to the nucleus of eukaryotic cells, no membrane surrounds the DNA. The ribosomes of prokaryotes (shown here in brown) are smaller and differ somewhat from those of eukaryotes. These molecular differences are the basis for the action of some antibiotics, such as tetracycline and streptomycin, which target prokaryotic ribosomes. Thus, protein synthesis can be block for the bacterium that's invaded you, but not for you, the eukaryote who is taking the drug.

Outside the plasma membrane (shown here in gray) of most prokaryotes is a fairly rigid, chemically complex cell wall (orange). The wall protects the cell and helps maintain its shape. Some antibiotics, such as penicillin, prevent the formation of these protective walls. Again, since your cells don't have such walls, these antibiotics can kill invading bacteria without harming your cells. Certain prokaryotes ha a sticky outer coat called a capsule (yellow) around the cell wall, helping to glue the cells to surfaces, such as sticks and rocks in fast-flowing streams or tissues within the human bo In addition to capsules, some prokaryotes have surface projections. Short projections help attach prokaryotes to each other or their substrate. Longer projections called **flagella** (singular, *flagellum*) propel a prokaryotic cell through its liqu environment.

It takes an electron microscope to see the details of any ce and this is especially true of prokaryotic cells (Figure 3.2, righ side). Most prokaryotic cells are about one-tenth the size of a typical eukaryotic cell. Eukaryotic cells are the main focus of this chapter, so we turn to these next.

? List three features that are common to prokaryotic and eukaryotic cells. List three features that differ.



A typical rod-shaped bacterium

A TEM of the bacterium *Bacillus coagulans*

▲ **Figure 3.2** A diagram (left) and electron micrograph (right) of a typical prokaryotic cell

---

3.3 Eukaryotic cells are partitioned into functional compartments

All eukaryotic cells—whether from animals, plants, protists, or fungi—are fundamentally similar to one another and profoundly different from prokaryotic cells. Let's look at an animal cell and a plant cell as representatives of the eukaryotes.

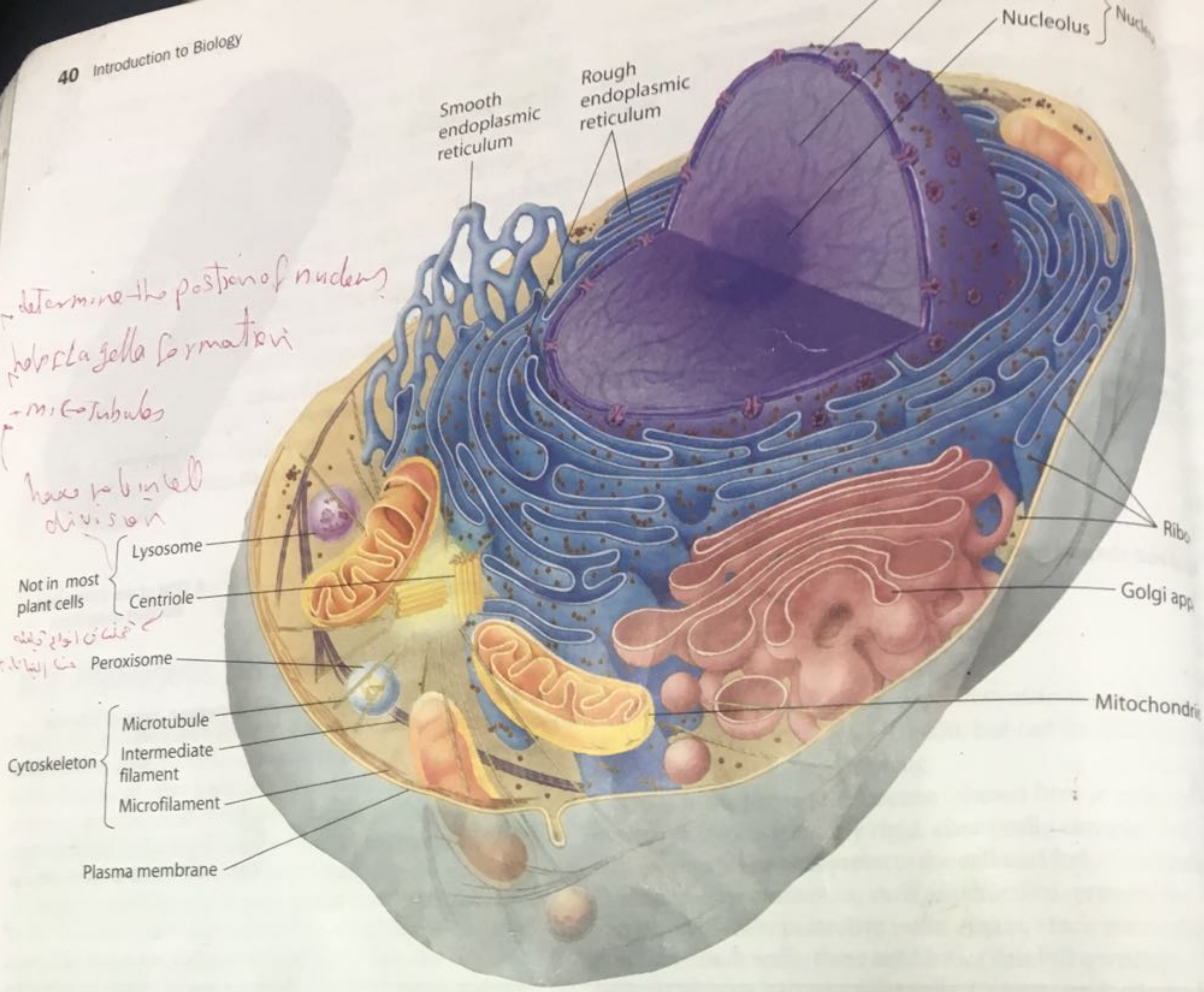
Figure 3.3A is a diagram of an idealized animal cell. No cell would look exactly like this. We color-code the various organelles and other structures in the diagrams for easier identification. And recall from the chapter introduction that in living cells many of these structures are moving and interacting.

The nucleus is the most obvious difference between a prokaryotic and eukaryotic cell. A eukaryotic cell also contains various other **organelles** ("little organs"), which perform specific functions in the cell. Just as the cell itself is wrapped in a membrane made of phospholipids and proteins that perform various functions, each organelle is bounded by a membrane with a lipid and protein composition that suits its function.

The organelles and other structures of eukaryotic cells can be organized into four basic functional groups as follows: (1) The nucleus and ribosomes carry out the genetic control of the cell. (2) Organelles involved in the manufacture, distribution, and breakdown of molecules include the ① endoplasmic reticulum, Golgi ② apparatus, lysosomes, vacuoles, and peroxisomes. (3) Mitochondria in all cells and chloroplasts in plant cells function in energy processing. (4) Structural support, movement, and communication between cells are the functions of the cytoskeleton, plasma membrane, and plant cell wall. These cellular components are identified in the figures on these two pages and will be examined in greater detail in the remaining modules of this chapter.

In essence, the internal membranes of a eukaryotic cell partition it into compartments. Many of the chemical activities of cells—activities known collectively as **cellular metabolism**—occur within organelles. In fact, many enzymatic proteins essential for metabolic processes are built into the membranes of organelles. The fluid-filled spaces within organelles are important as sites where specific chemical conditions are maintained. These conditions vary from one organelle to another and favor the metabolic processes occurring in each kind of organelle. For example, while a part of the endoplasmic reticulum is engaged in making steroid hormones, neighboring peroxisomes may be detoxifying harmful compounds and making hydrogen peroxide (H_2O_2) as a poisonous by-product of their activities.

1



- determine the position of nucleus
- help flagella formation
- microtubules

have role in cell division

تحتوي انواع قليلة
من النباتات

▲ **Figure 3.3A** An animal cell

But because the H_2O_2 is confined within peroxisomes, where it is quickly converted to H_2O by resident enzymes, the rest of the cell is protected from destruction.

Almost all of the organelles and other structures of animal cells are also present in plant cells. As you can see in Figure 3.3A, however, there are a few exceptions: Lysosomes and centrioles are not found in plant cells. Also, although some animal cells have flagella or cilia (not shown in Figure 3.3A), among plants, only the sperm cells of a few species have flagella. (The flagella of prokaryotic cells differ in both structure and function from eukaryotic flagella.)

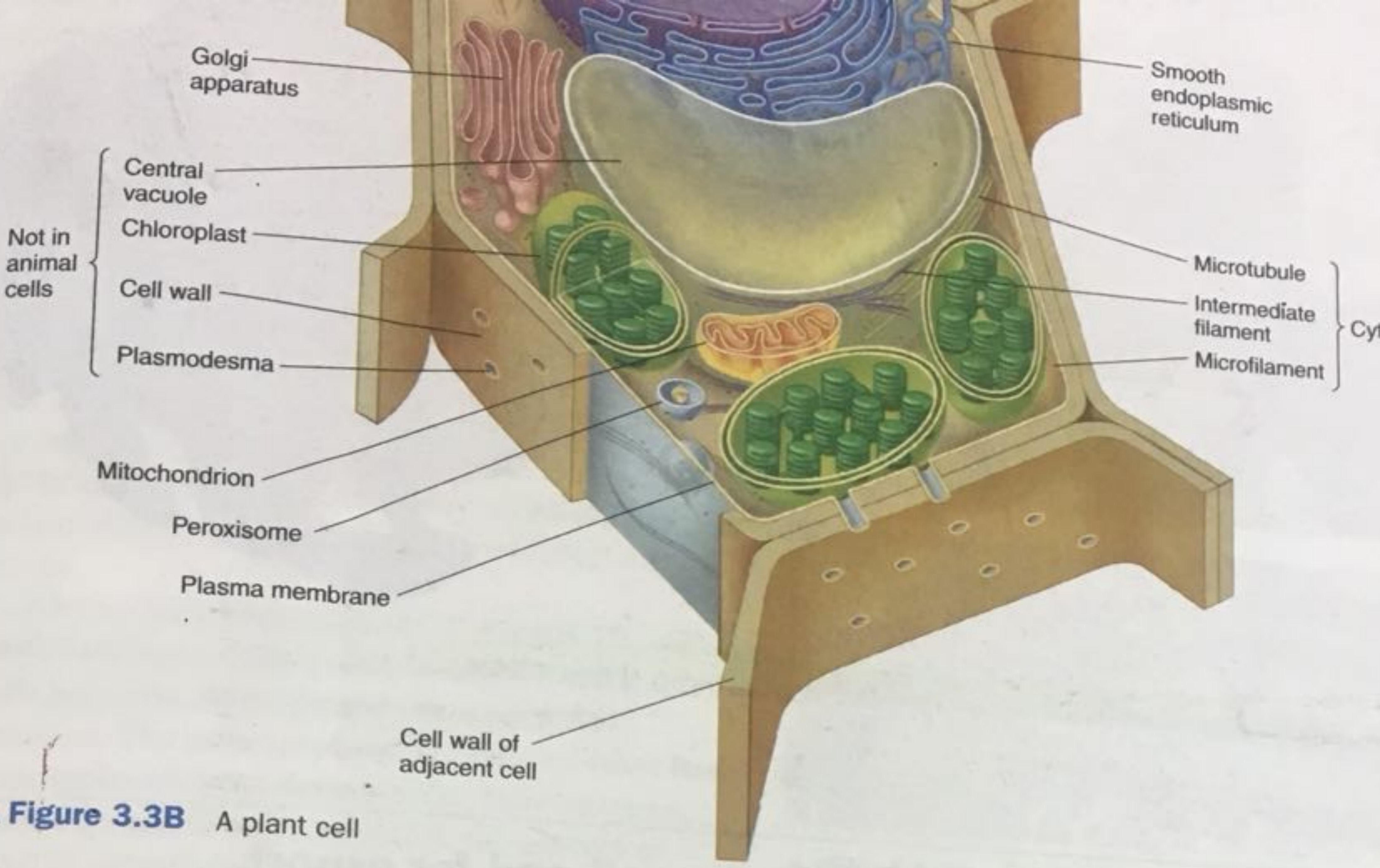
A plant cell **(Figure 3.3B)** also has some structures that an animal cell lacks. For example, a plant cell has a rigid, rather thick cell wall (as do the cells of fungi and many protists). Cell walls protect cells and help maintain their shape. Chemically different from prokaryotic cell walls, plant cell walls contain the polysaccharide cellulose. Plasmodesmata (singular, plasmodesma) are cytoplasmic channels through cell walls that connect adjacent cells. An important organelle found in plant cells is the chloroplast, where photosynthesis occurs. (Chloroplasts are also found in algae and some other protists.) Unique to plant cells is a large central vacuole, a compartment that stores water and a variety of chemicals.

Although we have emphasized organelles, eukaryotic cells contain nonmembranous structures as well. The cytoskeleton is composed of different types of protein fibers that extend throughout the cell. These networks provide for support and movement. As you can see by the many brown dots in both figures, ribosomes occur throughout the cytoplasm, as they do in prokaryotic cells. In addition, eukaryotic cells have many ribosomes attached to parts of the endoplasmic reticulum (making it appear "rough") and to the outer membrane of the nucleus.

Let's begin our in-depth tour of the eukaryotic cell, starting with the nucleus.

? **Which of the following cellular structures differs from the others in the list: mitochondrion, chloroplast, ribosome, lysosome, vacuole? How** **ffer?**

the list that is not bounded



▲ **Figure 3.3B** A plant cell

The Nucleus and Ribosomes

3.4 The nucleus is the cell's genetic control center

histones

The **nucleus** contains most of the cell's DNA—its master plans—and controls the cell's activities by directing protein synthesis. The DNA is associated with many proteins in the structures called chromosomes. The proteins help organize and coil the long DNA molecule. Indeed, the DNA of the 46 chromosomes in one of your cells laid end to end would stretch to a length of over 2 m, but it must coil up to fit into a nucleus only 5 μm in diameter. When a cell is not dividing, this complex of proteins and DNA, called **chromatin**, appears as a diffuse mass, as shown in the TEM (left) and diagram (right) of a nucleus in **Figure 3.4.**

As a cell prepares to divide, the DNA is copied so that each daughter cell can later receive an identical set of genetic instructions. Just prior to cell division, the thin chromatin fibers coil up further, becoming thick enough to be visible with a light microscope as the familiar separate structures you would probably recognize as chromosomes.

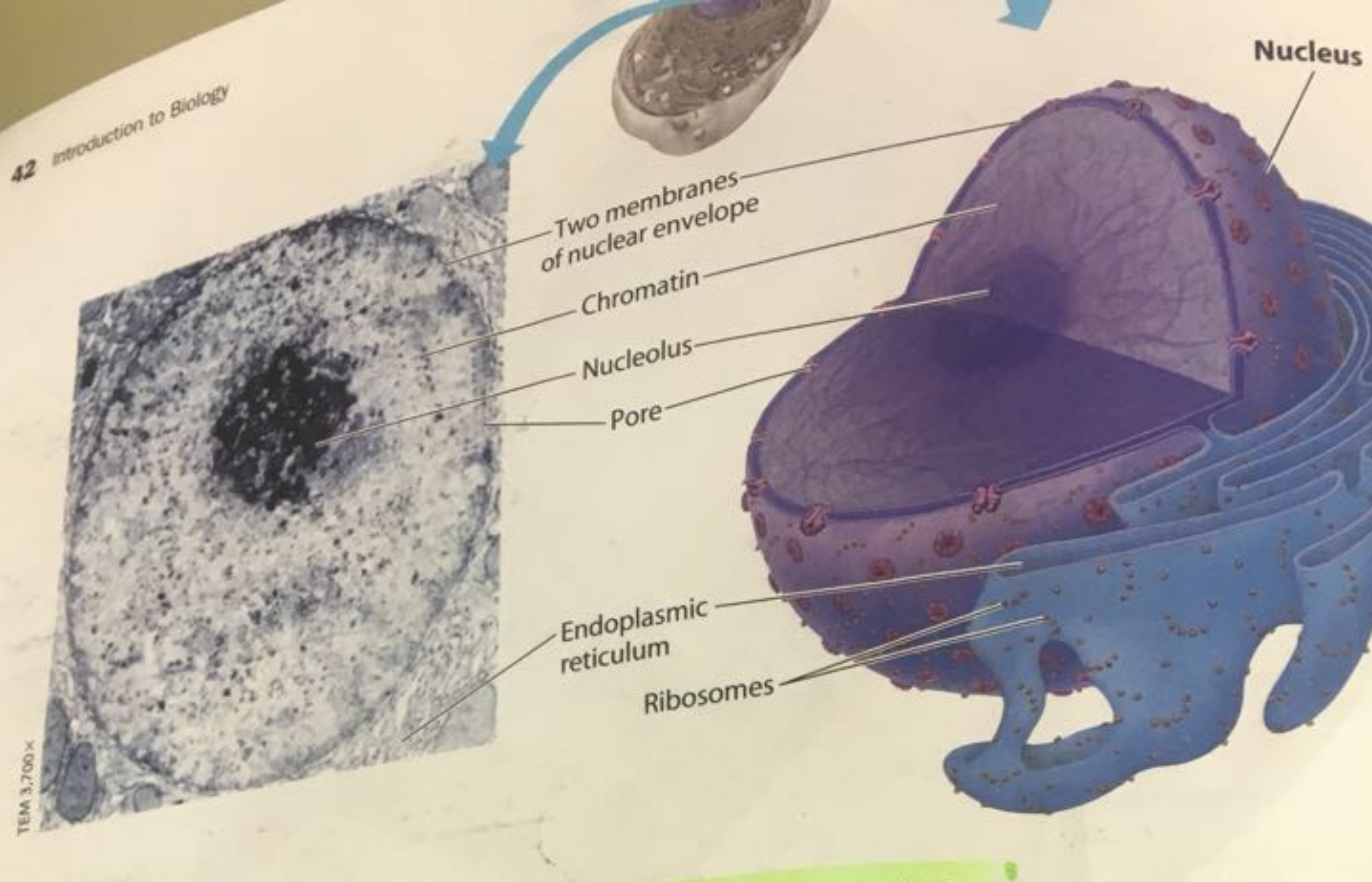
Enclosing the nucleus is a double membrane called the **nuclear envelope**. Each of the membranes is a separate phospholipid bilayer with associated proteins. Similar in function to the plasma membrane, the nuclear envelope controls the flow of materials into and out of the nucleus. As you can see in the diagram in Figure 3.4, the nuclear envelope is perforated with protein-lined pores that regulate the movement of large molecules and also connects with the cell's network of membranes called the endoplasmic reticulum.

The **nucleolus**, a prominent structure in the nucleus, is the site where a special type of RNA called *ribosomal RNA* (rRNA) is synthesized according to instructions in the DNA. Proteins brought in through the nuclear pores from the cytoplasm are assembled with this rRNA to form the subunits of ribosomes. These subunits then exit through the pores to the cytoplasm, where they will join to form functional ribosomes.

The nucleus directs protein synthesis by making another type of RNA, *messenger RNA* (mRNA). Essentially, mRNA is a transcription of protein-synthesizing instructions written in a gene's DNA (see Figure 2.12). The mRNA moves through the pores in the nuclear envelope to the cytoplasm. There it is translated by ribosomes into the amino acid sequences of proteins. Let's look at ribosomes next.

? **What are the main functions of the nucleus?**

● To house and copy DNA and pass it on to daughter cells in cell division; to build ribosomal subunits; to transcribe DNA instructions into RNA and thereby control the cell's functions.



▲ **Figure 3.4** Transmission electron micrograph (left) and diagram (right) of the nucleus

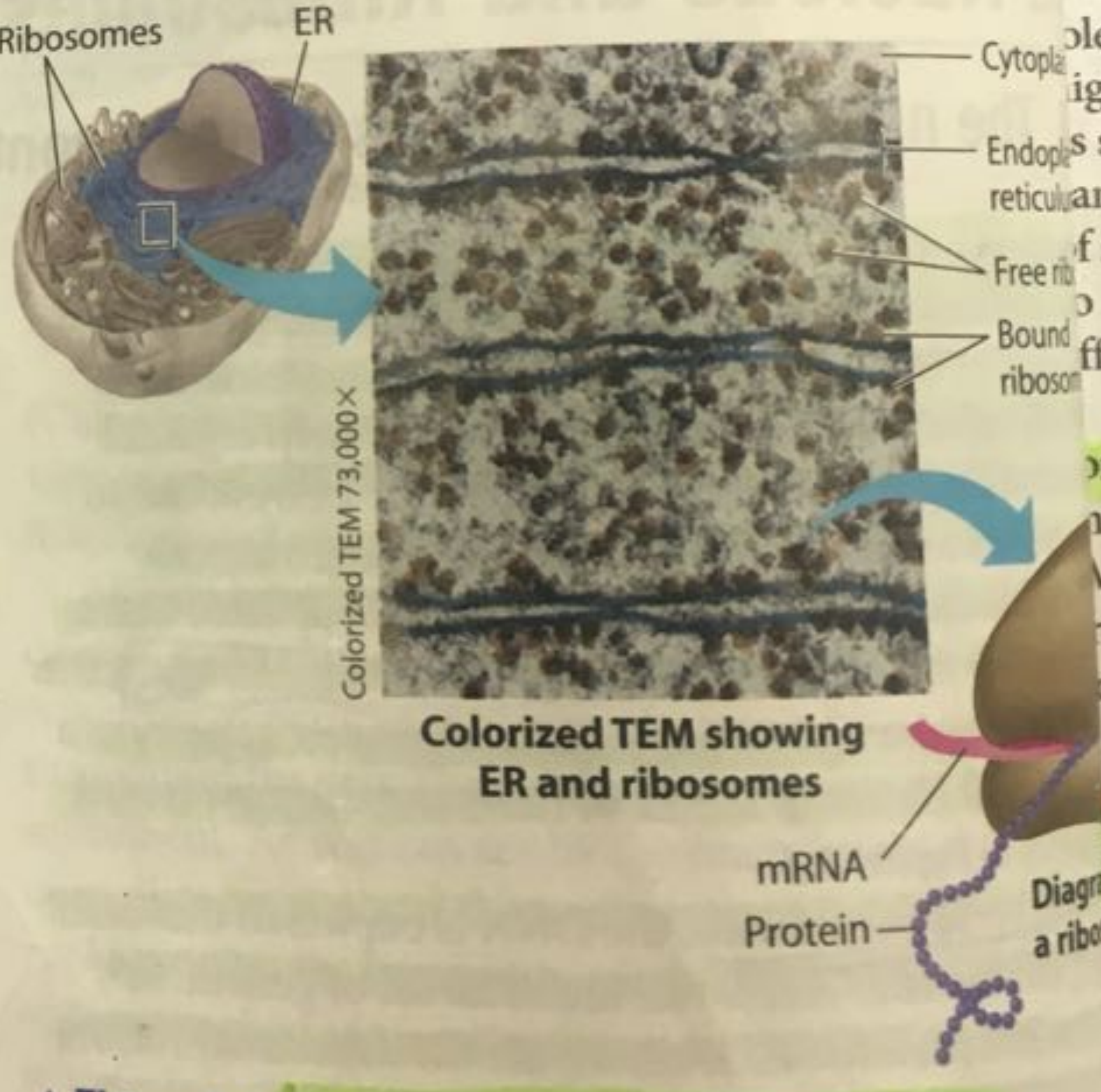
3.5 Ribosomes make proteins for use in the cell and for export

If the nucleus is the command center, then ribosomes are the machines on which those commands are carried out. Ribosomes are the cellular components that use instructions sent from the nucleus to carry out protein synthesis. Cells that make a lot of proteins have a large number of ribosomes. For example, a human pancreas cell producing digestive enzymes may contain a few million ribosomes. What other structure would you expect to be prominent in cells that are active in protein synthesis? As you just learned, nucleoli assemble the subunits of ribosomes out of ribosomal RNA and protein.

As shown in the colorized TEM in **Figure 3.5**, ribosomes are found in two locations in the cell. *Free ribosomes* are suspended in the fluid of the cytoplasm, while *bound ribosomes* are attached to the outside of the endoplasmic reticulum or nuclear envelope. Free and bound ribosomes are structurally identical, and ribosomes can alternate between the two locations.

Most of the proteins made on free ribosomes function within the cytoplasm; examples are enzymes that catalyze the first steps of sugar breakdown. In Module 3.6, you will see how bound ribosomes make proteins that will be inserted into membranes, packaged in certain organelles, or exported from the cell.

At the bottom right in Figure 3.5, you see how ribosomes interact with messenger RNA (carrying the instructions from a gene) to build a protein. The nucleotide sequence of an mRNA molecule is translated into the amino acid sequence of a polypeptide. Protein synthesis is explored in



▲ **Figure 3.5** The locations and structure of ribosomes

Chapter 6. Next let's look at more of the manufacturing department of the cell.

? What role do ribosomes play in carrying out the genetic instructions of a cell?

Active transport allows a cell to maintain internal concentrations of small molecules and ions that are different from concentrations in its surroundings. For example, the inside of an animal cell has a higher concentration of potassium ions (K^+) and a lower concentration of sodium ions (Na^+) than the solution outside the cell. The generation of nerve signals depends on these concentration differences, which a transport protein called the sodium-potassium pump helps maintain by shuttling Na^+ and K^+ against their concentration gradients.

? Cells actively transport Ca^{2+} out of the cell. Is calcium more concentrated inside or outside of the cell? Explain.

● Outside: Active transport moves calcium against its concentration gradient.

Export import bulk

4.6 Exocytosis and endocytosis transport large molecules across membranes

15 min

So far, we've focused on how water and small solutes enter and leave cells. The story is different for large molecules.

A cell uses the process of **exocytosis** (from the Greek *exo*, outside, and *kytos*, cell) to export bulky materials such as proteins or polysaccharides. As you saw in Figure 3.10, a transport vesicle filled with macromolecules buds from the Golgi apparatus and moves to the plasma membrane. Once there, the vesicle fuses with the plasma membrane, and the vesicle's contents spill out of the cell when the vesicle membrane becomes part of the plasma membrane. When we weep, for instance, cells in our tear glands use exocytosis to export a salty solution containing proteins. In another example, certain cells in the pancreas manufacture the hormone insulin and secrete it into the bloodstream by exocytosis.

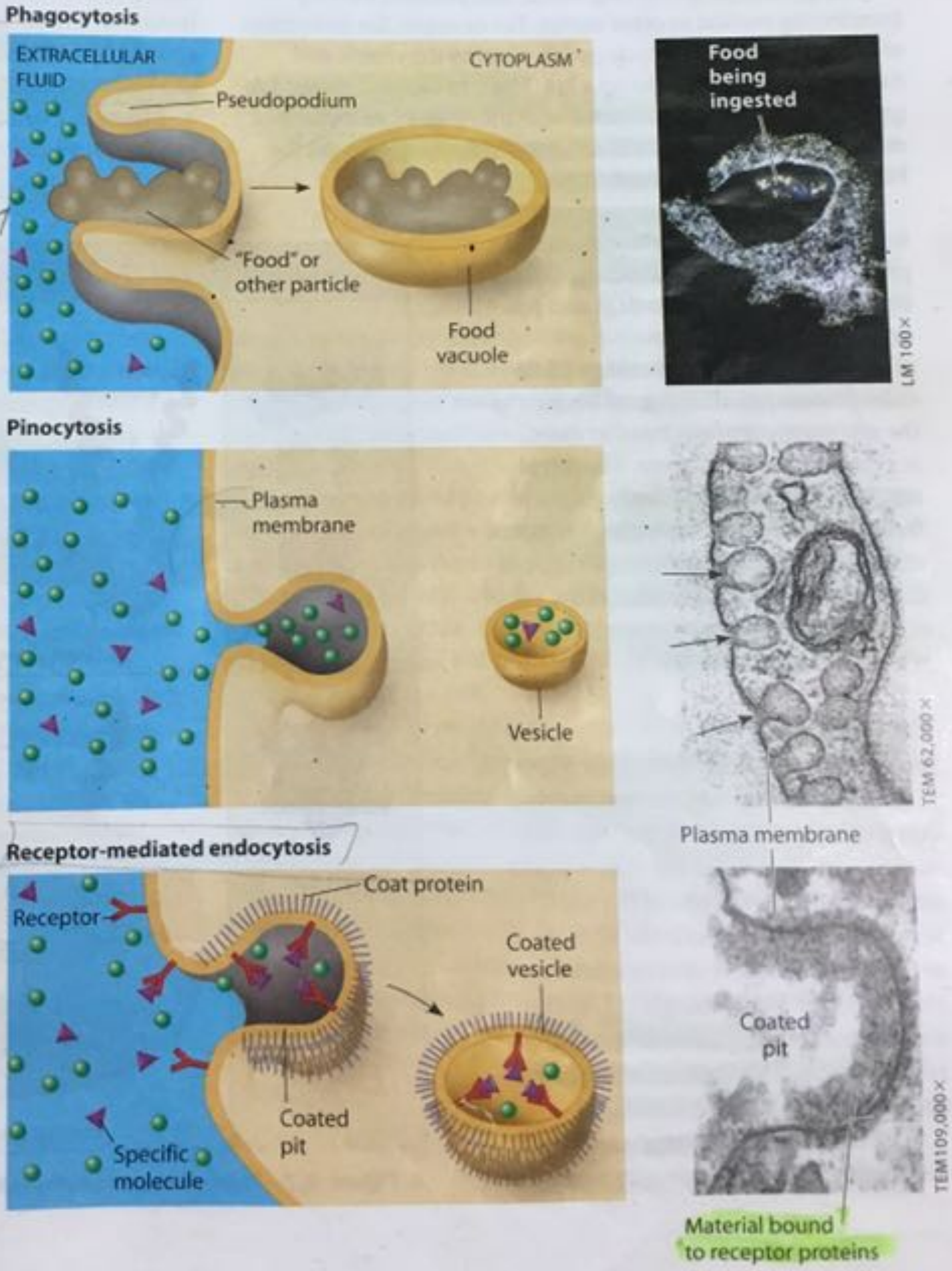
Endocytosis (*endo*, inside) is a transport process that is the opposite of exocytosis. In endocytosis, a cell takes in large molecules. A depression in the plasma membrane pinches in and forms a vesicle enclosing material that had been outside the cell.

Figure 4.6 shows three kinds of endocytosis. The top diagram illustrates **phagocytosis**, or "cellular eating." A cell engulfs a particle by wrapping extensions called pseudopodia around it and packaging it within a membrane-enclosed sac large enough to be called a vacuole. As described in Module 3.8, the vacuole then fuses with a lysosome, whose hydrolytic enzymes digest the contents of the vacuole. The micrograph on the top right shows an amoeba taking in a food particle via phagocytosis.

The center diagram shows **pinocytosis**, or "cellular drinking." The cell "gulps" droplets of fluid into tiny vesicles. Pinocytosis is not specific; it takes in any and all solutes dissolved in the droplets. The micrograph in the middle shows pinocytosis vesicles forming (arrows) in a cell lining a small blood vessel.

? As a cell grows, its plasma membrane expands. Does this involve endocytosis or exocytosis? Explain.

● Exocytosis: When a transport vesicle fuses with the plasma membrane, its contents are released and the vesicle membrane adds to the plasma membrane.



▲ **Figure 4.6** Three kinds of endocytosis

Active transport allows a cell to maintain internal concentrations of small molecules and ions that are different from concentrations in its surroundings. For example, the inside of an animal cell has a higher concentration of potassium ions (K^+) and a lower concentration of sodium ions (Na^+) than the solution outside the cell. The generation of nerve signals depends on these concentration differences, which a transport protein called the sodium-potassium pump helps maintain by shuttling Na^+ and K^+ against their concentration gradients.

? **Cells actively transport Ca^{2+} out of the cell. Is calcium more concentrated inside or outside of the cell? Explain.**

● Outside: Active transport moves calcium against its concentration gradient.

Export import bulk

4.6 Exocytosis and endocytosis transport large molecules across membranes

15 min

So far, we've focused on how water and small solutes enter and leave cells. The story is different for large molecules.

A cell uses the process of **exocytosis** (from the Greek *exo*, outside, and *kytos*, cell) to export bulky materials such as proteins or polysaccharides. As you saw in Figure 3.10, a transport vesicle filled with macromolecules buds from the Golgi apparatus and moves to the plasma membrane. Once there, the vesicle fuses with the plasma membrane, and the vesicle's contents spill out of the cell when the vesicle membrane becomes part of the plasma membrane. When we weep, for instance, cells in our tear glands use exocytosis to export a salty solution containing proteins. In another example, certain cells in the pancreas manufacture the hormone insulin and secrete it into the bloodstream by exocytosis.

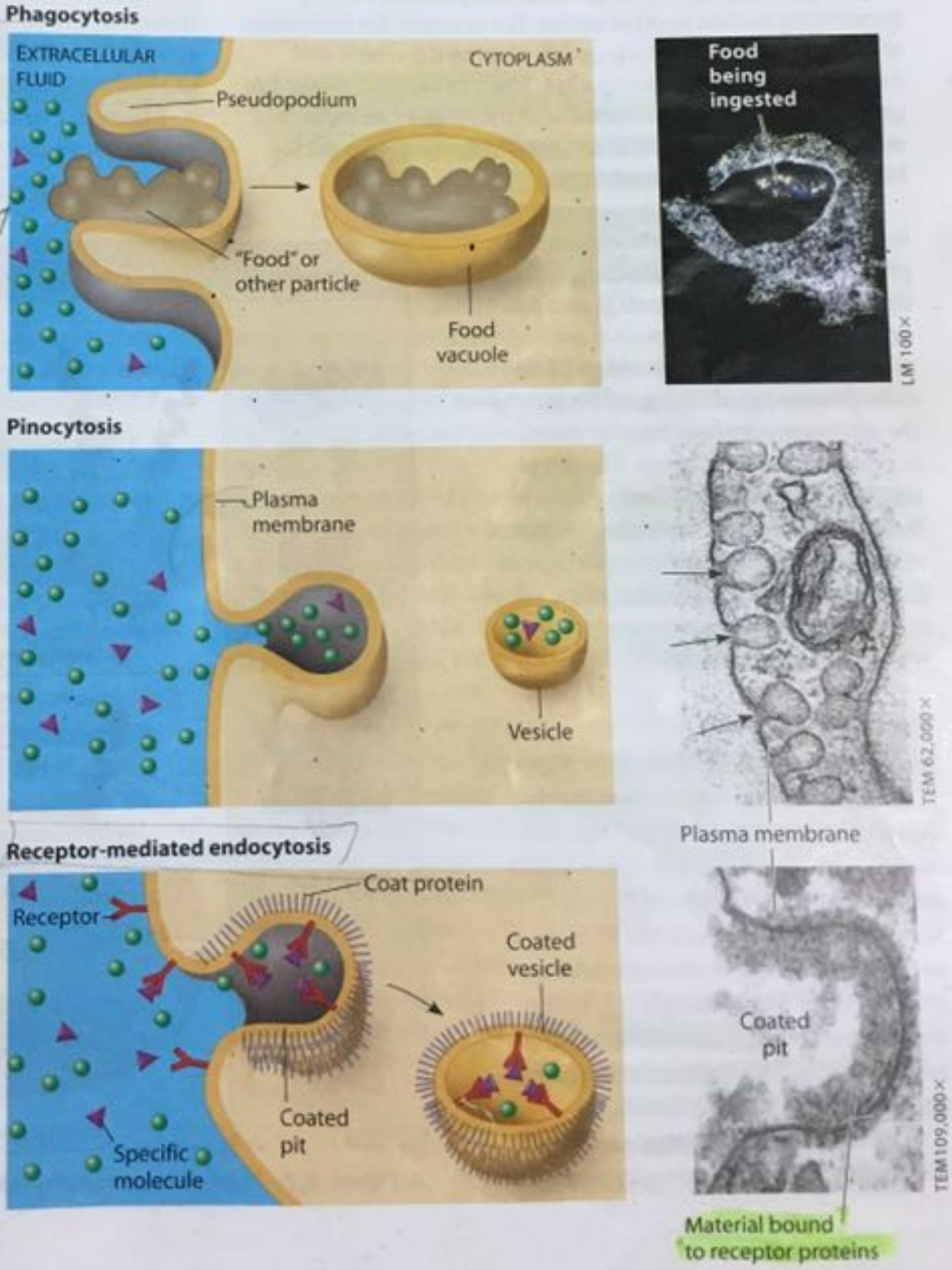
Endocytosis (*endo*, inside) is a transport process that is the opposite of exocytosis. In endocytosis, a cell takes in large molecules. A depression in the plasma membrane pinches in and forms a vesicle enclosing material that had been outside the cell.

? **As a cell grows, its plasma membrane expands. Does this involve endocytosis or exocytosis? Explain.**

● Exocytosis: When a transport vesicle fuses with the plasma membrane, its contents are released and the vesicle membrane adds to the plasma membrane.

Figure 4.6 shows three kinds of endocytosis. The top diagram illustrates **phagocytosis**, or "cellular eating." A cell engulfs a particle by wrapping extensions called pseudopodia around it and packaging it within a membrane-enclosed sac large enough to be called a vacuole. As described in Module 3.8, the vacuole then fuses with a lysosome, whose hydrolytic enzymes digest the contents of the vacuole. The micrograph on the top right shows an amoeba taking in a food particle via phagocytosis.

The center diagram shows **pinocytosis**, or "cellular drinking." The cell "gulps" droplets of fluid into tiny vesicles. Pinocytosis is not specific; it takes in any and all solutes dissolved in the droplets. The micrograph in the middle shows pinocytosis vesicles forming (arrows) in a cell lining a small blood vessel.



▲ **Figure 4.6** Three kinds of endocytosis

3.6 The endoplasmic reticulum is a biosynthetic factory

One of the major manufacturing sites in a cell is the endoplasmic reticulum. The diagram in **Figure 3.6A** shows a cutaway view of the interconnecting membranes of the smooth and rough ER. These two types of ER can be distinguished in the electron micrograph. **Smooth endoplasmic reticulum** is called *smooth* because it lacks attached ribosomes. **Rough endoplasmic reticulum** has ribosomes that stud the outer surface of the membrane; thus, it appears *rough* in the electron micrograph.

Smooth ER The smooth ER of various cell types functions in a variety of metabolic processes. Enzymes of the smooth ER are important in the synthesis of lipids, including oils, phospholipids, and steroids. In vertebrates, for example, cells of the ovaries and testes synthesize the steroid sex hormones. These cells are rich in smooth ER, a structural feature that fits their function by providing ample machinery for steroid synthesis.

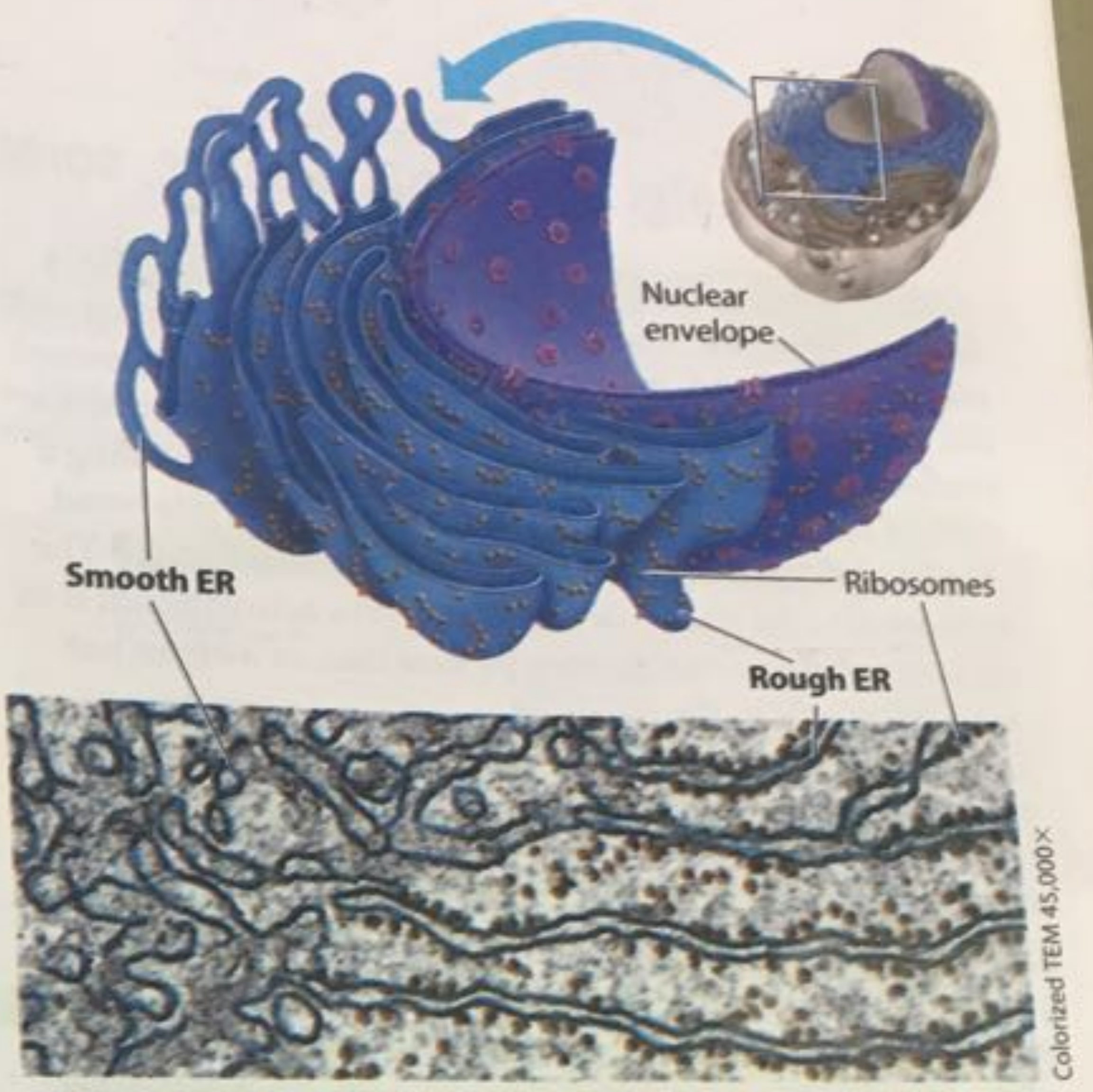
Our liver cells also have large amounts of smooth ER, with other important functions. Certain enzymes in the smooth ER of liver cells help process drugs and other potentially harmful substances. The sedative phenobarbital and other barbiturates are examples of drugs detoxified by these enzymes. As liver cells are exposed to such chemicals, the amount of smooth ER and its detoxifying enzymes increases, thereby increasing the rate of detoxification and thus the body's tolerance to the drugs. The result is a need for higher and higher doses of a drug to achieve a particular effect, such as sedation. Also, because detoxifying enzymes often cannot distinguish among related chemicals, the growth of smooth ER in response to one drug can increase tolerance to other drugs. Barbiturate abuse, for example, can decrease the effectiveness of certain antibiotics and other useful drugs.

Smooth ER has yet another function, the storage of calcium ions. In muscle cells, for example, a specialized smooth ER membrane pumps calcium ions into the interior of the ER. When a nerve signal stimulates a muscle cell, calcium ions rush from the smooth ER into the cytoplasmic fluid and trigger contraction of the cell.

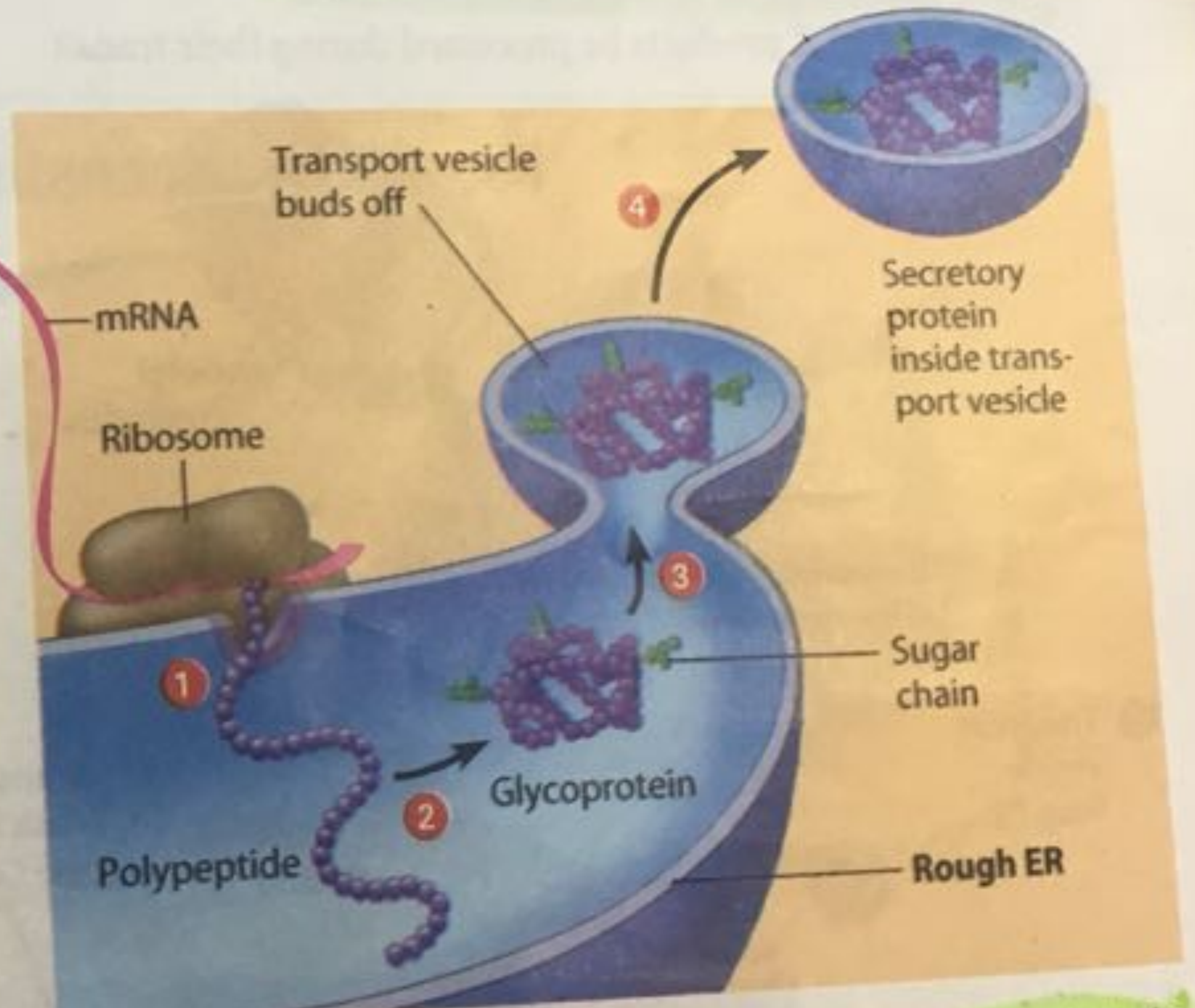
Rough ER One of the functions of rough ER is to make more membrane. Phospholipids made by enzymes of the rough ER membrane are inserted into the ER membrane. Thus, the ER membrane grows, and portions of it are transferred to other components of the endomembrane system as vesicles.

The bound ribosomes attached to rough ER produce proteins that will be inserted into the growing ER membrane, transported to other organelles, or secreted by the cell. An example of a secretory protein is insulin, a hormone secreted by specialized cells in the pancreas. Type 1 diabetes results when these cells are destroyed and a lack of insulin disrupts glucose metabolism in the body.

Figure 3.6B follows the synthesis, modification, and packaging of a secretory protein. ① As the polypeptide is synthesized by a bound ribosome following the instructions of an mRNA, it is threaded into the cavity of the rough ER. As it enters, the new protein folds into its three-dimensional shape. ② Short chains of sugars are often linked to the polypeptide, making the molecule a **glycoprotein** (*glyco* means "sugar"). ③ When the molecule is ready for export from the ER, it is packaged in a **transport vesicle**, a vesicle that moves from one part of the cell to another. ④ This vesicle buds off from the ER membrane.



▲ **Figure 3.6A** Smooth and rough endoplasmic reticulum



▲ **Figure 3.6B** Synthesis and packaging of a secretory protein by the rough ER

Membrane Structure and Function

4.1 Membranes are fluid mosaics of lipids and proteins with many functions

structure

The plasma membrane is the edge of life, the boundary that encloses a living cell. In eukaryotic cells, internal membranes partition the cell into specialized compartments. Membranes are composed of a bilayer of phospholipids with embedded and attached proteins. Biologists describe such a structure as a **fluid mosaic**.

In the cell, a membrane remains about as "fluid" as salad oil, with most of its components able to drift about like partygoers moving through a crowded room. Double bonds in the unsaturated fatty acid tails of some phospholipids produce kinks that prevent phospholipids from packing too tightly (see Module 2.7). In animal cell membranes, the steroid cholesterol helps stabilize the membrane at warm temperatures but also helps keep the membrane fluid at lower temperatures.

A membrane is a "mosaic" in having diverse protein molecules embedded in its fluid framework. The word *mosaic* can also refer to the varied functions of these proteins. Different types of cells have different membrane proteins, and the various membranes within a cell each contain a unique collection of proteins.

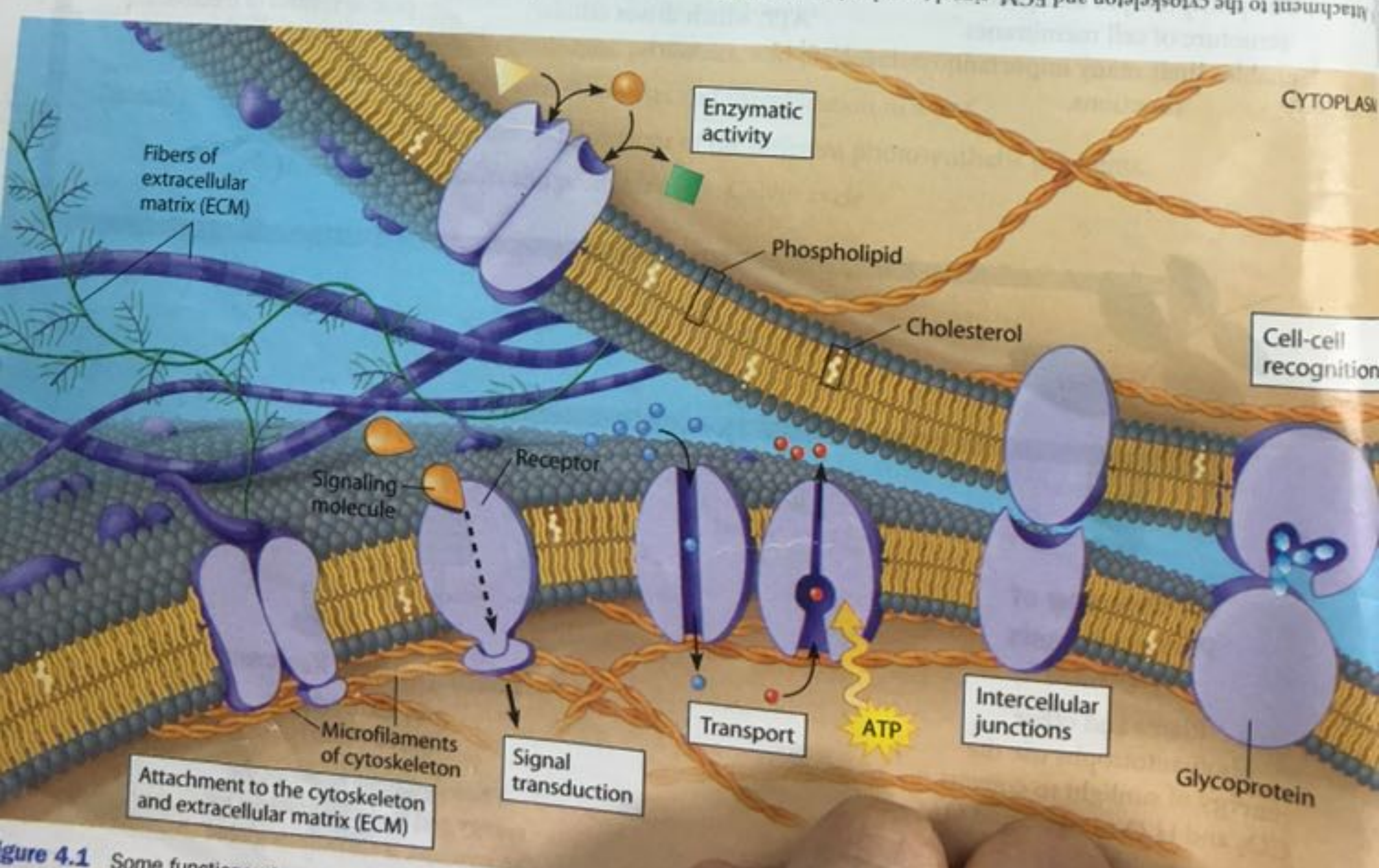
Figure 4.1, which diagrams the plasma membranes of two adjacent cells, illustrates six major functions performed by membrane proteins, represented by the purple oval structures. Some proteins help maintain cell shape and coordinate changes inside and outside the cell through their attachment to the cytoskeleton and extracellular matrix (ECM). Other proteins ② function as receptors for chemical messengers (signaling molecules) from other cells. The binding of a signaling molecule triggers a change in the protein, which relays the message into the cell, activating molecules that perform specific functions. This message-transfer process is called si transduction.

③ Some membrane proteins are enzymes, which may be grouped in a membrane to carry out sequential steps of a metabolic pathway. Membrane glycoproteins may be invol in cell-cell recognition. Their attached carbohydrates functi as identification tags that are recognized by membrane proteins of other cells. This recognition allows cells in an embr to sort into tissues and enables cells of the immune system t recognize and reject foreign cells, such as infectious bacteria Membrane proteins also participate in the intercellular junctions that attach adjacent cells.

A final critical function is in transport of substances acro the membrane. Membranes exhibit **selective permeability**; that is, they allow some substances to cross more easily than others. Many essential ions and molecules, such as glucose, require transport proteins to enter or leave the cell.

? **Review the six different types of functions that proteins in a plasma membrane can perform.**

attachment to the cytoskeleton and ECM, signal transduction, enzymatic
ity, cell-cell recognition, intercellular joining, and transport.



gure 4.1 Some functions of membran

Membrane Structure and Function

4.1 Membranes are fluid mosaics of lipids and proteins with many functions

structure

The plasma membrane is the edge of life, the boundary that encloses a living cell. In eukaryotic cells, internal membranes partition the cell into specialized compartments. Membranes are composed of a bilayer of phospholipids with embedded and attached proteins. Biologists describe such a structure as **a fluid mosaic**.

In the cell, a membrane remains about as "fluid" as salad oil, with most of its components able to drift about like partygoers moving through a crowded room. Double bonds in the unsaturated fatty acid tails of some phospholipids produce kinks that prevent phospholipids from packing too tightly (see Module 2.7). In animal cell membranes, the steroid cholesterol helps stabilize the membrane at warm temperatures but also helps keep the membrane fluid at lower temperatures.

A membrane is a "mosaic" in having diverse protein molecules embedded in its fluid framework. The word *mosaic* can also refer to the varied functions of these proteins. Different types of cells have different membrane proteins, and the various membranes within a cell each contain a unique collection of proteins.

Figure 4.1, which diagrams the plasma membranes of two adjacent cells, illustrates six major functions performed by membrane proteins, represented by the purple oval structures. Some proteins help maintain cell shape and coordinate changes inside and outside the cell through their attachment to the cytoskeleton and extracellular matrix (ECM). Other proteins function as receptors for chemical messengers (signaling molecules) from other cells. The binding of a signaling molecule triggers a change in the protein, which relays the message into the cell, activating molecules that perform specific functions. This message-transfer process is called signal transduction.

(2)

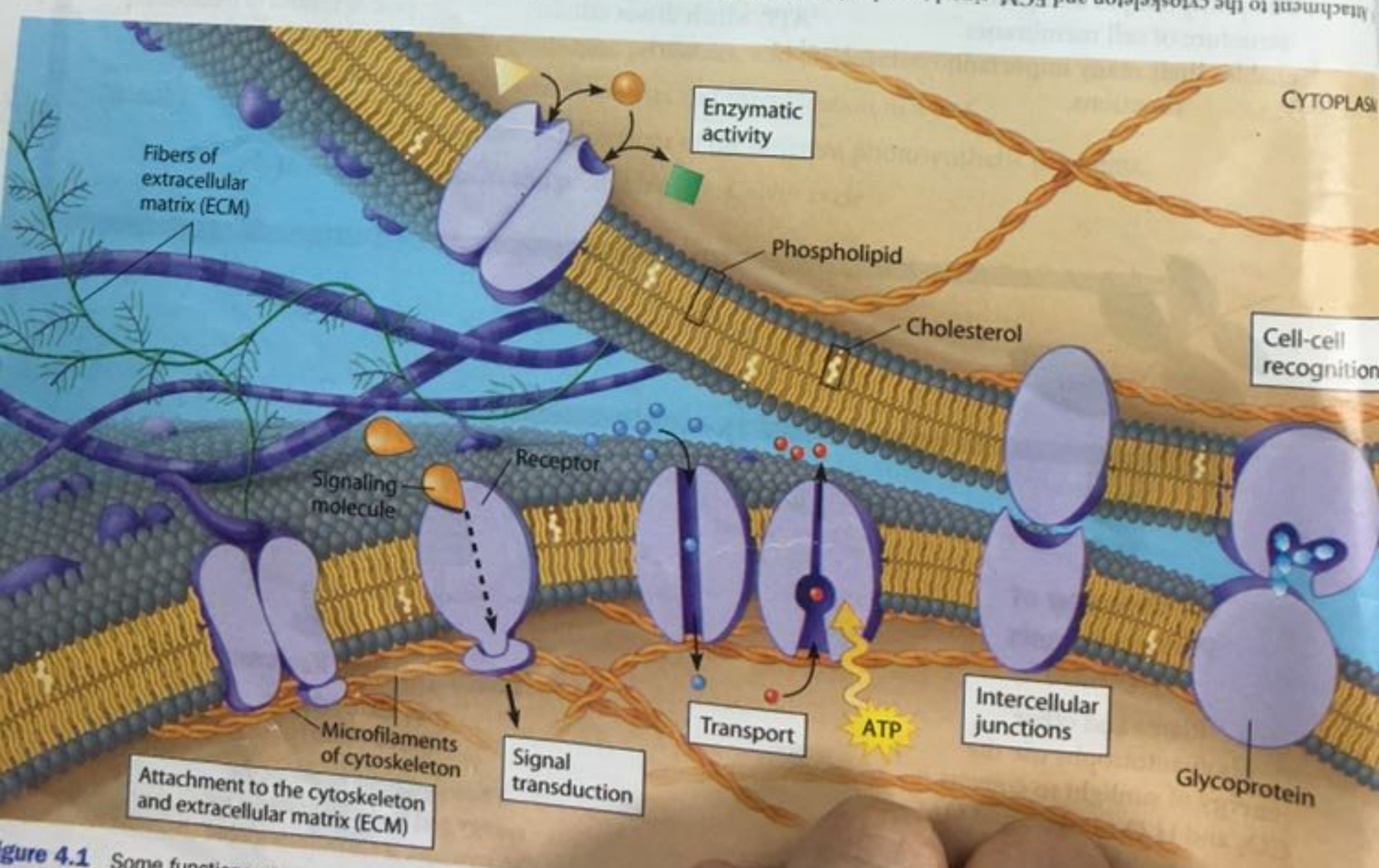
(3)

Some membrane proteins are enzymes, which may be grouped in a membrane to carry out sequential steps of a metabolic pathway. Membrane glycoproteins may be involved in cell-cell recognition. Their attached carbohydrates function as identification tags that are recognized by membrane proteins of other cells. This recognition allows cells in an embryo to sort into tissues and enables cells of the immune system to recognize and reject foreign cells, such as infectious bacteria. Membrane proteins also participate in the intercellular junctions that attach adjacent cells.

A final critical function is in transport of substances across the membrane. Membranes exhibit **selective permeability**; that is, they allow some substances to cross more easily than others. Many essential ions and molecules, such as glucose, require transport proteins to enter or leave the cell.

? **Review the six different types of functions that proteins in a plasma membrane can perform.**

attachment to the cytoskeleton and ECM, signal transduction, enzymatic ...ity, cell-cell recognition, intercellular joining, and transport.



gure 4.1 Some functions of membran

? **Explain why we say that the endoplasmic reticulum is a biosynthetic factory.**

The ER produces a huge variety of molecules, including phospholipids for cell membranes, steroid hormones, and proteins (synthesized by bound ribosomes) for membranes, other organelles, and secretion by the cell.

---

rts, and ships cell products

Golgi? Various Golgi enzymes modify the carbohydrate portions of the glycoproteins made in the ER, removing some sugars and substituting others. Molecular identification tags, such as phosphate groups, may be added that help the Golgi sort molecules into different batches for different destinations.

وسم

Until recently, the Golgi was viewed as a static structure, with products in various stages of processing moved from sac to sac by transport vesicles. Recent research has given new *maturation model* in which entire move from the receiving modifying

The vesicle now carries the protein to the Golgi apparatus (described in the next module) for further processing. From there, a transport vesicle containing the finished molecule makes its way to the plasma membrane and releases its contents from the cell.

? **Explain why we say that the endoplasmic reticulum is a biosynthetic factory.**

he ER produces a huge variety of molecules, including phospholipids for
embranes, steroid hormones, and proteins (synthesized by bound
omes) for membranes, other organelles, and secretion by the cell.

3.7 The Golgi apparatus finishes, sorts, and ships cell products

After leaving the ER, many transport vesicles travel to the **Golgi apparatus**. Using a light microscope and a staining technique he developed, Italian scientist Camillo Golgi discovered this membranous organelle in 1898. The electron microscope confirmed his discovery more than 50 years later, revealing a stack of flattened sacs, looking much like a pile of pita bread. A cell may contain many, even hundreds, of these stacks. The number of Golgi stacks correlates with how active the cell is in secreting proteins—a multistep process that, as we have just seen, is initiated in the rough ER.

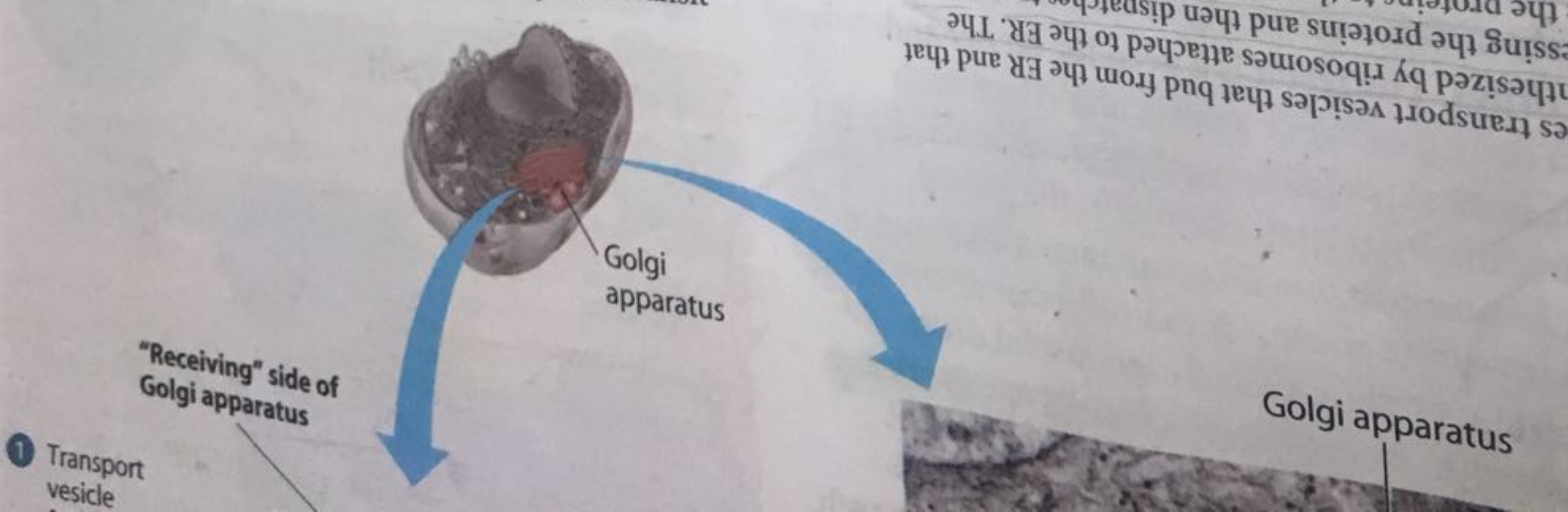
The Golgi apparatus serves as a molecular warehouse and finishing factory for products manufactured by the ER. You can follow this process in **Figure 3.7**. Note that the flattened Golgi sacs are not connected, as are ER sacs. ① One side of a Golgi stack serves as a receiving dock for transport vesicles produced by the ER. ② A vesicle fuses with a Golgi sac, adding its membrane and contents to the receiving side. ③ Products of the ER are modified during their transit through the Golgi. ④ The other side of the Golgi, the shipping side, gives rise to vesicles, which bud off and travel to other sites.

How might ER products be processed during their transit through the Golgi? Various Golgi enzymes modify the carbohydrate por
tions of the glycoproteins made in the ER, removing some s
ars and substituting others. Molecular identification tags, su
as phosphate groups, may be added that help the Golgi sort molecules into different batches for different destinations.

Until recently, the Golgi was viewed as a static structure, with products in various stages of processing moved from sa
to sac by transport vesicles. Recent research has given rise to new *maturation model* in which entire sacs "mature" as they move from the receiving to the shipping side, carrying and modifying their cargo as they go. The shipping side of the G
stack serves as a depot from which finished secretory produ
packaged in transport vesicles, move to the plasma membra
for export from the cell. Alternatively, finished products may become part of the plasma membrane itself or part of anoth
organelle, such as a lysosome, which we discuss next.

? **What is the relationship of the Golgi apparatus to the ER i protein-secreting cell?**

he Golgi receives transport vesicles that bud from the ER and that
ain proteins synthesized by ribosomes attached to the ER. The
finishes processing the proteins and then dispatches transport
es that secrete the proteins to the outside of the cell.



3.8

A lysos
name l
"break
are ma
lustrat
menta
its enz
Ly
protis
vacuo
vacuo
into
bacte
cycli
amo
lyso
tles
Wit
lack
eng
cel
dig
by
of

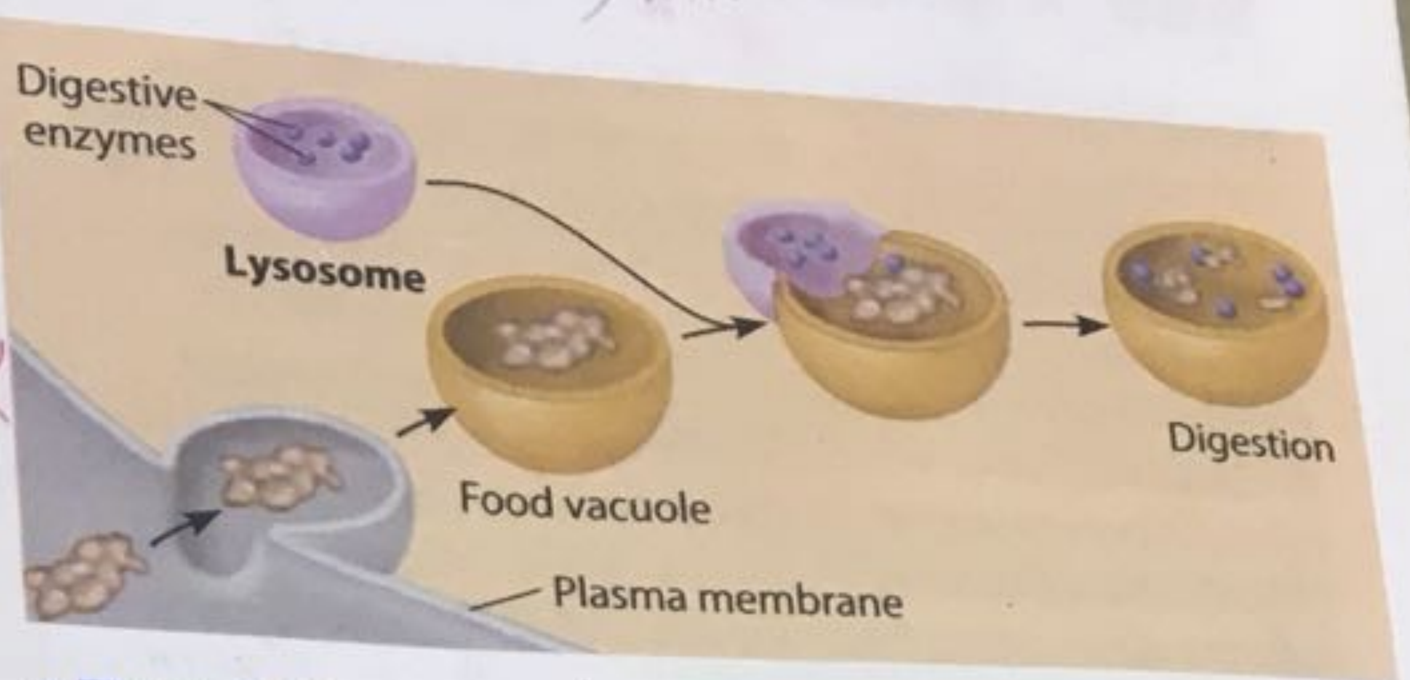
partments within a cell

5 min

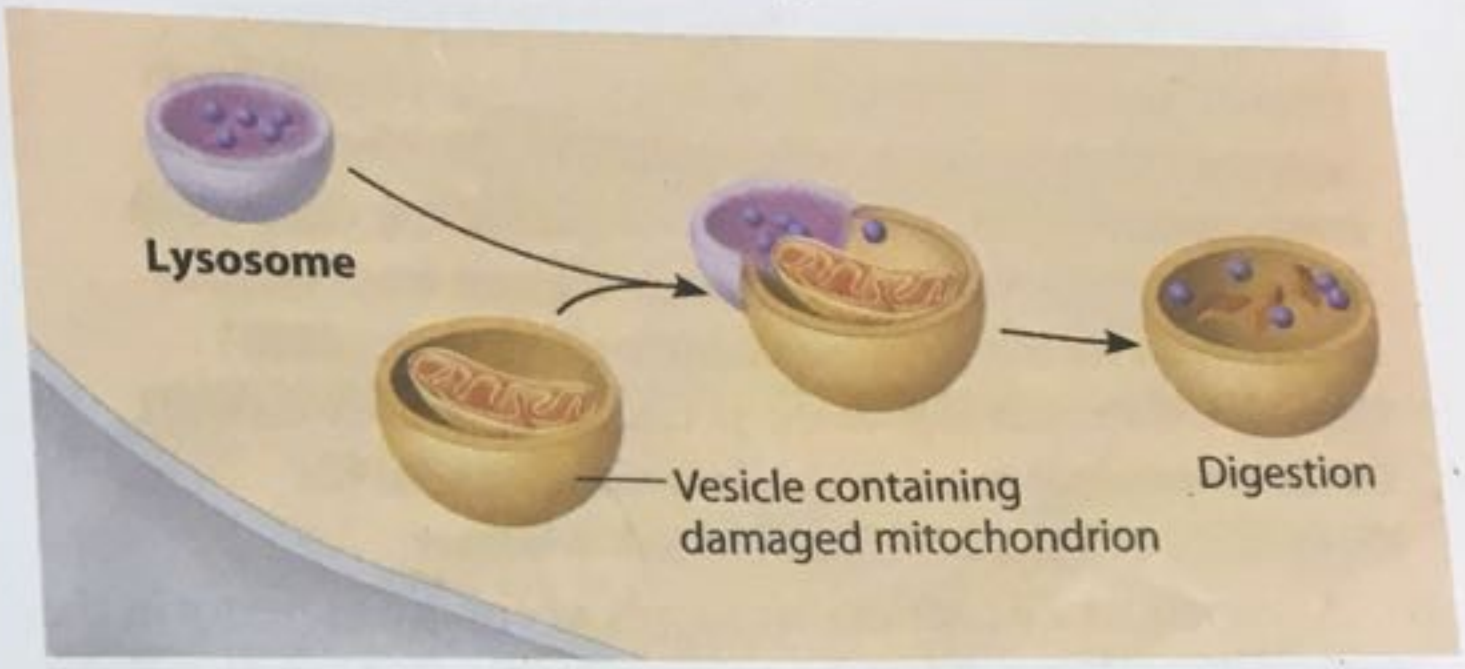
A **lysosome** is a membranous sac of digestive enzymes. The name *lysosome* is derived from two Greek words meaning "breakdown body." The enzymes and membranes of lysosomes are made by rough ER and processed in the Golgi apparatus. Illustrating a main theme of eukaryotic cell structure—compartmentalization—a lysosome provides an acidic environment for its enzymes, while safely isolating them from the rest of the cell.

Lysosomes have several types of digestive functions. Many protists engulf food particles into membranous sacs called food vacuoles. As **Figure 3.8A** shows, lysosomes fuse with food vacuoles and digest the food. The nutrients are then released into the cell fluid. Our white blood cells engulf and destroy bacteria using lysosomal enzymes. Lysosomes also serve as recycling centers for animal cells. Damaged organelles or small amounts of cell fluid become surrounded by a membrane. A lysosome fuses with such a vesicle **(Figure 3.8B)** and dismantles its contents, making organic molecules available for reuse. With the help of lysosomes, a cell continually renews itself.

The cells of people with inherited lysosomal storage diseases lack one or more lysosomal enzymes. The lysosomes become engorged with undigested material, eventually interfering with cellular function. In Tay-Sachs disease, for example, a lipid-digesting enzyme is missing, and brain cells become impaired by an accumulation of lipids. Lysosomal storage diseases are often fatal in early childhood.



▲ **Figure 3.8A** Lysosome fusing with a food vacuole and digesting food



▲ **Figure 3.8B** Lysosome fusing with a vesicle containing a damaged organelle and digesting and recycling its contents

? **How is a lysosome like a recycling center?**

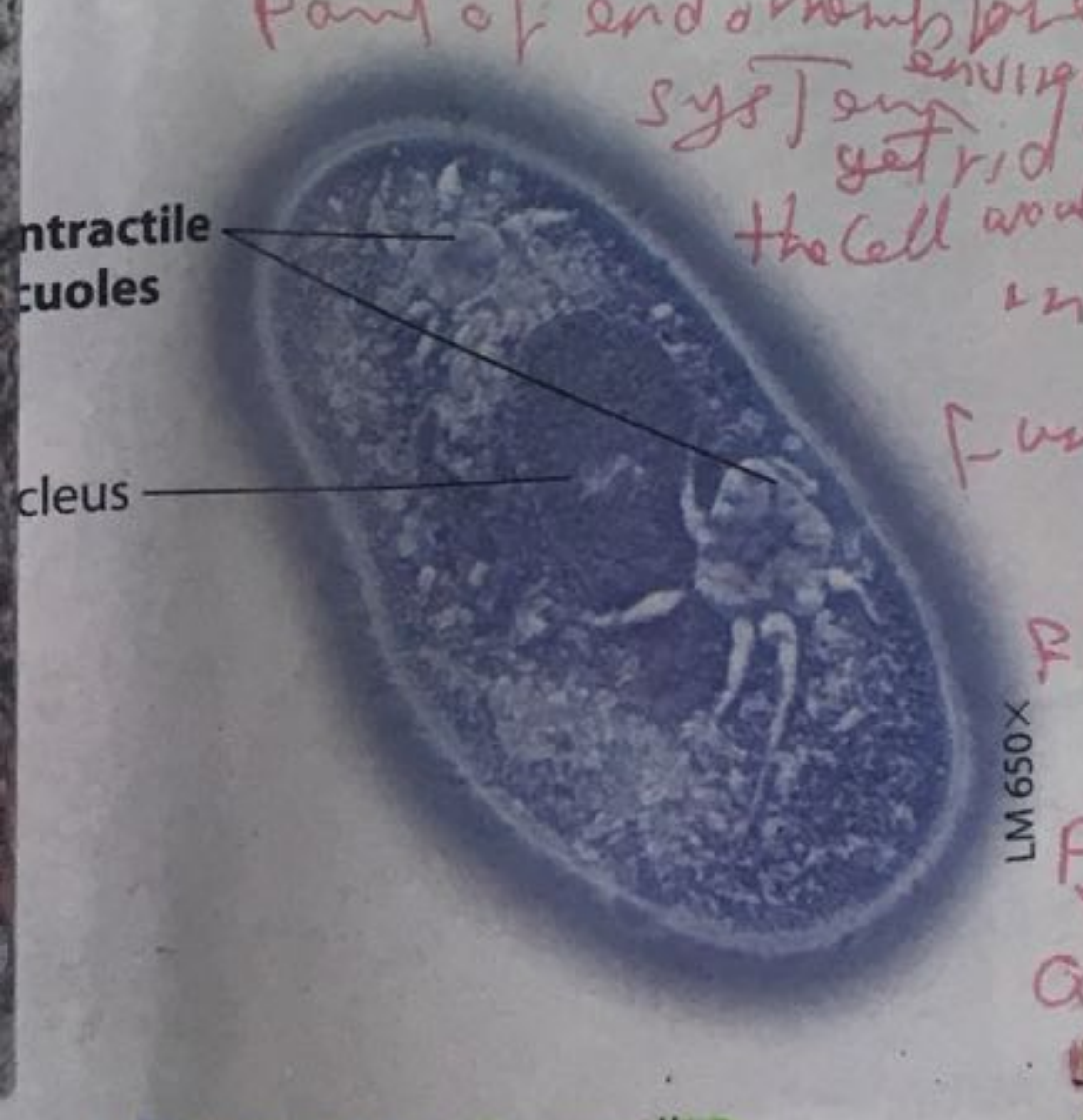
It breaks down damaged organelles and recycles their molecules.

3.9 Vacuoles function in the general maintenance of the cell

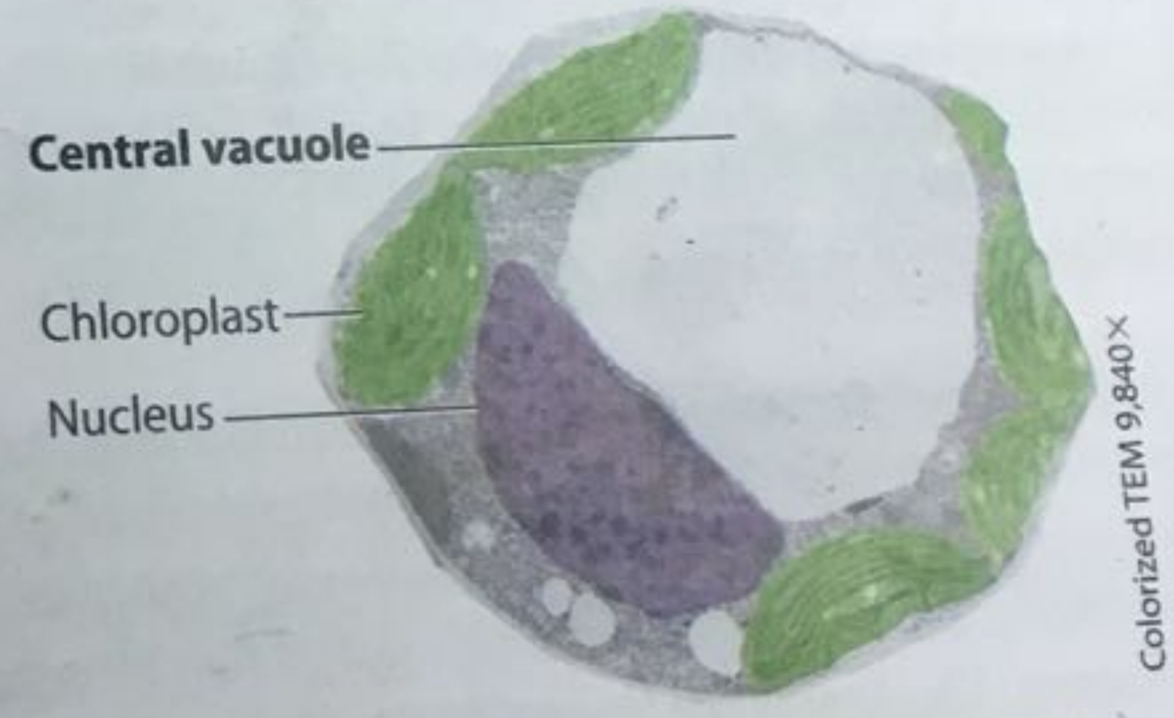
5 min

Vacuoles are large vesicles that have a variety of functions. In Figure 3.8A, you saw how a food vacuole forms as a cell ingests food. **Figure 3.9A** shows two contractile vacuoles in the protist *Paramecium*, looking somewhat like wheel hubs with radiating spokes. The "spokes" collect water from the cell, and the hub expels it to the outside. Freshwater protists Take in water from their environment. Without a way to get rid of excess water, the cell would swell and burst. In plants, some vacuoles have a digestive function similar to that of lysosomes in animal cells. Vacuoles in flowers petals contain Pigments that attract pollinating insects. Vacuoles may also Contain poisons or unpalatable compounds that protect the plant against herbivores; examples include nicotine, caffeine, and various chemicals use as pharmaceutical drugs. **Figure 3.9B** shows a plant ce large **central vacuole**, which helps the cell grow in size by absorbing water and enlarging. It also stockpiles vital cher and acts as a trash can, safely storing toxic waste products

Part of endomembrane system



▲ **Figure 3.9A** Contractile vacuoles in *Paramecium*, a single-celled organism



▲ **Figure 3.9B** Central vacuole in a plant cell

? **Is a food vacuole part of the endomembrane system?**

forms by pinching in from the plasma membrane, which is part
domembrane system.

3.10 A review of the structures involved in manufacturing and breakdown

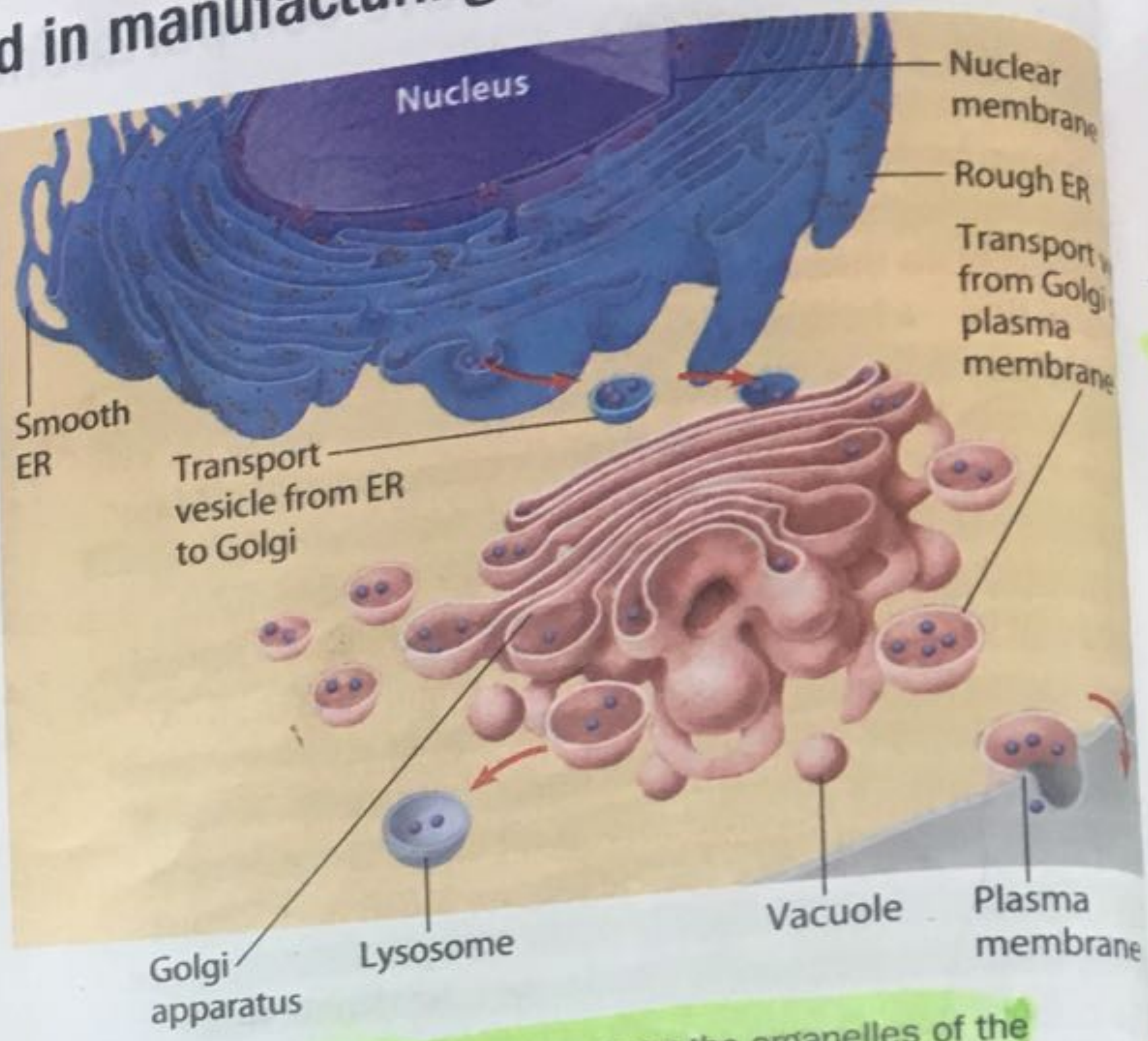
Figure 3.10 summarizes the relationships within the endomembrane system. You can see the direct *structural* connections between the nuclear envelope, rough ER, and smooth ER. The red arrows show the *functional* connections, as membranes and proteins produced by the ER travel in transport vesicles to the Golgi and on to other destinations. Some vesicles develop into lysosomes or vacuoles. Others transport products to the outside of the cell. When these vesicles fuse with the plasma membrane, their contents are secreted from the cell and their membrane is added to the plasma membrane.

5 min

Peroxisomes (see Figures 3.3A and B) are metabolic compartments that do not originate from the endomembrane system. In fact, how they are related to other organelles is still unknown. Some peroxisomes break down fatty acids to be used as cellular fuel. In your liver, peroxisomes detoxify harmful compounds, including alcohol. In these processes, enzymes transfer hydrogen from various compounds to oxygen, producing hydrogen peroxide (H_2O_2). Other enzymes in the peroxisome quickly convert this toxic product to water—another example of the importance of a cell's compartmental structure.

A cell requires a continuous supply of energy to perform the work of life. Next we consider two organelles that act as cellular power stations—mitochondria and chloroplasts.

Pez.



▲ **Figure 3.10** Connections among the organelles of the endomembrane system

? **How do transport vesicles help tie together the endomembrane system?**

…sport vesicles move membranes and substances they enclose between …ponents of the endomembrane system.

Energy-Converting Organelles

3.11 Mitochondria harvest chemical energy from food

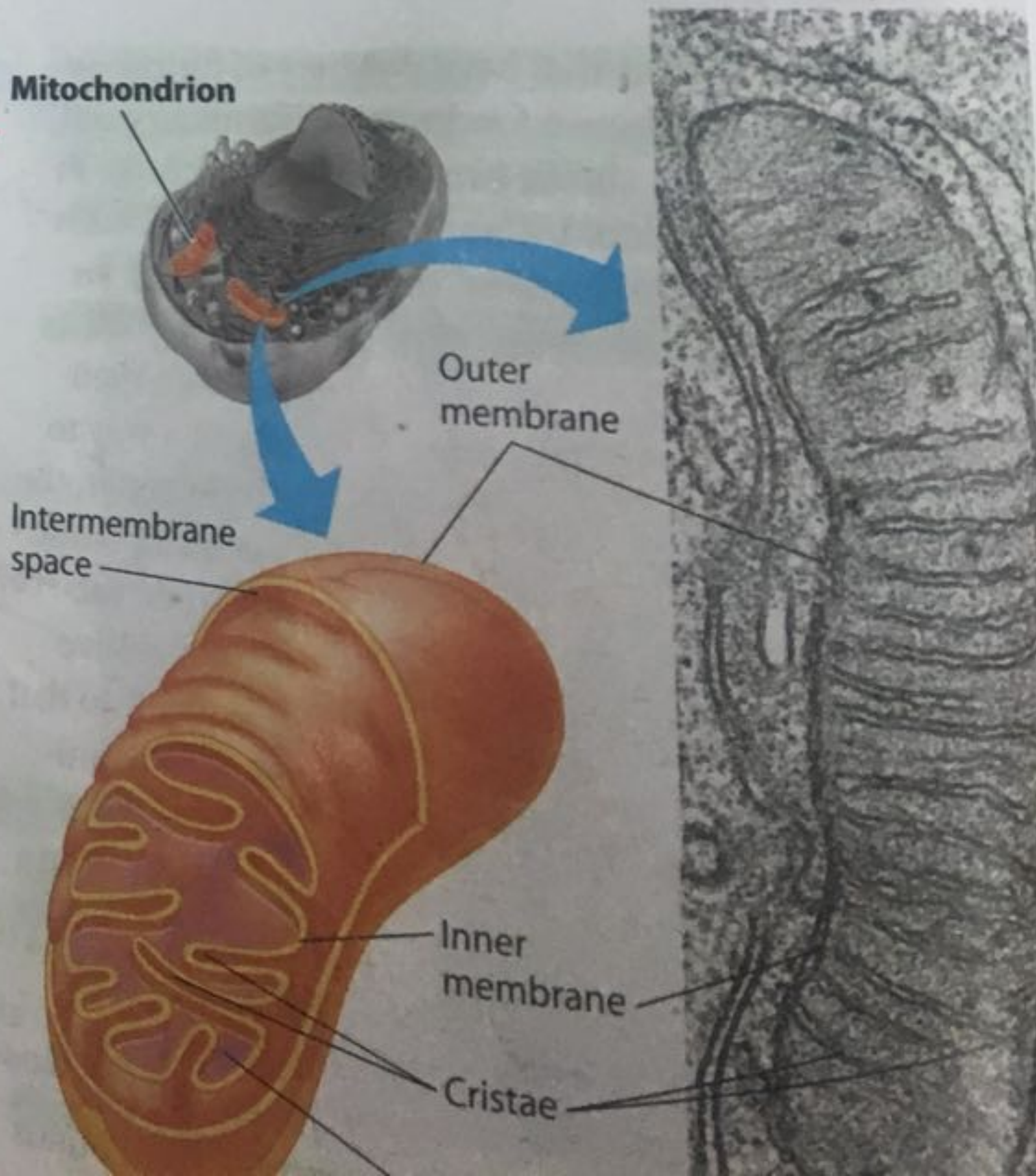
5 min

Mitochondria (singular, *mitochondrion*) are organelles that carry out cellular respiration in nearly all eukaryotic cells, converting the chemical energy of foods such as sugars to the chemical energy of the molecule called ATP (adenosine triphosphate). ATP is the main energy source for cellular work.

As you have come to expect, a mitochondrion's structure suits its function. It is enclosed by two membranes, each a phospholipid bilayer with a unique collection of embedded proteins (**Figure 3.11**). The mitochondrion has two internal compartments. The first is the intermembrane space, the narrow region between the inner and outer membranes. The inner membrane encloses the second compartment, the **mitochondrial matrix**, which contains mitochondrial DNA and ribosomes, as well as many enzymes that catalyze some of the reactions of cellular respiration. The inner membrane is highly folded and contains many embedded protein molecules that function in ATP synthesis. The folds, called **cristae**, increase the membrane's surface area, enhancing the mitochondrion's ability to produce ATP.

? **What is cellular respiration?**

…ss that converts the chemical energy of sugars and other food …molecules to the chemical energy of ATP.



3.12

Most of t
photosyn
to the ch
the phot
eukaryot
much m
by huma
Befitt
plex, mu
partitio
(Figure
inner ar
interme
the inn
which c
well as
sacs cal
compa
In som
stack is
chloro
chloro
trap sc

Th

3.1

The r
the m
short
Paran
Othe
cilia

5min

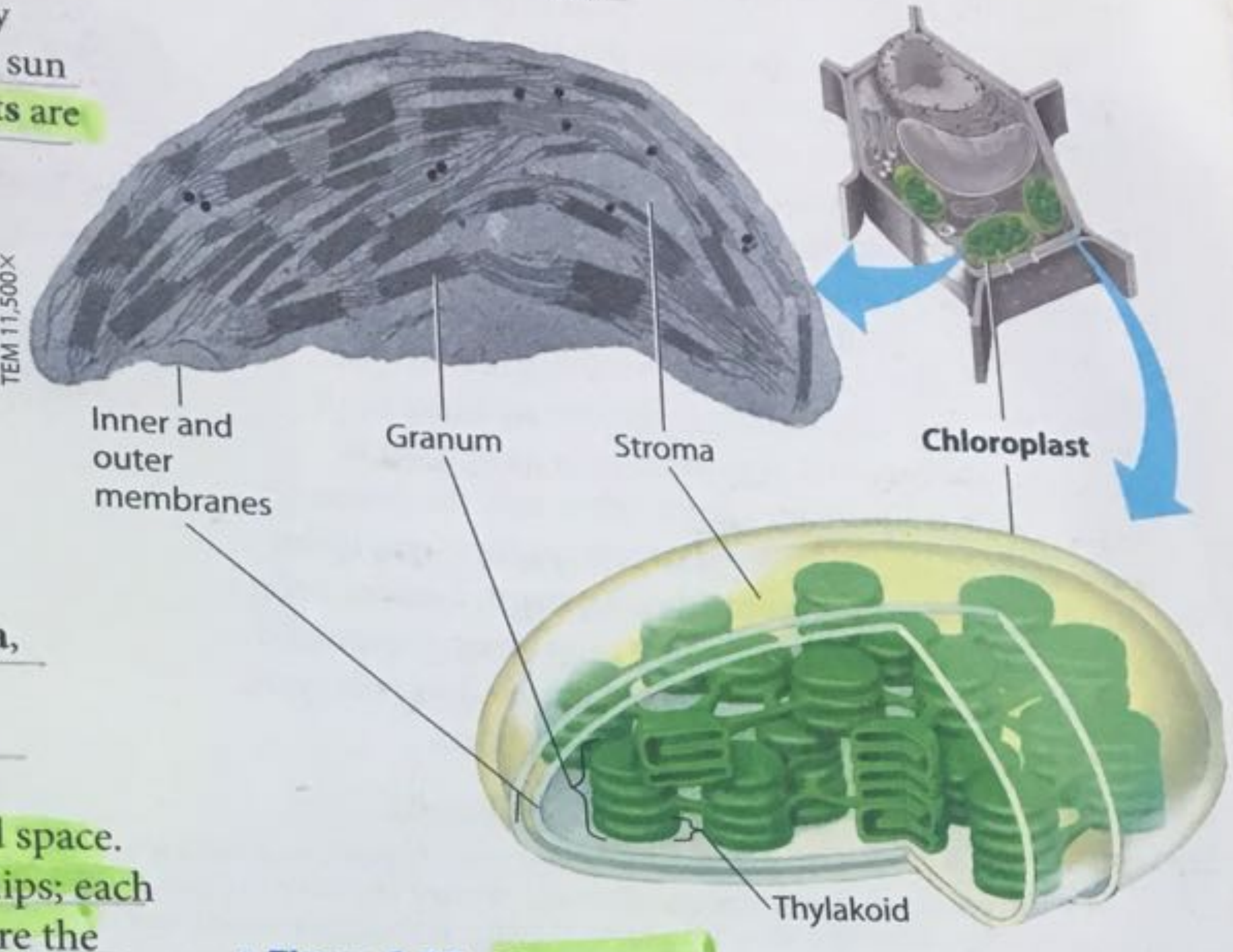
3.12 Chloroplasts convert solar energy to chemical energy

Most of the living world runs on the energy provided by photosynthesis, the conversion of light energy from the sun to the chemical energy of sugar molecules. **Chloroplasts** are the photosynthesizing organelles of all photosynthetic eukaryotes. The chloroplast's solar power system is much more efficient than anything yet produced by human ingenuity.

Befitting an organelle that carries out complex, multistep processes, internal membranes partition the chloroplast into compartments (**Figure 3.12**). The chloroplast is enclosed by an inner and outer membrane separated by a thin intermembrane space. The compartment inside the inner membrane holds a thick fluid called **stroma**, which contains chloroplast DNA and ribosomes as well as many enzymes. A network of interconnected sacs called **thylakoids** is inside the chloroplast. The compartment inside these sacs is called the thylakoid space. In some regions, thylakoids are stacked like poker chips; each stack is called a **granum** (plural, *grana*). The grana are the chloroplast's solar power packs—the sites where the green chlorophyll molecules embedded in thylakoid membranes trap solar energy.

hylakoid

glanum glan



▲ **Figure 3.12** The chloroplast

? **Which membrane in a chloroplast appears to be the most extensive? Why might this be so?**

● The thylakoid membranes are most extensive, providing a large area of membrane that contains chlorophyll for photosynthesis.

The Cytoskeleton and Cell Surfaces

3.13 Cilia and flagella

5 min

The role of the cytoskeleton in movement is clearly seen in the motile appendages that protrude from certain cells. The short, numerous appendages that propel protists such as *Paramecium* (see Figure 3.1A) are called **cilia** (singular, *cilium*). Other protists may move using flagella, which are longer than cilia and usually limited to one or a few per cell.

Some cells of multicellular organisms also have cilia or flagella. For example, **Figure 3.13A** shows cilia on cells lining the human windpipe. In this case, the cilia sweep mucus containing trapped debris out of your lungs. (This cleaning function is impaired by cigarette smoke, which paralyzes the cilia.) Most animals and some plants have flagellated sperm.

▲ **Figure 3.13A** Cilia on cells lining the respiratory tract

A flagellum, shown in **Figure 3.13B**, propels the cell by an undulating whiplike motion. In contrast, cilia work more like the coordinated oars of a rowing team.

Though different in length and beating pattern, cilia and flagella have a common structure and mechanism of movement (**Figure 3.13C**). Both are composed of microtubules wrapped in an extension of the plasma membrane. In nearly all eukaryotic cilia and flagella, a ring of nine microtubule doublets surrounds a central pair of microtubules. This arrangement is called the 9 + 2 pattern. The microtubule assembly extends into an anchoring structure called a basal body (not shown in the figure), which consists of a ring of nine microtubule triplets. Basal bodies are very similar in structure to centrioles, which are found in the microtubule-organizing center of animal cells.

How does this microtubule assembly produce the bending movement of cilia and flagella? Bending involves large motor proteins called dyneins (red in the figure) that are attached along each outer microtubule doublet. A dynein protein has two "feet" that "walk" along an adjacent doublet, one foot maintaining contact while the other releases and reattaches one step farther along its neighboring microtubule. The outer doublets and two central microtubules are held together by

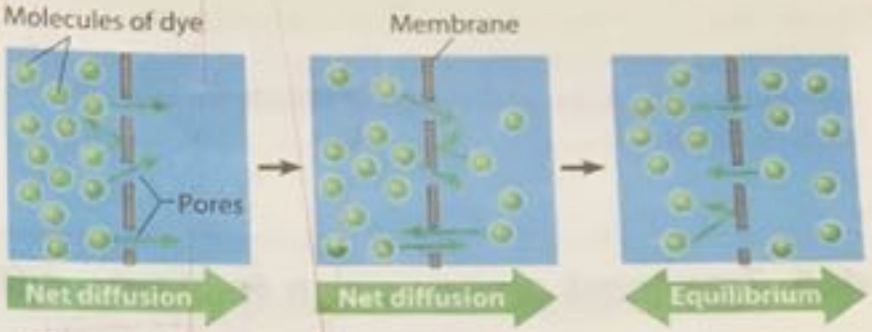
4.2 Passive transport is diffusion across a membrane with no energy investment

Molecules vibrate and move randomly as a result of a type of energy called thermal motion (heat). One result of this motion is **diffusion**, the tendency for particles of any kind to spread out evenly in an available space. How might diffusion affect the movement of substances into or out of a cell?

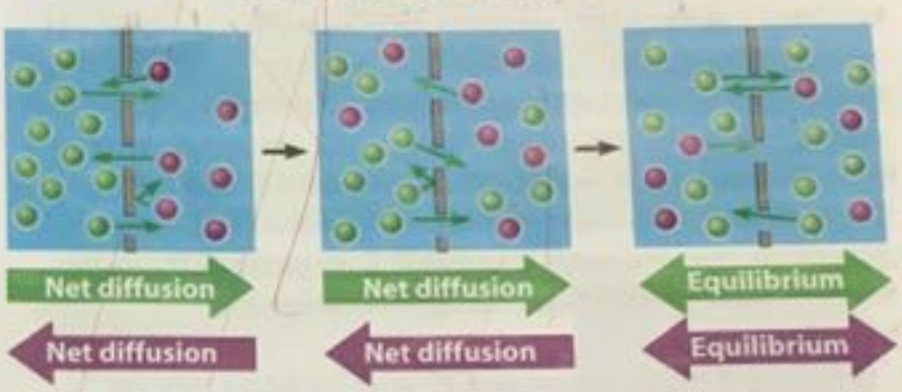
The figures to the right will help you to visualize diffusion across a membrane. **Figure 4.2A** shows a solution of green dye separated from pure water by a membrane. Assume that this membrane has microscopic pores through which dye molecules can move. Thus, we say it is permeable to the dye. Although each molecule moves randomly, there will be a *net* movement from the side of the membrane where dye molecules are more concentrated to the side where they are less concentrated. Put another way, the dye diffuses down its **concentration gradient**. Eventually, the solutions on both sides will have equal concentrations of dye. At this dynamic **equilibrium**, molecules still move back and forth, but there is no *net* change in concentration on either side of the membrane.

Figure 4.2B illustrates the important point that two or more substances diffuse independently of each other; that is, each diffuses down its own concentration gradient.

Because a cell does not have to do work when molecules diffuse across its membrane, such movement across a membrane is called **passive transport**. Much of the traffic across cell membranes occurs by diffusion. For example, diffusion down concentration gradients is the sole means by which oxygen (O_2), essential for metabolism, enters your cells and carbon dioxide (CO_2), a metabolic waste, passes out of them. Both O_2 and CO_2 are small, nonpolar molecules that diffuse easily across the phospholipid bilayer of a membrane.



▲ **Figure 4.2A** Passive transport of one type of molecule



▲ **Figure 4.2B** Passive transport of two types of molecules

But can ions and polar molecules also diffuse across the hydrophobic interior of a membrane? They can if they are moving down their concentration gradients and if they have transport proteins to help them cross.

? **Why is diffusion across a membrane called passive transport?**

● The cell does not expend energy to transport substances that are diffusing down their concentration gradients.

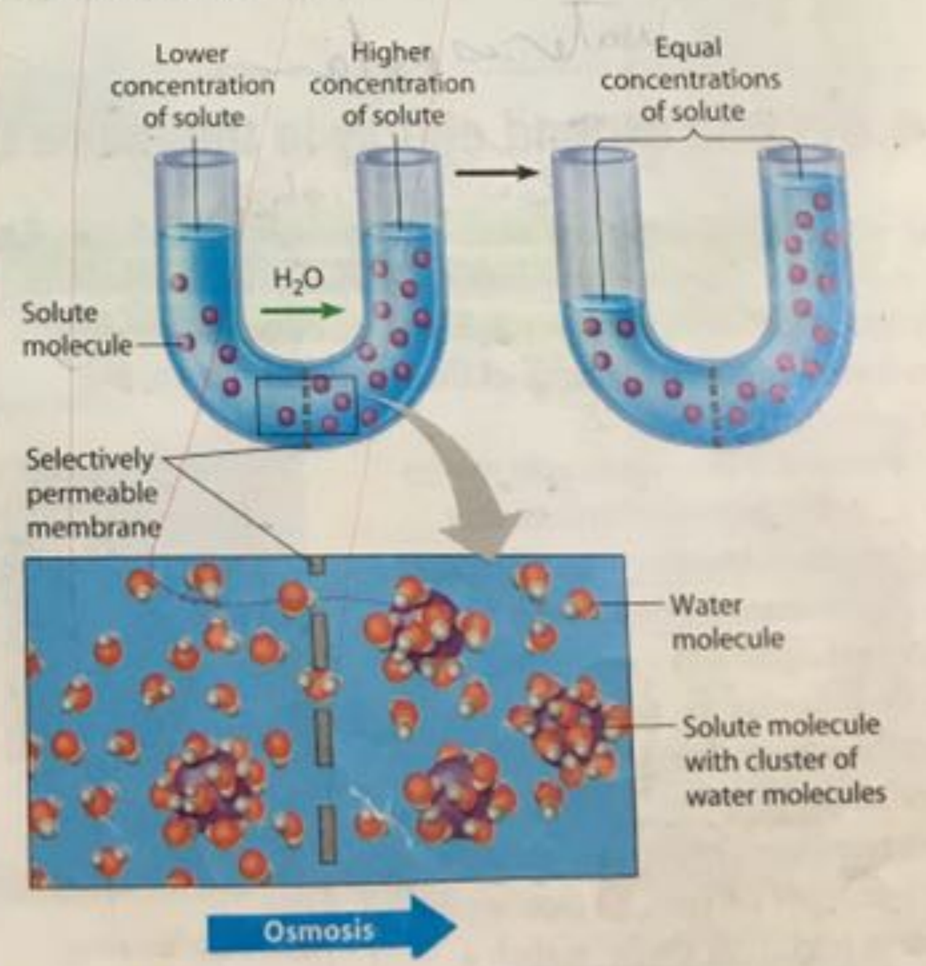
5 diffusion osmosis 5 5 facilitated diffusion

4.3 Osmosis is the diffusion of water across a membrane

One of the most important substances that crosses membranes by passive transport is water. Let's explore a physical model of the diffusion of water across a selectively permeable membrane, a process called **osmosis**. Remember that a selectively permeable membrane allows some substances to cross more easily than others.

The top of **Figure 4.3** shows what happens if a membrane permeable to water but not to a solute (such as glucose) separates two solutions with different concentrations of solute. (A solute is a substance that dissolves in a liquid solvent, producing a solution.) The solution on the right side initially has a higher concentration of solute than that on the left. As you can see, water crosses the membrane until the solute concentrations are equal on both sides.

In the close-up view at the bottom of Figure 4.3, you can see what happens at the molecular level. Polar water molecules cluster around hydrophilic (water-loving) solute molecules. The effect is that on the right side, there are fewer water molecules available to cross the membrane. The less concentrated solution on the left, with fewer solute molecules,



▲ **Figure 4.3** Osmosis, the diffusion of water across a membrane

4.2 Passive transport is diffusion across a membrane with no energy investment

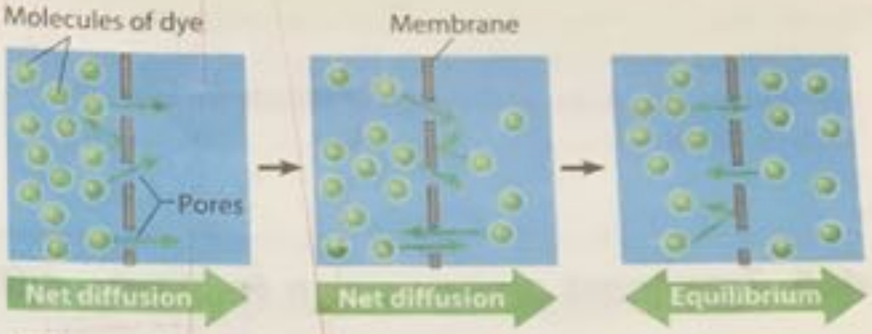
Molecules vibrate and move randomly as a result of a type of energy called thermal motion (heat). One result of this motion is **diffusion**, the tendency for particles of any kind to spread out evenly in an available space. How might diffusion affect the movement of substances into or out of a cell?

The figures to the right will help you to visualize diffusion across a membrane. **Figure 4.2A** shows a solution of green dye separated from pure water by a membrane. Assume that this membrane has microscopic pores through which dye molecules can move. Thus, we say it is permeable to the dye. Although each molecule moves randomly, there will be a *net* movement from the side of the membrane where dye molecules are more concentrated to the side where they are less concentrated. Put another way, the dye diffuses down its **concentration gradient**. Eventually, the solutions on both sides will have equal concentrations of dye. At this **dynamic equilibrium**, molecules still move back and forth, but there is no *net* change in concentration on either side of the membrane.

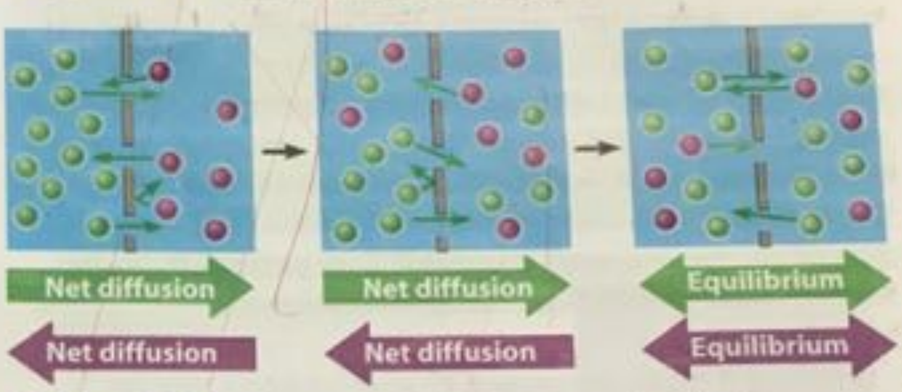
Figure 4.2B illustrates the important point that two or more substances diffuse independently of each other; that is, each diffuses down its own concentration gradient.

Because a cell does not have to do work when molecules diffuse across its membrane, such movement across a membrane is called **passive transport**. Much of the traffic across cell membranes occurs by diffusion. For example, diffusion down concentration gradients is the sole means by which oxygen (O_2), essential for metabolism, enters your cells and carbon dioxide (CO_2), a metabolic waste, passes out of them.

Both O_2 and CO_2 are small, nonpolar molecules that diffuse easily across the phospholipid bilayer of a membrane.



▲ **Figure 4.2A** Passive transport of one type of molecule



▲ **Figure 4.2B** Passive transport of two types of molecules

But can ions and polar molecules also diffuse across the hydrophobic interior of a membrane? They can if they are moving down their concentration gradients and if they have transport proteins to help them cross.

? **Why is diffusion across a membrane called passive transport?**

● The cell does not expend energy to transport substances that are diffusing down their concentration gradients.

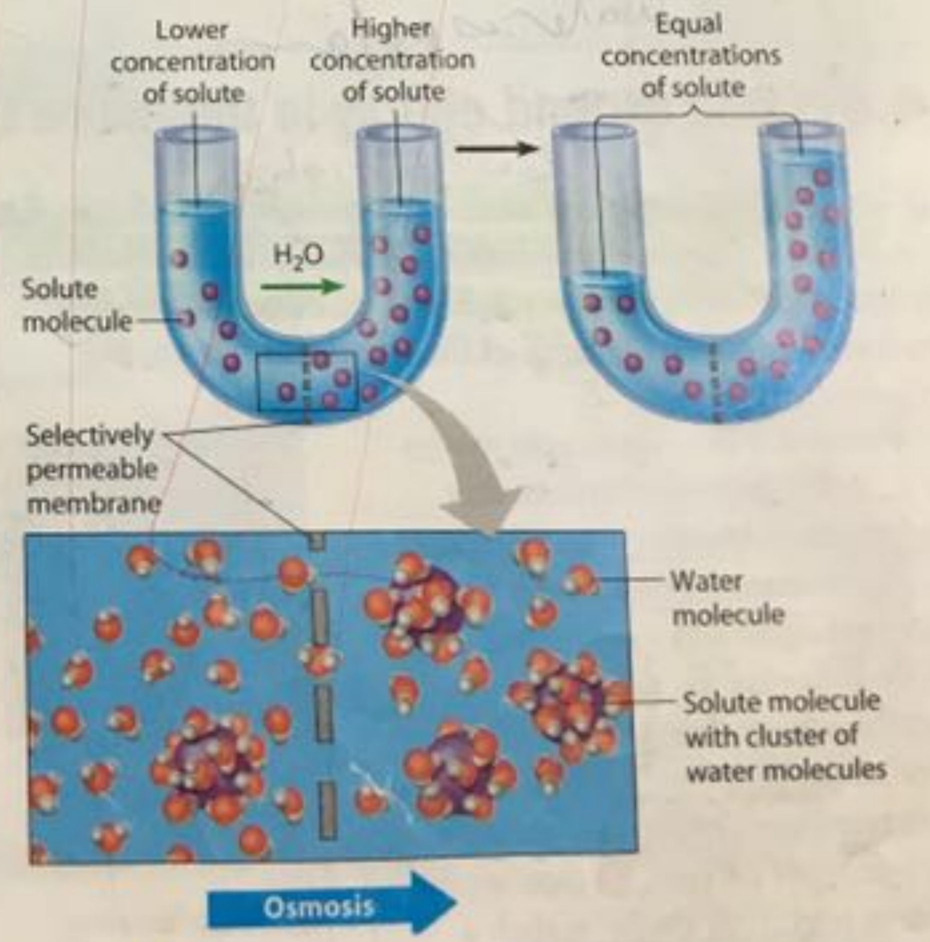
5 diffusion osmosis 5 5 facilitated diffusion

4.3 Osmosis is the diffusion of water across a membrane

One of the most important substances that crosses membranes by passive transport is water. Let's explore a physical model of the diffusion of water across a selectively permeable membrane, a process called **osmosis**. Remember that a selectively permeable membrane allows some substances to cross more easily than others.

The top of **Figure 4.3** shows what happens if a membrane permeable to water but not to a solute (such as glucose) separates two solutions with different concentrations of solute. (A solute is a substance that dissolves in a liquid solvent, producing a solution.) The solution on the right side initially has a higher concentration of solute than that on the left. As you can see, water crosses the membrane until the solute concentrations are equal on both sides.

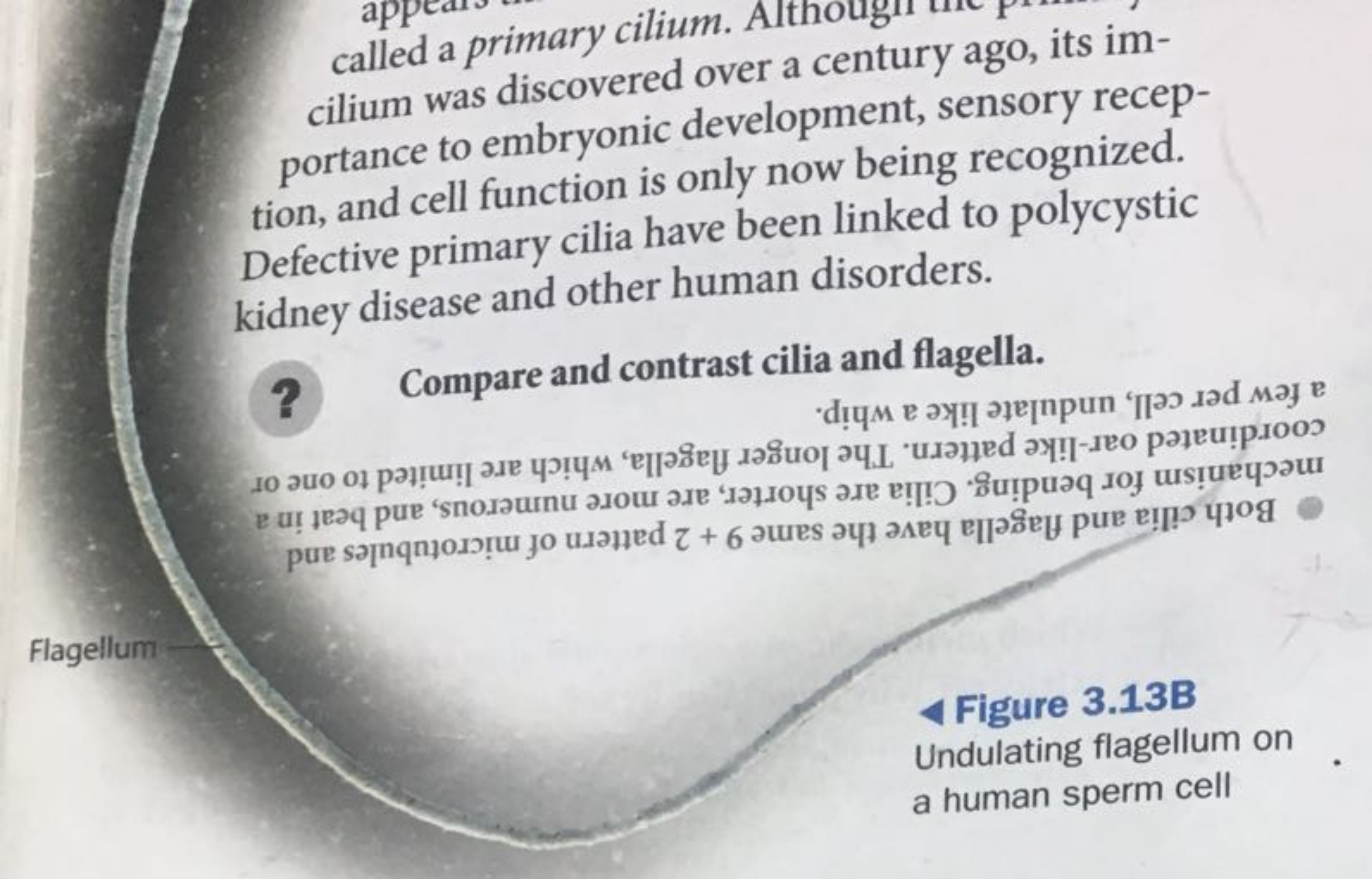
In the close-up view at the bottom of Figure 4.3, you can see what happens at the molecular level. Polar water molecules cluster around hydrophilic (water-loving) solute molecules. The effect is that on the right side, there are fewer water molecules available to cross the membrane. The less concentrated solution on the left, with fewer solute molecules,



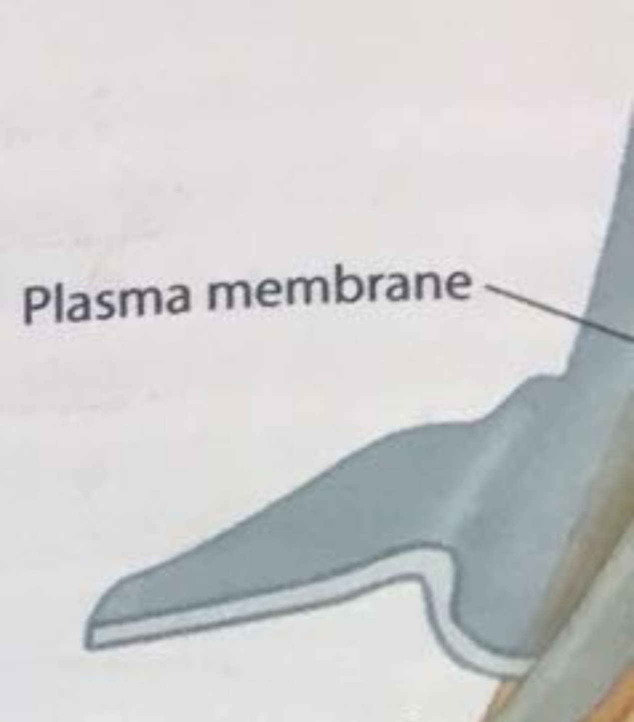
▲ **Figure 4.3** Osmosis, the diffusion of water across a membrane appe called a *primary cilium*. Althoug cilium was discovered over a century ago, its importance to embryonic development, sensory reception, and cell function is only now being recognized. Defective primary cilia have been linked to polycystic kidney disease and other human disorders.

? **Compare and contrast cilia and flagella.**

● Both cilia and flagella have the same 9 + 2 pattern of microtubules and mechanism for bending. Cilia are shorter, are more numerous, and beat in a coordinated oar-like pattern. The longer flagella, which are limited to one or a few per cell, undulate like a whip.



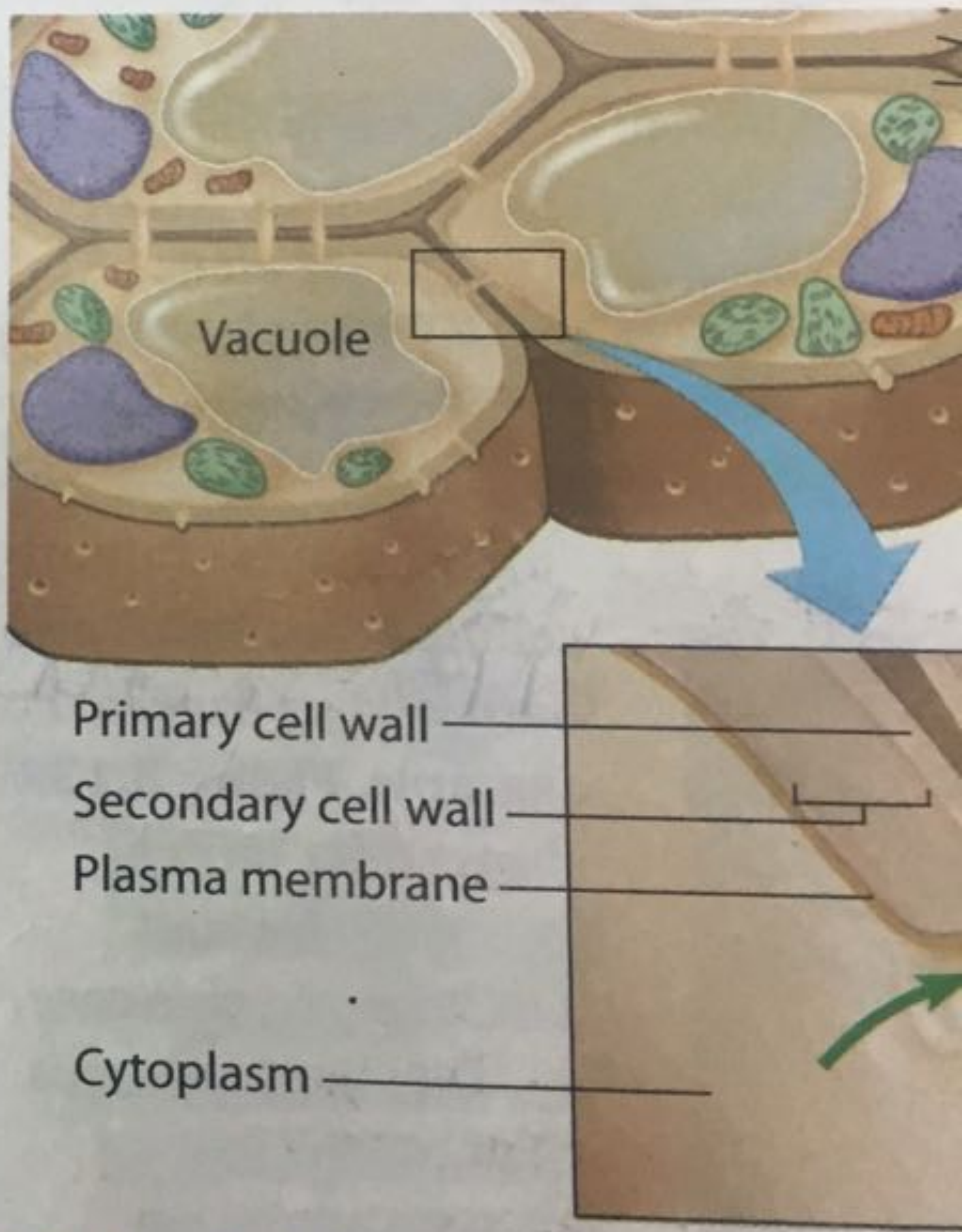
◀ Figure 3.13B Undulating flagellum on a human sperm cell



▲ Figure 3.13C Structure of a eukaryotic flagellum or cilium

3.14 Cell walls enclose and support plant cells

5 min



▲ Figure 3.14 Plant cell walls and plasn

The **cell wall** is one feature that distinguishes plant cells from animal cells. This rigid extracellular structure not only protects the cells but provides the skeletal support that keeps plants upright on land. Plant cell walls consist of fibers of cellulose embedded in a matrix of other polysaccharides and proteins. This fibers-in-a-matrix construction resembles that of fiberglass, a manufactured product also noted for its strength.

Figure 3.14 shows the layered structure of plant cell walls. Cells initially lay down a relatively thin and flexible primary wall, which allows the growing cell to continue to enlarge. Some cells then add a secondary wall deposited in laminated layers. Wood consists mainly of secondary walls, which are strengthened with rigid molecules called lignin. Between adjacent cells is a layer of sticky polysaccharides called pectins (shown here in dark brown), which glue the cells together. (Pectin is used to thicken jams and jellies.)

Despite their thickness, plant cell walls do not totally isolate the cells from each other. To function in a coordinated way as part of a tissue, the cells must have cell junctions, structures that connect them to one another. Figure 3.14 shows the numerous channels between adjacent plant cells, called **plasmodesmata** (singular, *plasmodesma*). Notice that the plasma membrane and the cytoplasm of the cells extend through the plasmodesmata, so that water and other small molecu cell to cell. Through plasmodesmata, share water, nourishment, and chemi

? **Which animal cell junction is anal** has more water molecules *free* to move. There is a net movement of water down its own concentration gradient, from the solution with more free water molecules (and lower solute concentration) to that with fewer free water molecules (and higher solute concentration). The result of this water movement is the difference in water levels you see at the top right of Figure 4.3.

Let's now apply to living cells what we have learned abou osmosis in artificial systems.

? Indicate the direction of net water movement between two solutions—a 0.5% sucrose solution and a 2% sucrose solution separated by a membrane not permeable to sucrose.

the 0.5% sucrose solution (lower solute concentration) to the 2% sucrose (higher solute concentration).

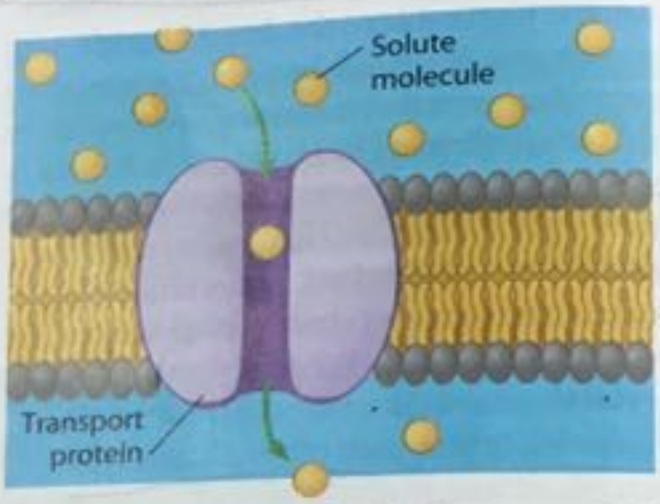
4.4 Transport proteins can facilitate diffusion across membranes

Recall that nonpolar, hydrophobic molecules can dissolve in the lipid bilayer of a membrane and cross it with ease. Polar or charged substances, meanwhile, can move across a membrane with the help of specific transport proteins in a process called **facilitated diffusion**. Without the transport protein, the substance cannot cross the membrane or it diffuses across it too slowly to be useful to the cell. Facilitated diffusion is a type of passive transport because it does not require energy. As in all passive transport, the driving force is the concentration gradient.

Figure 4.4 shows a common type of transport protein, which provides a hydrophilic channel that some molecules or ions use as a tunnel through the membrane. Another type of transport protein binds its passenger, changes shape, and releases its passenger on the other side. In both cases, the transport protein is specific for the substance it helps move across the membrane. The greater the number of transport proteins for a particular solute in a membrane, the faster the solute's rate of diffusion across the membrane.

Substances that use facilitated diffusion for crossing cell membranes include a number of sugars, amino acids, ions—and even water. The water molecule is very small, but because it is polar, its diffusion through a membrane's hydrophobic interior is relatively slow. The very rapid diffusion of water into and out of certain cells, such as plant cells, kidney cells, and red blood cells, is made possible by a protein channel called an **aquaporin**. A single aquaporin allows the entry or exit of up to 3 billion water molecules per second—a tremendous increase in water transport over simple diffusion.

Water is polar



◀ **Figure 4.4** Transport prote providing a chan for the diffusion a specific solute across a memb

? How do transport proteins contribute to a membrane's selective permeability?

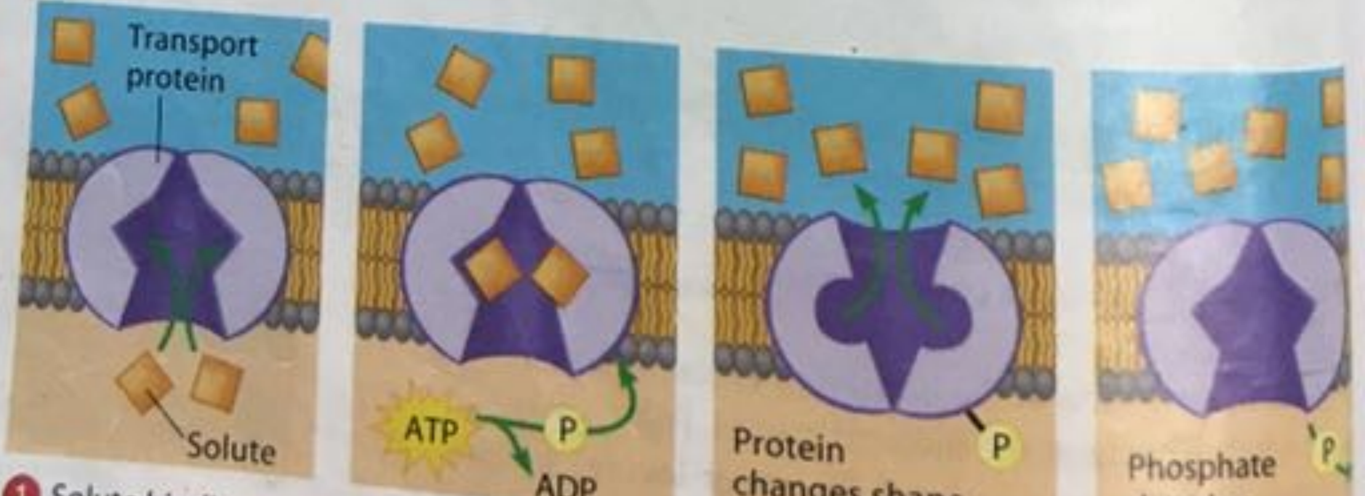
cause they are specific for the solutes they transport, the numbers and kinds nsport proteins affect a membrane's permeability to various solutes.

4.5 Cells expend energy in the active transport of a solute

low-To high

In **active transport**, a cell must expend energy to move a solute *against* its concentration gradient—that is, across a membrane toward the side where the solute is more concentrated. The energy molecule ATP supplies the energy for most active transport.

Figure 4.5 shows a simple model of an active transport system that pumps a solute out of the cell against its concentration gradient. ① The process begins when solute molecules on the cytoplasmic side of the plasma membrane attach to specific binding sites on the transport protein. ② ATP then transfers a phosphate group to the transport protein, ③ causing the protein to change shape in such a way that the solute is released on the other side of the membrane. ④ The phosphate group detaches, and the transport protein returns to its original shape.



① Solute binding ② Phosphate attaching ③ Transport ④ Protein reversion

▲ **Figure 4.5** Active transport of a

has more water molecules *free* to move. There is a net movement of water down its own concentration gradient, from the solution with more free water molecules (and lower solute concentration) to that with fewer free water molecules (and higher solute concentration). The result of this water movement is the difference in water levels you see at the top right of Figure 4.3.

Let's now apply to living cells what we have learned abou osmosis in artificial systems.

? Indicate the direction of net water movement between two solutions—a 0.5% sucrose solution and a 2% sucrose solution separated by a membrane not permeable to sucrose.

the 0.5% sucrose solution (lower solute concentration) to the 2% sucrose (higher solute concentration).

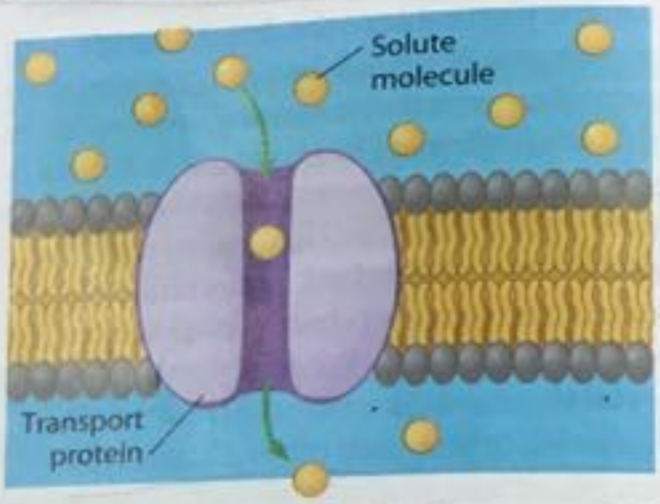
4.4 Transport proteins can facilitate diffusion across membranes

Recall that nonpolar, hydrophobic molecules can dissolve in the lipid bilayer of a membrane and cross it with ease. Polar or charged substances, meanwhile, can move across a membrane with the help of specific transport proteins in a process called **facilitated diffusion**. Without the transport protein, the substance cannot cross the membrane or it diffuses across it too slowly to be useful to the cell. Facilitated diffusion is a type of passive transport because it does not require energy. As in all passive transport, the driving force is the concentration gradient.

Figure 4.4 shows a common type of transport protein, which provides a hydrophilic channel that some molecules or ions use as a tunnel through the membrane. Another type of transport protein binds its passenger, changes shape, and releases its passenger on the other side. In both cases, the transport protein is specific for the substance it helps move across the membrane. The greater the number of transport proteins for a particular solute in a membrane, the faster the solute's rate of diffusion across the membrane.

Substances that use facilitated diffusion for crossing cell membranes include a number of sugars, amino acids, ions—and even water. The water molecule is very small, but because it is polar, its diffusion through a membrane's hydrophobic interior is relatively slow. The very rapid diffusion of water into and out of certain cells, such as plant cells, kidney cells, and red blood cells, is made possible by a protein channel called an **aquaporin**. A single aquaporin allows the entry or exit of up to 3 billion water molecules per second—a tremendous increase in water transport over simple diffusion.

Water is polar



◀ Figure 4.4 Transport protei providing a chan for the diffusion a specific solute across a membr

? How do transport proteins contribute to a membrane's selective permeability?

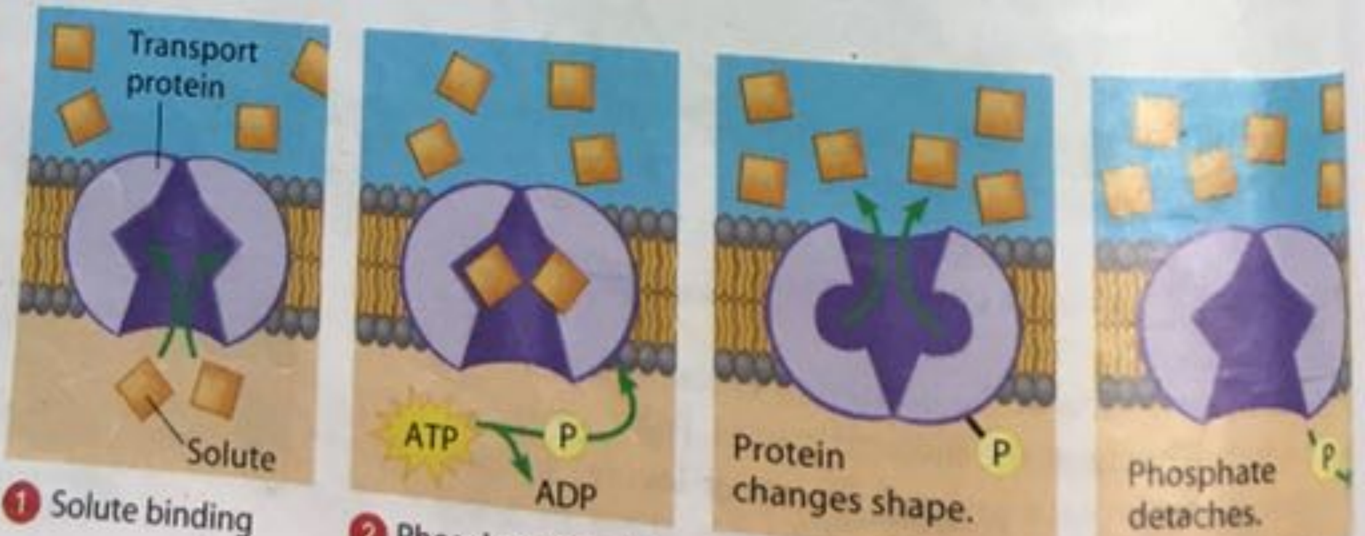
cause they are specific for the solutes they transport, the numbers and kinds nsport proteins affect a membrane's permeability to various solutes.

4.5 Cells expend energy in the active transport of a solute

low - To high

In **active transport**, a cell must expend energy to move a solute *against* its concentration gradient—that is, across a membrane toward the side where the solute is more concentrated. The energy molecule ATP supplies the energy for most active transport.

Figure 4.5 shows a simple model of an active transport system that pumps a solute out of the cell against its concentration gradient. ① The process begins when solute molecules on the cytoplasmic side of the plasma membrane attach to specific binding sites on the transport protein. ② ATP then transfers a phosphate group to the transport protein, ③ causing the protein to change shape in such a way that the solute is released on the other side of the membrane. ④ The phosphate group detaches, and the transport protein returns to its original shape.



① Solute binding ② Phosphate attaching ③ Transport ④ Protein reversio

▲ Figure 4.5 Active transport of

15

Energy and the Cell

4.7 Cells transform energy as they perform work

The title of this chapter is "The Working Cell." But just what type of work does a cell do? You just learned that a cell actively transports substances across membranes. The cell also builds those membranes and the proteins embedded in them. A cell is a miniature chemical factory in which thousands of reactions occur within a microscopic space. Some of these reactions release energy; others require energy. To understand how the cell works, you must have a basic knowledge of energy.

Forms of Energy We can define **energy** as the capacity to cause change or to perform work. There are two basic forms of energy: kinetic energy and potential energy. **Kinetic energy** is the energy of motion. Moving objects can perform work by transferring motion to other matter. For example, the movement of your legs can push bicycle pedals, turning the wheels and moving you and your bike up a hill. **Heat**, or thermal energy, is a type of kinetic energy associated with the random movement of atoms or molecules. Light, also a type of kinetic energy, can be harnessed to power photosynthesis.

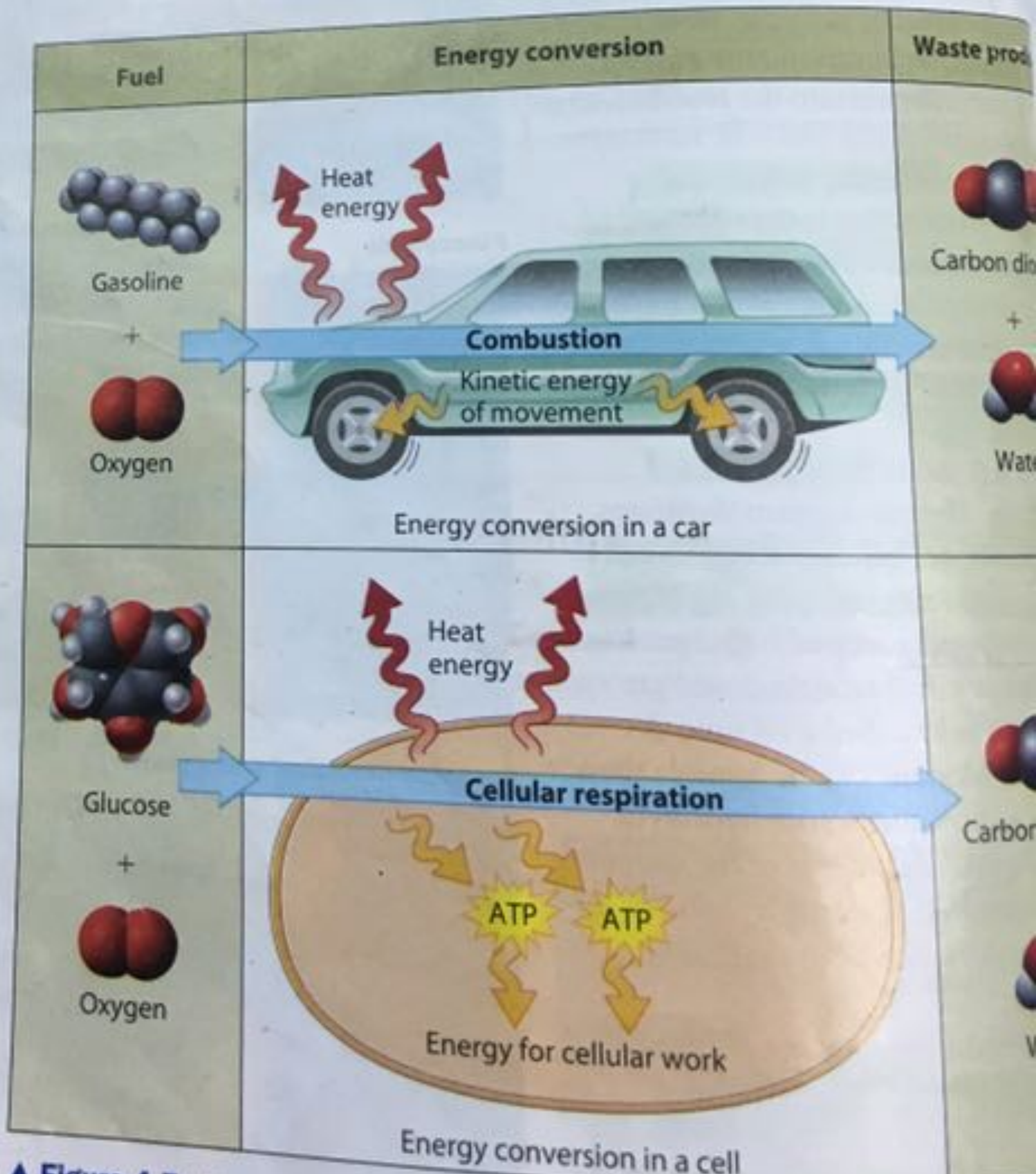
Potential energy, the second main form of energy, is energy that matter possesses as a result of its location or structure. Water behind a dam and you on your bicycle at the top of a hill possess potential energy. Molecules possess potential energy because of the arrangement of electrons in the bonds between their atoms. **Chemical energy** is the potential energy available for release in a chemical reaction. Chemical energy is the most important type of energy for living organisms; it is the energy that can be transformed to power the work of the cell.

Energy Transformations **Thermodynamics** is the study of energy transformations that occur in a collection of matter. Scientists use the word *system* for the matter under study and refer to the rest of the universe—everything outside the system—as the *surroundings*. A system can be an electric power plant, a single cell, or the entire planet. An organism is an open system; that is, it exchanges both energy and matter with its surroundings.

The **first law of thermodynamics**, also known as the law of energy conservation, states that the energy in the universe is constant ergy can be transferred and transformed, but it cannot be ated or destroyed. A power plant does not create energy; it merely converts it from one form (such as the energy stored coal) to the more convenient form of electricity. A plant ce converts light energy to chemical energy; it, too, is an ener transformer, not an energy producer.

If energy cannot be destroyed, then why can't organism simply recycle their energy? It turns out that during every transfer or transformation, some energy becomes unusab unavailable to do work. In most energy transformations, some energy is converted to heat, a disordered form of en ergy. Scientists use a quantity called **entropy** as a measure disorder, or randomness. The more randomly arranged a lection of matter is, the greater its entropy. According to second law of thermodynamics, energy conversions inc the entropy (disorder) of the universe.

Figure 4.7 compares a car and a cell to show how energy can be transformed and how entropy increases as a result.



▲ **Figure 4.7** Energy transformations (with an increase in entropy) in a car and a

15

Energy and the Cell

4.7 Cells transform energy as they perform work

The title of this chapter is "The Working Cell." But just what type of work does a cell do? You just learned that a cell actively transports substances across membranes. The cell also builds those membranes and the proteins embedded in them. A cell is a miniature chemical factory in which thousands of reactions occur within a microscopic space. Some of these reactions release energy; others require energy. To understand how the cell works, you must have a basic knowledge of energy.

Forms of Energy We can define **energy** as the capacity to cause change or to perform work. There are two basic forms of energy: kinetic energy and potential energy. **Kinetic energy** is the energy of motion. Moving objects can perform work by transferring motion to other matter. For example, the movement of your legs can push bicycle pedals, turning the wheels and moving you and your bike up a hill. **Heat**, or thermal energy, is a type of kinetic energy associated with the random movement of atoms or molecules. Light, also a type of kinetic energy, can be harnessed to power photosynthesis.

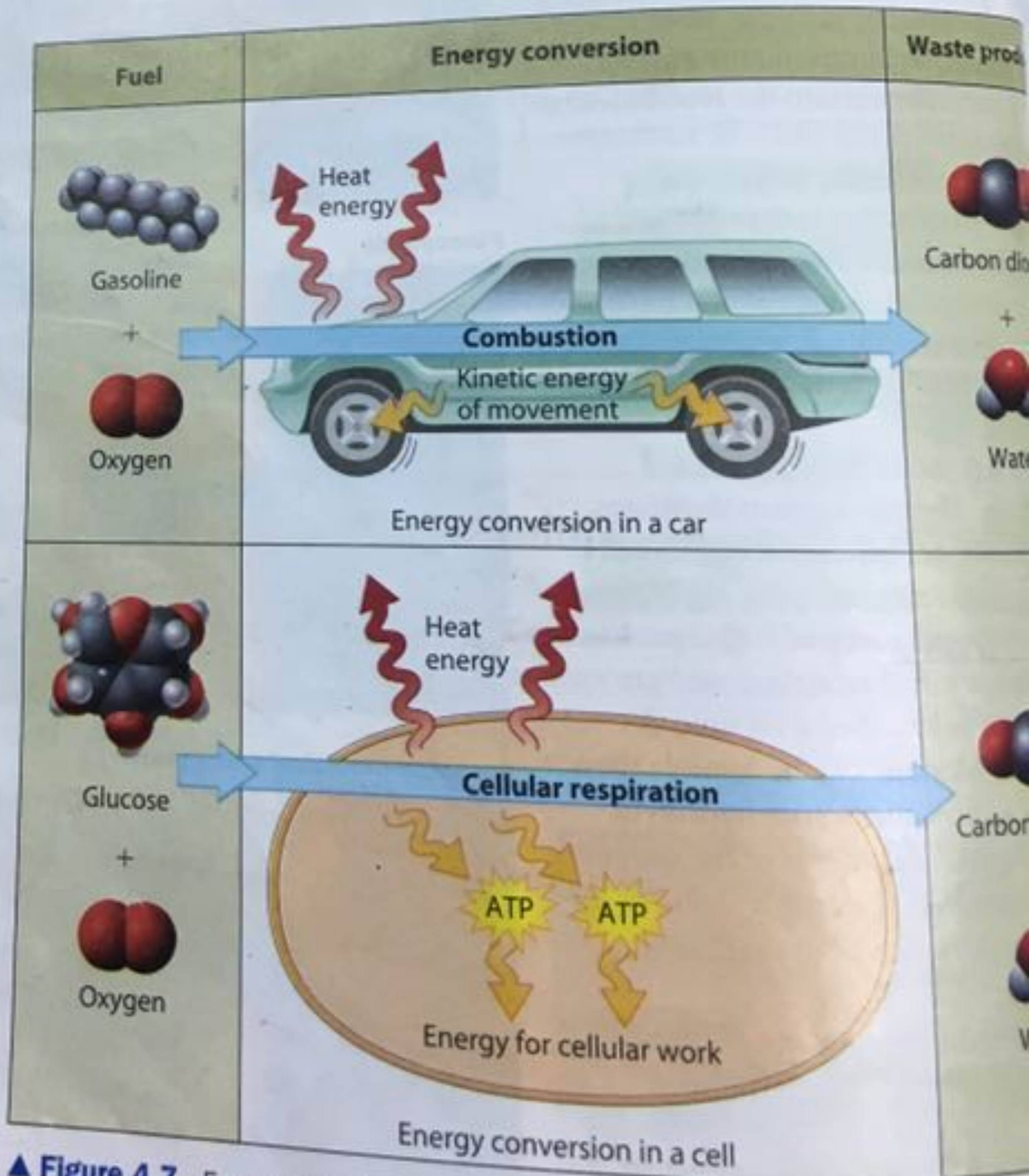
Potential energy, the second main form of energy, is energy that matter possesses as a result of its location or structure. Water behind a dam and you on your bicycle at the top of a hill possess potential energy. Molecules possess potential energy because of the arrangement of electrons in the bonds between their atoms. **Chemical energy** is the potential energy available for release in a chemical reaction. Chemical energy is the most important type of energy for living organisms; it is the energy that can be transformed to power the work of the cell.

Energy Transformations **Thermodynamics** is the study of energy transformations that occur in a collection of matter. Scientists use the word *system* for the matter under study and refer to the rest of the universe—everything outside the system—as the *surroundings*. A system can be an electric power plant, a single cell, or the entire planet. An organism is an open system; that is, it exchanges both energy and matter with its surroundings.

The **first law of thermodynamics**, also known as the law of energy conservation, states that the energy in the universe is constant ergy can be transferred and transformed, but it cannot be ated or destroyed. A power plant does not create energy; i merely converts it from one form (such as the energy store coal) to the more convenient form of electricity. A plant ce converts light energy to chemical energy; it, too, is an ener transformer, not an energy producer.

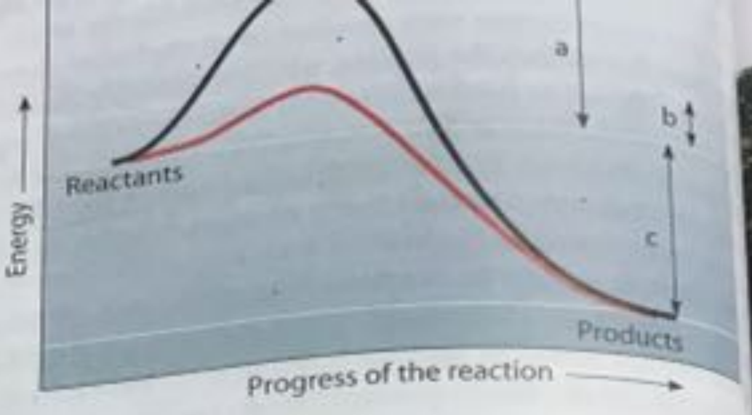
If energy cannot be destroyed, then why can't organism simply recycle their energy? It turns out that during every transfer or transformation, some energy becomes unusab unavailable to do work. In most energy transformations, some energy is converted to heat, a disordered form of energy. Scientists use a quantity called **entropy** as a measure disorder, or randomness. The more randomly arranged a c lection of matter is, the greater its entropy. According to t **second law of thermodynamics**, energy conversions inc the entropy (disorder) of the universe.

Figure 4.7 compares a car and a cell to show how energ can be transformed and how entropy increases as a result.

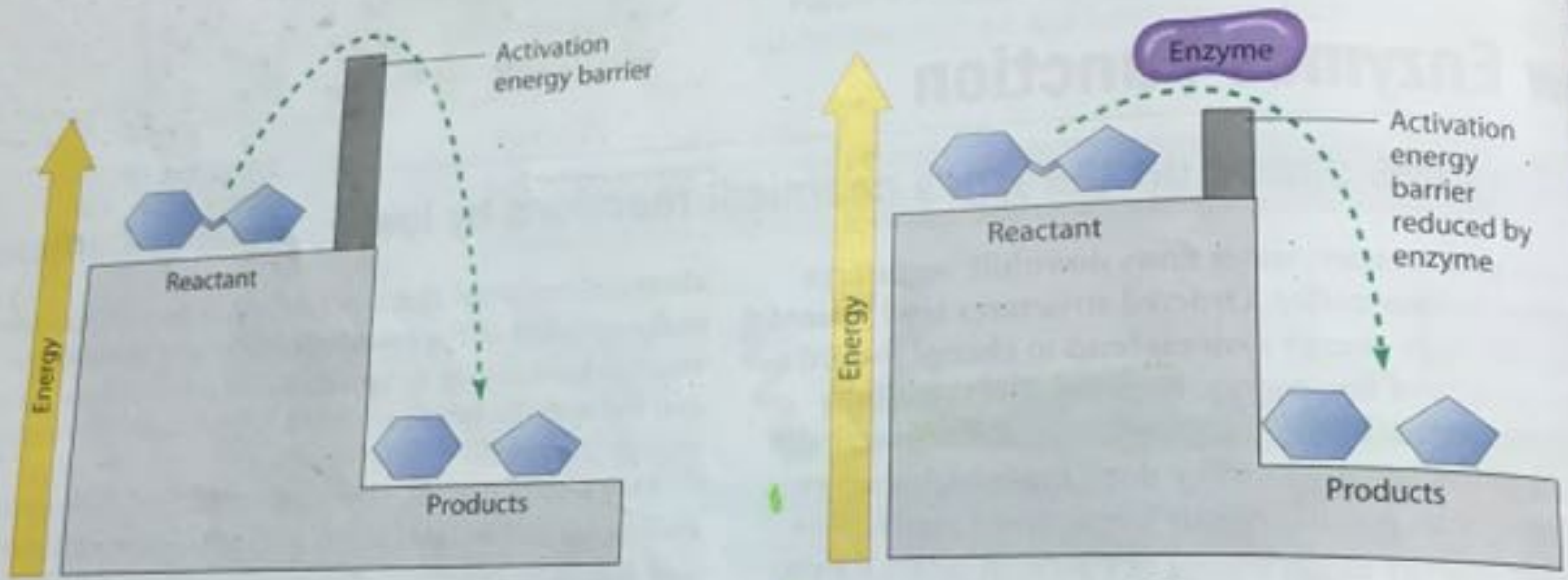


▲ **Figure 4.7** Energy transformations (with an increase in entropy) in a car and a

? The graph below illustrates the course of a reaction with and without an enzyme. Which curve represents the enzyme-catalyzed reaction? What energy changes are represented by the lines labeled a, b, and c?



red (lower) curve is the enzyme-catalyzed reaction. Line a is E_A without
b is E_A with enzyme; c is the change in energy between reactants and
which is the same for both the catalyzed and uncatalyzed reactions.



Without enzyme

With enzyme

▲ **Figure 4.8** The effect of an enzyme in lowering E_A

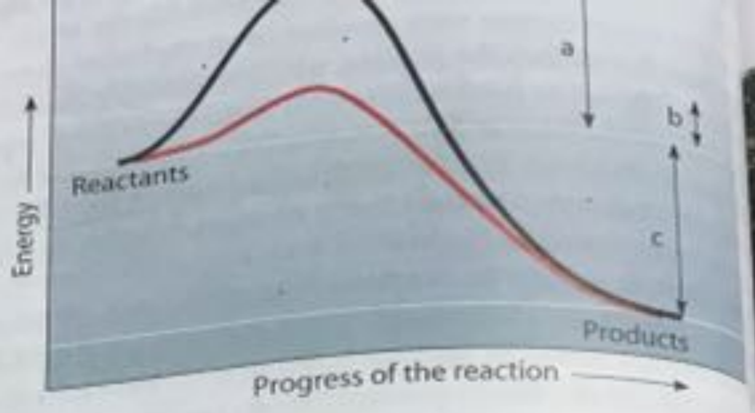
An Overview of Photosynthesis

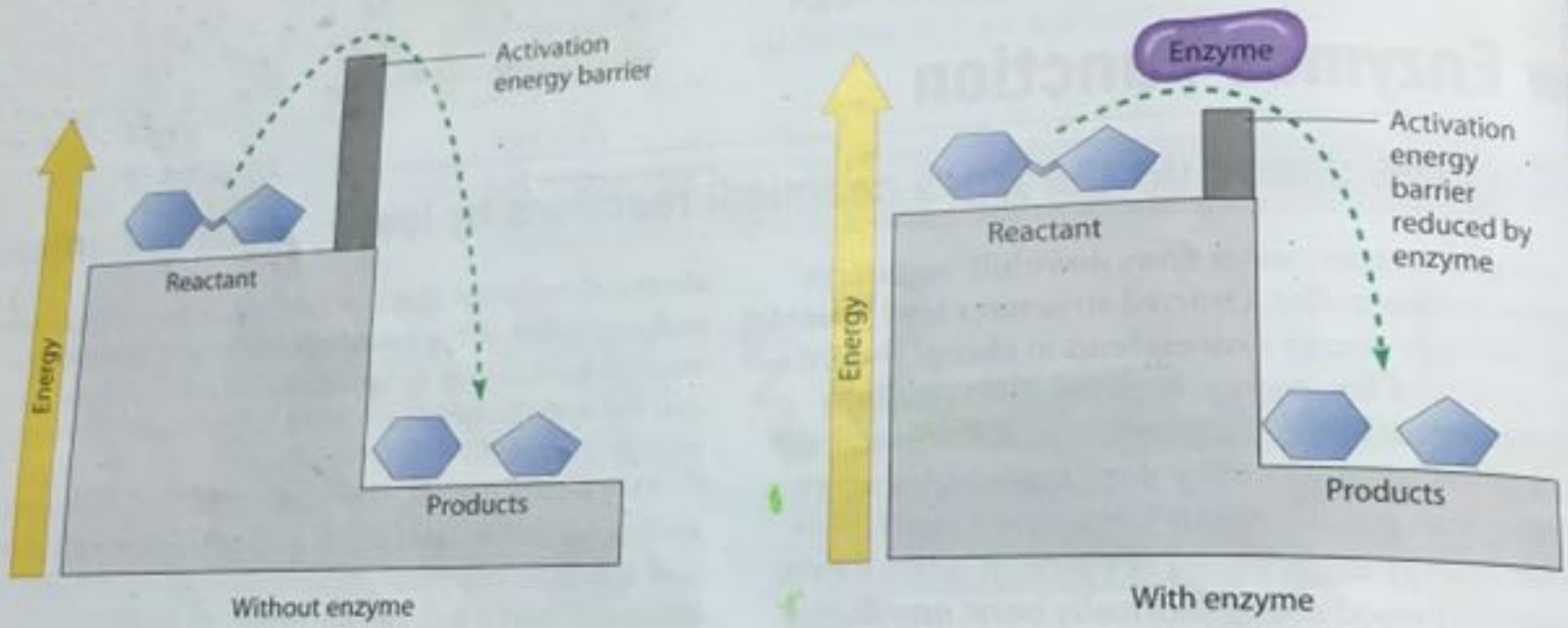
4.9 Autotrophs are the producers of the biosphere

Plants are **autotrophs** (meaning "self-feeders" in Greek) in that they make their own food and thus sustain themselves without consuming organic molecules derived from any other organisms. Plant cells capture light energy that has traveled 150 million kilometers from the sun and convert it to chemical energy. Because they use the energy of light, plants are specifically called *photoautotrophs*. Through the process of **photosynthesis**, plants convert CO_2 and H_2O to their own organic molecules and release O_2 as a by-prod uct. Photoautotrophs are the ultimate source of organic molecules for almost all other organisms. They are often referred to as the producers of the biosphere because the produce its food supply. Producers feed the consumers the biosphere—the **heterotrophs** that consume other pl or animals or decompose organic material (*hetero* mean "other").

chemoautotrophs

? The graph below illustrates the course of a reaction with and without an enzyme. Which curve represents the enzyme-catalyzed reaction? What energy changes are represented by the lines labeled a, b, and c?





▲ **Figure 4.8** The effect of an enzyme in lowering E_A

An Overview of Photosynthesis

4.9 Autotrophs are the producers of the biosphere

Plants are **autotrophs** (meaning "self-feeders" in Greek) in that they make their own food and thus sustain themselves without consuming organic molecules derived from any other organisms. Plant cells capture light energy that has traveled 150 million kilometers from the sun and convert it to chemical energy. Because they use the energy of light, plants are specifically called *photoautotrophs*. Through the process of **photosynthesis**, plants convert CO_2 and H_2O to their own organic molecules and release O_2 as a by-prod uct. Photoautotrophs are the ultimate source of organic molecules for almost all other organisms. They are often referred to as the producers of the biosphere because the produce its food supply. Producers feed the consumers the biosphere—the **heterotrophs** that consume other pl or animals or decompose organic material (*hetero* mea "other").

chemoautotrophs

Automobile engines and living cells use the same basic process to make the chemical energy of their fuel available for work. The engine mixes oxygen with gasoline in an explosive chemical reaction that pushes the pistons, which eventually move the wheels. The waste products emitted from the exhaust pipe are mostly carbon dioxide and water, energy-poor, simple molecules. Only about 25% of the chemical energy stored in gasoline is converted to the kinetic energy of the car's movement; the rest is lost as heat.

Cells also use oxygen in reactions that release energy from fuel molecules. In the process called **cellular respiration**, the chemical energy stored in organic molecules is converted to a form that the cell can use to perform work. Just like for the car, the waste products are mostly carbon dioxide and water. Cells are more efficient than car engines, however, converting about 34% of the chemical energy in their fuel to energy for cellular work. The other 66% generates heat, which explains why vigorous exercise makes you so warm.

ATP + metabolisms.

According to the second law of thermodynamics, energy transformations result in the universe becoming more disordered. How, then, can we account for biological order? A cell creates intricate structures from less organized materials. Although this increase in order corresponds to a decrease in entropy, it is accomplished at the expense of ordered forms of matter and energy taken in from the surroundings. As shown in Figure 4.7, cells extract the chemical energy of glucose and return disordered heat and lower-energy carbon dioxide and water to the surroundings. In a thermodynamic sense, a cell is an island of low entropy in an increasingly random universe.

? How does the second law of thermodynamics explain the diffusion of a solute across a membrane?

● Diffusion across a membrane results in equal concentrations of solute, which is a more disordered arrangement (higher entropy) than a high concentration on one side and a low concentration on the other.

How Enzymes Function

15min

4.8 Enzymes speed up the cell's chemical reactions by lowering energy barriers

Your room gets messier; water flows downhill; sugar crystals dissolve in your coffee. Ordered structures tend toward disorder, and high-energy systems tend to change toward a more stable state of low energy. Proteins, DNA, carbohydrates, lipids—most of the complex molecules of your cells are rich in potential energy. Why don't these high-energy, ordered molecules spontaneously break down into less ordered, lower-energy molecules? They remain intact for the same reason that wood doesn't normally burst into flames or the gas in an automobile's gas tank doesn't spontaneously explode.

There is an energy barrier that must be overcome before a chemical reaction can begin. Energy must be absorbed to contort or weaken bonds in reactant molecules so that they can break and new bonds can form. We call this the **activation energy** (abbreviated E_A for energy of activation). We can think of E_A as the amount of energy needed for reactant molecules to move "uphill" to a higher-energy, unstable state so that the "downhill" part of a reaction can begin.

The energy barrier of E_A protects the highly ordered molecules of your cells from spontaneously breaking down. But now we have a dilemma. Life depends on countless chemical reactions that constantly change a cell's molecular makeup. Most of the essential reactions of metabolism must occur quickly and precisely for a cell to survive. How can the specific reactions that a cell requires get over that energy barrier?

One way to speed reactions is to add heat. Heat speeds up molecules and agitates atoms so that bonds break more easily and reactions can proceed. Certainly, adding a match to kindling will start a fire, and the firing of a spark plug ignites gasoline in an engine. But heating a cell would speed up all chemical reactions, not just the necessary ones, and too much heat would kill the cell.

The answer to our dilemma lies in **enzymes**—molecules that function as biological catalysts, increasing the rate of a reaction without being consumed by the reaction. Almost all enzymes are proteins, although some RNA molecules can also function as enzymes. An enzyme speeds up a reaction by lowering the E_A needed for a reaction to begin. **Figure 4.8** compares a reaction without (left) and with (right) an enzyme. Notice how much easier it is for the reactant to get over the activation energy barrier when an enzyme is involved.

active site
substrate

Automobile engines and living cells use the same basic process to make the chemical energy of their fuel available for work. The engine mixes oxygen with gasoline in an explosive chemical reaction that pushes the pistons, which eventually move the wheels. The waste products emitted from the exhaust pipe are mostly carbon dioxide and water, energy-poor, simple molecules. Only about 25% of the chemical energy stored in gasoline is converted to the kinetic energy of the car's movement; the rest is lost as heat.

Cells also use oxygen in reactions that release energy from fuel molecules. In the process called **cellular respiration**, the chemical energy stored in organic molecules is converted to a form that the cell can use to perform work. Just like for the car, the waste products are mostly carbon dioxide and water. Cells are more efficient than car engines, however, converting about 34% of the chemical energy in their fuel to energy for cellular work. The other 66% generates heat, which explains why vigorous exercise makes you so warm.

ATP + metabolisms.

According to the second law of thermodynamics, energy transformations result in the universe becoming more disordered. How, then, can we account for biological order? A cell creates intricate structures from less organized materials. Although this increase in order corresponds to a decrease in entropy, it is accomplished at the expense of ordered forms of matter and energy taken in from the surroundings. As shown in Figure 4.7, cells extract the chemical energy of glucose and return disordered heat and lower-energy carbon dioxide and water to the surroundings. In a thermodynamic sense, a cell is an island of low entropy in an increasingly random universe.

? How does the second law of thermodynamics explain the diffusion of a solute across a membrane?

● Diffusion across a membrane results in equal concentrations of solute, which is a more disordered arrangement (higher entropy) than a high concentration on one side and a low concentration on the other.

How Enzymes Function

15min

4.8 Enzymes speed up the cell's chemical reactions by lowering energy barriers

Your room gets messier; water flows downhill; sugar crystals dissolve in your coffee. Ordered structures tend toward disorder, and high-energy systems tend to change toward a more stable state of low energy. Proteins, DNA, carbohydrates, lipids—most of the complex molecules of your cells are rich in potential energy. Why don't these high-energy, ordered molecules spontaneously break down into less ordered, lower-energy molecules? They remain intact for the same reason that wood doesn't normally burst into flames or the gas in an automobile's gas tank doesn't spontaneously explode.

There is an energy barrier that must be overcome before a chemical reaction can begin. Energy must be absorbed to contort or weaken bonds in reactant molecules so that they can break and new bonds can form. We call this the **activation energy** (abbreviated E_A for energy of activation). We can think of E_A as the amount of energy needed for reactant molecules to move "uphill" to a higher-energy, unstable state so that the "downhill" part of a reaction can begin.

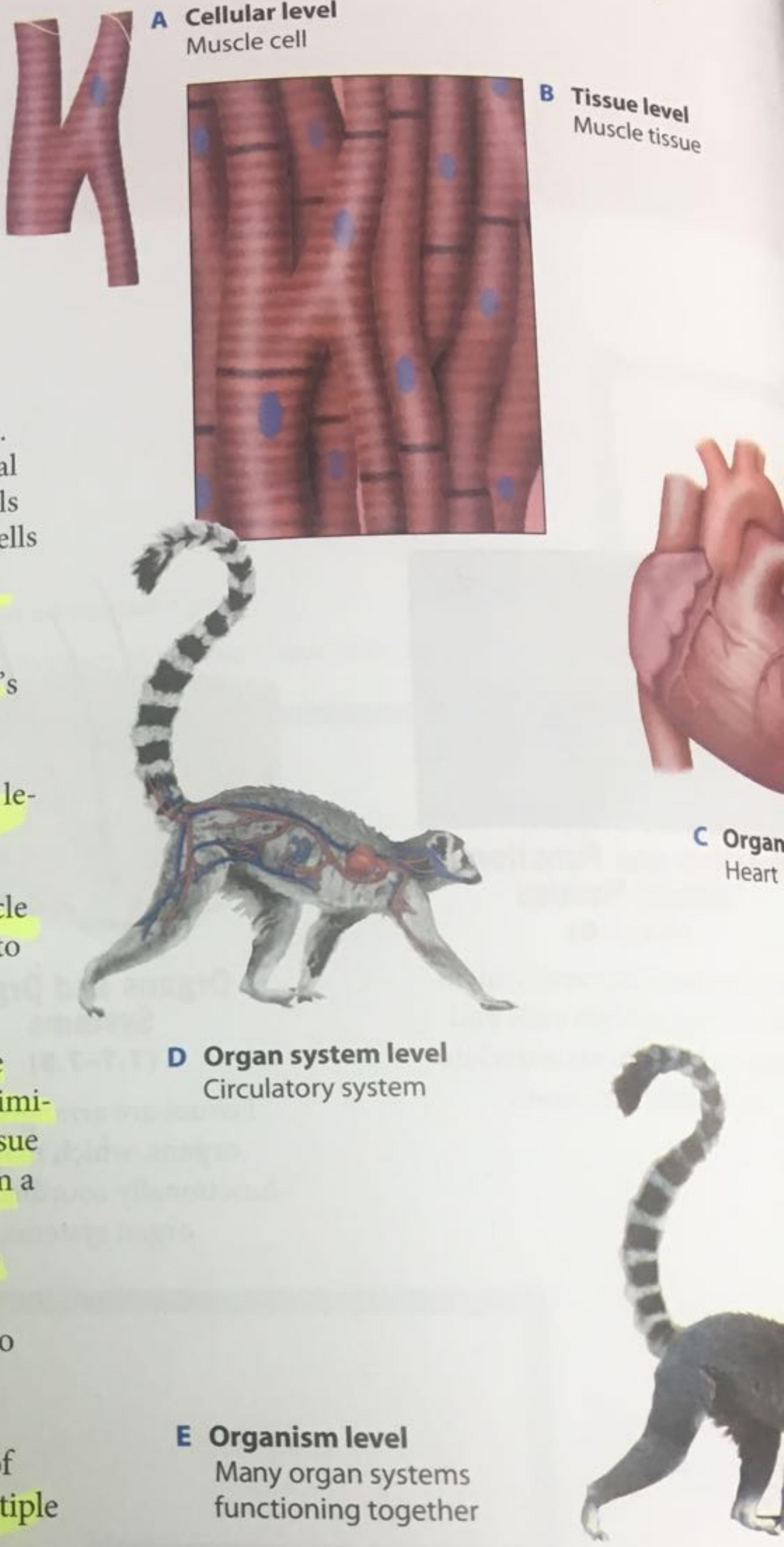
The energy barrier of E_A protects the highly ordered molecules of your cells from spontaneously breaking down. But now we have a dilemma. Life depends on countless chemical reactions that constantly change a cell's molecular makeup. Most of the essential reactions of metabolism must occur quickly and precisely for a cell to survive. How can the specific reactions that a cell requires get over that energy barrier?

One way to speed reactions is to add heat. Heat speeds up molecules and agitates atoms so that bonds break more easily and reactions can proceed. Certainly, adding a match to kindling will start a fire, and the firing of a spark plug ignites gasoline in an engine. But heating a cell would speed up all chemical reactions, not just the necessary ones, and too much heat would kill the cell.

The answer to our dilemma lies in **enzymes**—molecules that function as biological catalysts, increasing the rate of a reaction without being consumed by the reaction. Almost all enzymes are proteins, although some RNA molecules can also function as enzymes. An enzyme speeds up a reaction by lowering the E_A needed for a reaction to begin. **Figure 4.8** compares a reaction without (left) and with (right) an enzyme. Notice how much easier it is for the reactant to get over the activation energy barrier when an enzyme is involved.

active site
substrate

7.1 Structure fits function at all levels of organization in the animal body



▲ **Figure 7.1** A structural hierarchy in a ring-tailed le

When discussing structure and function, biologists distinguish anatomy from physiology. **Anatomy** is the study of the form of an organism's structures; **physiology** is the study of the functions of those structures. A biologist interested in anatomy, for instance, might focus on the arrangement of muscles and bones in a gecko's legs. A physiologist might study how a gecko's muscles function. Despite their different approaches, both scientists are working toward a better understanding of the connection between structure and function, such as how the structural adaptations of the hairs on its toes give the gecko its remarkable ability to walk on walls.

Structure in the living world is organized in hierarchical levels. We followed the progression from molecules to cells in Unit I. Now, let's trace the hierarchy in animals from cells to organisms. As we discussed in Module 1.2, emergent properties—novel properties that were not present at the preceding level of the hierarchy of life—arise as a result of the structural and functional organization of each level's component parts.

Figure 7.1 illustrates structural hierarchy in a ring-tailed lemur. **Part A** shows a single muscle cell in the lemur's heart. This cell's main function is to contract, and the stripes in the cell indicate the precise alignment of strands of proteins that perform that function. Each muscle cell is also branched, providing for multiple connections to other cells that ensure coordinated contractions of all the muscle cells in the heart.

Together, these heart cells make up a tissue **(Part B),** the second structural level. A **tissue** is an integrated group of similar cells that perform a common function. The cells of a tissue are specialized, and their structure enables them to perform a specific task—in this instance, coordinated contraction.

Part C, the heart itself, illustrates the organ level of the hierarchy. An **organ** is made up of two or more types of tissues that together perform a specific task. In addition to muscle tissue, the heart includes nervous, epithelial, and connective tissue.

Part D shows the circulatory system, the organ system of which the heart is a part. An **organ system** consists of multiple organs that together perform a vital body function. Other parts of the circulatory system include the blood and the blood vessels: arteries, veins, and capillaries.

In **Part E,** the lemur itself forms the final level of this hierarchy. An organism contains a number of organ systems, each specialized for certain tasks and all functioning together as an integrated, coordinated unit. For example, the lemur's circulatory system cannot function without oxygen supplied by the respiratory system and nutrients supplied by the digestive system. And it takes the coordination of several other organ systems to enable this animal to walk or climb trees.

The ability to climb trees or walls emerges from the specific arrangement of specialized structures. As we see throughout our study of the anatomy and physiology of anima function at each level of the structural hierarchy. I modules to come, we focus on the tissue level of t hierarchy.

? **Explain how the ability to pump blood is an emer of a heart, which is at the organ level of the biolog**

ctural organization and integration of the individual muscle, ial, and nervous tissues of a heart enable the function of

7.2 Tissues are groups of cells with a common structure and function

almost all animals, the cells of the body are organized into ues. The term *tissue* is from a Latin word meaning “weave,” d some tissues resemble woven cloth in that they consist of eshwork of nonliving fibers and other extracellular sub- ances surrounding living cells. Other tissues are held together a sticky glue that coats the cells or by special junctions be- een adjacent plasma membranes. The structure of tissues lates to their specific functions.

The specialization of complex body parts such as organs d organ systems is largely based on varied combinations a limited set of cells and tissue types. For example, your lungs and blood vessels have very distinct functions, but they are lined by tissues that are of the same basic type.

Your body is built from four main types of tissues: epithelial, connective, muscle, and nervous. We examine the structure and function of these tissue types in the next four modules.

? **How is a tissue different from a cell and an organ?**

● Tissues are collections of similar cells that perform a common function. Several different tissue types usually produce the structure of an organ.

7.3 Epithelial tissue covers the body and lines its organs and cavities

Epithelial tissues, or epithelia (singular, *epithelium*), are sheets of closely packed cells that cover your body surface and line your internal organs and cavities. The tightly knit cells form a protective barrier and, in some cases, a surface for exchange with the fluid or air on the other side. One side of an epithelium is attached to a basal lamina, a dense mat of extracellular matrix consisting of fibrous proteins and sticky polysaccharides that separates the epithelium from the underlying tissues. The other side, called the apical surface, faces the outside of an organ or the inside of a tube or passageway.

Epithelial tissues are named according to the number of cell layers they have and according to the shape of the cells on their apical surface. A simple epithelium has a single layer of cells, whereas a stratified epithelium has multiple layers. A pseudostratified epithelium has a single layer but appears stratified because the cells vary in length. The shape of the cells may be squamous (flat like floor tiles), cuboidal (like dice), or columnar (like bricks on end). **Figure 7.3** shows examples of different types of epithelia. In each case, the pink color identifies the cells of the epithelium itself.

The structure of each type of epithelium fits its function. Simple squamous epithelium **(Part A)** is thin and leaky and thus suitable for exchanging materials by diffusion. You would find it lining your capillaries and the air sacs of your lungs.

Both cuboidal and columnar epithelia have cells with a relatively large amount of cytoplasm, facilitating their role of secretion or absorption of materials. **Part B** shows a cuboidal epithelium forming a tube in the kidney. Such epithelia are also found in glands, such as the thyroid and salivary glands. A simple columnar epithelium **(Part C)** lines your intestines, where it secretes digestive juices and absorbs nutrients.

The many layers of the stratified squamous epithelium in **Part D** make it well suited for lining surfaces subject to abrasion, such as your outer skin and the linings of your mouth and esophagus. Stratified squamous epithelium regenerates rapidly by division of the cells near the basal lamina. New cells move toward the apical surface as older cells slough off.

The pseudostratified ciliated columnar epithelium in **Part E** forms a mucous membrane that lines portions of your respiratory tract and helps keep your lungs clean. Dust, pollen, and other particles are trapped in the mucus it secretes and then swept up and out of your respiratory tract by the beating of the cilia on its cells.

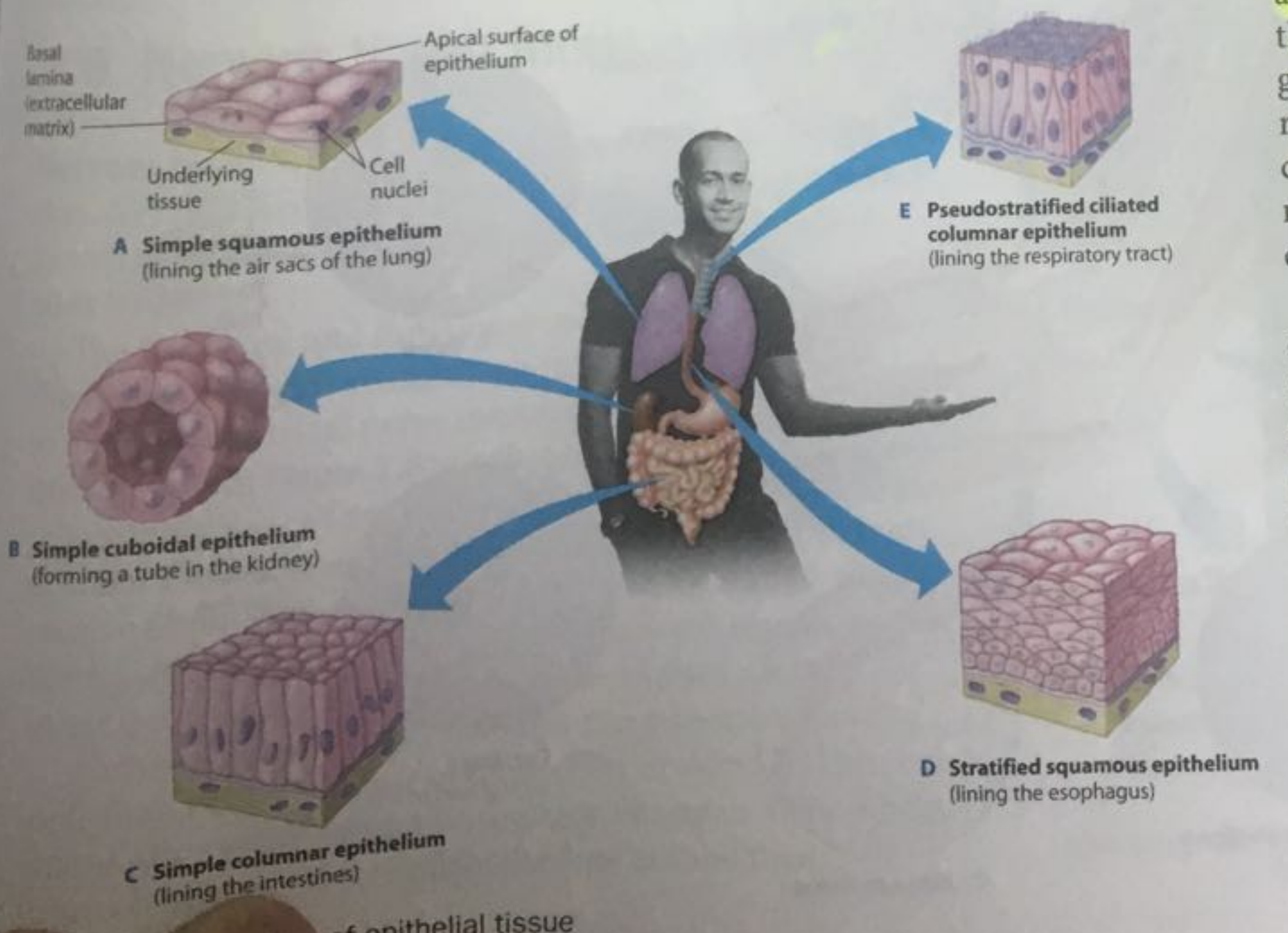
①

②

③

④

⑤



A **Simple squamous epithelium** (lining the air sacs of the lung)

B **Simple cuboidal epithelium** (forming a tube in the kidney)

C **Simple columnar epithelium** (lining the intestines)

D **Stratified squamous epithelium** (lining the esophagus)

E **Pseudostratified ciliated columnar epithelium** (lining the respiratory tract)

ure of epithelial tissue

? **Epithelial tissues are named according to the ________ of cells on their apical surface and the number of cell ________.**

● shape . . . layers.

7.5 Muscle tissue functions in movement

Muscle tissue is the most abundant tissue in most animals. It consists of long cells called muscle fibers, each containing many molecules of contractile proteins. **Figure 7.5** shows micrographs of the three types of vertebrate muscle tissue.

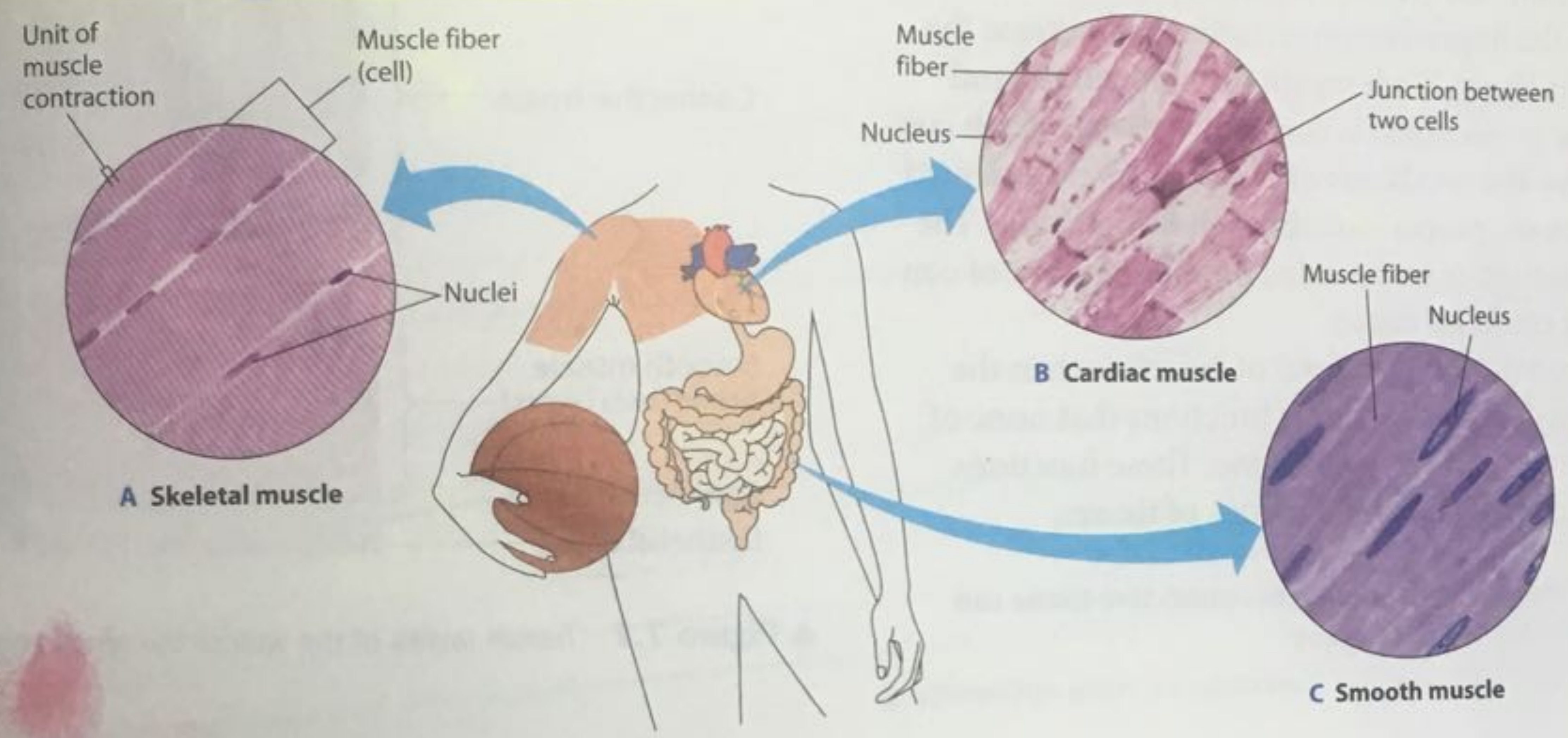
Skeletal muscle (Part A) is attached to your bones by tendons and is responsible for voluntary movements of your body, such as walking or bouncing a ball. The arrangement of the contractile units along the length of muscle fibers gives the cells a striped, or striated, appearance, as you can see in the micrograph below.

Cardiac muscle (Part B) forms the contractile tissue of your heart. It is striated like skeletal muscle, but it is under involuntary control, meaning that you cannot consciously control its contraction. Cardiac muscle fibers are branched, interconnecting at specialized junctions that rapidly relay the signal to contract from cell to cell during your heartbeat.

Smooth muscle (Part C) gets its name from its lack of striations. Smooth muscle is found in the walls of your digestive tract, arteries, and other internal organs. It is responsible for involuntary body activities, such as the movement of food through your intestines. Smooth muscle cells are spindle-shaped and contract more slowly than skeletal muscles, but can sustain contractions for a longer period of time.

? **The muscles responsible for a gecko climbing a wall are _____________ muscles.**

● skeletal.



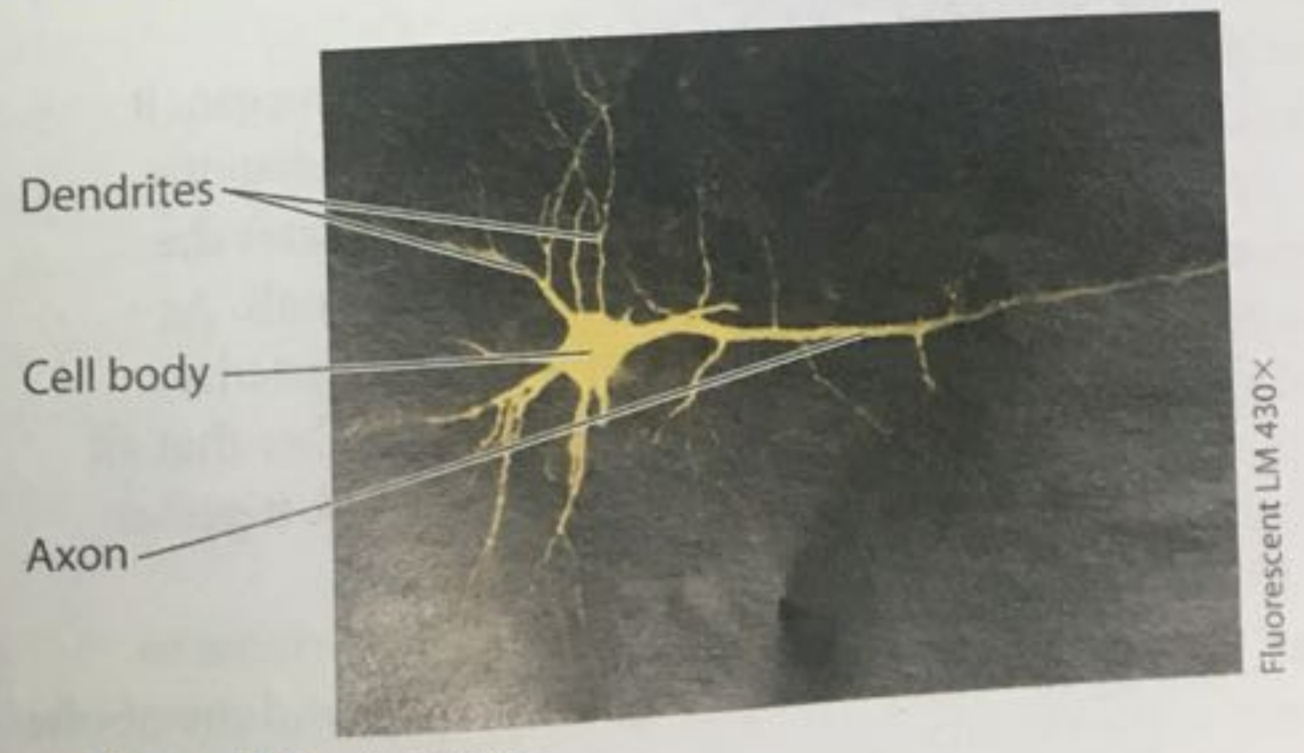
▲ **Figure 7.5** The three types of muscle tissue

7.6 Nervous tissue forms a communication network

Nervous tissue senses stimuli and rapidly transmits information. Nervous tissue is found in your brain and spinal cord, as well as in the nerves that transmit signals throughout your body.

The structural and functional unit of nervous tissue is the nerve cell, or **neuron**, which is uniquely specialized to conduct electrical nerve impulses. As you can see in the micrograph in **Figure 7.6**, a neuron consists of a cell body (containing the cell's nucleus and other organelles) and a number of slender extensions. Dendrites and the cell body receive nerve impulses from other neurons. Axons, which are often bundled together into nerves, transmit signals toward other neurons or to an effector, such as a muscle cell.

Nervous tissue actually contains many more supporting cells than neurons. Some of these cells surround and insulate axons, promoting faster transmission of signals. Others help nourish neurons and regulate the fluid around them.



▲ **Figure 7.6** A neuron

? **How does the long length of some axons (such as those that extend from your lower spine to your toes) relate to the function of a neuron?**

● It allows for the transmission of a nerve signal over a long distance directly to specific muscle cells.

7.4 Connective tissue binds and supports other tissues

In contrast to epithelium, **connective tissue** consists of a sparse population of cells scattered throughout an extracellular material called a matrix. The cells produce and secrete the matrix, which usually consists of a web of fibers embedded in a liquid, jelly, or solid. Connective tissues may be grouped into six major types. **Figure 7.4** shows micrographs of each type and illustrates where each would be found in your arm, for example.

The most widespread connective tissue in your body is called **loose connective tissue (Part A)** because its matrix is a loose weave of fibers. Many of the fibers consist of the strong, rope-like protein collagen. Other fibers are more elastic, making the tissue resilient as well as strong. Loose connective tissue serves mainly to bind epithelia to underlying tissues and hold organs in place. In the figure, we show the loose connective tissue that lies directly under the skin.

Fibrous connective tissue (Part B) has densely packed parallel bundles of collagen fibers, an arrangement that maximizes its strength. This tissue forms tendons, which attach your muscles to bone, and ligaments, which connect your bones at joints.

Adipose tissue (Part C) stores fat in large, closely packed adipose cells held in a matrix of fibers. This tissue pads and insulates your body and stores energy. Each adipose cell contains a large fat droplet that swells when fat is stored and shrinks when fat is used as fuel.

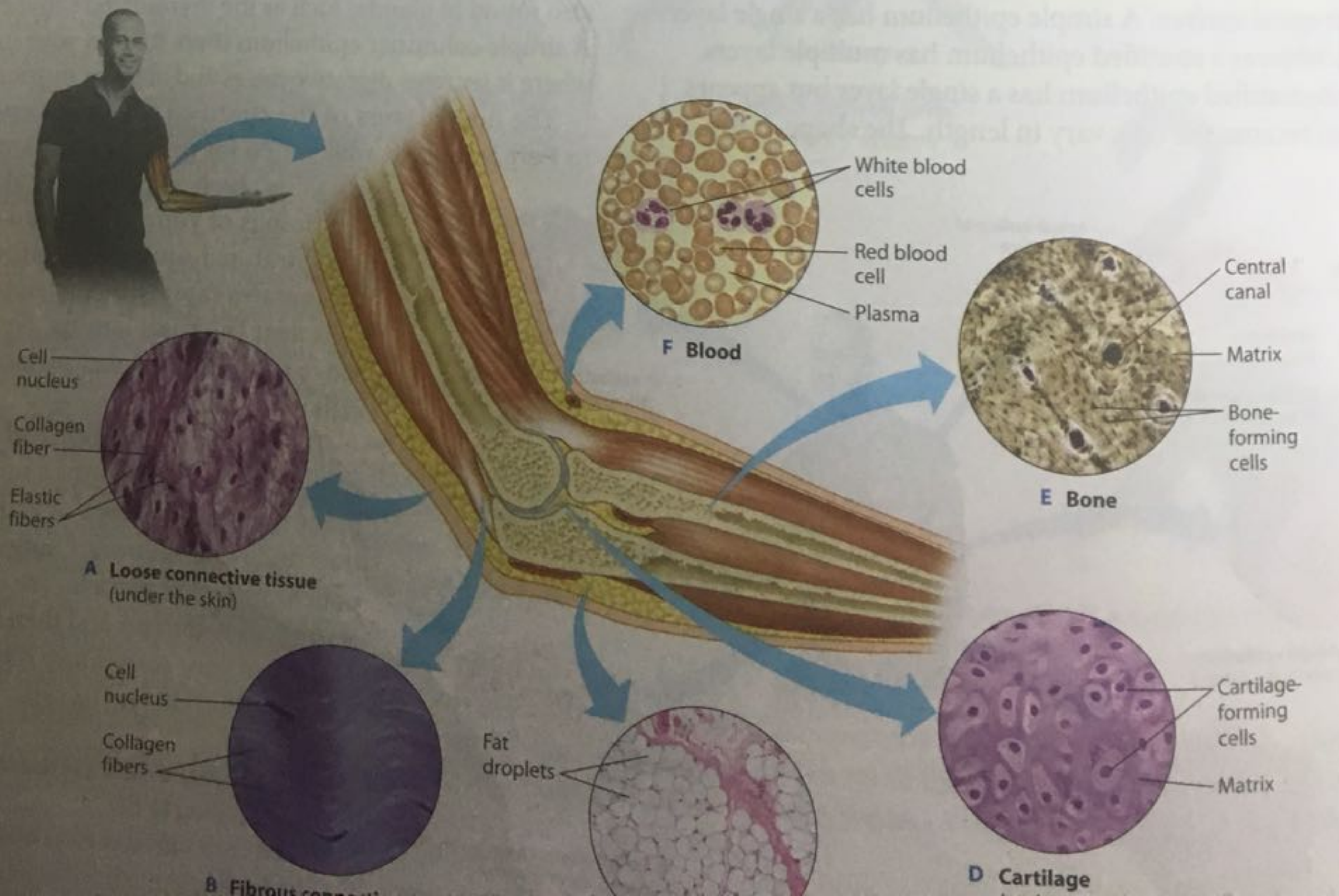
The matrix of **cartilage (Part D)**, a connective tissue that forms a strong but flexible skeletal material, consists of collagen fibers embedded in a rubbery material. Cartilage commonly surrounds the ends of bones, providing a shock-absorbing surface. It also supports your ears and nose and forms the cushioning disks between your vertebrae.

Bone (Part E) has a matrix of collagen fibers embedded in a hard mineral substance made of calcium, magnesium, and phosphate. The combination of fibers and minerals makes bone strong without being brittle. The microscopic structure of compact regions of bones contains repeating circular layers of matrix, each with a central canal containing blood vessels and nerves. Like other tissues, bone contains living cells and can therefore grow as you grow and mend when broken.

Blood (Part F) transports substances throughout your body and thus functions differently from other connective tissues. Its extensive extracellular matrix is a liquid called plasma, which consists of water, salts, and dissolved proteins. Suspended in the plasma are red blood cells, which carry oxygen; white blood cells, which function in defense against disease; and platelets, which aid in blood clotting.

? Why does blood qualify as a type of connective tissue?

Because it consists of a relatively sparse population of cells surrounded by a noncellular matrix, which in this case is a fluid called plasma.



that plays a central role in converting solar energy to chemical energy.

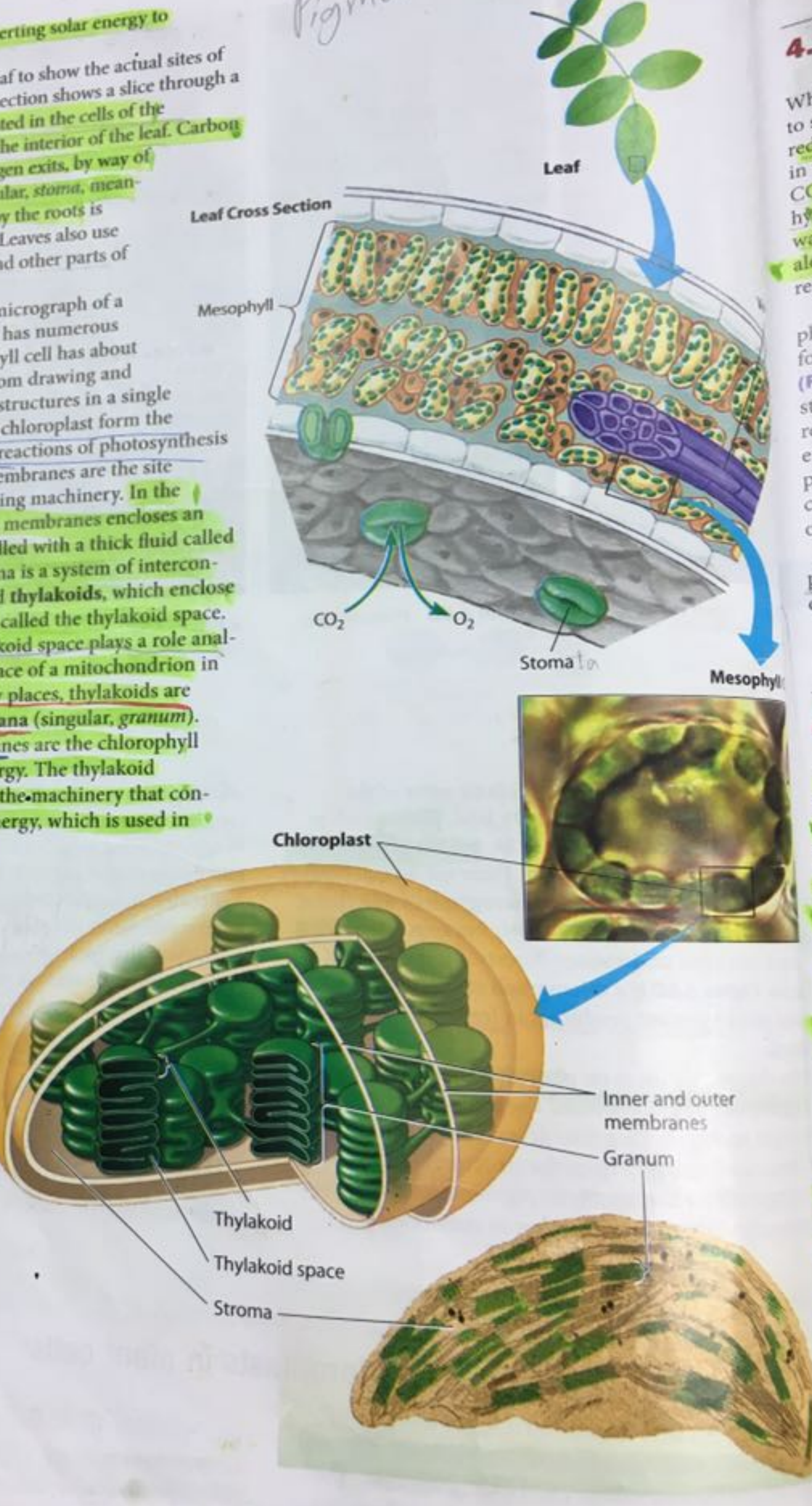
Figure 4.10 zooms in on a leaf to show the actual sites of photosynthesis. The leaf cross section shows a slice through a leaf. Chloroplasts are concentrated in the cells of the **mesophyll**, the green tissue in the interior of the leaf. Carbon dioxide enters the leaf, and oxygen exits, by way of tiny pores called **stomata** (singular, *stoma*, meaning "mouth"). Water absorbed by the roots is delivered to the leaves in veins. Leaves also use veins to export sugar to roots and other parts of the plant.

As you can see in the light micrograph of a single mesophyll cell, each cell has numerous chloroplasts. A typical mesophyll cell has about 30 to 40 chloroplasts. The bottom drawing and electron micrograph show the structures in a single chloroplast. Membranes in the chloroplast form the framework where many of the reactions of photosynthesis occur, just as mitochondrial membranes are the site for much of the energy-harvesting machinery. In the chloroplast, an envelope of two membranes encloses an inner compartment, which is filled with a thick fluid called **stroma**. Suspended in the stroma is a system of interconnected membranous sacs, called **thylakoids**, which enclose another internal compartment, called the thylakoid space. (As you will see later, this thylakoid space plays a role analogous to the intermembrane space of a mitochondrion in the generation of ATP.) In many places, thylakoids are concentrated in stacks called **grana** (singular, *granum*). Built into the thylakoid membranes are the chlorophyll molecules that capture light energy. The thylakoid membranes also house much of the machinery that converts light energy to chemical energy, which is used in the stroma to make sugar.

? **How do the reactant molecules of photosynthesis reach the chloroplasts in leaves?**

● CO_2 enters leaves through stomata, and H_2O enters the roots and is carried to leaves through veins.

Pigments types



Pigments types

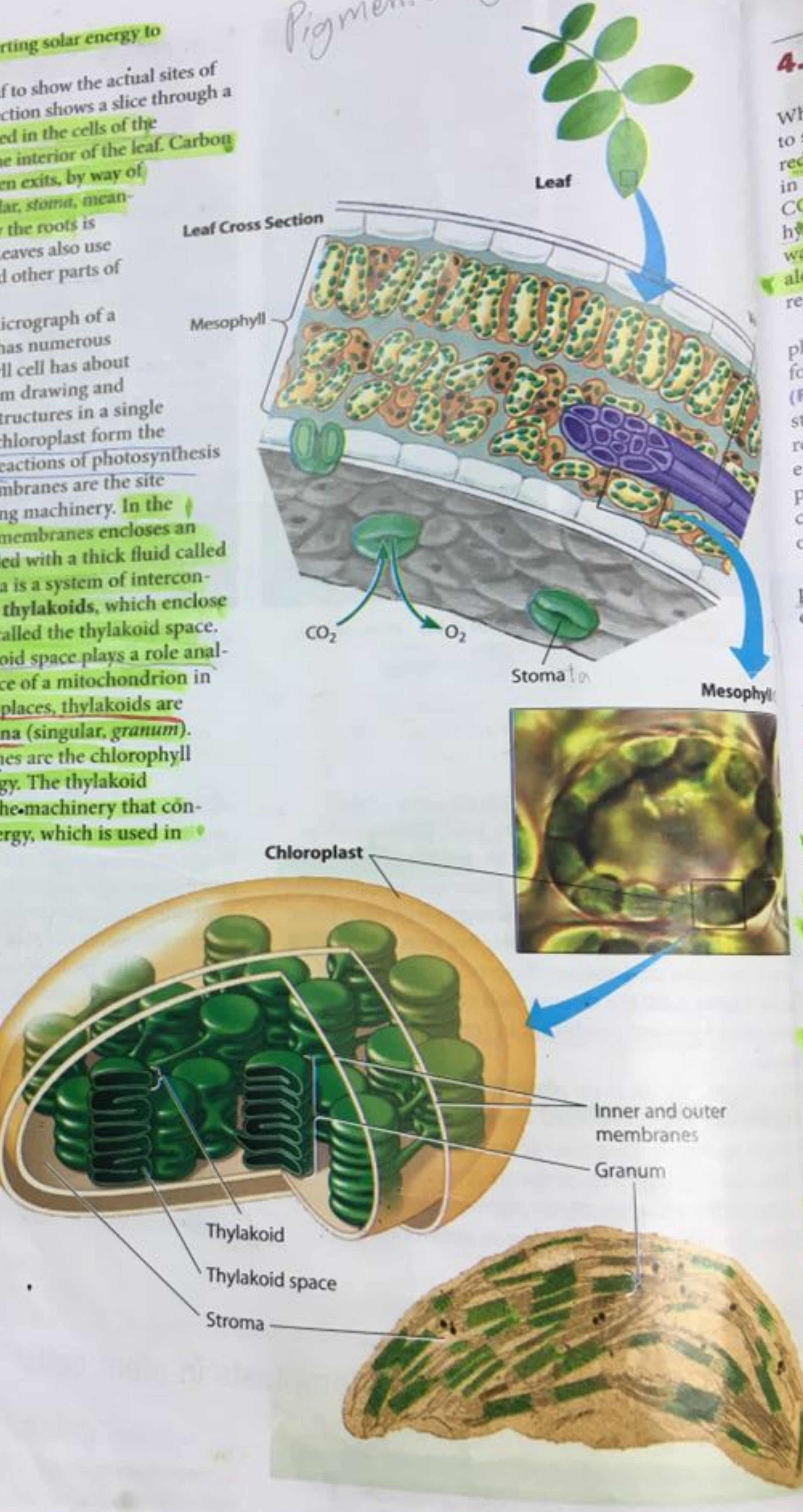
that plays a central role in converting solar energy to chemical energy.

Figure 4.10 zooms in on a leaf to show the actual sites of photosynthesis. The leaf cross section shows a slice through a leaf. Chloroplasts are concentrated in the cells of the **mesophyll**, the green tissue in the interior of the leaf. Carbon dioxide enters the leaf, and oxygen exits, by way of tiny pores called **stomata** (singular, *stoma*, meaning "mouth"). Water absorbed by the roots is delivered to the leaves in veins. Leaves also use veins to export sugar to roots and other parts of the plant.

As you can see in the light micrograph of a single mesophyll cell, each cell has numerous chloroplasts. A typical mesophyll cell has about 30 to 40 chloroplasts. The bottom drawing and electron micrograph show the structures in a single chloroplast. Membranes in the chloroplast form the framework where many of the reactions of photosynthesis occur, just as mitochondrial membranes are the site for much of the energy-harvesting machinery. In the chloroplast, an envelope of two membranes encloses an inner compartment, which is filled with a thick fluid called **stroma**. Suspended in the stroma is a system of interconnected membranous sacs, called **thylakoids**, which enclose another internal compartment, called the thylakoid space. (As you will see later, this thylakoid space plays a role analogous to the intermembrane space of a mitochondrion in the generation of ATP.) In many places, thylakoids are concentrated in stacks called **grana** (singular, *granum*). Built into the thylakoid membranes are the chlorophyll molecules that capture light energy. The thylakoid membranes also house much of the machinery that converts light energy to chemical energy, which is used in the stroma to make sugar.

? How do the reactant molecules of photosynthesis reach the chloroplasts in leaves?

● CO_2 enters leaves through stomata, and H_2O enters the roots and is carried to leaves through veins.




▲ **Figure 4.9A** Forest plants

▲ **Figure 4.9B** Photosynthetic protists


▲ **Figure 4.9C** Kelp, a multicellular alga

▲ **Figure 4.9D** Cyanobacteria (photosynthetic prokaryotes)

The photographs on this page illustrate some of the diversity among photoautotrophs. On land, plants, such as those in the forest scene in **Figure 4.9A**, are the predominant producers. In aquatic environments, there are several types of photoautotrophs. **Figure 4.9B** is a micrograph of unicellular photosynthetic protists. **Figure 4.9C** shows kelp, a large alga that forms extensive underwater "forests" off the coast of California. **Figure 4.9D** is a micrograph of cyanobacteria, abundant and important producers in freshwater and marine ecosystems.

In this chapter, we focus on photosynthesis in plants, which takes place in chloroplasts. The remarkable ability to harness light energy and use it to drive the synthesis of organic compounds emerges from the structural organization of these organelles: Photosynthetic pigments, enzymes, and other molecules are grouped together in membranes, allowing the sequences of reactions to be carried out efficiently. The process of photosynthesis most likely originated in a group of bacteria that had infolded regions of the plasma membrane containing such clusters of enzymes and other molecules. In fact, according to the widely accepted theory of endosymbiosis, chloroplasts originated from a photosynthetic prokaryote that took up residence inside a eukaryotic cell.

Let's begin our study of photosynthesis with an overview of the location and structure of plant chloroplasts.

? **What do "self-feeding" photoautotrophs require from the environment in order to make their own food?**

Light, carbon dioxide, and water. (Minerals are also required; you'll learn about the needs of plants later in this book.)

4.10 Photosynthesis occurs in chloroplasts in plant cells

All green parts of a plant have chloroplasts in their cells and can carry out photosynthesis. In most plants, however, the leaves have the most chloroplasts (about half a million in a square millimeter surface area of a leaf) and are the major sites of photosynthesis. Their green color comes from **chlorophyll**, a light-absorbing pigment in the chloroplasts

▲ **Figure 4.9A** Forest plants

▲ **Figure 4.9B** Photosynthetic protists

▲ **Figure 4.9C** Kelp, a multicellular alga

▲ **Figure 4.9D** Cyanobacteria (photosynthetic prokaryotes)

The photographs on this page illustrate some of the diversity among photoautotrophs. On land, plants, such as those in the forest scene in **Figure 4.9A**, are the predominant producers. In aquatic environments, there are several types of photoautotrophs. **Figure 4.9B** is a micrograph of unicellular photosynthetic protists. **Figure 4.9C** shows kelp, a large alga that forms extensive underwater "forests" off the coast of California. **Figure 4.9D** is a micrograph of cyanobacteria, abundant and important producers in freshwater and marine ecosystems.

In this chapter, we focus on photosynthesis in plants, which takes place in chloroplasts. The remarkable ability to harness light energy and use it to drive the synthesis of organic compounds emerges from the structural organization of these organelles: Photosynthetic pigments, enzymes, and other molecules are grouped together in membranes, allowing the sequences of reactions to be carried out efficiently. The process of photosynthesis most likely originated in a group of bacteria that had infolded regions of the plasma membrane containing such clusters of enzymes and other molecules. In fact, according to the widely accepted theory of endosymbiosis, chloroplasts originated from a photosynthetic prokaryote that took up residence inside a eukaryotic cell.

Let's begin our study of photosynthesis with an overview of the location and structure of plant chloroplasts.

? **What do "self-feeding" photoautotrophs require from the environment in order to make their own food?**

Light, carbon dioxide, and water. (Minerals are also required; you'll learn about the needs of plants later in this book.)

4.10 Photosynthesis occurs in chloroplasts in plant cells

All green parts of a plant have chloroplasts in their cells and can carry out photosynthesis. In most plants, however, the leaves have the most chloroplasts (about half a million in a square millimeter surface area of a leaf) and are the major sites of photosynthesis. Their green color comes from **chlorophyll**, a light-absorbing pigment in the chloroplasts

4.11 Photosynthesis is a redox process, as is cellular respiration

endergonic

What actually happens when CO_2 and water are converted to sugar and O_2? Photosynthesis is a redox (oxidation-reduction) process, just as cellular respiration is. As indicated in the summary equation for photosynthesis (**Figure 4.11A**), CO_2 becomes reduced to sugar as electrons, along with hydrogen ions (H^+) from water, are added to it. Meanwhile, water molecules are oxidized; that is, they lose electrons, along with hydrogen ions. Recall that oxidation and reduction always go hand in hand.

Now compare the food-producing equation for photosynthesis with the energy-releasing equation for cellular respiration that you learned about in Chapter 5 (**Figure 4.11B**). Overall, cellular respiration harvests energy stored in a glucose molecule by oxidizing the sugar and reducing O_2 to H_2O. This process involves a number of energy-releasing redox reactions, with electrons losing potential energy as they "fall" down an electron transport chain to O_2. Along the way, the mitochondrion uses some of the energy to synthesize ATP.

In contrast, the food-producing redox reactions of photosynthesis require energy. The potential energy of electrons increases as they move from H_2O to CO_2 during photosynthesis. The light energy captured by chlorophyll molecules in the chloroplast provides this energy boost. Photosynthesis converts light energy to chemical energy and stores it in the chemical bonds of sugar molecules, which can provide energy for later use or raw materials for biosynthesis.

$$\overset{\text{Becomes reduced}}{6CO_2} + \underset{\text{Becomes oxidized}}{6H_2O} \longrightarrow C_6H_{12}O_6 + 6O_2$$

silly

▲ **Figure 4.11A** Photosynthesis (uses light energy)

$$\overset{\text{Becomes oxidized}}{C_6H_{12}O_6} + \underset{\text{Becomes reduced}}{6O_2} \longrightarrow 6CO_2 + 6H_2O$$

▲ **Figure 4.11B** Cellular respiration (releases chemical energy)

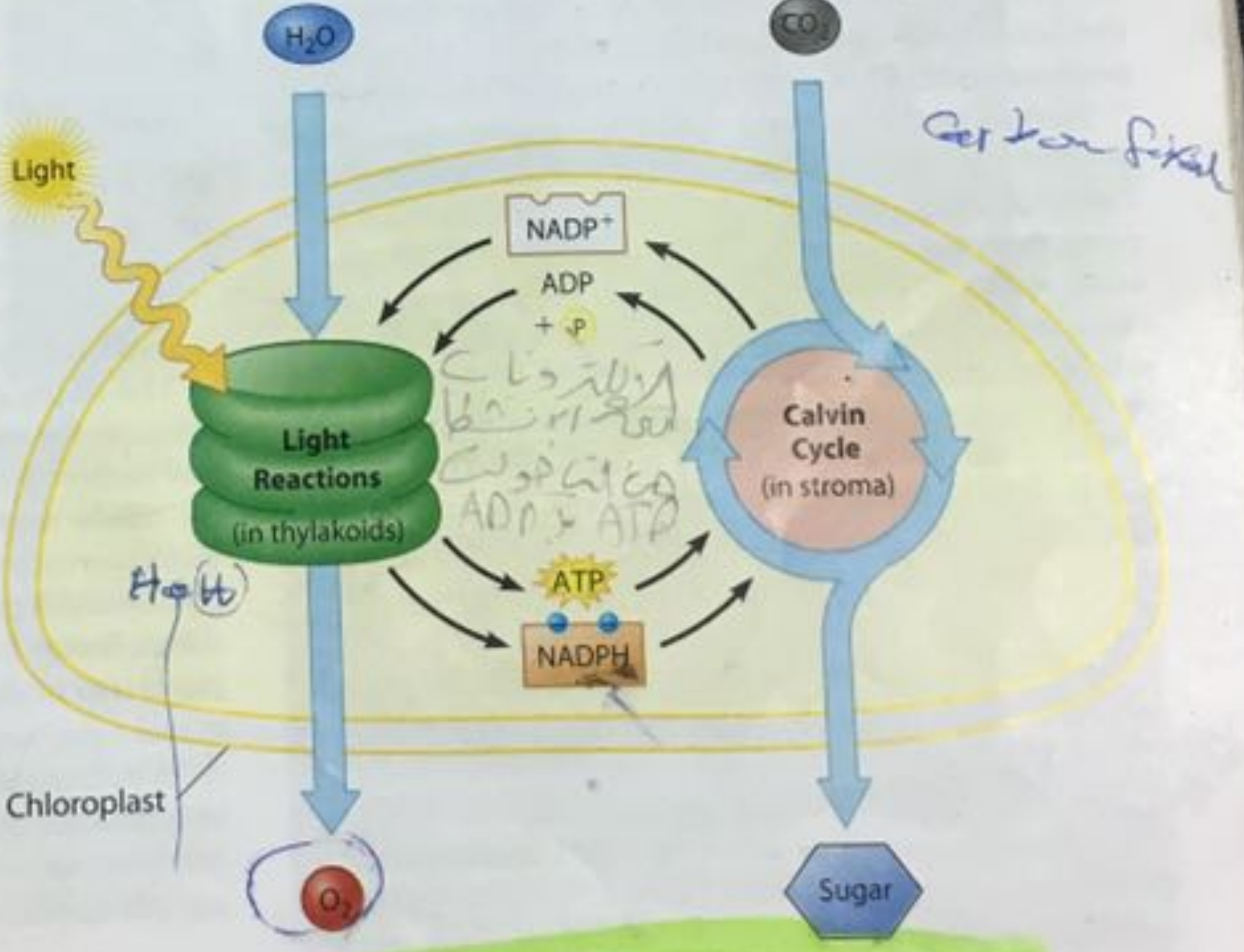
? **Which redox process, photosynthesis or cellular respiration, is endergonic?**

● Photosynthesis.

4.12 Overview: The two stages of photosynthesis are linked by ATP and NADPH

The equation for photosynthesis is a simple summary of a very complex process. Actually, photosynthesis occurs in two stages, each with multiple steps. **Figure 4.12** shows the inputs and outputs of the two stages and how the stages are related.

The **light reactions** include the steps that convert light energy to chemical energy and release O_2. As shown in the figure, the light reactions occur in the thylakoid membranes. Water is split, providing a source of electrons and giving off O_2 as a by-product. Light energy absorbed by chlorophyll molecules built into the membranes is used to drive the transfer of electrons and H^+ from water to the electron acceptor **NADP$^+$**, reducing it to NADPH. This electron carrier is first cousin to NADH, which transports electrons in cellular respiration; the two differ only in the extra phosphate group in NADPH. NADPH temporarily stores electrons and hydrogen ions and provides "reducing power" to the Calvin cycle. The light reactions also generate ATP from ADP and a phosphate group.



▲ **Figure 4.12** An overview of the two stages of photosynthesis in a chloroplast

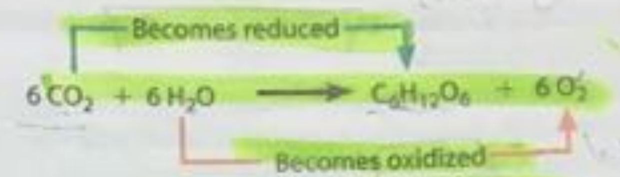
4.11 Photosynthesis is a redox process, as is cellular respiration

What actually happens when CO_2 and water are converted to sugar and O_2? Photosynthesis is a redox (oxidation-reduction) process, just as cellular respiration is. As indicated in the summary equation for photosynthesis (**Figure 4.11A**), CO_2 becomes reduced to sugar as electrons, along with hydrogen ions (H^+) from water, are added to it. Meanwhile, water molecules are oxidized; that is, they lose electrons, along with hydrogen ions. Recall that oxidation and reduction always go hand in hand.

Now compare the food-producing equation for photosynthesis with the energy-releasing equation for cellular respiration that you learned about in Chapter 5 (**Figure 4.11B**). Overall, cellular respiration harvests energy stored in a glucose molecule by oxidizing the sugar and reducing O_2 to H_2O. This process involves a number of energy-releasing redox reactions, with electrons losing potential energy as they "fall" down an electron transport chain to O_2. Along the way, the mitochondrion uses some of the energy to synthesize ATP.

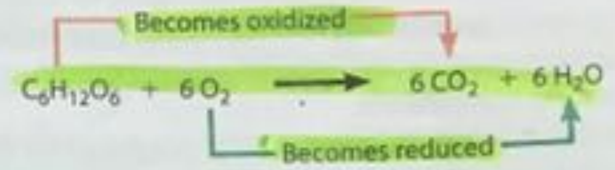
In contrast, the food-producing redox reactions of photosynthesis require energy. The potential energy of electrons increases as they move from H_2O to CO_2 during photosynthesis. The light energy captured by chlorophyll molecules in the chloroplast provides this energy boost. Photosynthesis converts light energy to chemical energy and stores it in the chemical bonds of sugar molecules, which can provide energy for later use or raw materials for biosynthesis.

endergonic



$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$$

▲ **Figure 4.11A** Photosynthesis (uses light energy)



$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$$

▲ **Figure 4.11B** Cellular respiration (releases chemical energy)

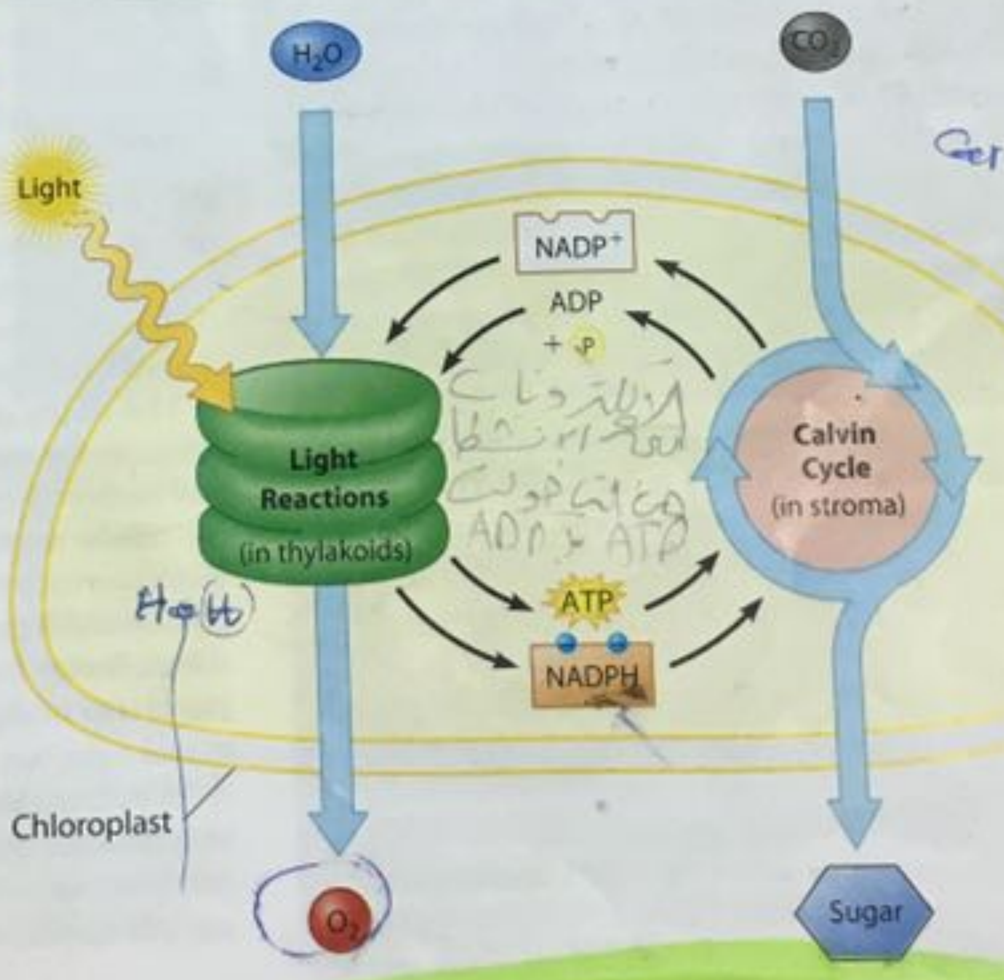
? **Which redox process, photosynthesis or cellular respiration, is endergonic?**

● Photosynthesis.

4.12 Overview: The two stages of photosynthesis are linked by ATP and NADPH

The equation for photosynthesis is a simple summary of a very complex process. Actually, photosynthesis occurs in two stages, each with multiple steps. **Figure 4.12** shows the inputs and outputs of the two stages and how the stages are related.

The **light reactions** include the steps that convert light energy to chemical energy and release O_2. As shown in the figure, the light reactions occur in the thylakoid membranes. Water is split, providing a source of electrons and giving off O_2 as a by-product. Light energy absorbed by chlorophyll molecules built into the membranes is used to drive the transfer of electrons and H^+ from water to the electron acceptor **NADP**$^+$, reducing it to NADPH. This electron carrier is first cousin to NADH, which transports electrons in cellular respiration; the two differ only in the extra phosphate group in NADPH. NADPH temporarily stores electrons and hydrogen ions and provides "reducing power" to the Calvin cycle. The light reactions also generate ATP from ADP and a phosphate group.



▲ **Figure 4.12** An overview of the two stages of photosynthesis in a chloroplast

Organs and Organ Systems

7.7 Organs are made up of tissues

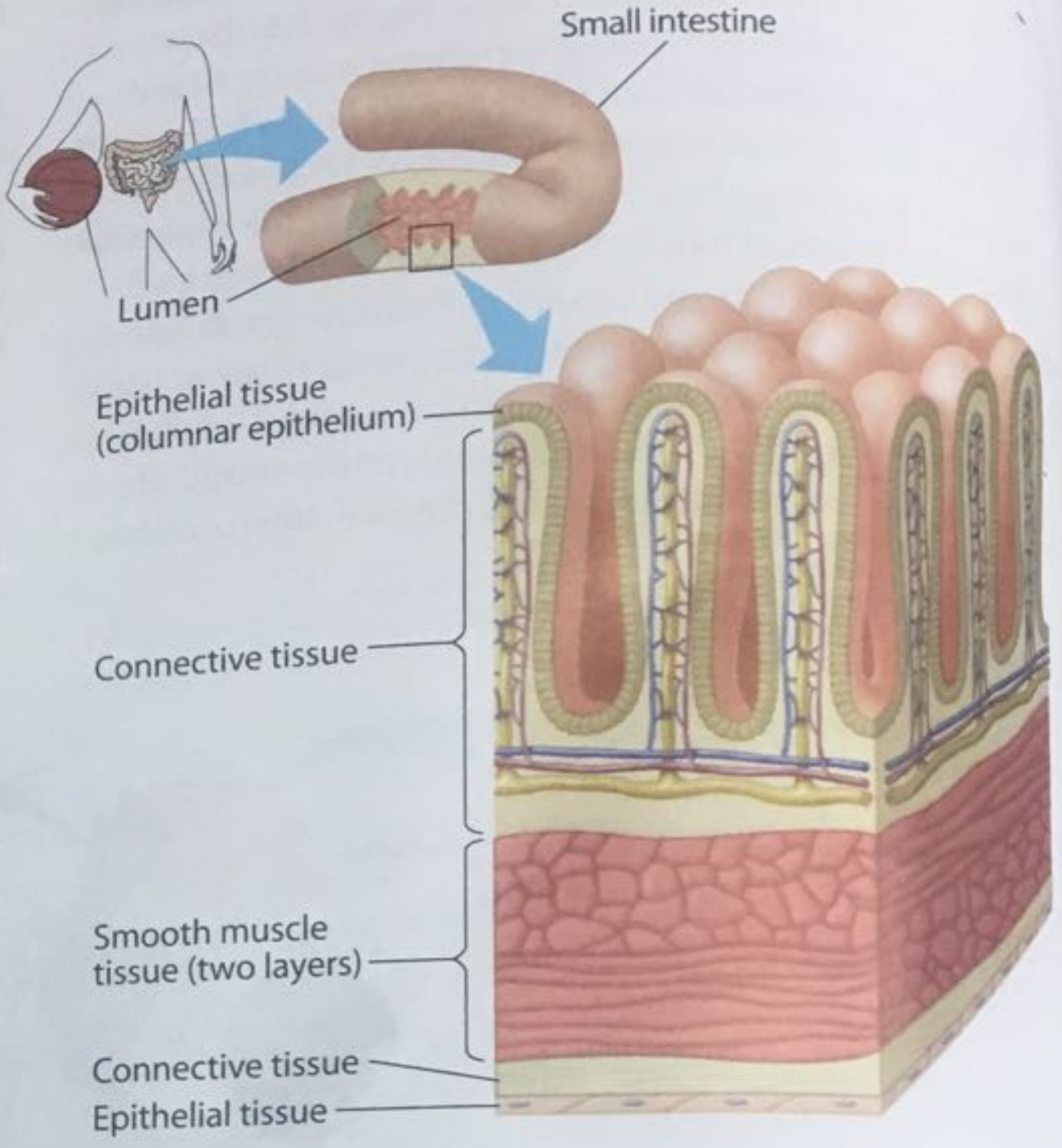
In all but the simplest animals, tissues are arranged into organs that perform specific functions. The heart, for example, while mostly muscle, also has epithelial, connective, and nervous tissues. Epithelial tissue lining the heart chambers prevents leakage and provides a smooth surface over which blood can flow. Connective tissue makes the heart elastic and strengthens its walls. Neurons regulate the contractions of cardiac muscle.

In some organs, tissues are organized in layers, as you can see in the diagram of the small intestine in **Figure 7.7**. The lumen, or interior space, of the small intestine is lined by a columnar epithelium that secretes digestive juices and absorbs nutrients. Notice the finger-like projections that increase the surface area of this lining. Underneath the epithelium (and extending into the projections) is connective tissue, which contains blood vessels. The two layers of smooth muscle, oriented in different directions, propel food through the intestine. The smooth muscle, in turn, is surrounded by another layer of connective tissue and epithelial tissue.

An organ represents a higher level of structure than the tissues composing it, and it performs functions that none of its component tissues can carry out alone. These functions emerge from the coordinated interactions of tissues.

? **Explain why a disease that damages connective tissue can impair most of the body's organs.**

● Connective tissue is a component of most organs.



▲ **Figure 7.7** Tissue layers of the wall of the small intestine

7.8 Organ systems work together to perform life's functions

Just as it takes several different tissues to build an organ, it takes the integration of several organs into organ systems to perform the body's functions. **Figure 7.8** illustrates the organ systems found in humans and other mammals. As you read through the brief descriptions of these systems and study their components in the figure, remember that all of the organ systems are interdependent and work together to create a functional organism.

A The **circulatory system** delivers O_2 and nutrients to your body cells and transports CO_2 to the lungs and metabolic wastes to the kidneys.

B The **respiratory system** exchanges gases with the environment, supplying your blood with O_2 and disposing of CO_2.

C The **integumentary system** protects your body against physical injury, infection, excessive heat or cold, and drying out.

D The **skeletal system** supports your body, protects organs such as your brain and lungs, and provides the framework for muscles to produce movement.

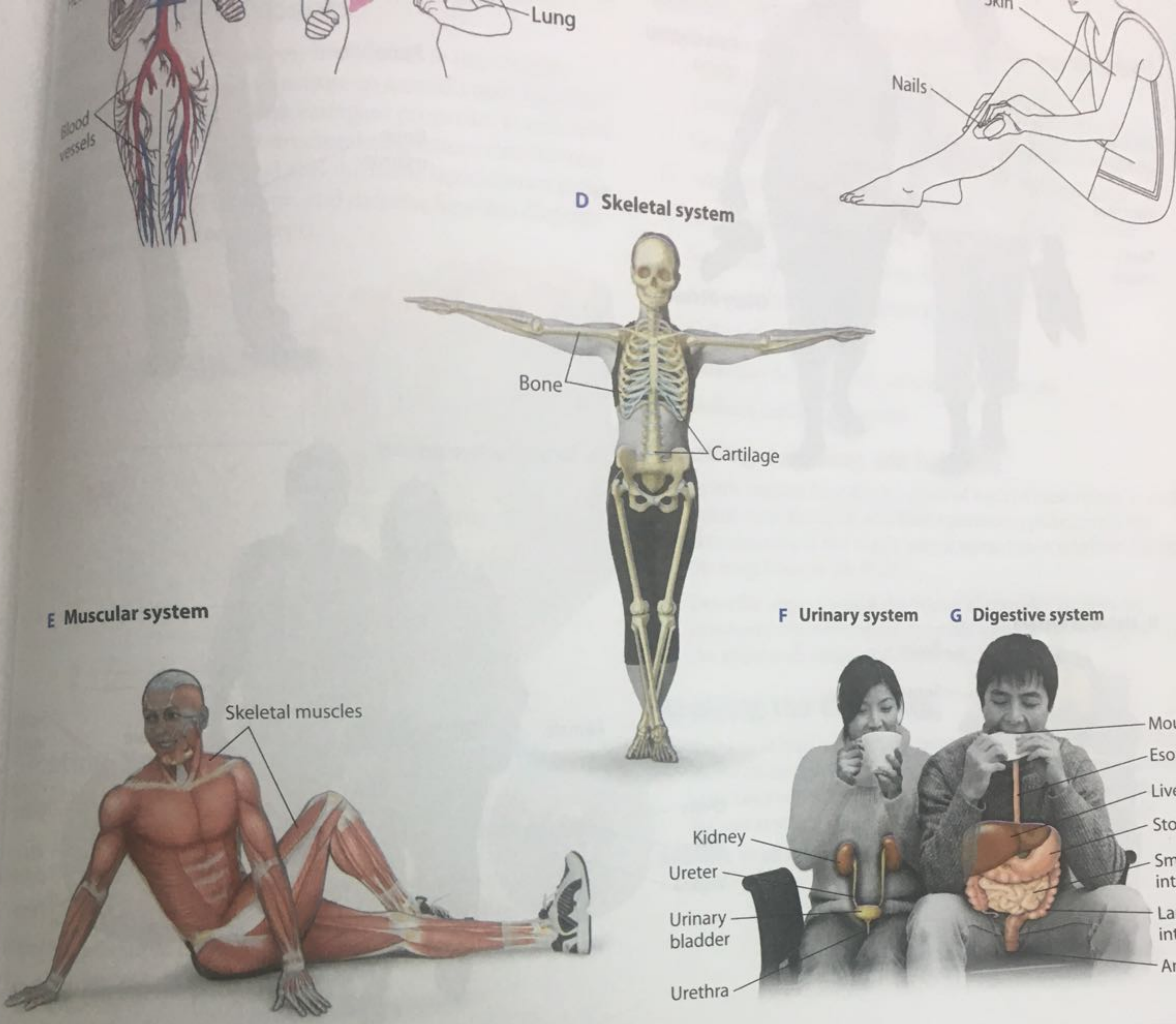
E The **muscular system** moves your body, maintains posture, and produces heat.

F The **urinary system** removes waste products from your blood and excretes urine. It also regulates the chemical makeup, pH, and water balance of your blood.

G The **digestive system** ingests and digests your food, absorbs nutrients, and eliminates undigested material.

H The **endocrine system** secretes hormones that regulate the activities of your body, thus maintaining an internal steady state called homeostasis.

I The **lymphatic system** returns excess body fluid to the circulatory system and functions as part of the immune system.



▲ **Figure 7.8** Human organ systems and their component parts

J The **immune system** defends your body against infections and cancer.

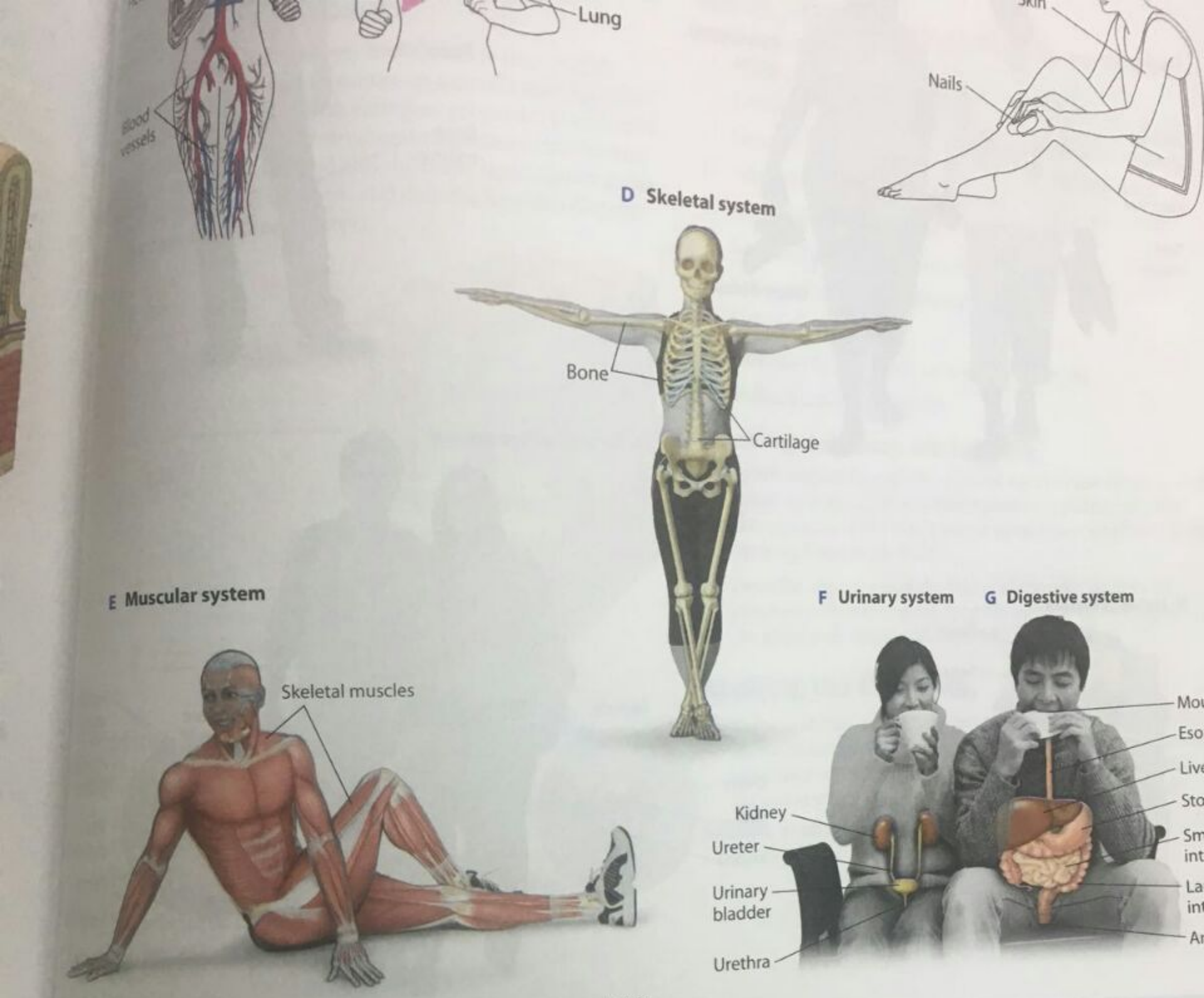
K The **nervous system** coordinates your body's activities by detecting stimuli, integrating information, and directing the body's responses.

L The **reproductive system** produces gametes and sex hormones. The female system supports a developing embryo and produces milk.

The ability to perform life's functions emerges from the ganization and coordination of all the body's organ system Indeed, the whole is greater than the sum of its parts.

? **Which two organ systems are most directly involved in regulating all other systems?**

nervous system and the endocrine system.



▲ **Figure 7.8** Human organ systems and their component parts

J The **immune system** defends your body against infections and cancer.

K The **nervous system** coordinates your body's activities by detecting stimuli, integrating information, and directing the body's responses.

L The **reproductive system** produces gametes and sex hormones. The female system supports a developing embryo and produces milk.

The ability to perform life's functions emerges from the ganization and coordination of all the body's organ system Indeed, the whole is greater than the sum of its parts.

? **Which two organ systems are most directly involved in regulating all other systems?**

nervous system and the endocrine system.

7.4 Connective tissue binds and supports other tissues

In contrast to epithelium, **connective tissue** consists of a sparse population of cells scattered throughout an extracellular material called a matrix. The cells produce and secrete the matrix, which usually consists of a web of fibers embedded in a liquid, jelly, or solid. Connective tissues may be grouped into six major types. **Figure 7.4** shows micrographs of each type and illustrates where each would be found in your arm, for example.

The most widespread connective tissue in your body is called **loose connective tissue** **(Part A)** because its matrix is a loose weave of fibers. Many of the fibers consist of the strong, ropelike protein collagen. Other fibers are more elastic, making the tissue resilient as well as strong. Loose connective tissue serves mainly to bind epithelia to underlying tissues and hold organs in place. In the figure, we show the loose connective tissue that lies directly under the skin.

Fibrous connective tissue **(Part B)** has densely packed parallel bundles of collagen fibers, an arrangement that maximizes its strength. This tissue forms tendons, which attach your muscles to bone, and ligaments, which connect your bones at joints.

Adipose tissue **(Part C)** stores fat in large, closely packed adipose cells held in a matrix of fibers. This tissue pads and insulates your body and stores energy. Each adipose cell contains a large fat droplet that swells when fat is stored and shrinks when fat is used as fuel.

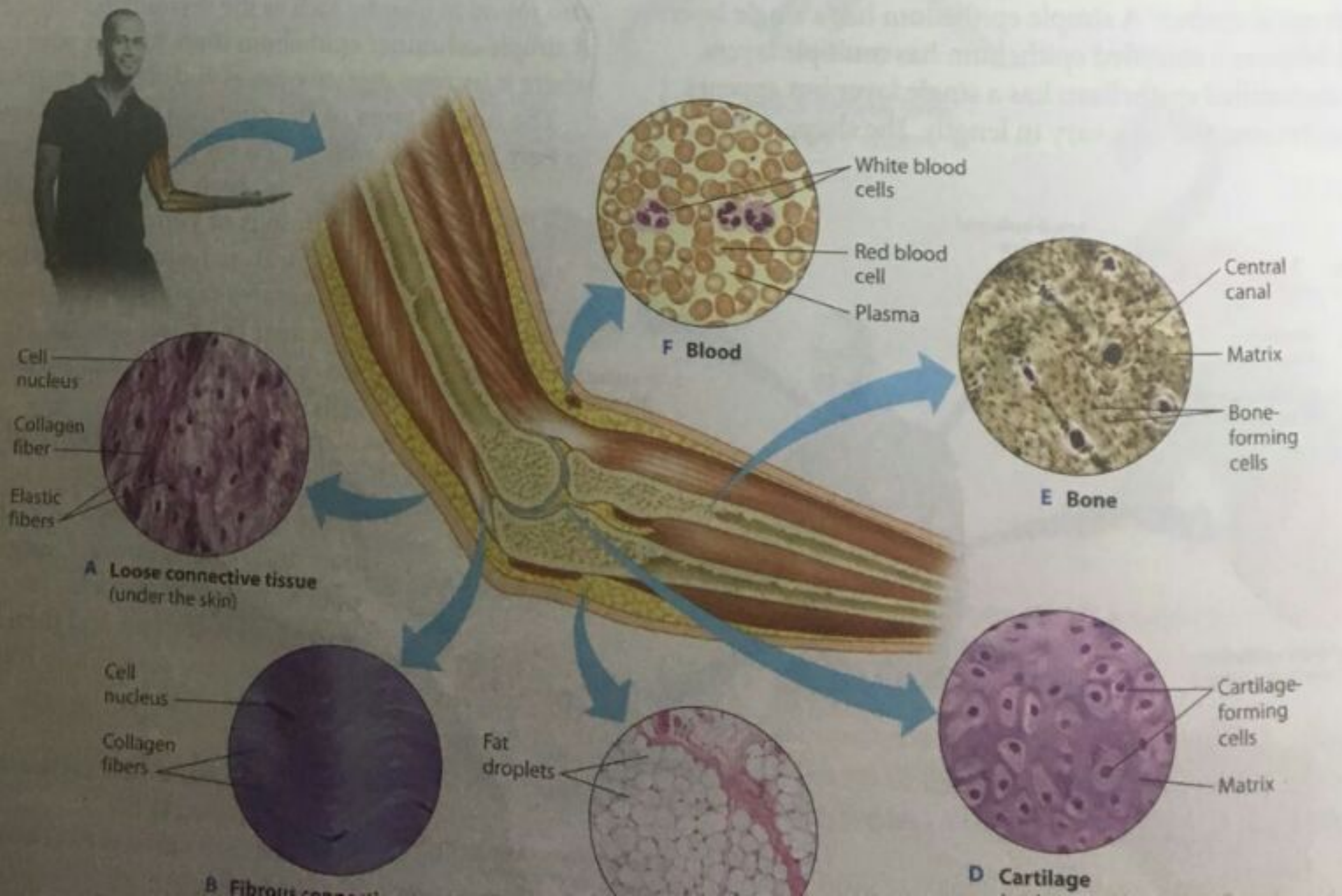
The matrix of **cartilage** **(Part D)**, a connective tissue that forms a strong but flexible skeletal material, consists of collagen fibers embedded in a rubbery material. Cartilage commonly surrounds the ends of bones, providing a shock-absorbing surface. It also supports your ears and nose and forms the cushioning disks between your vertebrae.

Bone **(Part E)** has a matrix of collagen fibers embedded in a hard mineral substance made of calcium, magnesium, and phosphate. The combination of fibers and minerals makes bone strong without being brittle. The microscopic structure of compact regions of bones contains repeating circular layers of matrix, each with a central canal containing blood vessels and nerves. Like other tissues, bone contains living cells and can therefore grow as you grow and mend when broken.

Blood **(Part F)** transports substances throughout your body and thus functions differently from other connective tissues. Its extensive extracellular matrix is a liquid called plasma, which consists of water, salts, and dissolved proteins. Suspended in the plasma are red blood cells, which carry oxygen; white blood cells, which function in defense against disease; and platelets, which aid in blood clotting.

? **Why does blood qualify as a type of connective tissue?**

Because it consists of a relatively sparse population of cells surrounded by a noncellular matrix, which in this case is a fluid called plasma.



7.2 Tissues are groups of cells with a common structure and function

In almost all animals, the cells of the body are organized into tissues. The term *tissue* is from a Latin word meaning "weave," and some tissues resemble woven cloth in that they consist of a meshwork of nonliving fibers and other extracellular substances surrounding living cells. Other tissues are held together by a sticky glue that coats the cells or by special junctions between adjacent plasma membranes. The structure of tissues relates to their specific functions.

The specialization of complex body parts such as organs and organ systems is largely based on varied combinations of a limited set of cells and tissue types. For example, your lungs and blood vessels have very distinct functions, but they are lined by tissues that are of the same basic type.

Your body is built from four main types of tissues: epithelial, connective, muscle, and nervous. We examine the structure and function of these tissue types in the next four modules.

? **How is a tissue different from a cell and an organ?**

Tissues are collections of similar cells that perform a common function. Several different tissue types usually produce the structure of an organ.

7.3 Epithelial tissue covers the body and lines its organs and cavities

Epithelial tissues, or epithelia (singular, *epithelium*), are sheets of closely packed cells that cover your body surface and line your internal organs and cavities. The tightly knit cells form a protective barrier and, in some cases, a surface for exchange with the fluid or air on the other side. One side of an epithelium is attached to a basal lamina, a dense mat of extracellular matrix consisting of fibrous proteins and sticky polysaccharides that separates the epithelium from the underlying tissues. The other side, called the apical surface, faces the outside of an organ or the inside of a tube or passageway.

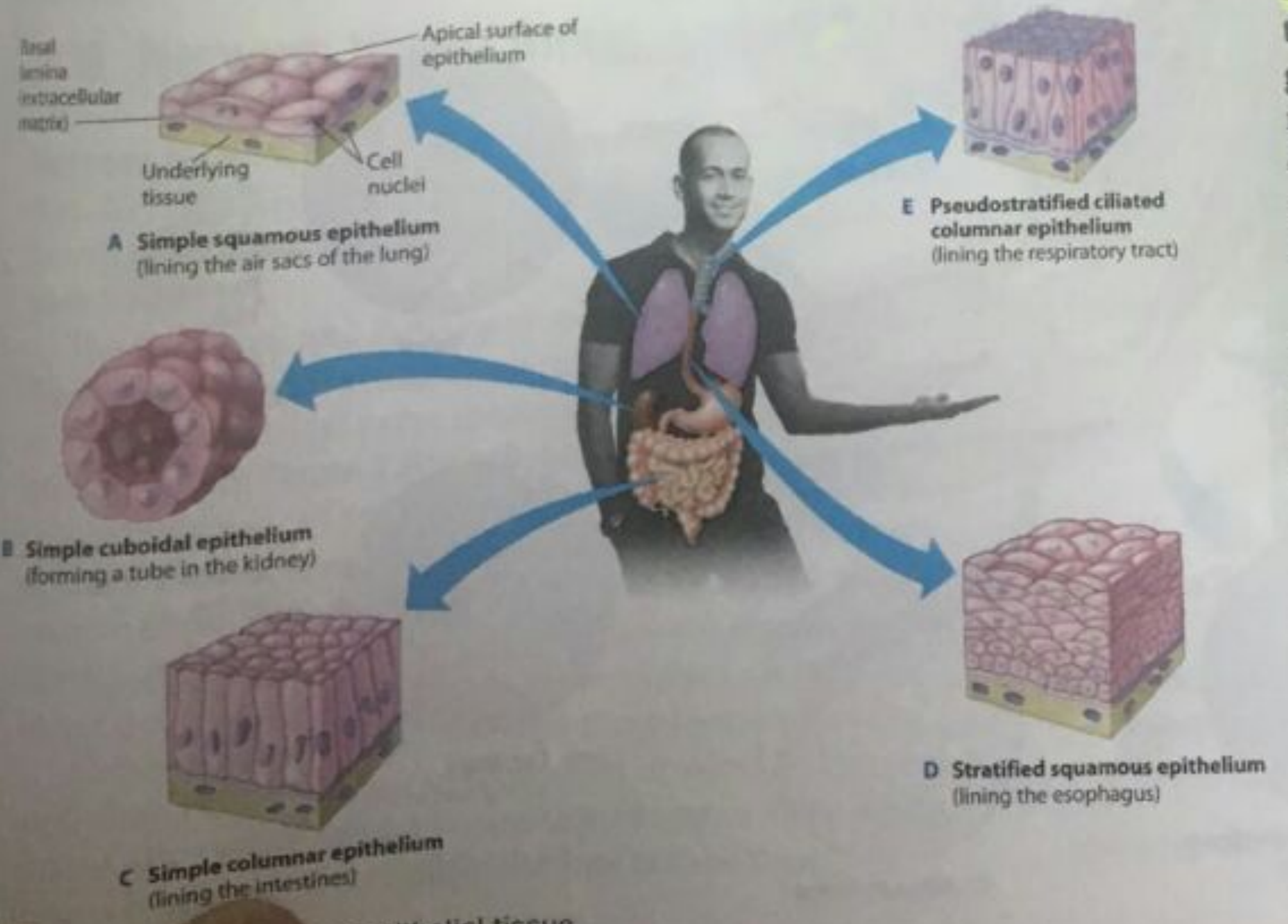
Epithelial tissues are named according to the number of cell layers they have and according to the shape of the cells on their apical surface. A simple epithelium has a single layer of cells, whereas a stratified epithelium has multiple layers. A pseudostratified epithelium has a single layer but appears stratified because the cells vary in length. The shape of the cells may be squamous (flat like floor tiles), cuboidal (like dice), or columnar (like bricks on end). **Figure 7.3** shows examples of different types of epithelia. In each case, the pink color identifies the cells of the epithelium itself.

The structure of each type of epithelium fits its function. Simple squamous epithelium **(Part A)** is thin and leaky and thus suitable for exchanging materials by diffusion. You would find it lining your capillaries and the air sacs of your lungs. ①

Both cuboidal and columnar epithelia have cells with a relatively large amount of cytoplasm, facilitating their role of secretion or absorption of materials. **Part B** shows a cuboidal epithelium forming a tube in the kidney. Such epithelia are also found in glands, such as the thyroid and salivary glands. ② A simple columnar epithelium **(Part C)** lines your intestines, where it secretes digestive juices and absorbs nutrients. ③

The many layers of the stratified squamous epithelium in **Part D** make it well suited for lining surfaces subject to abrasion, such as your outer skin and the linings of your mouth and esophagus. Stratified squamous epithelium regenerates rapidly by division of the cells near the basal lamina. New cells move toward the apical surface as older cells slough off. ④

The pseudostratified ciliated columnar epithelium in **Part E** forms a mucous membrane that lines portions of your respiratory tract and helps keep your lungs clean. Dust, pollen, and other particles are trapped in the mucus it secretes and then swept up and out of your respiratory tract by the beating of the cilia on its cells. ⑤



ure of epithelial tissue

? **Epithelial tissues are named according to the _______ of cells on their apical surface and the number of cell _______.**

shape . . . layers

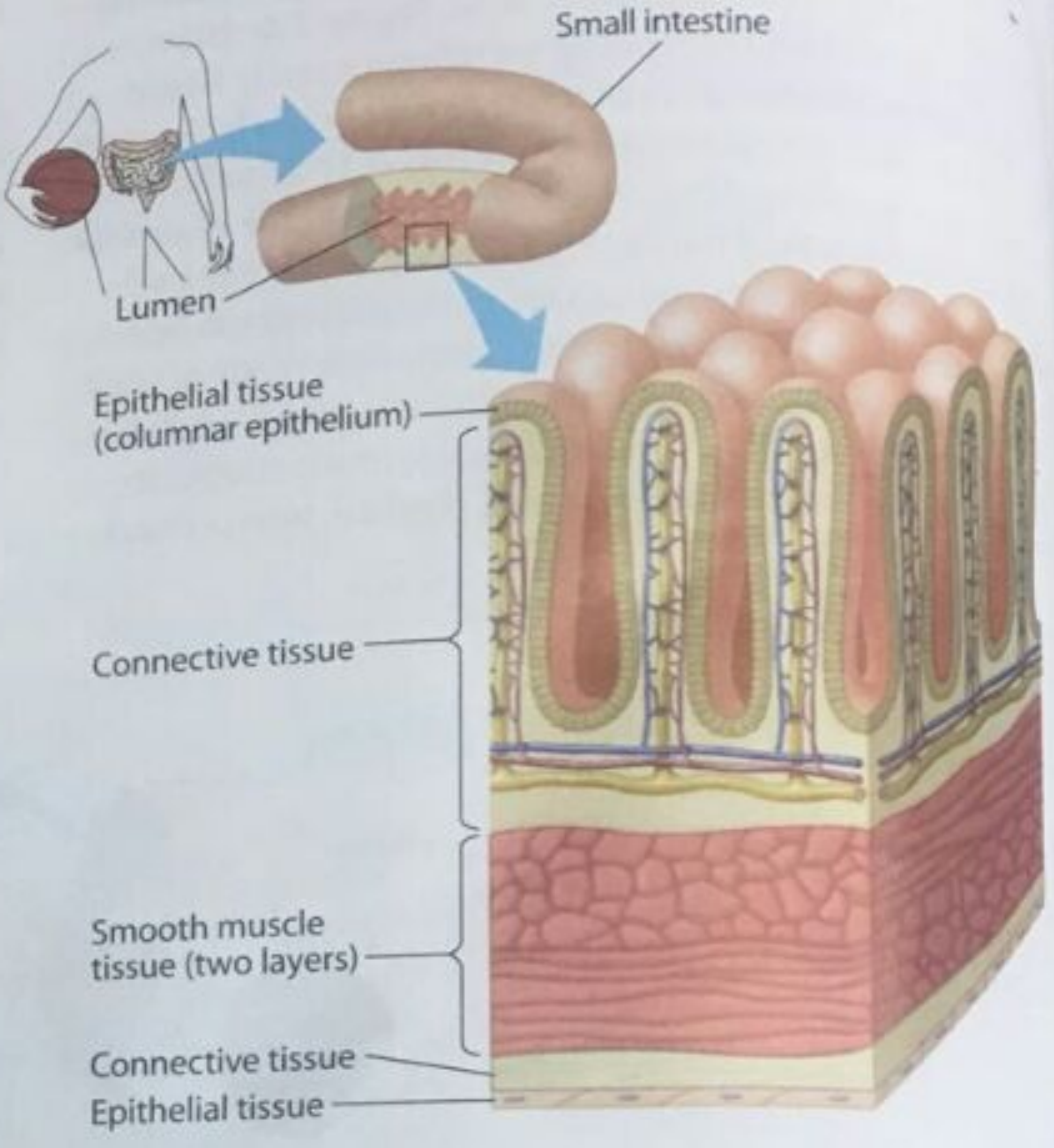
Organs and Organ Systems

7.7 Organs are made up of tissues

In all but the simplest animals, tissues are arranged into organs that perform specific functions. The heart, for example, while mostly muscle, also has epithelial, connective, and nervous tissues. Epithelial tissue lining the heart chambers prevents leakage and provides a smooth surface over which blood can flow. Connective tissue makes the heart elastic and strengthens its walls. Neurons regulate the contractions of cardiac muscle.

In some organs, tissues are organized in layers, as you can see in the diagram of the small intestine in **Figure 7.7**. The lumen, or interior space, of the small intestine is lined by a columnar epithelium that secretes digestive juices and absorbs nutrients. Notice the finger-like projections that increase the surface area of this lining. Underneath the epithelium (and extending into the projections) is connective tissue, which contains blood vessels. The two layers of smooth muscle, oriented in different directions, propel food through the intestine. The smooth muscle, in turn, is surrounded by another layer of connective tissue and epithelial tissue.

An organ represents a higher level of structure than the tissues composing it, and it performs functions that none of its component tissues can carry out alone. These functions emerge from the coordinated interactions of tissues.



▲ **Figure 7.7** Tissue layers of the wall of the small intestine

? **Explain why a disease that damages connective tissue can impair most of the body's organs.**

● Connective tissue is a component of most organs.

7.8 Organ systems work together to perform life's functions

Just as it takes several different tissues to build an organ, it takes the integration of several organs into organ systems to perform the body's functions. **Figure 7.8** illustrates the organ systems found in humans and other mammals. As you read through the brief descriptions of these systems and study their components in the figure, remember that all of the organ systems are interdependent and work together to create a functional organism.

A The **circulatory system** delivers O_2 and nutrients to your body cells and transports CO_2 to the lungs and metabolic wastes to the kidneys.

B The **respiratory system** exchanges gases with the environment, supplying your blood with O_2 and disposing of CO_2.

C The **integumentary system** protects your body against physical injury, infection, excessive heat or cold, and drying out.

D The **skeletal system** supports your body, protects organs such as your brain and lungs, and provides the framework for muscles to produce movement.

E The **muscular system** moves your body, maintains posture, and produces heat.

F The **urinary system** removes waste products from your blood and excretes urine. It also regulates the chemical makeup, pH, and water balance of your blood.

G The **digestive system** ingests and digests your food, absorbs nutrients, and eliminates undigested material.

H The **endocrine system** secretes hormones that regulate the activities of your body, thus maintaining an internal steady state called homeostasis.

I The **lymphatic system** returns excess body fluid to the circulatory system and functions as part of the immune system.

7.1 Structure fits function at all levels of organization in the animal body

When discussing structure and function, biologists distinguish anatomy from physiology. **Anatomy** is the study of the form of an organism's structures; **physiology** is the study of the functions of those structures. A biologist interested in anatomy, for instance, might focus on the arrangement of muscles and bones in a gecko's legs. A physiologist might study how a gecko's muscles function. Despite their different approaches, both scientists are working toward a better understanding of the connection between structure and function, such as how the structural adaptations of the hairs on its toes give the gecko its remarkable ability to walk on walls.

Structure in the living world is organized in hierarchical levels. We followed the progression from molecules to cells in Unit I. Now, let's trace the hierarchy in animals from cells to organisms. As we discussed in Module 1.2, emergent properties—novel properties that were not present at the preceding level of the hierarchy of life—arise as a result of the structural and functional organization of each level's component parts.

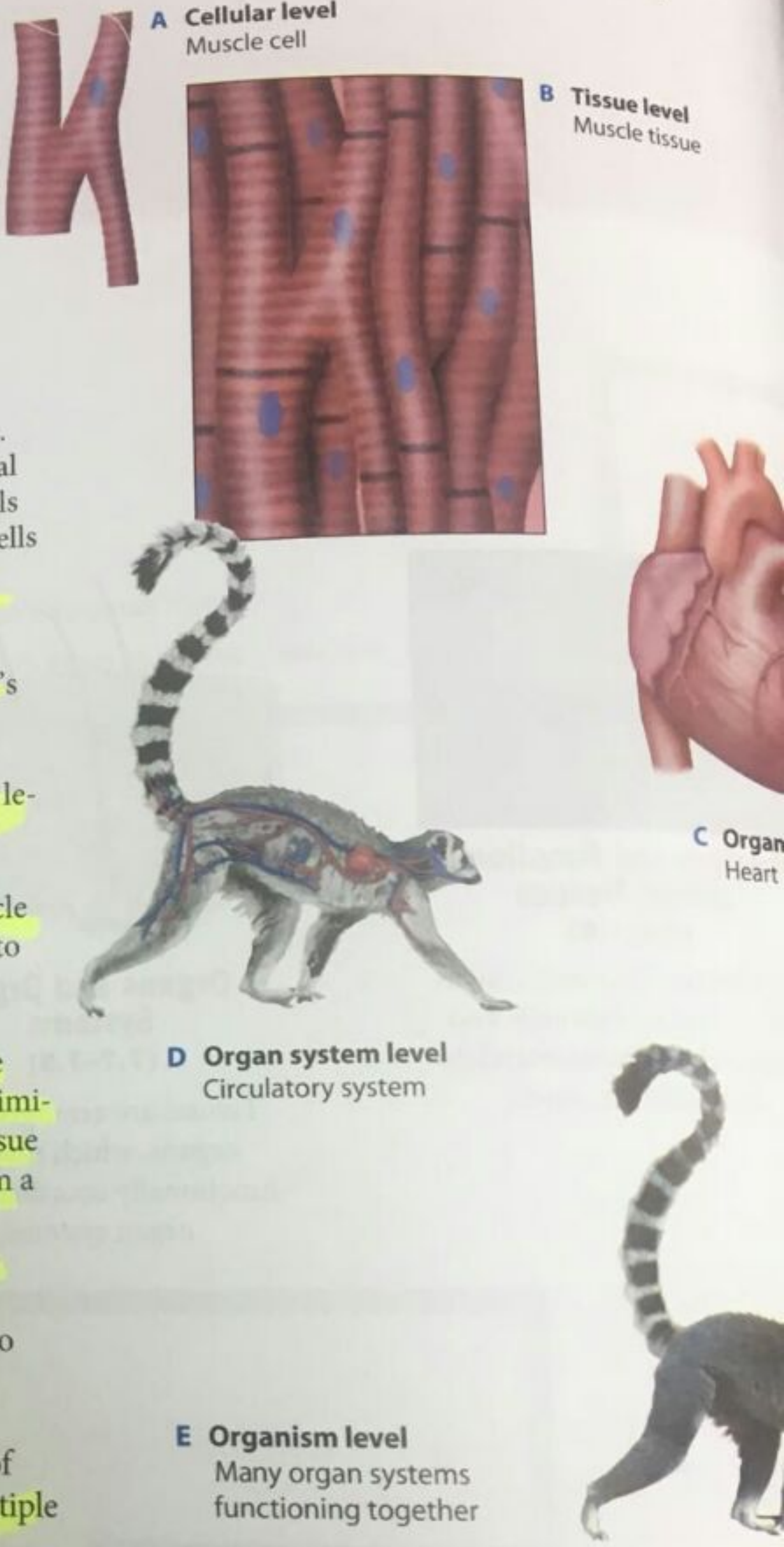
Figure 7.1 illustrates structural hierarchy in a ring-tailed lemur. **Part A** shows a single muscle cell in the lemur's heart. This cell's main function is to contract, and the stripes in the cell indicate the precise alignment of strands of proteins that perform that function. Each muscle cell is also branched, providing for multiple connections to other cells that ensure coordinated contractions of all the muscle cells in the heart.

Together, these heart cells make up a tissue **(Part B)**, the second structural level. A **tissue** is an integrated group of similar cells that perform a common function. The cells of a tissue are specialized, and their structure enables them to perform a specific task—in this instance, coordinated contraction.

Part C, the heart itself, illustrates the organ level of the hierarchy. An **organ** is made up of two or more types of tissues that together perform a specific task. In addition to muscle tissue, the heart includes nervous, epithelial, and connective tissue.

Part D shows the circulatory system, the organ system of which the heart is a part. An **organ system** consists of multiple organs that together perform a vital body function. Other parts of the circulatory system include the blood and the blood vessels: arteries, veins, and capillaries.

In **Part E,** the lemur itself forms the final level of this hierarchy. An organism contains a number of organ systems, each specialized for certain tasks and all functioning together as an integrated, coordinated unit. For example, the lemur's circulatory system cannot function without oxygen supplied by the respiratory system and nutrients supplied by the digestive system. And it takes the coordination of several other organ systems to enable this animal to walk or climb trees.



▲ **Figure 7.1** A structural hierarchy in a ring-tailed le

The ability to climb trees or walls emerges from the specific arrangement of specialized structures. As we see throughout our study of the anatomy and physiology of anim function at each level of the structural hierarchy. I modules to come, we focus on the tissue level of t hierarchy.

? **Explain how the ability to pump blood is an emer of a heart, which is at the organ level of the biolog**

In summary, the light reactions absorb solar energy and convert it to chemical energy stored in both ATP and NADPH. Notice that these reactions produce no sugar; sugar is not made until the Calvin cycle, which is the second stage of photosynthesis.

The **Calvin cycle** occurs in the stroma of the chloroplast (see Figure 4.12). It is a cyclic series of reactions that assembles sugar molecules using CO_2 and the energy-rich products of the light reactions. The incorporation of carbon from CO_2 into organic compounds, shown in the figure as CO_2 entering the Calvin cycle, is called **carbon fixation**. After carbon fixation, enzymes of the cycle make sugars by further reducing the carbon compounds.

As the figure suggests, it is NADPH produced by the light reactions that provides the electrons for reducing carbon in the Calvin cycle. And ATP from the light reactions provides chemical energy that powers several of the steps of the Calvin cycle. The Calvin cycle is sometimes referred to as the d reactions, or light-independent reactions, because none the steps requires light directly. However, in most plants, Calvin cycle occurs during daylight, when the light reac power the cycle's sugar assembly line by supplying it wit NADPH and ATP.

The word *photosynthesis* encapsulates the two stages *Photo*, from the Greek word for "light," refers to the ligh reactions; *synthesis*, meaning "putting together," refers to sugar construction by the Calvin cycle. In the next seve modules, we look at these two stages in more detail. But let's consider some of the properties of light, the energy source that powers photosynthesis.

? For chloroplasts to produce sugar from carbon dioxide in dark, they would need to be supplied with ______ and

NADPH

Photosynthesis Reviewed and Extended

4.13 Review: Photosynthesis uses light energy, carbon dioxide, and water to make organic molecules

Life on Earth is solar powered. As we have discussed, most of the living world depends on the food-making machinery of photosynthesis. **Figure 4.13** summarizes this vital process. The production of sugar from CO_2 is an emergent property that arises from the structure of a chloroplast—a structural arrangement that integrates the two stages of photosynthesis.

Starting on the left in the diagram, you see a summary of the light reactions, which occur in the thylakoid membranes. Two photosystems in the membranes capture solar energy, energizing electrons in chlorophyll molecules. Simultaneously, water is split, and O_2 is released. The photoexcited electrons are transferred through an electron transport chain, where energy is harvested to make ATP, and finally to $NADP^+$, reducing it to the high-energy compound NADPH.

The chloroplast's sugar factory is the Calvin cycle, the second stage of photosynthesis. In the stroma, the enzyme rubisco combines CO_2 with RuBP. ATP and NADPH are used to reduce 3-PGA to G3P. Sugar molecules made from G3P serve as a plant's own food supply.

About 50% of the carbohydrate made by photosynthesis is consumed as fuel for cellular respiration in the mitochondria of plant cells. Sugars also serve as starting material for making other organic molecules, such as a plant's proteins and lipids. Many glucose molecules are linked together to make cellulose, the main component of cell walls. Cellulose is the most abundant organic molecule in a plant—and probably on the surface of the planet. Most plants make much more food each day than they need. They store the excess in roots, tubers, seeds, and fruits.

Plants (and other photosynthesizers) not only feed themselves but also are the ultimate source of food for virtually all other organisms. Humans and other animals make none of own food and are totally dependent on the organic matter by photosynthesizers. Even the energy we acquire when we meat was originally captured by photosynthesis. The energ hamburger, for instance, came from sunlight that was origi converted to a chemical form in the grasses eaten by cattle.

The collective productivity of the tiny chloroplasts is amazing: Photosynthesis makes an estimated 160 billion ric tons of carbohydrate per year (about 176 billion tons). That's equivalent in mass to a stack of about 100 trillion copies of this textbook. No other chemical process on E can match the output of photosynthesis.

This review of photosynthesis is an appropriate place to reflect on the metabolic ground we have covered in this ch and the previous one. Virtually all organisms, plants inclu use cellular respiration to obtain the energy they need fro molecules such as glucose. Following the chemical pathw glycolysis and the citric acid cycle, which oxidize glucose release energy from it, we have now come full circle, seei plants trap sunlight energy and use it to reduce carbon d to make glucose.

In tracing glucose synthesis and its breakdown, we ha seen that cells use several of the same mechanisms—ele transport, redox reactions, and chemiosmosis—in energ age (photosynthesis) and energy harvest (cellular respir

? Explain this statement: No process is more importan photosynthesis to the welfare of life on Earth.

thesis is the ultimate source of the food for almost all organisms
gen they need for cellular respiration.

In summary, the light reactions absorb solar energy and convert it to chemical energy stored in both ATP and NADPH. Notice that these reactions produce no sugar; sugar is not made until the Calvin cycle, which is the second stage of photosynthesis.

The **Calvin cycle** occurs in the stroma of the chloroplast (see Figure 4.12). It is a cyclic series of reactions that assembles sugar molecules using CO_2 and the energy-rich products of the light reactions. The incorporation of carbon from CO_2 into organic compounds, shown in the figure as CO_2 entering the Calvin cycle, is called **carbon fixation**. After carbon fixation, enzymes of the cycle make sugars by further reducing the carbon compounds.

As the figure suggests, it is NADPH produced by the light reactions that provides the electrons for reducing carbon in the Calvin cycle. And ATP from the light reactions provides chemical energy that powers several of the steps of the Calvin cycle. The Calvin cycle is sometimes referred to as the da reactions, or light-independent reactions, because none the steps requires light directly. However, in most plants, Calvin cycle occurs during daylight, when the light reac power the cycle's sugar assembly line by supplying it wit NADPH and ATP.

The word *photosynthesis* encapsulates the two stage *Photo*, from the Greek word for "light," refers to the ligh reactions; *synthesis*, meaning "putting together," refers to sugar construction by the Calvin cycle. In the next seve modules, we look at these two stages in more detail. But let's consider some of the properties of light, the energy source that powers photosynthesis.

? For chloroplasts to produce sugar from carbon dioxide in dark, they would need to be supplied with _____ and _____

HdDVN ··· d

Photosynthesis Reviewed and Extended

4.13 Review: Photosynthesis uses light energy, carbon dioxide, and water to make organic molecules

Life on Earth is solar powered. As we have discussed, most of the living world depends on the food-making machinery of photosynthesis. **Figure 4.13** summarizes this vital process. The production of sugar from CO_2 is an emergent property that arises from the structure of a chloroplast—a structural arrangement that integrates the two stages of photosynthesis.

Starting on the left in the diagram, you see a summary of the light reactions, which occur in the thylakoid membranes. Two photosystems in the membranes capture solar energy, energizing electrons in chlorophyll molecules. Simultaneously, water is split, and O_2 is released. The photoexcited electrons are transferred through an electron transport chain, where energy is harvested to make ATP, and finally to $NADP^+$, reducing it to the high-energy compound NADPH.

The chloroplast's sugar factory is the Calvin cycle, the second stage of photosynthesis. In the stroma, the enzyme rubisco combines CO_2 with RuBP. ATP and NADPH are used to reduce 3-PGA to G3P. Sugar molecules made from G3P serve as a plant's own food supply.

About 50% of the carbohydrate made by photosynthesis is consumed as fuel for cellular respiration in the mitochondria of plant cells. Sugars also serve as starting material for making other organic molecules, such as a plant's proteins and lipids. Many glucose molecules are linked together to make cellulose, the main component of cell walls. Cellulose is the most abundant organic molecule in a plant—and probably on the surface of the planet. Most plants make much more food each day than they need. They store the excess in roots, tubers, seeds, and fruits.

Plants (and other photosynthesizers) not only feed themselves but also are the ultimate source of food for virtually all other organisms. Humans and other animals make none of own food and are totally dependent on the organic matter by photosynthesizers. Even the energy we acquire when we meat was originally captured by photosynthesis. The energ hamburger, for instance, came from sunlight that was origi converted to a chemical form in the grasses eaten by cattle.

The collective productivity of the tiny chloroplasts is amazing: Photosynthesis makes an estimated 160 billion ric tons of carbohydrate per year (about 176 billion tons). That's equivalent in mass to a stack of about 100 trillion copies of this textbook. No other chemical process on E can match the output of photosynthesis.

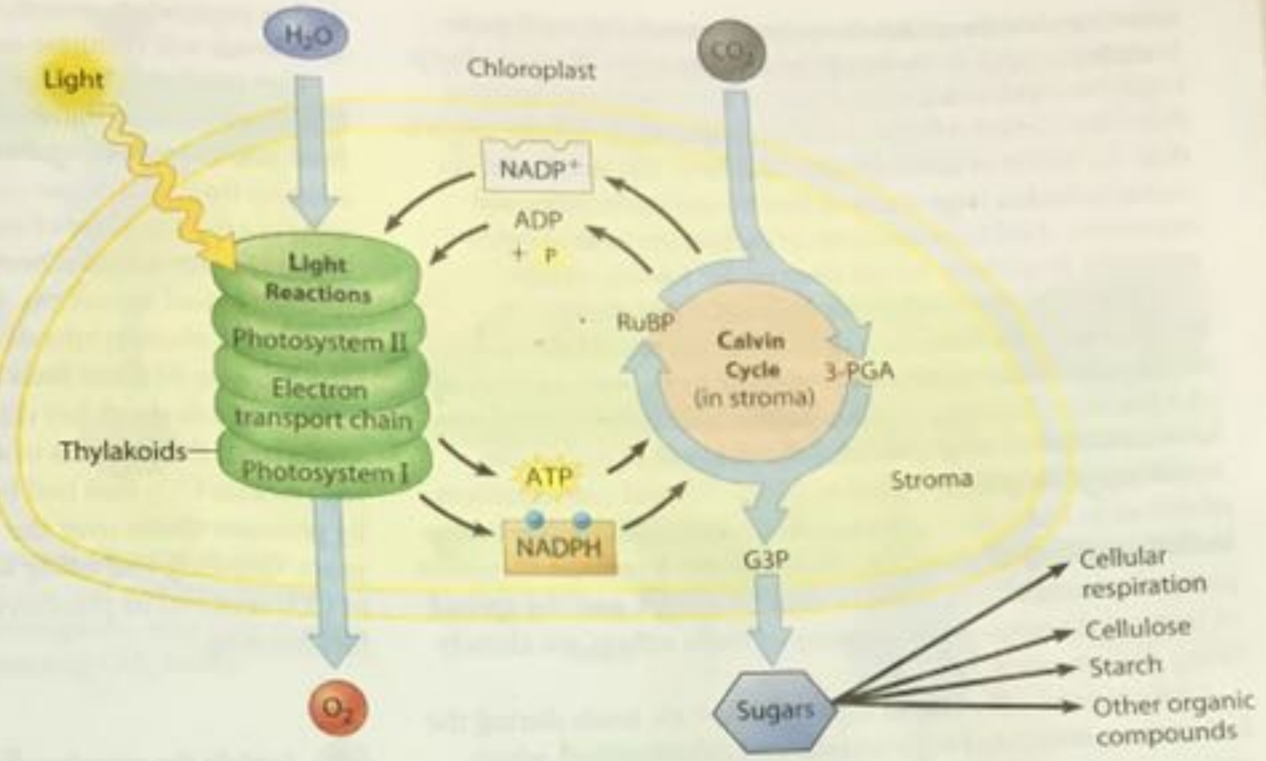
This review of photosynthesis is an appropriate place to reflect on the metabolic ground we have covered in this ch and the previous one. Virtually all organisms, plants inclu use cellular respiration to obtain the energy they need fro molecules such as glucose. Following the chemical pathw glycolysis and the citric acid cycle, which oxidize glucose release energy from it, we have now come full circle, seei plants trap sunlight energy and use it to reduce carbon d to make glucose.

In tracing glucose synthesis and its breakdown, we ha seen that cells use several of the same mechanisms—ele transport, redox reactions, and chemiosmosis—in energ age (photosynthesis) and energy harvest (cellular respir

? Explain this statement: No process is more importan photosynthesis to the welfare of life on Earth.

thesis is the ultimate source of the food for almost all organisms
gen they need for cellular respiration.

▶ **Figure 4.13** A summary of photosynthesis



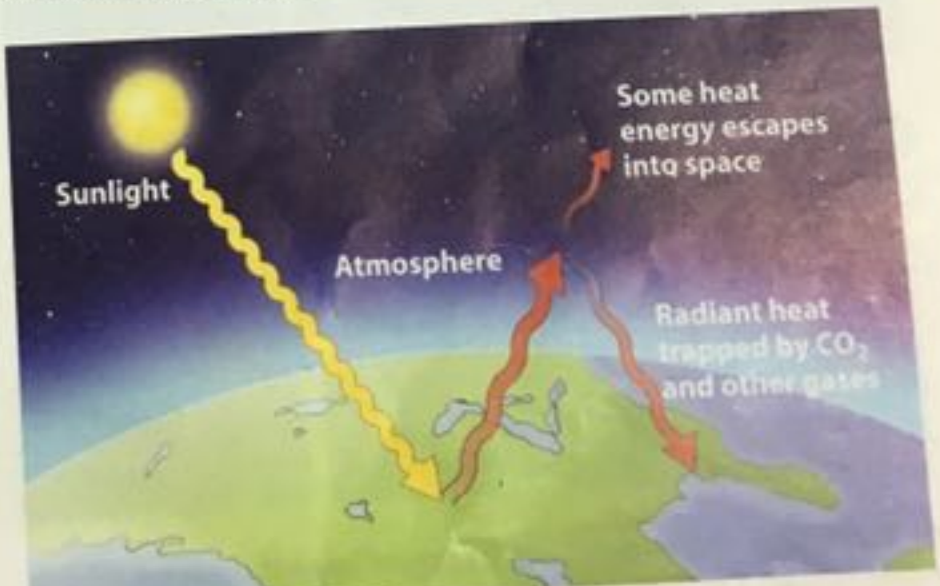
CONNECTION

4.14 Photosynthesis may moderate global climate change

The greenhouse in **Figure 4.14A** is used to grow plants when the weather outside is too cold. The glass or plastic walls of a greenhouse allow solar radiation to pass through. The sunlight heats the soil, which in turn warms the air. The walls trap the warm air, raising the temperature inside.

An analogous process, called the **greenhouse effect**, operates on a global scale (**Figure 4.14B**). Solar radiation reaching Earth's atmosphere includes ultraviolet radiation and visible light. The ozone layer filters out most of the damaging UV radiation. Visible light passes through and is absorbed by the planet's surface, warming it. Heat radiating from the warmed planet is absorbed by gases in the atmosphere, which then reflect some of the heat back to Earth. This natural heating effect is highly beneficial. Without it, Earth would be much colder, and most life as we know it could not exist.

▲ **Figure 4.14A** Plants growing in a greenhouse

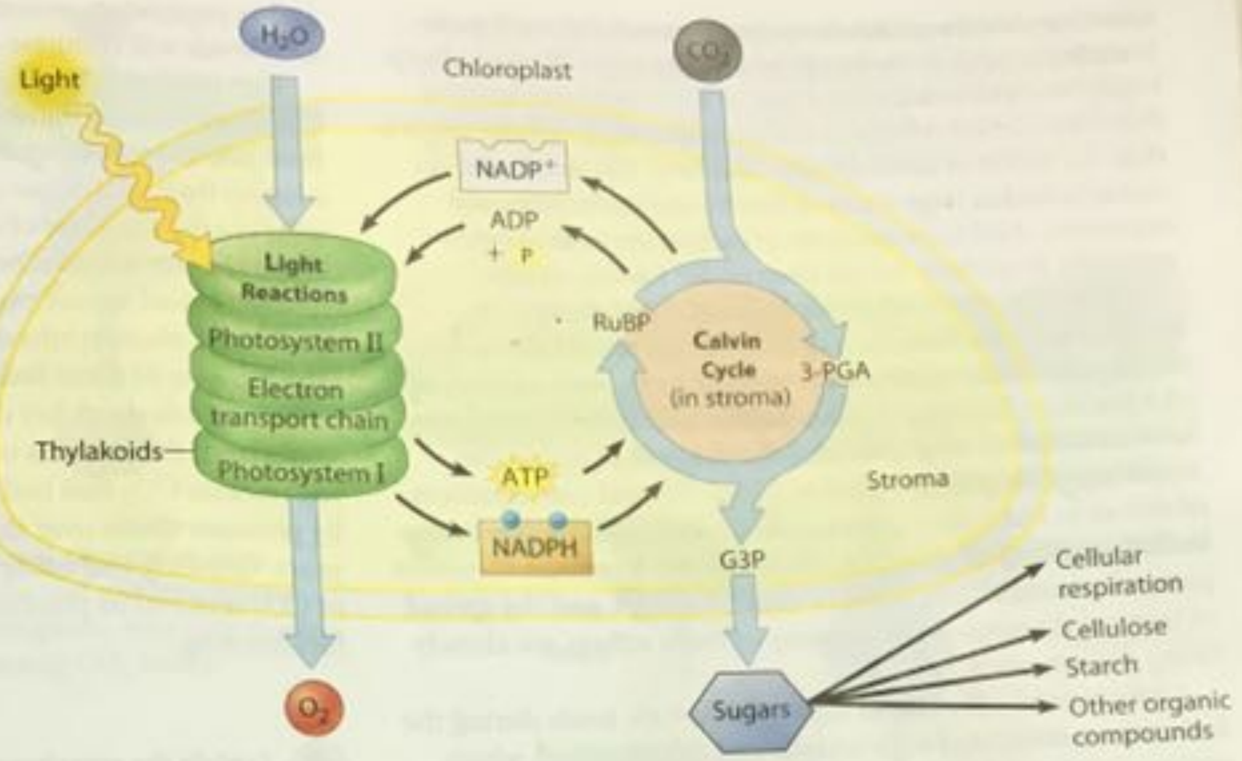


▲ **Figure 4.14B** CO_2 in the atmosphere and the greenhouse effect

The gases in the atmosphere that absorb heat radiation are called greenhouse gases. Some occur naturally, such as water vapor, carbon dioxide, and methane, while others are synthetic, such as chlorofluorocarbons. Human activities add to the levels of these greenhouse gases.

Carbon dioxide is one of the most important greenhouse gases. You have just learned that CO_2 is a raw material for photosynthesis and a waste product of cellular respiration. These two processes, taking place in microscopic chloroplasts and

▸ **Figure 4.13** A summary of photosynthesis



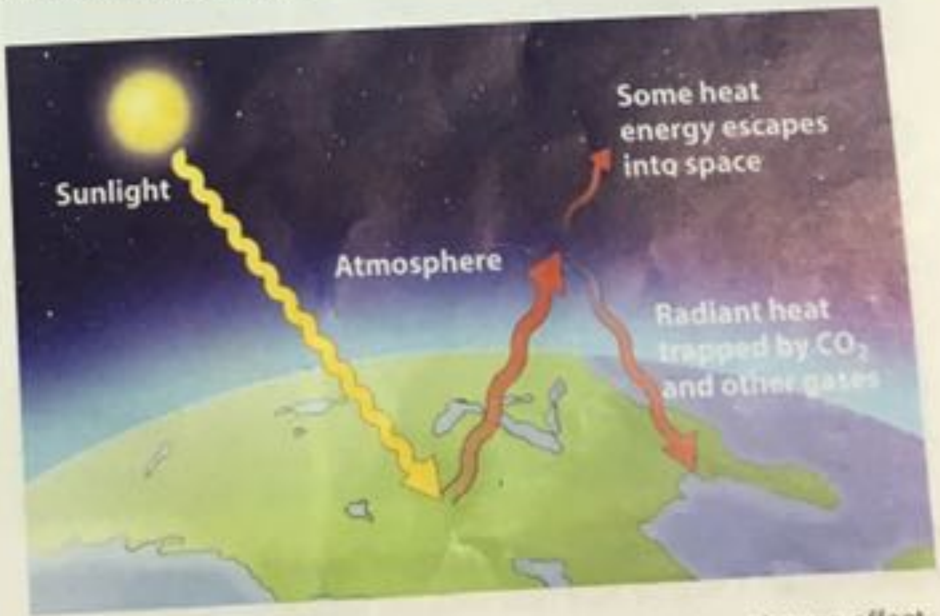
CONNECTION

4.14 Photosynthesis may moderate global climate change

▲ **Figure 4.14A** Plants growing in a greenhouse

The greenhouse in **Figure 4.14A** is used to grow plants when the weather outside is too cold. The glass or plastic walls of a greenhouse allow solar radiation to pass through. The sunlight heats the soil, which in turn warms the air. The walls trap the warm air, raising the temperature inside.

An analogous process, called the **greenhouse effect**, operates on a global scale (**Figure 4.14B**). Solar radiation reaching Earth's atmosphere includes ultraviolet radiation and visible light. The ozone layer filters out most of the damaging UV radiation. Visible light passes through and is absorbed by the planet's surface, warming it. Heat radiating from the warmed planet is absorbed by gases in the atmosphere, which then reflect some of the heat back to Earth. This natural heating effect is highly beneficial. Without it, Earth would be much colder, and most life as we know it could not exist.



▲ **Figure 4.14B** CO_2 in the atmosphere and the greenhouse effect

The gases in the atmosphere that absorb heat radiation are called greenhouse gases. Some occur naturally, such as water vapor, carbon dioxide, and methane, while others are synthetic, such as chlorofluorocarbons. Human activities add to the levels of these greenhouse gases.

Carbon dioxide is one of the most important greenhouse gases. You have just learned that CO_2 is a raw material for photosynthesis and a waste product of cellular respiration. These two processes, taking place in microscopic chloroplasts and

7.5 Muscle tissue functions in movement

Muscle tissue is the most abundant tissue in most animals. It consists of long cells called muscle fibers, each containing many molecules of contractile proteins. **Figure 7.5** shows micrographs of the three types of vertebrate muscle tissue.

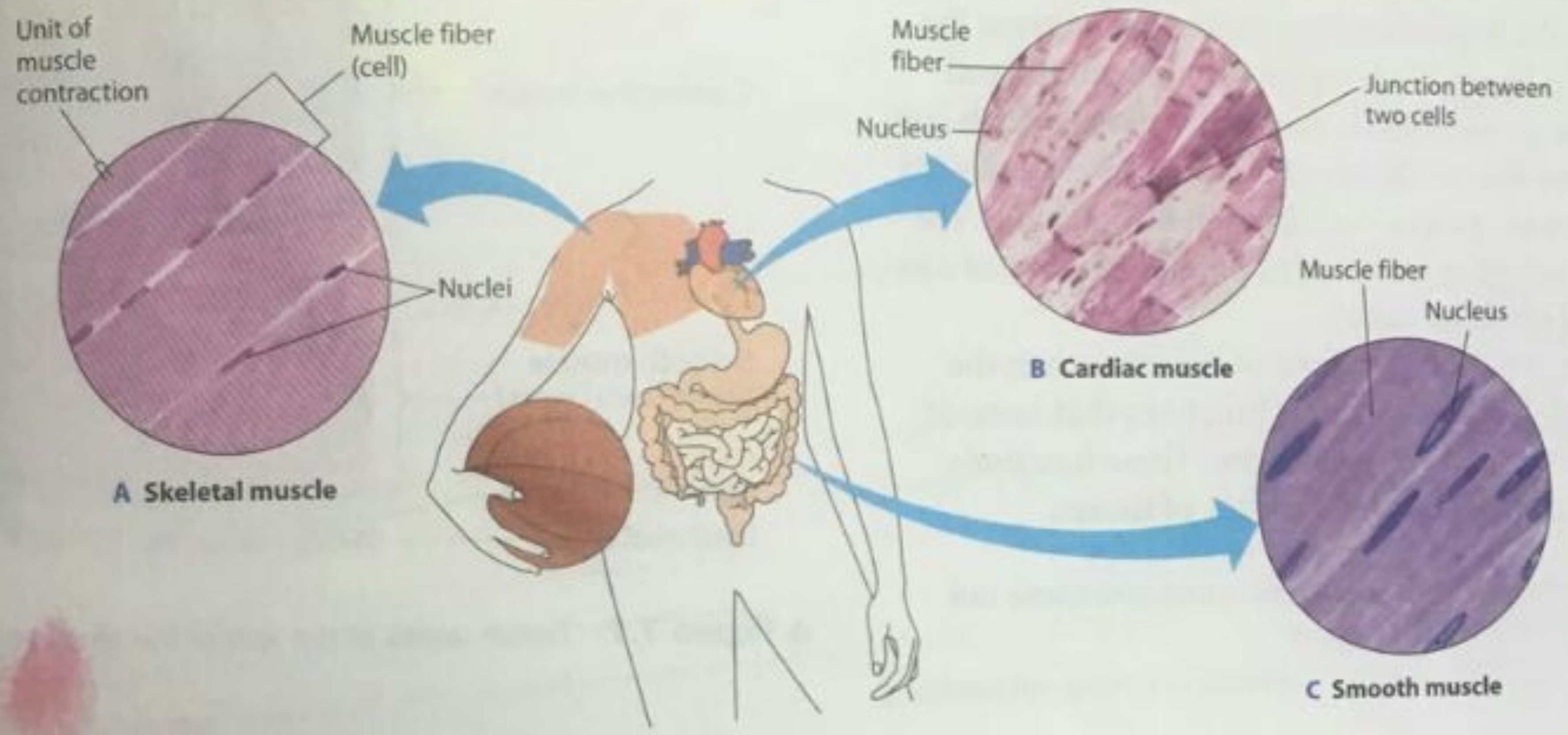
Skeletal muscle (Part A) is attached to your bones by tendons and is responsible for voluntary movements of your body, such as walking or bouncing a ball. The arrangement of the contractile units along the length of muscle fibers gives the cells a striped, or striated, appearance, as you can see in the micrograph below.

Cardiac muscle (Part B) forms the contractile tissue of your heart. It is striated like skeletal muscle, but it is under involuntary control, meaning that you cannot consciously control its contraction. Cardiac muscle fibers are branched, interconnecting at specialized junctions that rapidly relay the signal to contract from cell to cell during your heartbeat.

Smooth muscle (Part C) gets its name from its lack of striations. Smooth muscle is found in the walls of your digestive tract, arteries, and other internal organs. It is responsible for involuntary body activities, such as the movement of food through your intestines. Smooth muscle cells are spindle-shaped and contract more slowly than skeletal muscles, but can sustain contractions for a longer period of time.

? **The muscles responsible for a gecko climbing a wall are ________________ muscles.**

● skeletal



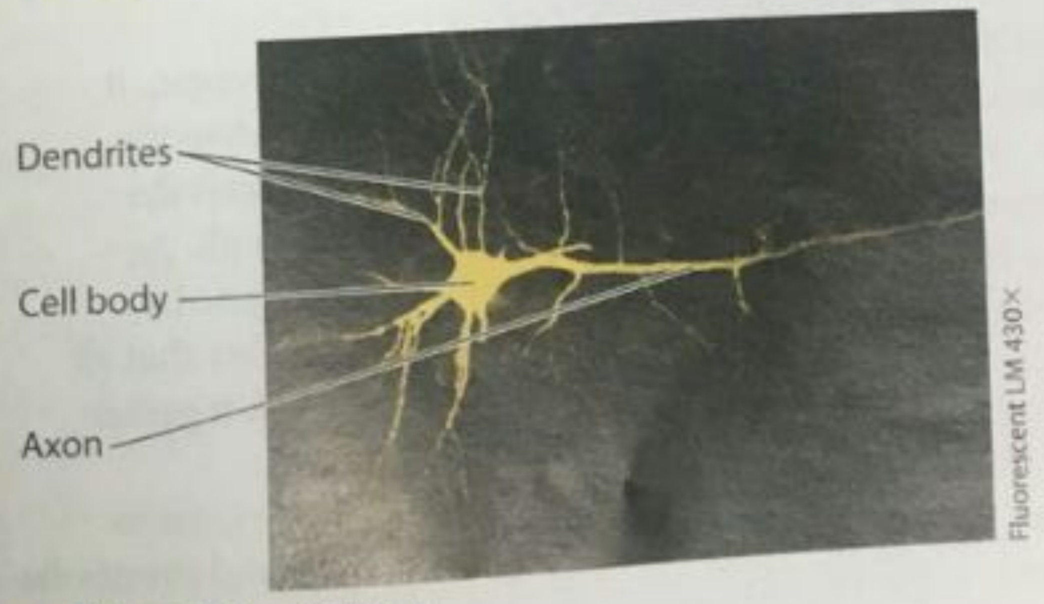
▲ **Figure 7.5** The three types of muscle tissue

7.6 Nervous tissue forms a communication network

Nervous tissue senses stimuli and rapidly transmits information. Nervous tissue is found in your brain and spinal cord, as well as in the nerves that transmit signals throughout your body.

The structural and functional unit of nervous tissue is the nerve cell, or **neuron**, which is uniquely specialized to conduct electrical nerve impulses. As you can see in the micrograph in **Figure 7.6**, a neuron consists of a cell body (containing the cell's nucleus and other organelles) and a number of slender extensions. Dendrites and the cell body receive nerve impulses from other neurons. Axons, which are often bundled together into nerves, transmit signals toward other neurons or to an effector, such as a muscle cell.

Nervous tissue actually contains many more supporting cells than neurons. Some of these cells surround and insulate axons, promoting faster transmission of signals. Others help nourish neurons and regulate the fluid around them.



▲ **Figure 7.6** A neuron

? **How does the long length of some axons (such as those that extend from your lower spine to your toes) relate to the function of a neuron?**

● It allows for the transmission of a nerve signal over a long distance directly to specific muscle cells.

mitochondria, keep carbon cycling between CO_2 and more complex organic compounds on a global scale. Photosynthetic organisms absorb billions of tons of CO_2 each year. Most of that fixed carbon returns to the atmosphere via cellular respiration, the action of decomposers, and fires. But much of it remains locked in large tracts of forests and undecomposed organisms. And large amounts of carbon are in long-term storage in fossil fuels buried deep under Earth's surface.

Since 1850, the start of the Industrial Revolution, the atmospheric concentration of CO_2 has increased about 40%, mostly due to the combustion of fossil fuels, such as coal, oil, and gasoline. Increasing concentrations of greenhouse gases have been linked to **global climate change**, of which the major aspect is *global warming*. The predicted consequences of this slow but steady increase in average global temperature include melting of polar ice, rising sea levels, extreme weather patterns, droughts, increased extinction rates, and the spread of tropical diseases. Indeed, many of these effects are already being documented.

Unfortunately, the rise in atmospheric CO_2 levels during the last century coincided with widespread deforestation, which aggravated the global warming problem by reducing an effective CO_2 sink. As forests are cleared for lumber or agriculture, and as population growth increases the demand for fossil fu CO_2 levels will continue to rise.

Can photosynthesis offset this increase in atmospheric C Certainly, slowing the destruction of our forests will sustain their photosynthetic and carbon-storing contributions. Tak a lesson from plants, we can explore technologies that utiliz solar energy for some of our energy needs. And as you read in the chapter introduction, biofuels hold out the promise of renewable fuel source. As the plants or algae used for biofue grow, their photosynthesis removes CO_2 from the atmosphe The burning of these fuels releases CO_2 to the atmosphere, b as fossils fuels do. A key difference, however, is that fossil fu come from the remains of ancient organisms, and their burn ing releases CO_2 that had been removed from the atmosphe by photosynthesis over the course of hundreds of millions of years. Growing and using alternative fuels could keep the cy of CO_2 removal in photosynthesis balanced with CO_2 releas fuel burning.

? **Explain the greenhouse effect.**

ight warms Earth's surface, which radiates heat to the atmosphere. CO_2
er greenhouse gases absorb and radiate some heat back to Earth.

CHAPTER 4 REVIEW

Reviewing the Concepts

embrane Structure and Function (4.1–4.6)

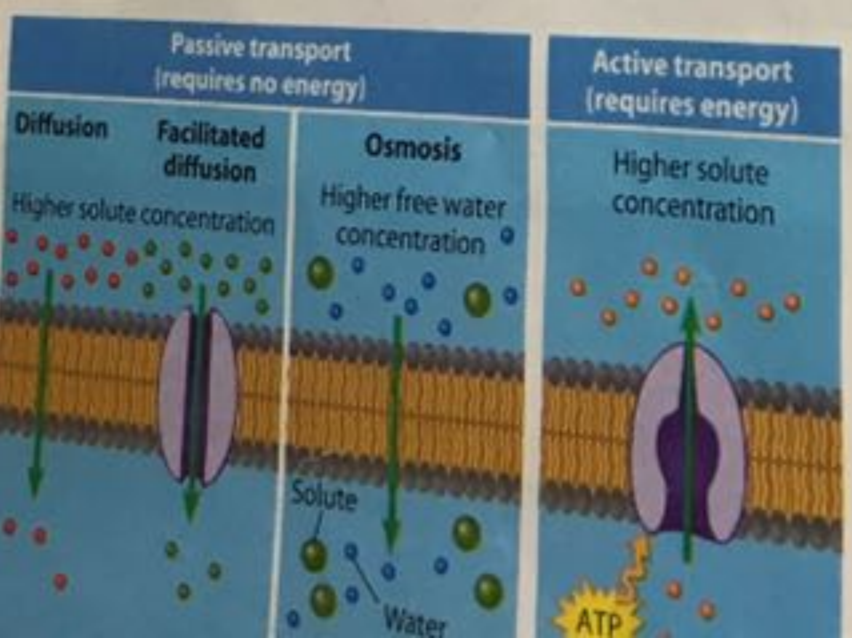
1 Membranes are fluid mosaics of lipids and proteins with many functions. The proteins embedded in a membrane's phospholipid bilayer perform various functions.

4.2 Passive transport is diffusion across a membrane with no energy investment. Solutes diffuse across membranes down their concentration gradients.

4.3 Osmosis is the diffusion of water across a membrane.

4.4 Transport proteins can facilitate diffusion across membranes.

4.5 Cells expend energy in the active transport of a solute.



Energy and the Cell (4.7)

4.7 Cells transform energy as they perform work. Kinetic is the energy of motion. Potential energy is energy stored i cation or structure of matter. Chemical energy is potential available for release in a chemical reaction. According to t of thermodynamics, energy can change form but cannot ated or destroyed, and energy transformations increase d or entropy, with some energy being lost as heat.

How Enzymes Function (4.8)

4.8 Enzymes speed up the cell's chemical reactions by energy barriers. Enzymes are protein catalysts that decr activation energy (E_A) needed to begin a reaction.

An Overview of Photosynthesis (4.9–4.12)

4.9 Autotrophs are the producers of the biosphere. P and some protists and bacteria are photoautotrophs, t of food consumed by virtually all heterotrophic organ

4.10 Photosynthesis occurs in chloroplasts in plant c Chloroplasts are surrounded by a double membrane stacks of thylakoids and a thick fluid called stroma.

4.11 Photosynthesis is a redox process, as is cellula In photosynthesis, H_2O is oxidized mitochondria, keep carbon cycling between CO_2 and more complex organic compounds on a global scale. Photosynthetic organisms absorb billions of tons of CO_2 each year. Most of that fixed carbon returns to the atmosphere via cellular respiration, the action of decomposers, and fires. But much of it remains locked in large tracts of forests and undecomposed organisms. And large amounts of carbon are in long-term storage in fossil fuels buried deep under Earth's surface.

Since 1850, the start of the Industrial Revolution, the atmospheric concentration of CO_2 has increased about 40%, mostly due to the combustion of fossil fuels, such as coal, oil, and gasoline. Increasing concentrations of greenhouse gases have been linked to **global climate change**, of which the major aspect is *global warming*. The predicted consequences of this slow but steady increase in average global temperature include melting of polar ice, rising sea levels, extreme weather patterns, droughts, increased extinction rates, and the spread of tropical diseases. Indeed, many of these effects are already being documented.

Unfortunately, the rise in atmospheric CO_2 levels during the last century coincided with widespread deforestation, which aggravated the global warming problem by reducing an effective CO_2 sink. As forests are cleared for lumber or agriculture, and as population growth increases the demand for fossil fu CO_2 levels will continue to rise.

Can photosynthesis offset this increase in atmospheric C Certainly, slowing the destruction of our forests will sustain their photosynthetic and carbon-storing contributions. Tak a lesson from plants, we can explore technologies that utiliz solar energy for some of our energy needs. And as you read in the chapter introduction, biofuels hold out the promise of renewable fuel source. As the plants or algae used for biofue grow, their photosynthesis removes CO_2 from the atmosphe The burning of these fuels releases CO_2 to the atmosphere, b as fossils fuels do. A key difference, however, is that fossil fu come from the remains of ancient organisms, and their burn ing releases CO_2 that had been removed from the atmosphe by photosynthesis over the course of hundreds of millions of years. Growing and using alternative fuels could keep the cy of CO_2 removal in photosynthesis balanced with CO_2 releas fuel burning.

? **Explain the greenhouse effect.**

light warms Earth's surface, which radiates heat to the atmosphere. CO_2 er greenhouse gases absorb and radiate some heat back to Earth.

CHAPTER 4 REVIEW

Reviewing the Concepts

embrane Structure and Function (4.1–4.6)

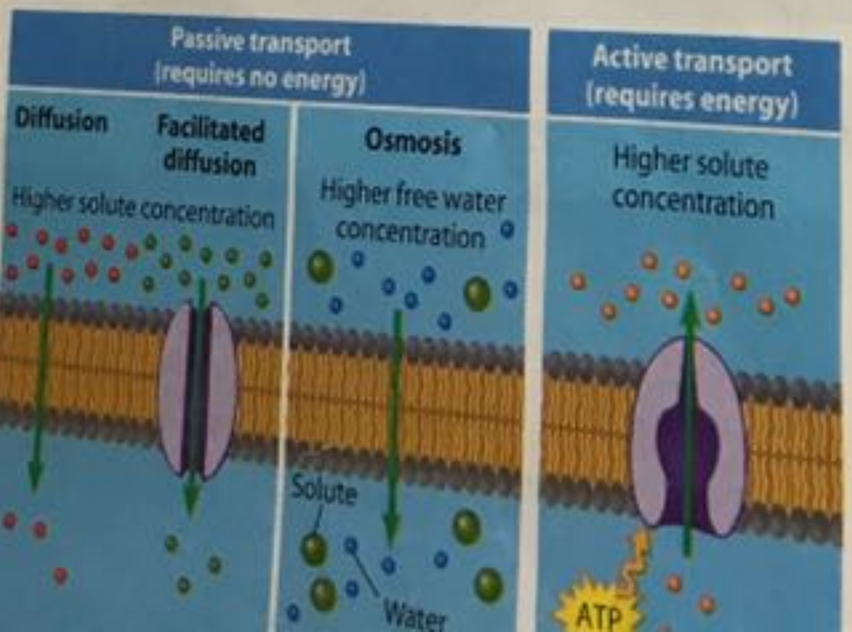
1 **Membranes are fluid mosaics of lipids and proteins with many functions.** The proteins embedded in a membrane's phospholipid bilayer perform various functions.

4.2 **Passive transport is diffusion across a membrane with no energy investment.** Solutes diffuse across membranes down their concentration gradients.

4.3 **Osmosis is the diffusion of water across a membrane.**

4.4 **Transport proteins can facilitate diffusion across membranes.**

4.5 **Cells expend energy in the active transport of a solute.**



Energy and the Cell (4.7)

4.7 **Cells transform energy as they perform work.** Kinetic is the energy of motion. Potential energy is energy stored i cation or structure of matter. Chemical energy is potential available for release in a chemical reaction. According to t of thermodynamics, energy can change form but cannot b ated or destroyed, and energy transformations increase d or entropy, with some energy being lost as heat.

How Enzymes Function (4.8)

4.8 **Enzymes speed up the cell's chemical reactions by energy barriers.** Enzymes are protein catalysts that decr activation energy (E_A) needed to begin a reaction.

An Overview of Photosynthesis (4.9–4.12)

4.9 **Autotrophs are the producers of the biosphere.** P and some protists and bacteria are photoautotrophs, t of food consumed by virtually all heterotrophic organ

4.10 **Photosynthesis occurs in chloroplasts** in plant c Chloroplasts are surrounded by a double membrane stacks of thylakoids and a thick fluid called stroma.

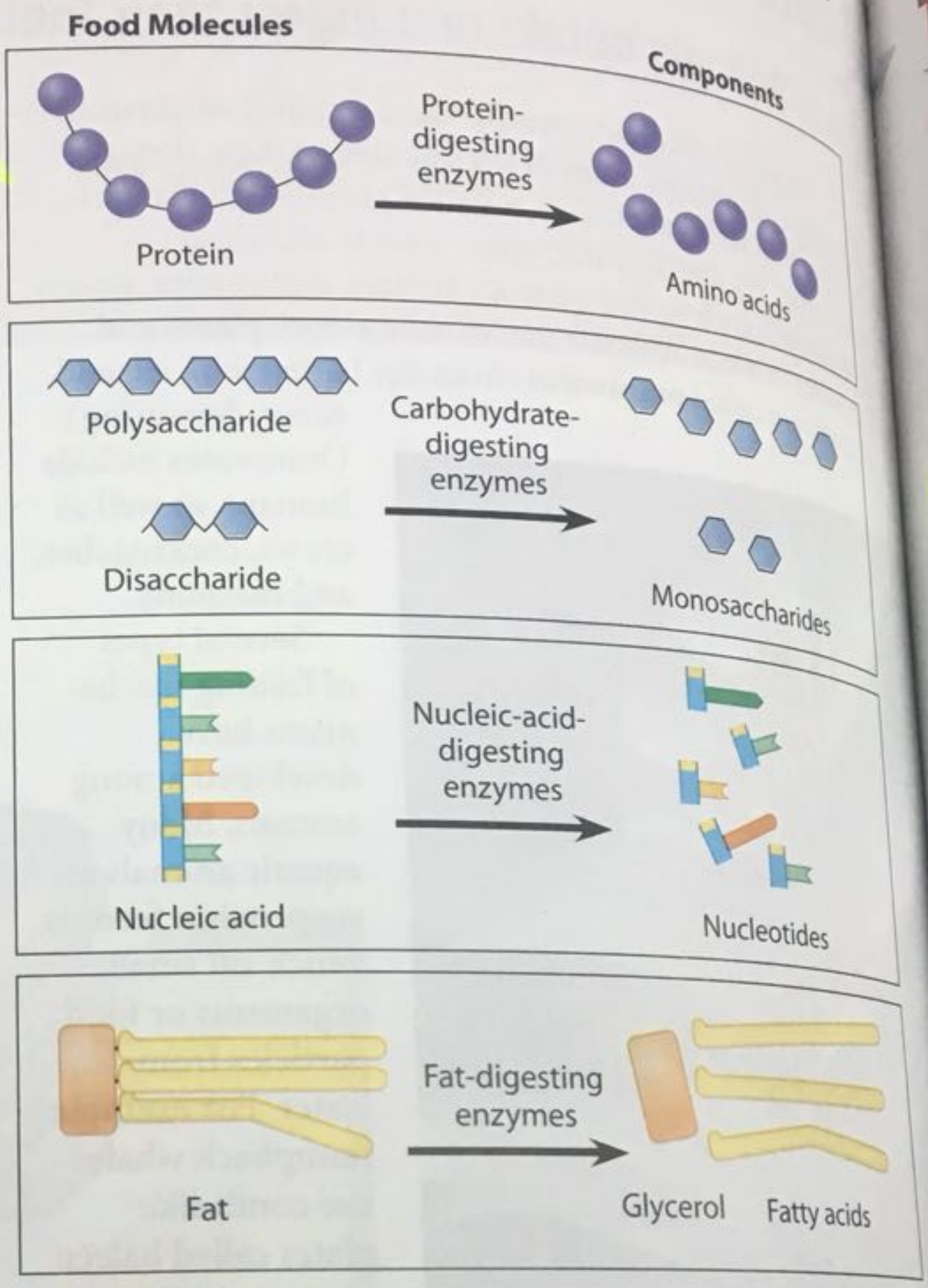
4.11 **Photosynthesis is a redox process, as is cellula** In photosynthesis, H_2O is oxidized and

8.2 Overview: Food processing occurs in four stages

So far we have discussed what animals eat and how they feed. As shown in **Figure 8.2A**, ① **ingestion**, the act of eating, is only the first of four main stages of food processing. The second stage, ② **digestion**, is the breaking down of food into molecules small enough for the body to absorb. Digestion typically occurs in two phases. First, food may be mechanically broken into smaller pieces. In animals with teeth, the process of chewing or tearing breaks large chunks of food into smaller ones. The second phase of digestion is the chemical breakdown process called hydrolysis. Catalyzed by specific enzymes, hydrolysis breaks the chemical bonds in food molecules by adding water to them (see Module 2.3).

Most of the organic matter in food consists of proteins, fats, and carbohydrates—all large molecules. Animals cannot use these materials directly for two reasons. First, these molecules are too large to pass through plasma membranes into the cells. Second, an animal needs small components to make the molecules of its own body. Most food molecules, for instance, the proteins in the cat's food shown in the figure below, are different from those that make up an animal's body.

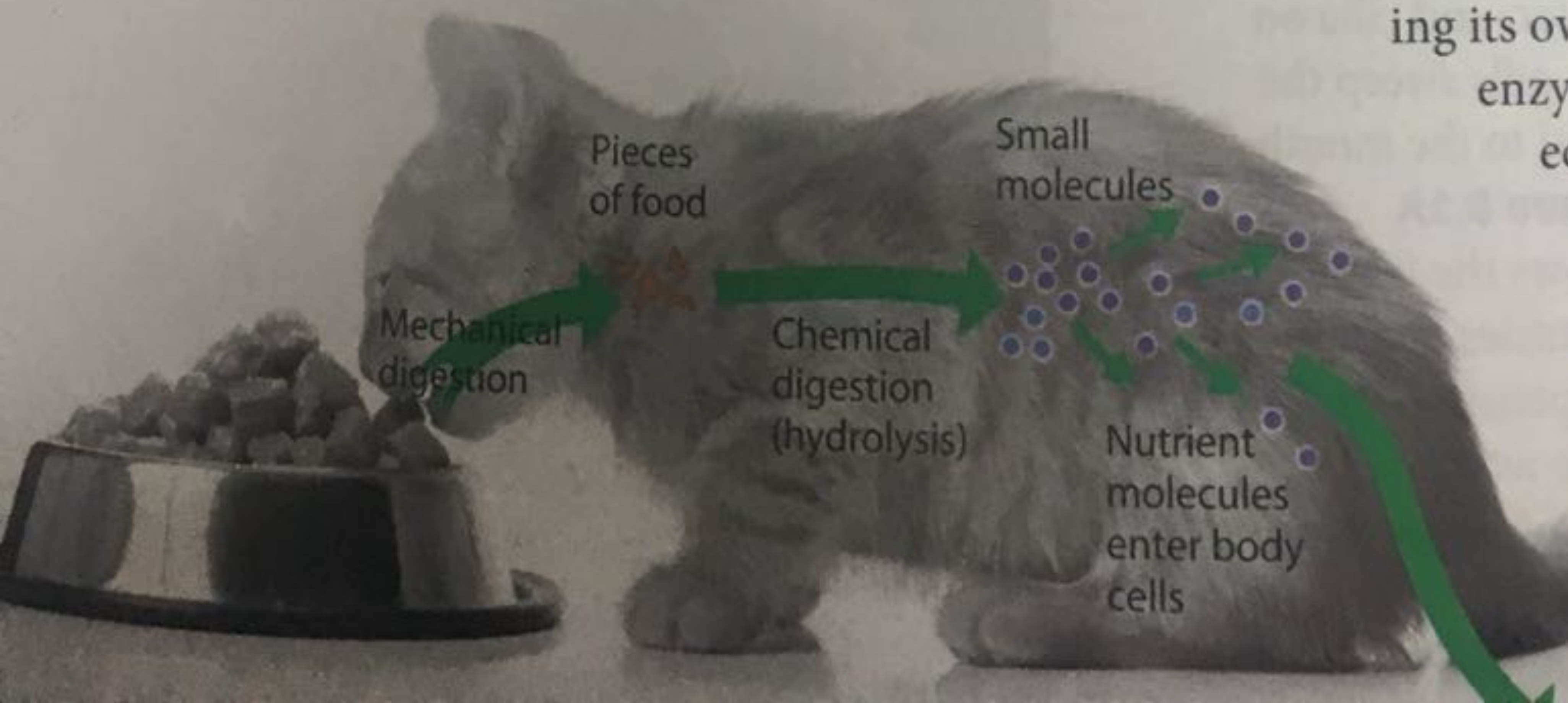
All organisms use the same building blocks to make their macromolecules. For instance, cats, caterpillars, and humans all make their proteins from the same 20 amino acids. Digestion breaks the polymers in food into monomers. As shown in **Figure 8.2B**, proteins are split into amino acids, polysaccharides and disaccharides are broken down into monosaccharides, and nucleic acids are split into nucleotides (and their components). Fats are not polymers, but they are split into their components, glycerol and fatty acids. The animal can then use these small molecules to make the specific large molecules it needs (see Module 5.9).



▲ **Figure 8.2B** Chemical digestion: the breakdown of large organic molecules to their components

In the third stage of food processing, ③ **absorption**, the cells lining the digestive tract take up, or absorb, the products of digestion—small molecules such as amino acids and simple sugars. From the digestive tract, these nutrients travel in the blood to body cells, where they are used to build a cell's large molecules or broken down further to provide energy. In an animal that eats much more than its body immediately uses, many of the nutrient molecules are converted to fat for storage. In the fourth and last stage of food processing, ④ **elimination**, undigested material passes out of the digestive tract.

How can an animal digest food without digesting its own cells and tissues? After all, digestive enzymes hydrolyze the same biological molecules that animals are made of—and it is obviously important to avoid digesting ourselves! The developmental adaptation found in most animal species is the chemical digestion of food within specialized compartments. We discuss digestive compartments in the next module.



The Human Digestive System

8.3 The human digestive system consists of an alimentary canal and accessory glands

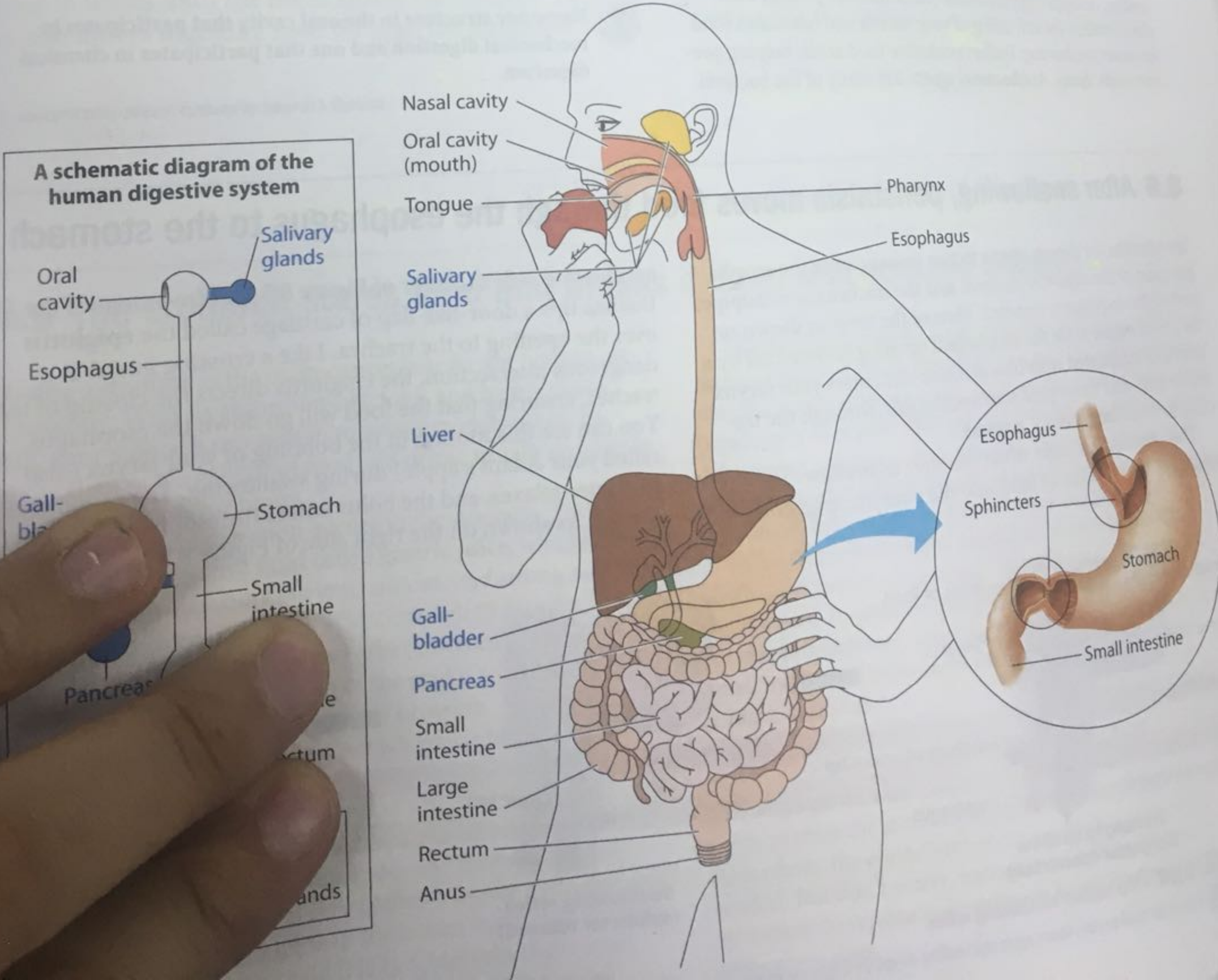
As an introduction to our own digestive system, **Figure 8.3** illustrates the human alimentary canal and its accessory glands. The schematic diagram on the left gives you an overview of the sequence of the organs and the locations of the accessory glands. These glands—the salivary glands, gallbladder, liver, and pancreas—are labeled in blue on the figure. They secrete digestive juices that enter the alimentary canal through ducts.

Food is ingested and chewed in the mouth, or **oral cavity**, and then pushed by the tongue into the pharynx. Once food is swallowed, muscles propel it through the alimentary canal by **peristalsis**, alternating waves of contraction and relaxation of the smooth muscles lining the canal. It is peristalsis that enables you to process and digest food even while lying down. After chewing a bite of food, it only takes 5–10 seconds for it to pass from the pharynx down the esophagus and into your stomach.

As shown in the enlargement, below right, muscular ringlike valves, called **sphincters**, regulate the passage of food into and out of the stomach. The sphincter controlling the passage out of the stomach works like a drawstring to close the stomach off, keeping food there for about 2–6 hours, long enough for stomach acids and enzymes to begin digestion. The final steps of digestion and nutrient absorption occur in the small intestine over a period of 5–6 hours. Undigested material moves slowly through the large intestine (taking 12–24 hours), and feces are stored in the rectum and then expelled through the anus.

? By what process does food move from the pharynx to the stomach of an astronaut in the weightless environment of a space station?

● Peristalsis.

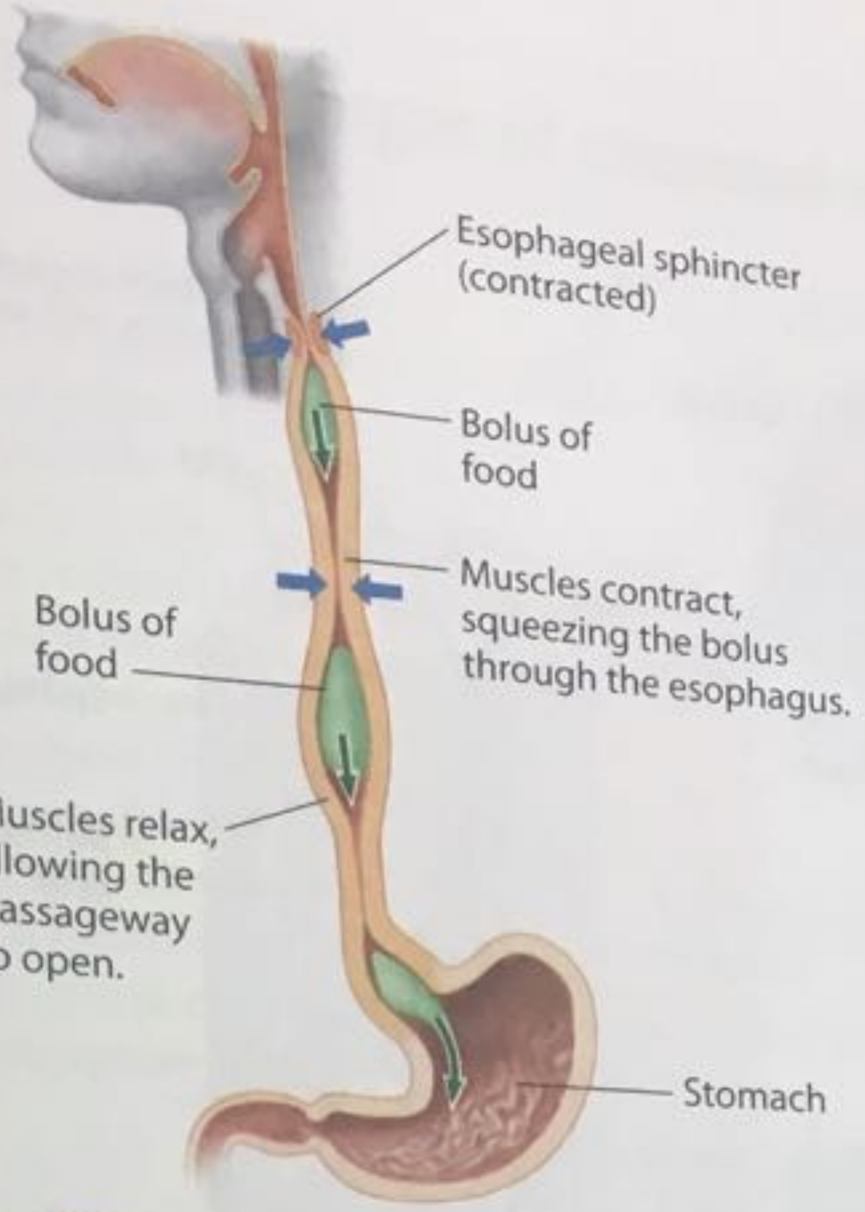


Esophageal sphincter

esophagus fits its function. It has tough yet elastic connective tissues that allow it to stretch …date a bolus, layers

geal sphincter then contracts above the bolus, and the epiglottis tips again, reopening the breathing tube.

The esophagus is a muscular tube that conveys food from the pharynx to the stomach. The muscles at the top of the esophagus are under voluntary control; thus, you begin the act of swallowing voluntarily. But then involuntary contractions of smooth muscles in the rest of the esophagus take over. **Figure 8.5B** shows how muscle contractions—peristalsis—squeeze a bolus toward the stomach; in this figure, one bolus of food is shown at three successive locations as it moves through the esophagus. Muscle contractions continue in waves until the bolus enters the stomach. Peristalsis also moves digesting food through the intestines.



▲ **Figure 8.5B** A food bolus shown at three points as it moves through the esophagus

The structure of the esophagus fits its function. It has tough yet elastic connective tissues that allow it to stretch to accommodate a bolus, layers of circular and longitudinal smooth muscles for peristalsis, and a stratified epithelial lining that replenishes cells abraded off during swallowing. The length of the esophagus varies by species. For example, fishes have no lungs to bypass and have a very short esophagus. And it will come as no surprise that giraffes have a very long esophagus.

? **What is happening in the trachea when food "goes down the wrong pipe"?**

● An incorrectly positioned epiglottis lets food enter the trachea (rather than the esophagus), which triggers a strong cough reflex.

8.6 The stomach stores food and breaks it down with acid and enzymes

Having a stomach is the main reason you do not need to eat constantly. With its accordion-like folds and highly elastic wall, your stomach can stretch to accommodate about 2 L (more than half a gallon) of food and drink, usually enough to satisfy your needs for hours.

Some chemical digestion occurs in the stomach. The stomach secretes a digestive fluid called **gastric juice**, which is made up of a protein-digesting enzyme, mucus, and strong acid. The pH of gastric juice is about 2, acidic enough to dissolve iron nails and also most bacteria and other microbes that are swallowed with food. One function of the acid is to break apart the cells in food and denature (unravel) proteins.

The interior surface of the stomach wall is highly folded and is dotted with pits leading to tubular gastric glands (**Figure 8.6**). The gastric glands have three types of cells that secrete different components of gastric juice. Mucous cells (shown here in dark pink) secrete mucus, which lubricates and protects the cells lining the stomach. Parietal cells (yellow) secrete hydrogen and chloride ions, which combine in the lumen (cavity) of the stomach to form hydrochloric acid (HCl). Chief cells (light pink) secrete pepsinogen, an inactive form of the enzyme pepsin.

The diagram on the far right of the figure indicates how active pepsin is formed. ① Pepsinogen and HCl are secreted into the lumen of the stomach. ② Next, the HCl converts some pepsinogen to pepsin. ③ Pepsin itself then helps activate more pepsinogen, starting a chain reaction. This series of events is an example of positive feedback, in which the end product of a process promotes the formation of more end product.

What does all this active pepsin do? Pepsin begins the chemical digestion of proteins—those in your cheese snack, for instance. It splits the polypeptide chains of proteins into smaller polypeptides, which will be broken down further in the small intestine. Unlike most enzymes, pepsin works best under acidic conditions.

What prevents gastric juice from digesting away the stomach lining? Secreting pepsin in the inactive form of pepsinogen helps protect the cells of the gastric glands, and mucus helps protect the stomach lining from both pepsin and acid. Regardless, the epithelium of the stomach is constantly eroded. But don't worry, enough new cells are generated by mitosis to replace your stomach lining completely about every three days.

Plant Animal $\underset{3}{\overset{2}{\rightleftarrows}}$

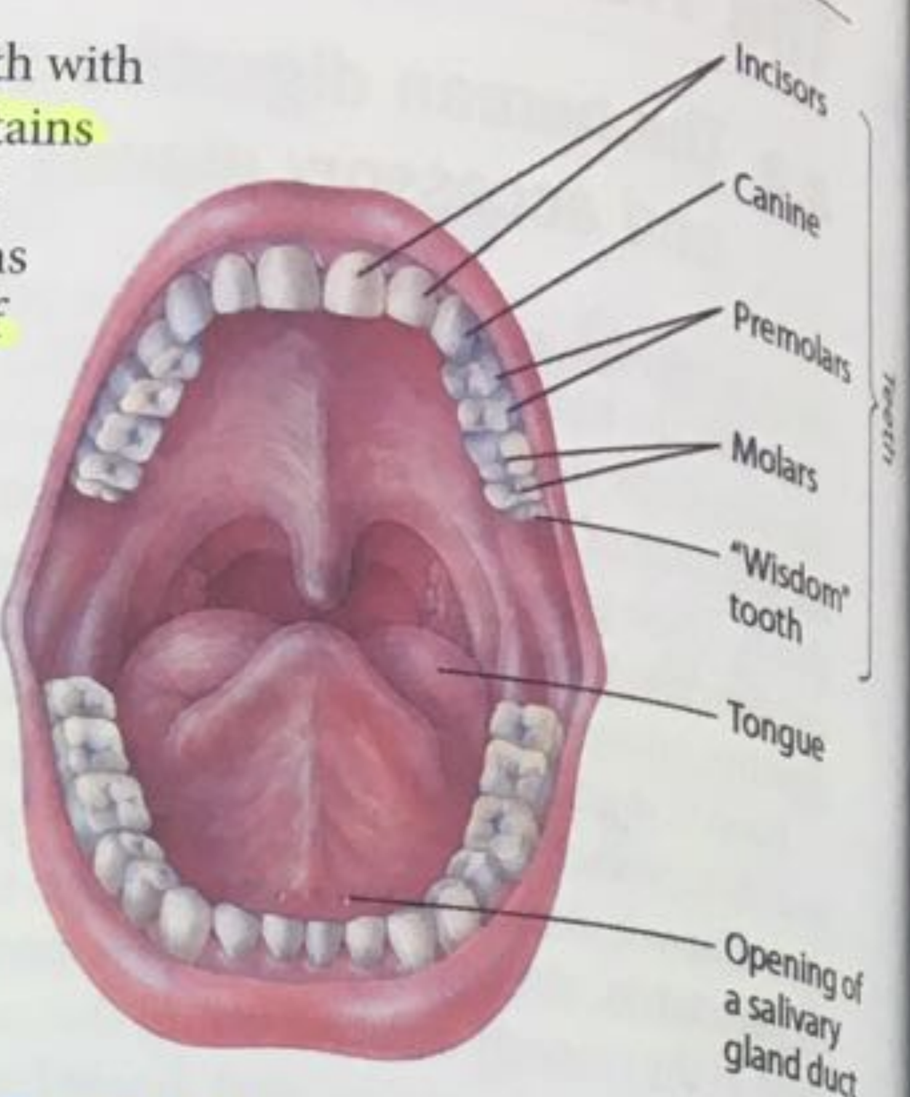
8.4 Digestion begins in the oral cavity

The oral cavity is where we ingest food and begin to digest it. Mechanical digestion begins here as teeth cut, smash, and grind food. Breaking food into smaller bits makes it easier to swallow and exposes more food surface to digestive enzymes. As **Figure 8.4** shows, you have several kinds of teeth that aid in this breaking. Starting at the front on one side of the upper or lower jaw, there are two bladelike incisors. You use these for biting into your apple. Behind the incisors is a single pointed canine tooth. (Canine teeth are much bigger in carnivores—think of the fangs of a dog or wolf—which use them to kill and rip apart prey.) Next come two premolars and three molars, which grind and crush your food. You use these to pulverize your apple, cheese, and crackers. The third molar, a "wisdom" tooth, does not appear in all people, and in some people it pushes against the other teeth and must be removed.

The anticipation of food stimulates three pairs of **salivary glands** to deliver saliva through ducts to the oral cavity. The presence of food in the oral cavity continues to stimulate salivation. In a typical day, your salivary glands secrete more than a liter (1 L) of saliva. You can see the duct opening in Figure 8.4.

Saliva contains several substances important in food processing. A slippery glycoprotein (carbohydrate-protein complex) protects the soft lining of your mouth and lubricates food for easier swallowing. Buffers neutralize food acids, helping prevent tooth decay. Antibacterial agents kill many of the bacteria that enter your mouth with food. Saliva also contains the digestive enzyme amylase, which begins chemical digestion of the starch in your cracker into the disaccharide maltose.

Also prominent in the oral cavity is the tongue, a muscular organ covered with taste buds. Besides enabling you to taste your meal, the tongue manipulates food and helps shape it into a ball called a **bolus**. As you'll see in the next module, the tongue pushes the bolus into the pharynx during the act of swallowing.



▲ **Figure 8.4** The human oral cavity

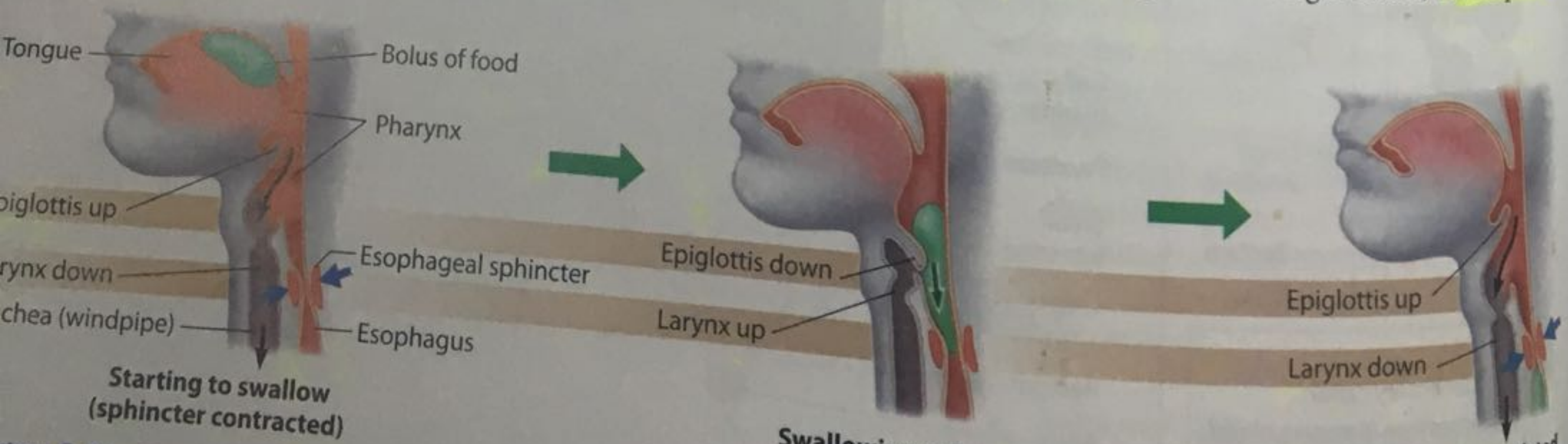
? **Name one structure in the oral cavity that participates in mechanical digestion and one that participates in chemical digestion.**

● mechanical: teeth; chemical: salivary glands

8.5 After swallowing, peristalsis moves food through the esophagus to the stomach

The pharynx, or throat, opens to two passageways: the esophagus (part of the digestive system) and the trachea (or windpipe, part of the respiratory system). Most of the time, as shown on the left in **Figure 8.5A**, the esophageal opening is closed off by a sphincter (indicated with blue arrows). Air enters your larynx (voice box) and flows past your vocal cords, through the trachea, to your lungs (black arrows).

This situation changes when you start to swallow. The tongue pushes a bolus of food into the pharynx, triggering the swallowing reflex (center of Figure 8.5A). Movement of the trachea tips a door-like flap of cartilage called the **epiglottis** over the opening to the trachea. Like a crossing guard at a dangerous intersection, the epiglottis directs the closing of the trachea, ensuring that the food will go down the esophagus. You can see this motion in the bobbing of your larynx (also called your Adam's apple) during swallowing. The esophageal sphincter relaxes, and the bolus enters the esophagus (green arrow). As shown on the right side of Figure 8.5A, the esopha-



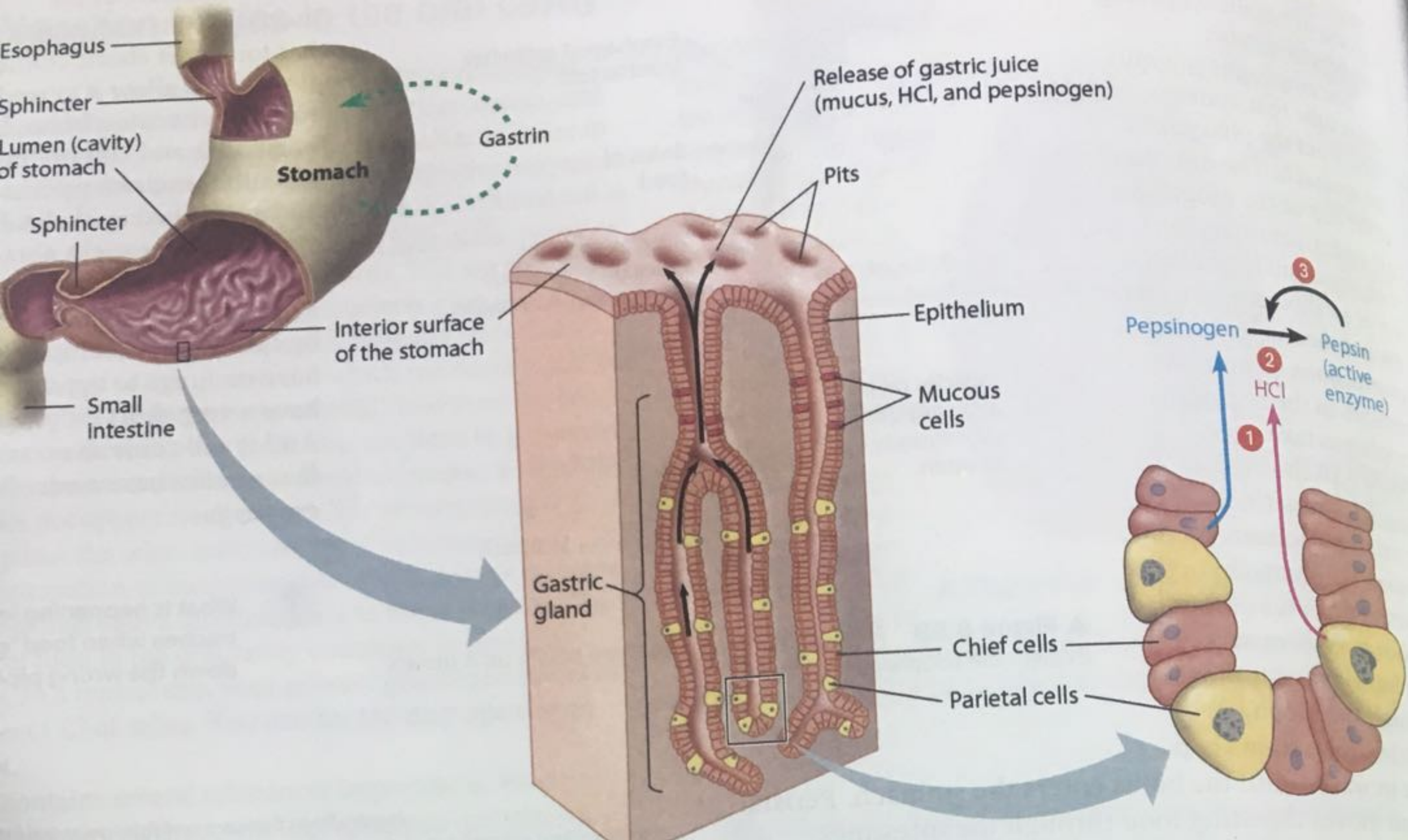
Starting to swallow (sphincter contracted)

Swallowing reflex (sphincter relaxed)

Swallowing completed (sphincter contracted)

gure 8.5A The human swallowing reflex

is Place your hand on your Adam's apple and swallow. As you do, follow the three



8.6 The stomach and its production
juice

her protection for the stomach is that gastric glands do
ete acidic gastric juice constantly. Their activity is reg-
y a combination of nerve signals and hormones. When
, smell, or taste food, a signal from your brain stimulates
stric glands. And as food arrives in your stomach, it
es the stomach walls and triggers the release of the hor-
astrin. Gastrin circulates in the bloodstream, returning
tomach (green dashed line in the top section of Figure
here it stimulates additional secretion of gastric juice. As
as 3 L of gastric juice may be secreted in a day.
at prevents too much gastric juice from being secreted?
the stomach contents become too acidic, this inhibits
ease of gastrin. Lower levels of gastrin in the blood cause
glands to secrete less gastric juice. This is an example of
ative feedback mechanism.
out every 20 seconds, your stomach muscles contract,
n churns and mixes your stomach contents. If you haven't
for several hours, the contractions may be strong: You
experience these contractions as hunger pangs. When
food is present, these contractions mix food with enzymes; what began in the stomach as a recently swallowed apple, cracker, and cheese snack soon becomes an acidic, nutrient-rich broth known as **chyme**. The sphincter between the stomach and the small intestine regulates the downstream passage of chyme, which leaves the stomach and enters the small intestine a squirt at a time. It usually takes 2–6 hours for the stomach to completely empty after a meal. Stomach "growling" results when your stomach muscles contract after the stomach has been emptied.

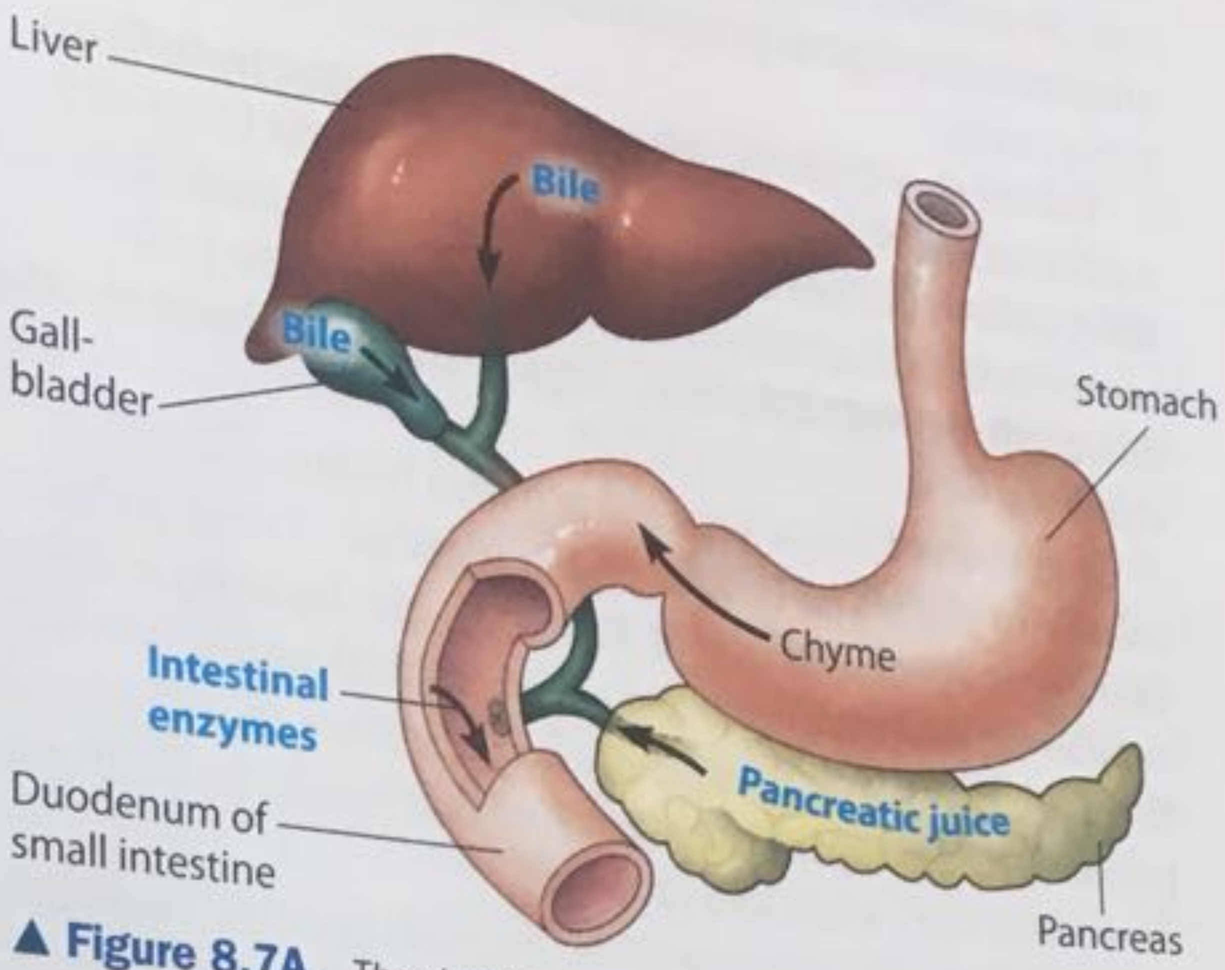
We'll continue with the digestion of your snack elsewhere. But first, let's consider some digestive problems.

? If you add pepsinogen to a test tube containing protein dissolved in distilled water, not much protein will be digested. What inorganic chemical could you add to the tube to accelerate protein digestion? What effect will it have?

HCl or some other acid will convert inactive pepsinogen to active pepsin, which will begin digestion of the protein and also activate more pepsinogen.

8.7 The small intestine is the major organ of chemical digestion and nutrient absorption

Let's return to your snack of an apple and some crackers and cheese: What happens after it passes out of the stomach and into the small intestine? At this point in its journey through the digestive tract, the food has been mechanically reduced to smaller pieces and mixed with digestive juices; it now resembles a thick soup. Chemically, the digestion of starch in the cracker began in the mouth (via amylase), and the breakdown of protein in the cheese began in the stomach (via pepsin). The rest of the digestion of the large molecules in your snack is achieved by an arsenal of enzymes in the **small intestine.** With a length of more than 6 m, the small intestine is the longest organ of the alimentary canal, but it is only about 2.5 cm in diameter (the width of a quarter). It is also the master organ for chemical digestion and for absorption of nutrients into the bloodstream.



▲ **Figure 8.7A** The duodenum and associated digestive organs

Sources of Digestive Enzymes and Bile The first section of the small intestine, about 25 cm (10 inches) in length, is called the **duodenum.** This is where chyme squirted from the stomach mixes with digestive juices from the pancreas, liver, gallbladder, and gland cells in the intestinal wall (**Figure 8.7A**). The **pancreas** produces pancreatic juice, a mixture of digestive enzymes and an alkaline solution that neutralizes the acidity of chyme as it enters the small intestine.

In addition to its many other functions, the **liver** produces a chemical mixture called bile. **Bile** contains bile salts, which act as emulsifiers (detergents) that break up fats into small droplets, making the fats more susceptible to attack by digestive enzymes. The **gallbladder** stores bile until it is needed in the small intestine. In response to chyme, hormones produced by the duodenum stimulate the release of bile from the liver, as well as digestive juices from the pancreas. Within the gallbladder, bile sometimes crystallizes to form gallstones, which can cause pain by obstructing the gallbladder or its ducts. Often the only cure is surgical removal of the gallbladder, which usually has no long-lasting effect on digestion because the liver still produces and secretes bile.

Digestion in the Small Intestine **Table 8.1** summarizes enzymatic digestion in the small intestine of all four types of large molecules—carbohydrates, proteins, nucleic acids, and fats. As we discuss the digestion of each, the table will help you keep track of the enzymes involved (in blue type).

The digestion of carbohydrates, such as those in your cracker, began in the oral cavity and is completed in the small intestine. The enzyme pancreatic amylase hydrolyzes polysaccharides into the disaccharide maltose. The enzyme maltase then splits maltose into the monosaccharide glucose. Maltase is one of a family of enzymes, each specific for the hydrolysis of a different disaccharide. For example, sucrase hydrolyzes table sugar (sucrose), and lactase digests lactose, common in milk and cheese. Undigested lactose cannot be absorbed, so it passes to the large intestine. There, prokaryotes consume the lactose, releasing gases such as methane. This produces the uncomfortable symptoms associated with lactose intolerance, such as painful gaseous bloating.

The small intestine also completes the digestion of proteins that was begun in the stomach. The pancreas and the duodenum produce enzymes that completely dismantle polypeptides into amino acids. The enzymes trypsin and chymotrypsin

TABLE 8.1 | ENZYMATIC DIGESTION IN THE SMALL INTESTINE

Carbohydrates				
Polysaccharides	Pancreatic amylase →	Maltose (and other disaccharides)	Maltase, sucrase, lactase, etc. →	Monosaccharides
Proteins				
Polypeptides	Trypsin, chymotrypsin →	Smaller polypeptides	Various peptidases →	Amino acids
Nucleic Acids				
DNA and RNA	Nucleases →	Nucleotides	Other enzymes →	Nitrogenous bases, sugars, and phosphates
Fats				
Fat globules	Bile salts →	Fat droplets	Lipase →	Fatty acids and glycerol

break polypeptides into smaller polypeptides. Several types of enzymes called peptidases then split off one amino acid at a time from these smaller polypeptides. Working together, this enzyme team digests proteins much faster than any single enzyme could.

Yet another team of enzymes, the nucleases, hydrolyzes nucleic acids. Nucleases from the pancreas split DNA and RNA (which are present in the cells of food sources) into their component nucleotides. The nucleotides are then broken down into nitrogenous bases, sugars, and phosphates by other enzymes.

Digestion of fats is a special problem because fats are insoluble in water and tend to clump together in large globules. How is this problem solved? First, bile salts separate and coat smaller fat droplets, a process called emulsification. When there are many small droplets, a larger surface area of fat is exposed to lipase, a pancreatic enzyme that breaks fat molecules down into fatty acids and glycerol.

By the time the mixture of chyme and digestive juices has moved through your duodenum, chemical digestion of your snack is just about complete. The main function of the rest of the small intestine is to absorb nutrients.

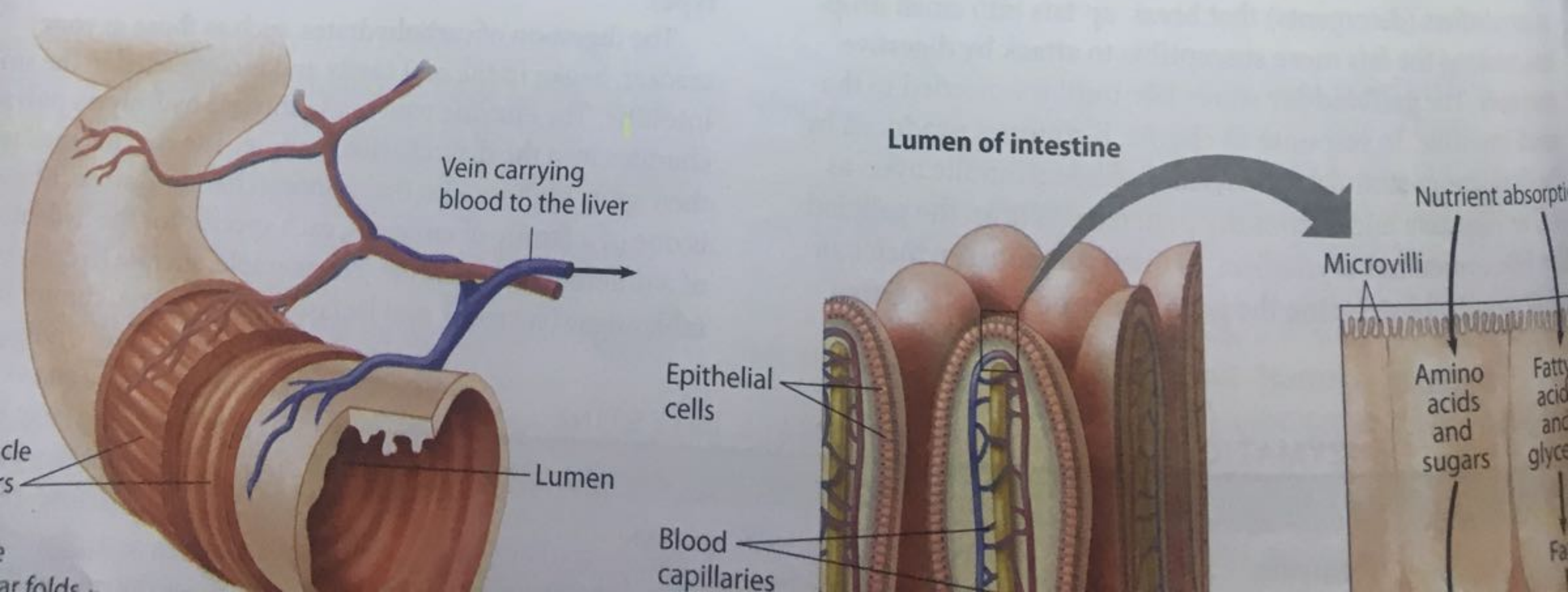
Absorption in the Small Intestine While enzymatic hydrolysis proceeds, peristalsis moves the mixture of chyme and digestive juices along the small intestine. Most digestion is completed in the duodenum. The remaining regions of the small intestine, the jejunum and ileum, are the major site for absorption of nutrients. Structurally, the small intestine is well suited for its task of absorbing nutrients. As you can see in **Figure 8.7B**, the inner wall of the small intestine has large circular folds with numerous small, finger-like projections called **villi** (singular, *villus*). Each of the epithelial cells on the surface of a villus has many tiny projections, called **microvilli**. This combination of folds and projections greatly increases the surface area across which nutrients are absorbed. Indeed, the lining of your small intestine has a huge surface area—roughly 300 m^2, about the size of a tennis court! This enormous surface area greatly increases the rate of nutrient absorption.

Some nutrients are absorbed by simple diffusion; others are pumped against concentration gradients into the epithelial cells. Notice that a small lymph vessel (shown in yellow in the figure) penetrates the core of each villus. After fatty acids and glycerol are absorbed by an epithelial cell, these building blocks are recombined into fats, which are then coated with proteins and transported into a lymph vessel. These vessels are part of the lymphatic system.

Notice that each villus is surrounded by a network of capillaries. Many absorbed nutrients, such as amino acids and sugars, pass directly out of the intestinal epithelium and then across the thin walls of the capillaries into the blood. Where does this nutrient-laden blood go? To the liver, where we also head in the next module.

? **At what point do food molecules actually enter the body's cells?**

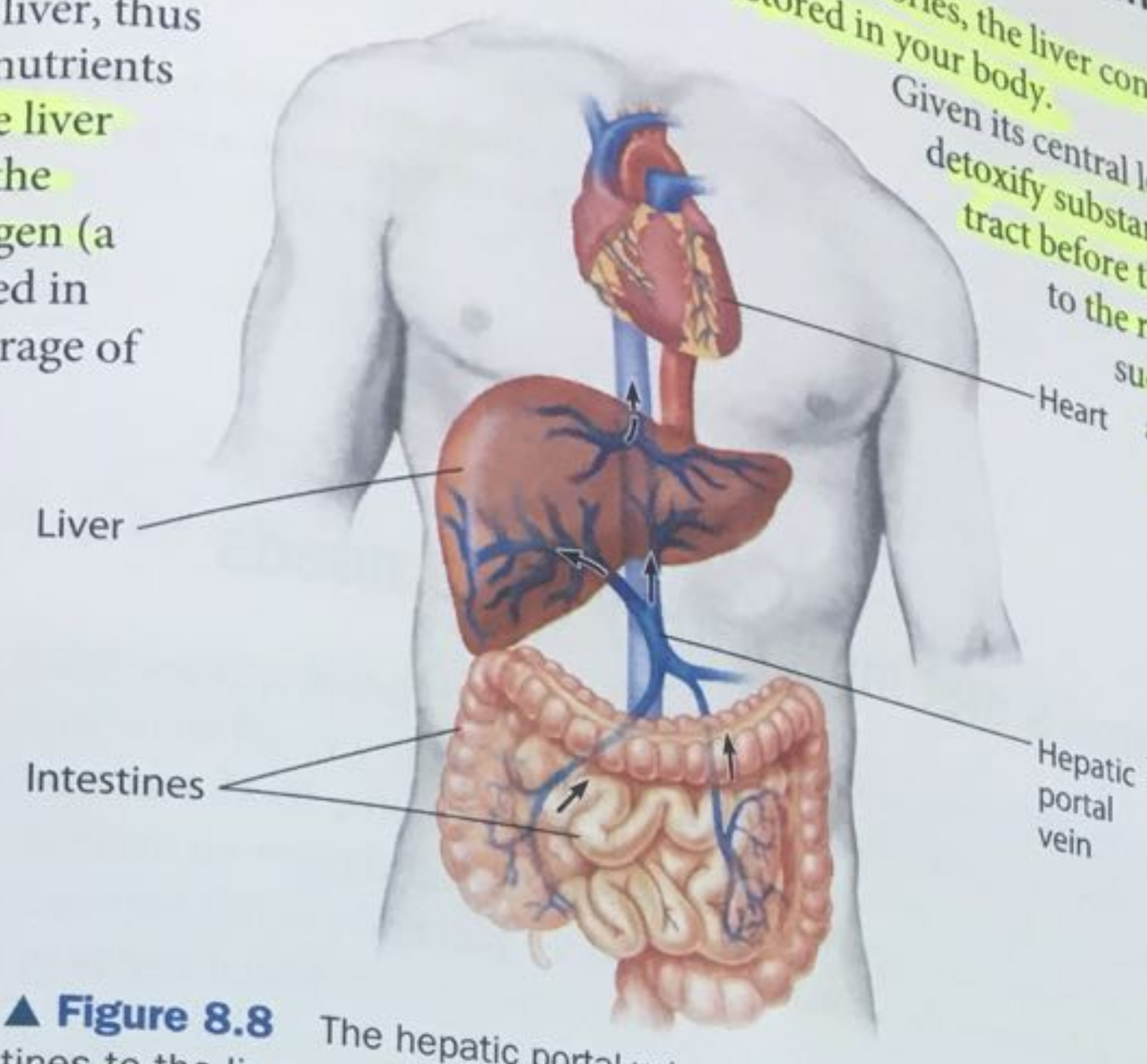
During absorption into the epithelial cells lining the villi of the small intestine



od from the intestines

ver has a strateg y—between the nes and the heart. Capillaries from the small and large nes converge into veins that lead into the tic **portal vein** (**Figure 8.8**). This large d transports blood to the liver, thus g the liver first access to nutrients rbed in the intestines. The liver ves excess glucose from the d and converts it to glycogen (a saccharide), which is stored in cells. In balancing the storage of ogen with the release of ose to the blood, your r plays a key role in reg- ting metabolism.

The liver also converts y of the nutrients it re- es to new substances. In er words, blood leaving liver may have a very erent nutrient makeup n the blood that entered. r example, liver cells thesize many essential teins, such as plasma teins important in blood clotting and in maintaining the otic balance of the blood, and lipoproteins that transport s and cholesterol to body cells. If your diet includes too many calories, the liver converts the excess to fat, which is stored in your body.



▲ **Figure 8.8** The hepatic portal vein carrying blood from the intestines to the liver

Given its central location, the liver can modify and detoxify substances absorbed by the digestive tract before the blood carries these materials to the rest of the body. It converts toxins such as alcohol or other drugs to inactive products that are excreted in the urine. These breakdown products are what are looked for in urine tests for various drugs. As liver cells detoxify alcohol or process some over-the-counter and prescription drugs, however, they can be damaged. The combination of alcohol and certain drugs, such as acetaminophen, is particularly harmful.

The liver and other accessory organs empty into the small intestine. From there, what remains of food passes into the large intestine, the subject of the next module.

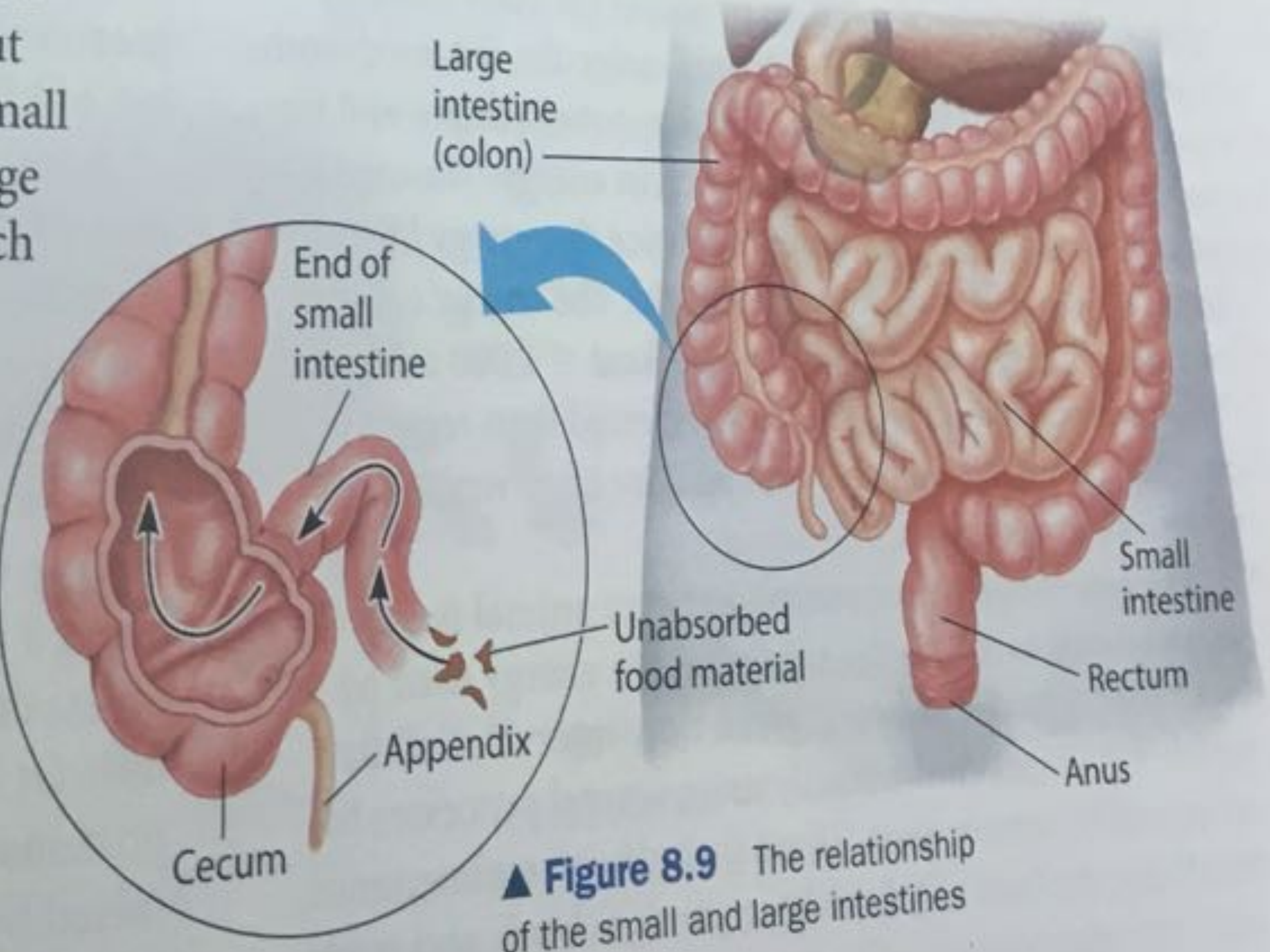
? **In what way does the location of the liver in the body aid its functions?**

As blood is delivered directly from the intestines, the liver can process and regulate the absorbed nutrients and remove toxic substances.

9 The large intestine reclaims water and compacts the feces

e time your snack has reached the intestines, most of utrients have been absorbed. The large intestine then esses whatever remains. The **large intestine** is about n long and 5 cm in diameter (twice as wide as the small stine). At the T-shaped junction of the small and large stines, a sphincter controls passage into a small pouch d the **cecum** (**Figure 8.9**). Compared with many r mammals, we humans have a small cecum. The endix, a small, finger-like extension of the cecum, ins a mass of white blood cells that make a r contribution to immunity. If the junction be- n the appendix and the rest of the large intestine es blocked, appendicitis—a bacterial infection appendix—may result. If this occurs, emergency ry is usually required to remove the appendix and t the spread of infection.

e main portion of the large intestine is the **colon**. One function of the colon is to complete the reabsorption of that was begun in the small intestine. Altogether, about digestive juice enters the lumen of your digestive tract y. About 90% of the water contained in digestive juice bed back into the blood via osmosis by the small intes- d colon.



▲ **Figure 8.9** The relationship of the small and large intestines

The wastes of the digestive system, called **feces**, become more solid as water is reabsorbed and they move along the colon by peristalsis. It takes approximately 12–24 hours for material to travel the length of the colon. The feces consist mainly of indigestible plant fibers—cellulose from your apple, for instance—and enormous numbers of prokaryotes that normally live in the colon. Some colon bacteria, such as *Escherichia coli*, produce important vitamins, including several B vitamins and vitamin K. These substances are absorbed into the bloodstream and supplement your dietary intake of vitamins.

Feces are stored in the final portion of the colon, called the **rectum**, until they can be eliminated. Contractions of the colon create the urge to defecate. Two rectal sphincters, one voluntary and the other involuntary, regulate the opening of the anus. When the voluntary sphincter is relaxed, contractions of the rectum expel feces.

If the lining of the colon is irritated—by a viral or bacterial infection, for instance—the colon is less effective in reclaiming water, and diarrhea may result. The opposite problem, constipation, occurs when peristalsis moves the feces along too slowly; the colon reabsorbs too much water, and the feces become too compacted. Constipation often results from a diet that does not include enough plant fiber.

? **Explain why treatment with antibiotics for an extended period may cause a vitamin K deficiency.**

The antibiotics may kill the bacteria that synthesize vitamin K in the colon.

Nutrition

8.10 Overview: An animal's diet must satisfy three needs

All animals—whether herbivores like koalas, carnivores like coyotes, or omnivores like humans—have the same basic nutritional needs. All animals must obtain (1) fuel to power all body activities; (2) organic molecules to build the animal's own molecules; and (3) essential nutrients, substances the animal cannot make for itself.

We have seen that digestion dismantles the large molecules in food. Cells can then use the resulting small molecules for energy or assemble them into their own complex molecules—the proteins, carbohydrates, lipids, and nucleic acids needed to build and maintain cell structure and function.

Eating too little food, too much food, or the wrong mixture of foods can endanger an animal's health. Starting with the need for fuel and paying particular attention to humans, we discuss basic nutritional needs in the rest of this chapter.

? **What are the three needs that an adequate diet fills?**

Fuel, organic building materials, and essential nutrients.

8.11 Chemical energy powers the body

It takes energy to read this book. It also takes energy to digest your snack, walk to class, and perform all the other activities of your body. Cellular respiration produces the body's energy currency, ATP, by oxidizing organic molecules obtained from food (see Chapter 5). Usually, cells use carbohydrates and fats as fuel sources. Fats are especially rich in energy: The oxidation of a gram of fat liberates more than twice the energy liberated from a gram of carbohydrate or protein. The energy content of food is measured in **kilocalories (1 kcal = 1,000 calories)**. The calories listed on food labels or referred to in regard to nutrition are actually kilocalories and are often written as Calories (capital C).

The rate of energy consumption by an animal is called its **metabolic rate**. It is the sum of all the energy used by biochemical reactions over a given time interval. Cellular metabolism must continuously drive several processes for an animal to remain alive. These include cell maintenance, breathing, the beating of the heart, and, in birds and mammals, the maintenance of body temperature. The number of kilocalories a resting animal requires to fuel these essential processes for a given time is called the **basal metabolic rate (BMR)**. The BMR for humans averages 1,300–1,500 kcal per day for adult females and about 1,600–1,800 kcal per day for adult males. This is about equivalent to the rate of energy use by a 75-watt light bulb. But this is only a basal (base) rate—the amount of energy you "burn" lying motionless. Any activity, even working at your desk, consumes kilocalories in addition to the BMR. The more active you are, the greater your actual metabolic rate and the greater the number of kilocalories your body uses per day.

Table 8.2 gives you an idea of the amount of activity it takes for a 68-kg (150-pound) person to use up the kilocalories contained in several common foods. What happens when you take in more Calories than you use? Rather than discarding the extra energy, your cells store it in various forms. Your liver and muscles store energy in the form of glycogen, a polymer of glucose molecules. Most of us store enough glycogen to supply about a day's worth of basal metabolism. Your body also stores excess energy as fat. This happens even if your diet contains little fat because the liver converts excess carbohydrates and proteins to fat. The average human's energy needs can be fueled by the oxidation of only 0.3 kg of fat per day. Most healthy people have enough stored fat to sustain them through several weeks of starvation. Let's consider the essential nutrients that must be supplied in the diet.

? **What is the difference between metabolic rate and basal metabolic rate?**

Metabolic rate is the total energy used for all activities in a unit of time; BMR is the minimum number of kilocalories that a resting animal needs to maintain life's basic processes for a unit of time.

TABLE 8.2 EXER

Speed of exercise

kcal "burned" per h

Cheeseburger (quar

Pepperoni pizza (1

Non-diet soft drink

Whole wheat brea

These data are for a

8.12 An a

Besides providi diet must also s that must be o mal's cells can trients are esse only by certai nutrient for h birds and sna needed. Ther fatty acids, e

Essential F by combini

TABLE 8.2 EXERCISE REQUIRED TO "BURN" THE CALORIES (KCAL) IN COMMON FOODS

	Jogging	Swimming	Walking
Speed of exercise	9 min/mi	30 min/mi	20 min/mi
kcal "burned" per hour	775	408	245
Cheeseburger (quarter-pound), 417 kcal	32 min	1 hr, 1 min	1 hr, 42 min
Pepperoni pizza (1 large slice), 280 kcal	22 min	42 min	1 hr, 8 min
Non-diet soft drink (12 oz), 152 kcal	12 min	22 min	37 min
Whole wheat bread (1 slice), 65 kcal	5 min	10 min	16 min

These data are for a person weighing 68 kg (150 pounds).

8.12 An animal's diet must supply essential nutrients

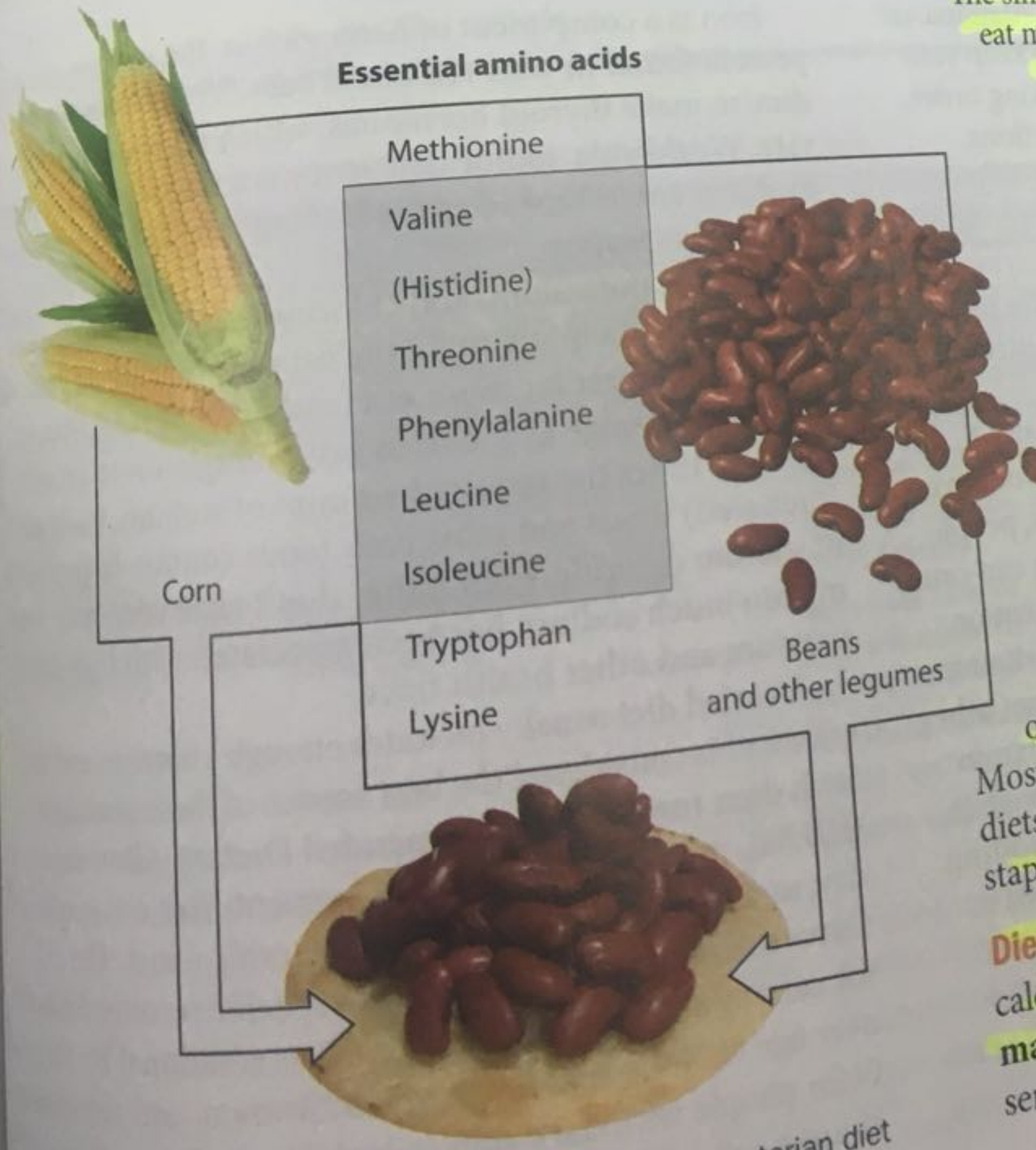
Besides providing fuel and organic raw materials, an animal's diet must also supply **essential nutrients**. These are materials that must be obtained in preassembled form because the animal's cells cannot make them from *any* raw material. Some nutrients are essential for all animals, whereas others are needed only by certain species. For example, vitamin C is an essential nutrient for humans and other primates, guinea pigs, and some birds and snakes, but most animals can make vitamin C as needed. There are four classes of essential nutrients: essential fatty acids, essential amino acids, vitamins, and minerals.

Essential Fatty Acids Our cells make fats and other lipids by combining fatty acids with other molecules, such as glycerol (see Module 2.7). We can make most of the fatty acids we need. Those we cannot make, called **essential fatty acids**, must be obtained from our diet. One essential fatty acid, linoleic acid, is especially important because it is needed to make some of the phospholipids of cell membranes. Because seeds, grains, and vegetables generally provide ample amounts of essential fatty acids, deficiencies are rare.

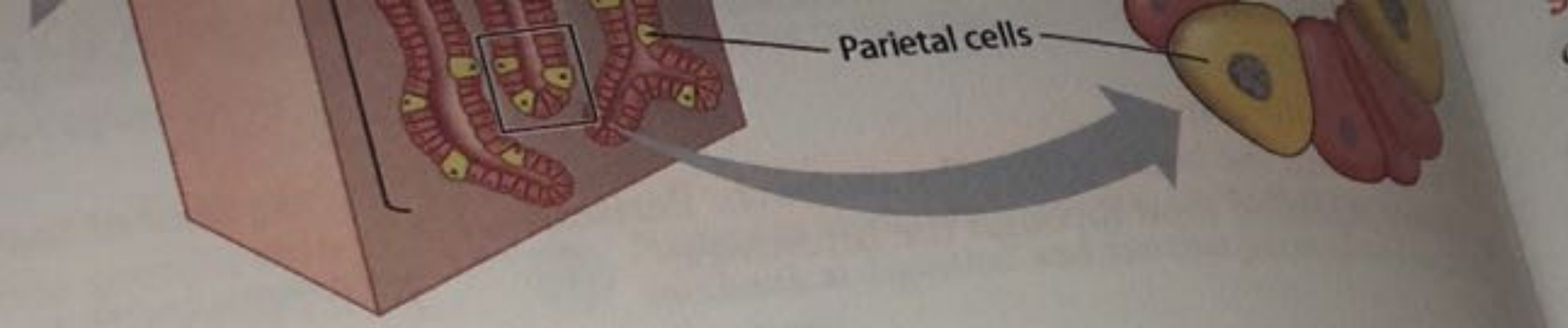
Essential Amino Acids Proteins are built from 20 different kinds of amino acids. Adult humans can make 12 of these amino acids from other compounds. The remaining eight, known as the **essential amino acids**, must be obtained from the diet. Infants also require a ninth, histidine. A deficiency of a single essential amino acid impairs protein synthesis and can lead to protein deficiency.

The simplest way to get all the essential amino acids is to eat meat and animal by-products such as eggs, milk, and cheese. The proteins in these products are said to be "complete," meaning they provide all the essential amino acids in the proportions needed by the human body. In contrast, most plant proteins are "incomplete," or deficient in one or more essential amino acids. If you are vegetarian (by choice, or, as for much of the world's population, by economic necessity), the key to good nutrition is to eat a varied diet of plant proteins that together supply sufficient quantities of all the essential amino acids. Simply by eating a combination of beans and corn, for example, vegetarians can get all the essential amino acids (**Figure 8.12**). The combination of a legume (such as beans, peanuts, or soybeans) and a grain often provides the right balance. Most societies have, by trial and error, developed balanced diets that prevent protein deficiency. The Latin American staple of rice and beans is an example.

Dietary Deficiencies A diet that is chronically deficient in calories or lacks one or more essential nutrients results in **malnutrition**. Failing to obtain adequate nutrition can have serious health consequences.



▲ **Figure 8.12** Essential amino acids from a vegetarian diet



▲ **Figure 8.6** The stomach and its production of gastric juice

Another protection for the stomach is that gastric glands do not secrete acidic gastric juice constantly. Their activity is regulated by a combination of nerve signals and hormones. When you see, smell, or taste food, a signal from your brain stimulates your gastric glands. And as food arrives in your stomach, it stretches the stomach walls and triggers the release of the hormone **gastrin**. Gastrin circulates in the bloodstream, returning to the stomach (green dashed line in the top section of Figure 8.6), where it stimulates additional secretion of gastric juice. As much as 3 L of gastric juice may be secreted in a day.

What prevents too much gastric juice from being secreted? When the stomach contents become too acidic, this inhibits the release of gastrin. Lower levels of gastrin in the blood cause gastric glands to secrete less gastric juice. This is an example of a negative feedback mechanism.

About every 20 seconds, your stomach muscles contract, which churns and mixes your stomach contents. If you haven't eaten for several hours, the contractions may be strong: You may experience these contractions as hunger pangs. When food is present, these contractions mix food with enzymes. What began in the stomach as a recently swallowed apple, cracker, and cheese snack soon becomes an acidic, nutrient-rich broth known as **chyme**. The sphincter between the stomach and the small intestine regulates the downstream passage of chyme, which leaves the stomach and enters the small intestine a squirt at a time. It usually takes 2–6 hours for the stomach to completely empty after a meal. Stomach "growling" results when your stomach muscles contract after the stomach has been emptied.

We'll continue with the digestion of your snack elsewhere. But first, let's consider some digestive problems.

? **If you add pepsinogen to a test tube containing protein dissolved in distilled water, not much protein will be digested. What inorganic chemical could you add to the tube to accelerate protein digestion? What effect will it have?**

some other acid will convert inactive pepsinogen to active pepsin, begin digestion of the protein and also activate more pepsinogen.

of the
called the du
the stomach mixes wi
liver, gallbladder, and gland cells in the intestinal wall
(Figure 8.7A). The **pancreas** produces pancreatic juice,
ture of digestive enzymes and an alkaline solution th
tralizes the acidity of chyme as it enters the small i

In addition to its many other functions, the liv
chemical mixture called bile. **Bile** contains bile
as emulsifiers (detergents) that break up fats in
lets, making the fats more susceptible to atta
enzymes. The **gallbladder** stores bile until
small intestine. In response to chyme, ho
the duodenum stimulate the release of b
well as digestive juices from the pancr
der, bile sometimes crystallizes to for
cause pain by obstructing the gallbl

TABLE 8.1 | ENZYMATI

Carbohydrates	
Polysaccharides	Pancreati amylase
Proteins	
Polypeptides	Tryp ryp
Nucleic Acids	
DNA and RNA	
Fats	
Fat globules	

Living in a country where food is plentiful and most people can afford it, you may find it hard to relate to starvation. But more than 1 billion people in the world do not have enough to eat, and an estimated 4.5 million die of hunger each year, most of them children. Undernutrition, which occurs when diets do not supply sufficient chemical energy, may occur when food supplies are disrupted by drought, wars, or other crises and when severe poverty prevents people from obtaining sufficient food.

The most common type of human malnutrition is protein deficiency resulting from a diet that must depend on a single plant staple—just corn, rice, or potatoes, for instance. Protein deficiency often begins when a child's diet shifts from breast milk alone to food that is mostly starch or other carbohydrates. Such children, if they survive infancy, often have impaired physical and mental development.

Depending on food availability and choices, it is even possible for an overnourished (obese) individual to be malnourished. For example, malnutrition can result from a steady diet of junk food, which offers little nutritional value.

Another cause of undernutrition is anorexia nervosa, an eating disorder in which individuals, most often females, starve themselves compulsively, in response to an intense fear of gaining weight. Bulemia is a pattern of binge eating followed by purging through induced vomiting, abuse of laxatives, or excessive exercise. Both disorders are serious health problems and can even lead to death.

In the next module, we continue our look at essential nutrients—this time vitamins and minerals.

? Look carefully at Figure 8.12. A diet consisting strictly of corn would probably result in a deficiency of which essential amino acids?

● Tryptophan and lysine.

8.13 A healthy human diet includes 13 vitamins and many essential minerals

A **vitamin** is an organic nutrient required in your diet, but only in very small amounts. For example, 1 tablespoon of vitamin B_{12} could provide the daily requirement for nearly a million people. Depending on the vitamin, the required daily amount ranges from about 0.01 to 100 mg. To help you imagine how small these amounts are, consider that a small peanut weighs about 1 g, so 100 mg would be one-tenth of a small peanut. And some vitamin requirements are one-ten-thousandth of that!

Table 8.3A lists 13 essential vitamins and their major dietary sources. As you can see from the functions in the body and symptoms of deficiency listed in the table, vitamins are absolutely necessary to your health—helping to keep your skin healthy, your nervous system in good working order, and your vision clear, among dozens of other actions.

Vitamins are classified as water-soluble or fat-soluble. Water-soluble vitamins include the B vitamins and vitamin C. Many B vitamins function in the body as coenzymes, enabling the catalytic functions of enzymes that are used over and over in metabolic reactions. Vitamin C is required in the production of connective tissue.

Fat-soluble vitamins include vitamins A, D, E, and K. Vitamin A is a component of the visual pigments in your eyes. Among populations subsisting on simple rice diets, people are often afflicted with vitamin A deficiency, which can cause blindness or death. Vitamin D aids in calcium absorption and bone formation. Your dietary requirement for vitamin D is variable because you synthesize this vitamin from other molecules when your skin is exposed to sunlight. Vitamin E functions as an antioxidant that helps prevent damage to your cells. Vitamin K is necessary for proper blood clotting.

Minerals are simple inorganic nutrients, also required in small amounts—from less than 1 mg to about 2,500 mg per day. **Table 8.3B**, on the facing page, lists your daily mineral requirements. As you can see from the table, you need the first seven minerals in amounts greater than 200 mg per day (about two-tenths of that small peanut). You need the rest in much smaller quantities. The table includes the dietary sources for each mineral, and lists the functions and the symptoms of deficiency for most of these minerals.

Along with other vertebrates, we humans require relatively large amounts of calcium and phosphorus to construct and maintain our skeleton. Too little calcium, especially before the age of 30, can result in the degenerative bone disease osteoporosis. Calcium is also necessary for the normal functioning of nerves and muscles, and phosphorus is an ingredient of ATP and nucleic acids.

Iron is a component of hemoglobin, the oxygen-carrying protein found in your red blood cells. Vertebrates need iodine to make thyroid hormones, which regulate metabolic rate. Worldwide, iodine deficiency is a serious human health problem and is ranked as the leading cause of preventable mental retardation.

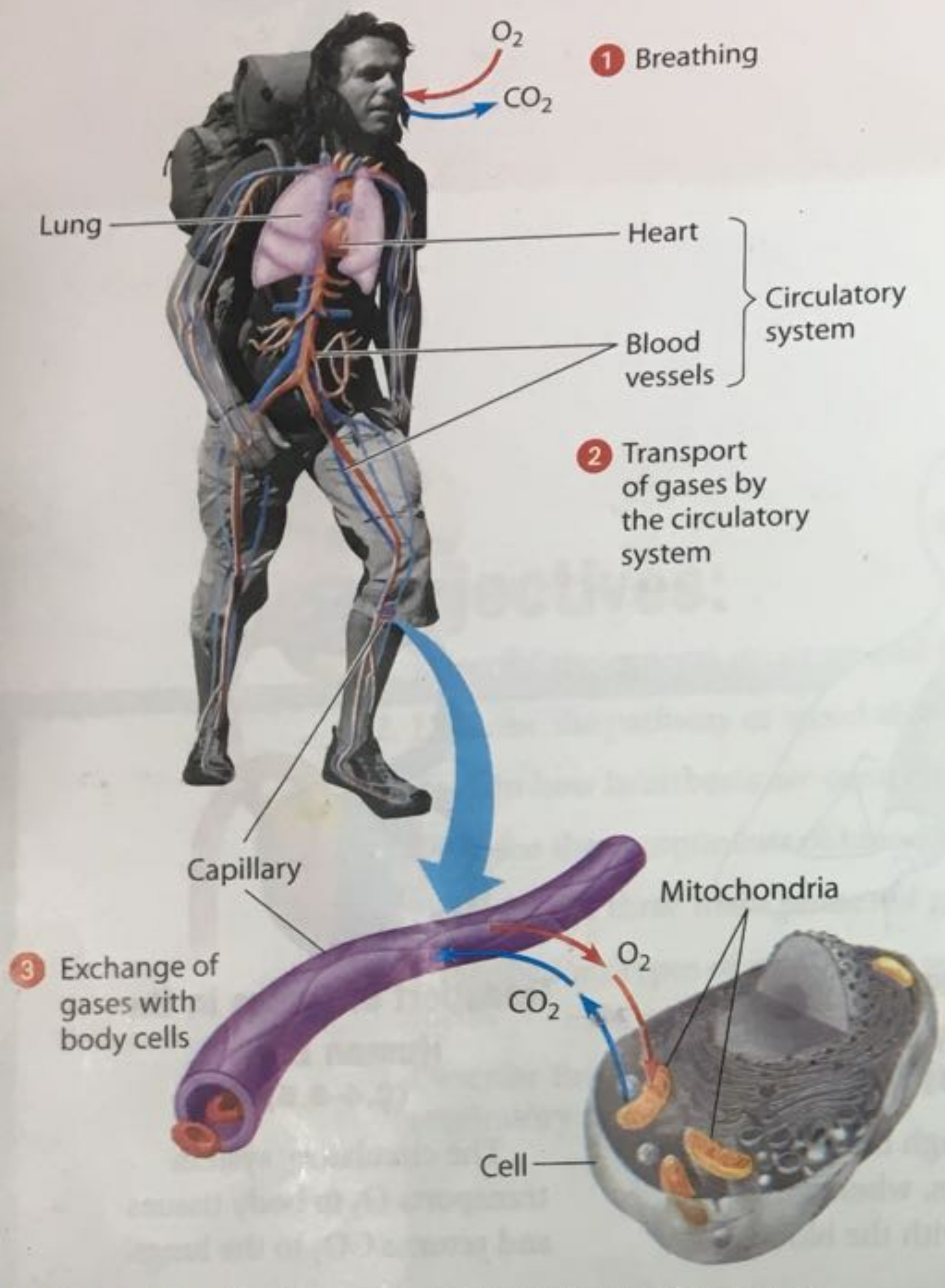
Sodium, potassium, and chlorine are important in nerve function and help maintain the osmotic balance of your cells. Most of us ingest far more salt (sodium chloride) than we need. The average U.S. citizen eats enough salt to provide about 20 times the required amount of sodium. Packaged (prepared) foods and most junk foods contain large amounts of sodium chloride, even if they don't taste very salty. Ingesting too much sodium has been associated with high blood pressure and other health risks.

A varied diet usually includes enough vitamins and minerals and is considered the best source of these nutrients. Such diets meet the **Recommended Dietary Allowances (RDAs)**, minimum amounts of nutrients that are needed each day, as determined by a national scientific panel. The U.S. Department of Agriculture makes specific recommendations for certain population groups, such as additional B_{12} for people over age 50, folic acid for pregnant women, and extra vitamin D for people with dark skin (which blocks the synthesis of this vitamin) and for those exposed to insufficient sunlight.

5 min

Mechanisms of Gas Exchange

9.1 Overview: Gas exchange in humans involves breathing, transport of gases, and exchange with body cells



▲ **Figure 9.1** The three phases of gas exchange in a human

Gas exchange makes it possible for you to put to work the food molecules the digestive system provides. **Figure 9.1** presents an overview of the three phases of gas exchange in humans and other animals with lungs. ① Breathing: As you inhale, a large, moist internal surface is exposed to the air entering the lungs. Oxygen (O_2) diffuses across the cells lining the lungs and into surrounding blood vessels. At the same time, carbon dioxide (CO_2) diffuses from the blood into the lungs. As you exhale, CO_2 leaves your body.

② Transport of gases by the circulatory system: The O_2 that diffused into the blood attaches to hemoglobin in red blood cells. The red vessels in the figure are transporting O_2-rich blood from the lungs to capillaries in the body's tissues. CO_2 is also transported in blood, from the tissues back to the lungs, carried in the blue vessels shown here.

③ Exchange of gases with body cells: Your cells take up O_2 from the blood and release CO_2 to the blood. As you learned in Chapter 5, O_2 functions in cellular respiration in the mitochondria as the final electron acceptor in the stepwise breakdown of fuel molecules. H_2O and CO_2 are waste products, and ATP is produced that will power cellular work. The gas exchange occurring as we breathe is often called respiration; do not confuse this exchange with cellular respiration.

Cellular respiration requires a continuous supply of O_2 and the disposal of CO_2. Gas exchange involves both the respiratory and circulatory systems in servicing your body's cells.

? Humans cannot survive for more than a few minutes without O_2. Why?

● Cells require a steady supply of O_2 for cellular respiration to produce enough ATP to function. Without enough ATP, cells and then organism die.

5m

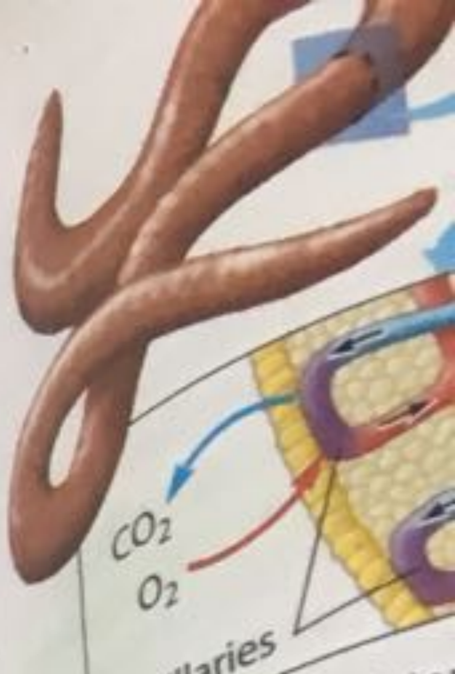
9.2 Animals exchange O_2 and CO_2 across moist body surfaces

The part of an animal's body where gas exchange with the environment occurs is called the respiratory surface. Respiratory surfaces are made up of living cells, and like all cells, their plasma membranes must be wet to function properly. Thus, respiratory surfaces are always moist.

Gas exchange takes place by diffusion. The surface area of the respiratory surface must be large enough to take up sufficient O_2 for every cell in the body. Usually, a single layer of cells forms the respiratory surface. This thin, moist layer allows O_2 to diffuse rapidly into the circulatory system or directly into body tissues and also allows CO_2 to diffuse out.

The four figures on the next page illustrate, in simplified form, four types of respiratory organs, structures in which gas exchange with the external environment occurs. In each of these figures, the circle represents a cross section of the animal's body through the respiratory surface. The yellow areas represent the respiratory surfaces; the green outer circles represent body surfaces with little or no role in gas exchange. The boxed enlargements show gas exchange occurring across the respiratory surface.

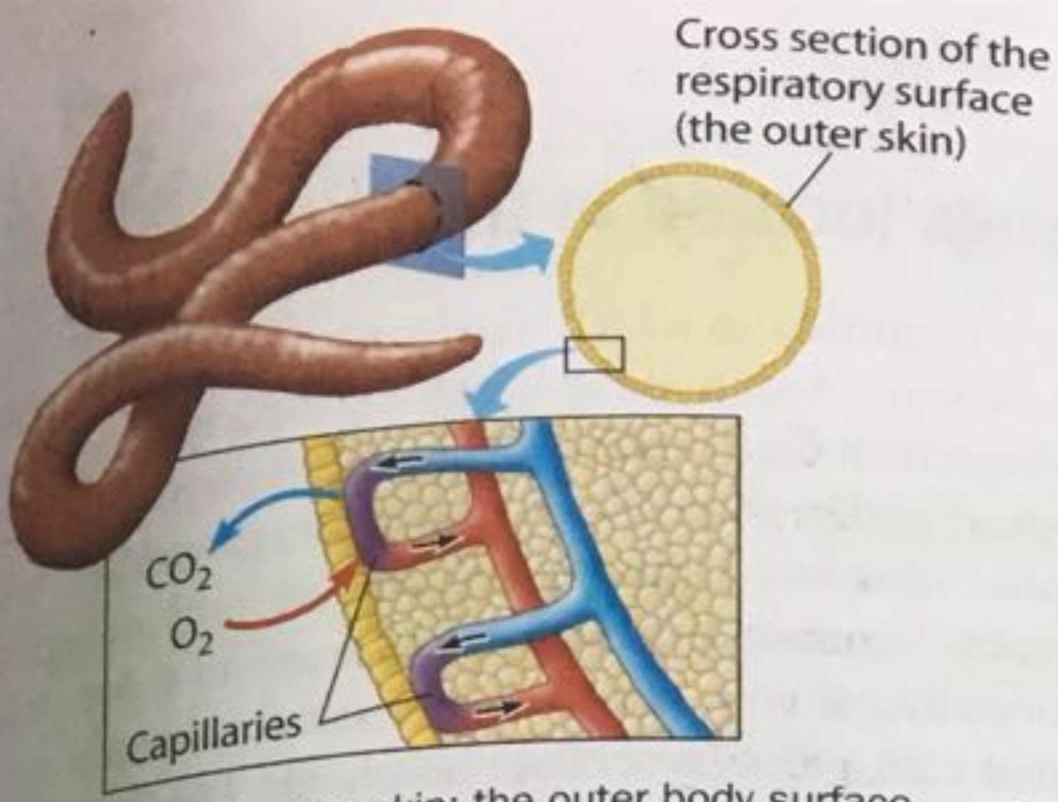
Some animals use their entire outer skin as a gas exchange organ. The earthworm in **Figure 9.2A** is an example. The cross-sectional diagram shows its whole body surface as yellow; there are no specialized gas exchange surfaces. Oxygen diffuses into a dense network of thin-walled capillaries lying just beneath the skin. Earthworms and other skin-breathers must live in damp places or in water because their whole body surface has to stay moist. Animals that breathe only through



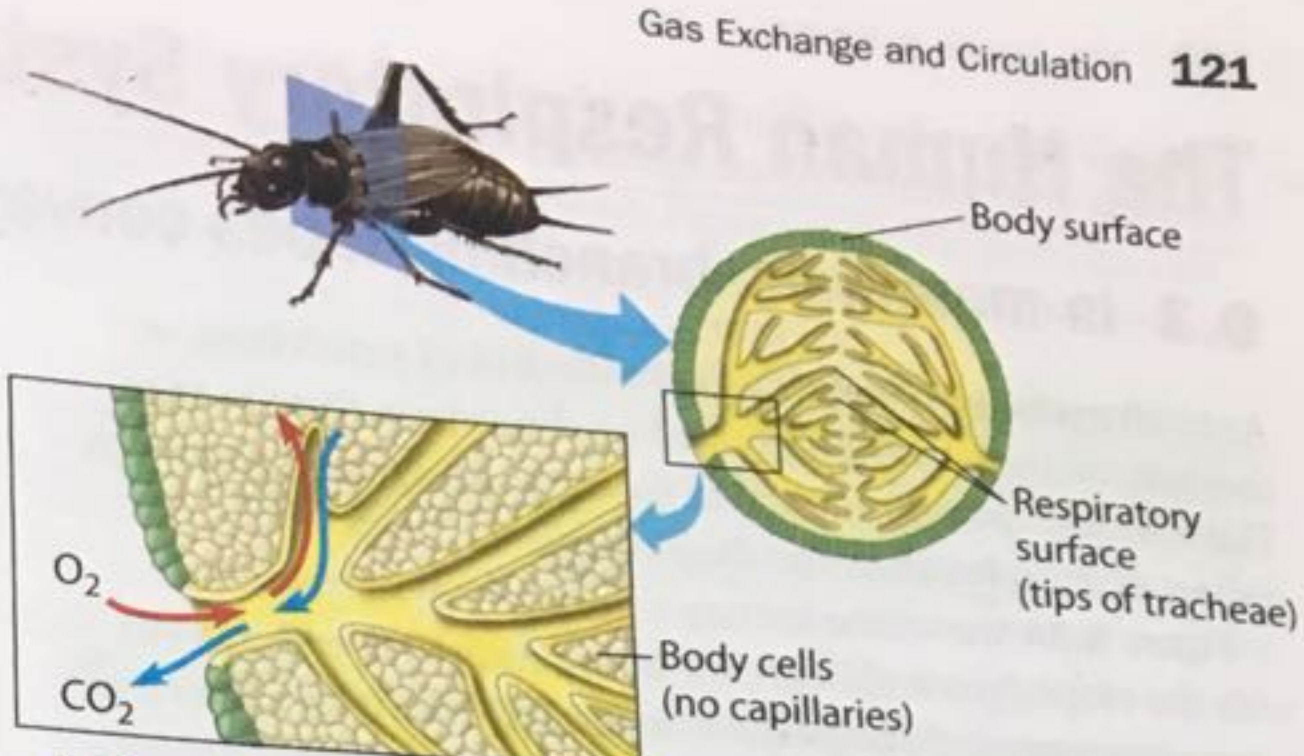
▲ Figure 9.2A The skin

▲ Figure 9.2B Gills

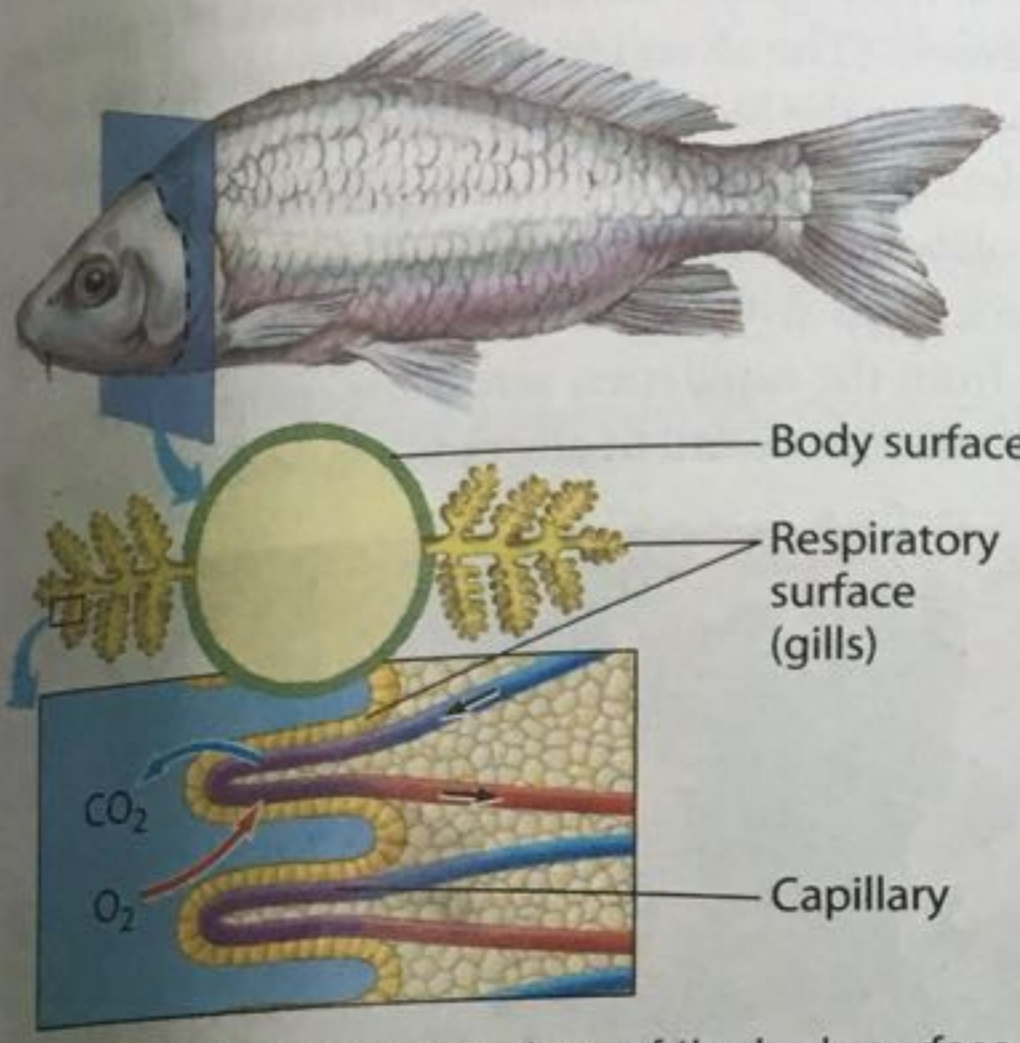
their skin are gene
flattened. These sh
face to body volun
the cells in the bo
In most anima
exchange gases fo
of the body have
tory surfaces wit
organs include g
Gills have dev
extensions, or o
for gas exchang
extend from ea
are clustered in
set of feather-li
the enlargemen
the water and
aquatic anima
surface moist
In most ter
into the body
surface opens



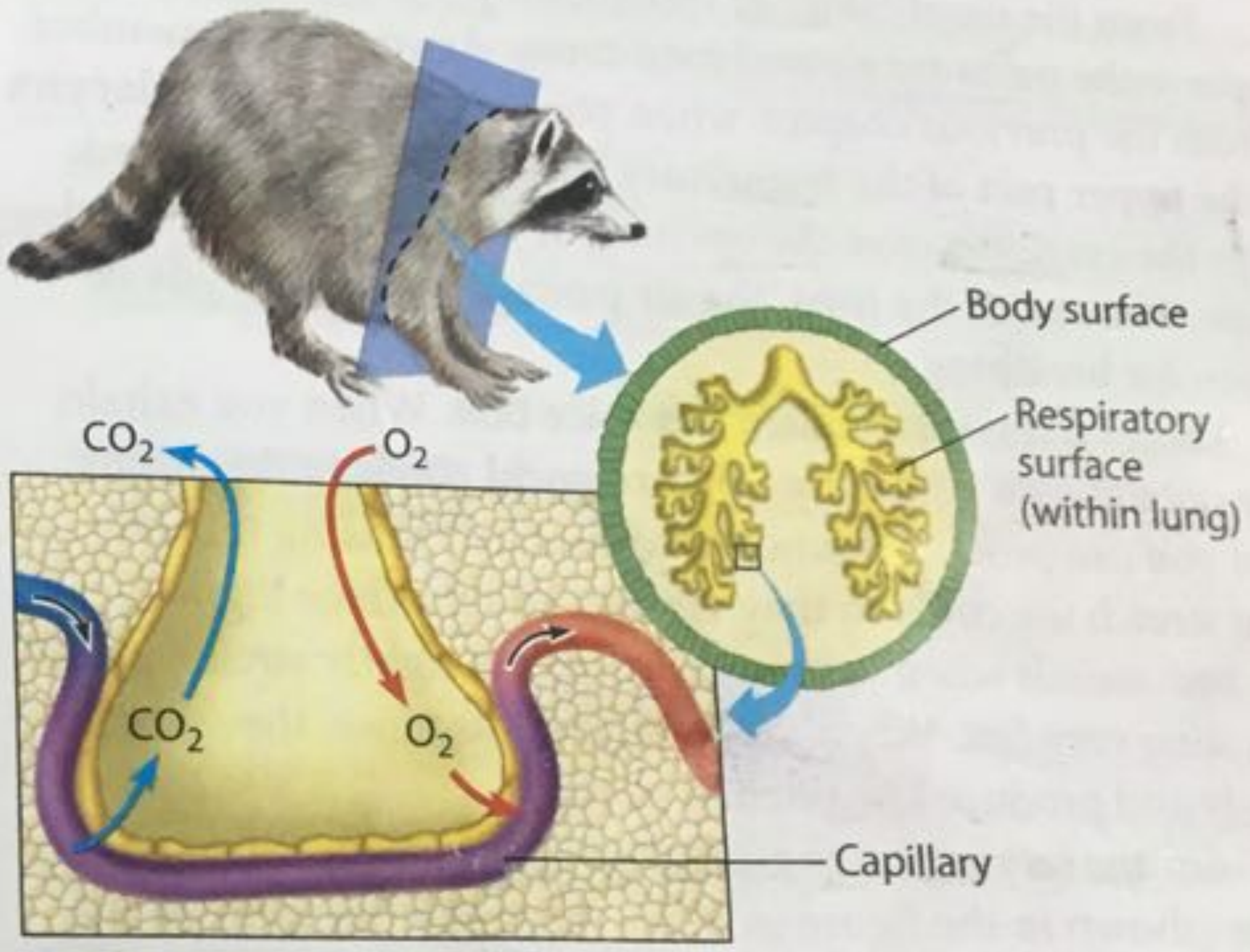
▲ **Figure 9.2A** The skin: the outer body surface



▲ **Figure 9.2C** A tracheal system: air tubes that extend throughout the body



▲ **Figure 9.2B** Gills: extensions of the body surface



▲ **Figure 9.2D** Lungs: internal thin-walled sacs

their skin are generally small, and many are long and thin or flattened. These shapes provide a high ratio of respiratory surface to body volume, allowing for sufficient gas exchange for all the cells in the body.

In most animals, the skin surface is not extensive enough to exchange gases for the whole body. Consequently, certain parts of the body have become adapted as highly branched respiratory surfaces with large surface areas. Such gas exchange organs include gills, tracheal systems, and lungs.

Gills have developed in most aquatic animals. **Gills** are extensions, or outfoldings, of the body surface specialized for gas exchange. Many marine worms have flap-like gills that extend from each body segment. The gills of clams and crayfish are clustered in one body location. A fish (**Figure 9.2B**) has a set of feather-like gills on each side of its head. As indicated in the enlargement, gases diffuse across the gill surface between the water and the blood. Because the respiratory surfaces of aquatic animals extend into the surrounding water, keeping the surface moist is not a problem.

In most terrestrial animals, the respiratory surface is folded into the body rather than projecting from it. The infolded surface opens to the air only through narrow tubes, an arrangement that helps retain the moisture that is essential for the cells of the respiratory surfaces to function.

The **tracheal system** of insects (**Figure 9.2C**) is an extensive system of branching internal tubes called tracheae, with a moist, thin epithelium forming the respiratory surface at their tips. The smallest branches exchange gases directly with body cells. Thus, gas exchange in insects requires no assistance from the circulatory system.

Most terrestrial vertebrates have **lungs** (**Figure 9.2D**), which are internal sacs lined with moist epithelium. As the diagram indicates, the inner surfaces of the lungs are extensively subdivided, forming a large respiratory surface. Gases are carried between the lungs and the body cells by the circulatory system.

? How does the structure of the respiratory surface of a gill or lung fit its function?

These respiratory surfaces are moist and thin so that gases can easily diffuse
oss them and into or out of the closely associated capillaries. They are highly
nched or subdivided, providing a large surface area for exchange.

The Human Respiratory System

15 min

9.3 In mammals, branching tubes convey air to lungs located in the chest cavity

As in all mammals, your lungs are located in your chest, or thoracic cavity, and are protected by the supportive rib cage. The thoracic cavity is separated from the abdominal cavity by a sheet of muscle called the **diaphragm**.

Figure 9.3A shows the human respiratory system (along with the esophagus and heart, for orientation). Air enters your respiratory system through the nostrils. It is filtered by hairs and warmed, humidified, and sampled for odors as it flows through a maze of spaces in the nasal cavity. You can also draw in air through your mouth, but mouth breathing does not allow the air to be processed by your nasal cavity.

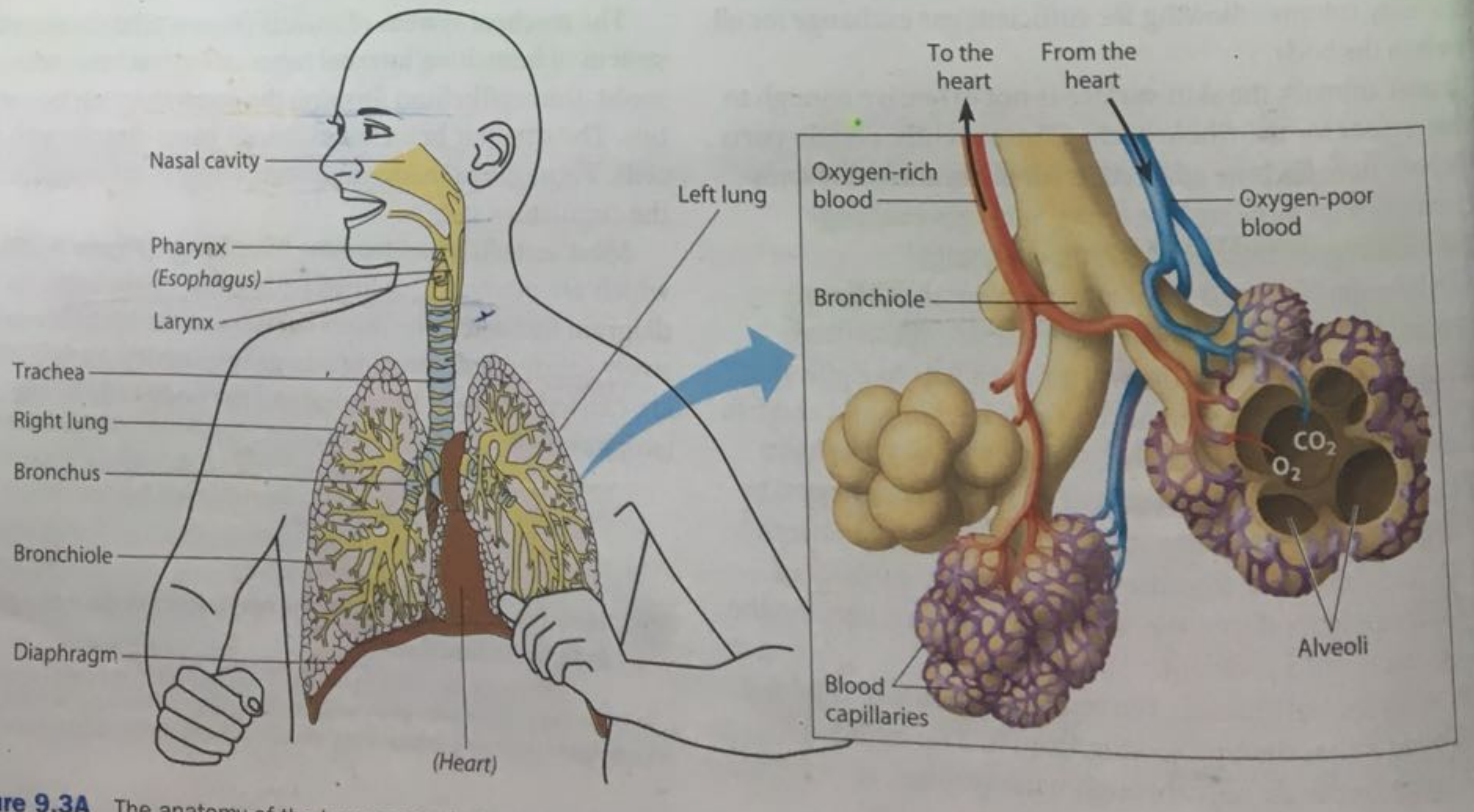
From the nasal cavity or mouth, air passes to the **pharynx**, where the paths for air and food cross. As you will remember from the previous chapter, when you swallow food, the **larynx** (the upper part of the respiratory tract) moves upward and tips the epiglottis over the opening of your **trachea**, or windpipe. The rest of the time, the air passage in the pharynx is open for breathing.

The larynx is often called the voice box. When you exhale, the outgoing air rushes by a pair of **vocal cords** in the larynx, and you can produce sounds by voluntarily tensing muscles that stretch the cords so they vibrate. You produce high-pitched sounds when your vocal cords are tightly stretched and vibrating very fast. When the cords are less tense, they vibrate slowly and produce low-pitched sounds.

From the larynx, air passes into your trachea. Rings of cartilage (shown in the figure in blue) reinforce the walls of the larynx and trachea, keeping this part of the airway open. The trachea forks into two **bronchi** (singular, *bronchus*), one leading to each lung. Within the lung, the bronchus branches repeatedly into finer and finer tubes called **bronchioles**. Bronchitis is a condition in which these small tubes become inflamed and constricted, making breathing difficult.

As the enlargement on the right of Figure 9.3A shows, the bronchioles dead-end in grapelike clusters of air sacs called **alveoli** (singular, *alveolus*). Each of your lungs contains millions of these tiny sacs. Together they have a surface area of about 100 m^2, 50 times that of your skin. The inner surface of each alveolus is lined with a thin layer of epithelial cells. The O_2 in inhaled air dissolves in a film of moisture on the epithelial cells. It then diffuses across the epithelium and into the dense web of blood capillaries that surrounds each alveolus. **Figure 9.3B** is a scanning electron micrograph showing the network of capillaries enclosing the alveoli. (The alveoli in this micrograph appear as empty spaces because the blood vessels were injected with a solution that hardened to form casts of the capillaries, and the tissues of the alveoli were then dissolved.) This close association between capillaries and alveoli also enables CO_2 to diffuse the opposite way—from the capillaries, across the epithelium of the alveolus, into the air space, and finally out in the exhaled air.

▲ **Figure 9.3B** A colorized electron micrograph showing the network of capillaries that surround the alveoli in the lung



▲ **Figure 9.3A** The anatomy of the human respiratory system (left) and details of the alveoli (right)

The major branches of
a moist epithelium covere
The cilia and mucus are th
system. The beating cilia
pollen, and other contam
where it is usually swallov

Respiratory Problems
secretions called **surfact**
sticking shut from the su
Respiratory distress syn
is a common disease see
fore their due dates. Sur
after 33 weeks of embry
curs at 38 weeks. Artific
through a breathing tub
Alveoli are highly sus
Defensive white blood c
particles. However, if to

Transport

9.4 Blood tran

How does oxygen get f
your body, and how do
to your lungs? To answ
basic organization of th
Figure 9.4 is a diagr
your circulatory systen
start with the heart, in
the heart handles oxyg
side handles oxygen-r
left of the diagram, ox
from capillaries in bo
to the alveolar capilla
between air in the alv
diagram). Blood that
the heart and is then
The exchange of g
around them occurs
of pressure. A mixtur
see evidence of gas p
releasing the pressur
in a mixture account
mixture. Thus, each
Molecules of each ki
their own partial pr
the bottom of the fi
rich blood, through
because it diffuses f
region of lower par
gradient as they co
produced as a wast
down its own parti
into the capillaries.
also accounts for g
? What is the ph

ated in the chest

condition in which these small

constricted, making breathing diff

gement on the right of Figure 9.3A

d-end in grapelike clusters of air sa

r, *alveolus*). Each of your lungs conta

s. Together they have a surface area of

s that of your skin. The inner surface of

with a thin layer of epithelial cells. The

lves in a film of moisture on the epi

cross the epithelium and into the de

that surrounds each alveolus. Figure 9

n micrograph showing the network of

eoli. (The alveoli in this micrograph a

cause the blood vessels were injected w

ned to form casts of the capillaries, an

i were then dissolved.) This close a

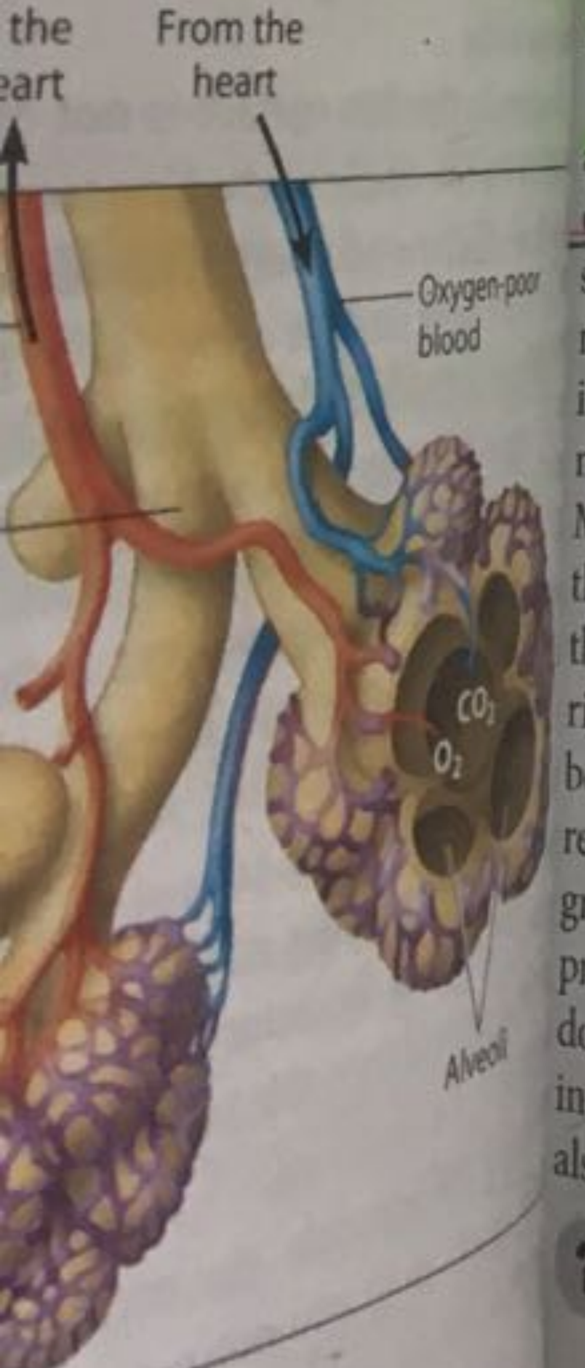
es and alveoli also enables CO_2 to di

om the capillaries, across the epithe

air space, and finally out in the exha

colorized electron micrograph showing t

round the alveoli in the lung



The major branches of your respiratory system are lined by a moist epithelium covered by cilia and a thin film of mucus. The cilia and mucus are the respiratory system's cleaning system. The beating cilia move mucus with trapped dust, pollen, and other contaminants upward to the pharynx, where it is usually swallowed.

Respiratory Problems Alveoli are so small that specialized secretions called **surfactants** are required to keep them from sticking shut from the surface tension of their moist surface. Respiratory distress syndrome due to a lack of lung surfactant is a common disease seen in babies born 6 weeks or more before their due dates. Surfactants typically appear in the lungs after 33 weeks of embryonic development; birth normally occurs at 38 weeks. Artificial surfactants are now administered through a breathing tube to treat such preterm infants.

Alveoli are highly susceptible to airborne contaminants. Defensive white blood cells patrol them and engulf foreign particles. However, if too much particulate matter reaches the alveoli, the delicate lining of these small sacs becomes damaged and the efficiency of gas exchange drops. Studies have shown a significant association between exposure to fine particles and premature death. Air pollution and tobacco smoke are two sources of these lung-damaging particles.

Exposure to such pollutants can cause continual irritation and inflammation of the lungs and lead to chronic obstructive pulmonary disease (COPD). COPD includes two main conditions: emphysema and chronic bronchitis. In emphysema, the delicate walls of alveoli become permanently damaged and the lungs lose the elasticity that helps expel air during exhalation. With COPD, both lung ventilation and gas exchange are severely impaired. Patients experience labored breathing, coughing, and frequent lung infections. COPD is a major cause of disability and death in the United States.

? How does the structure of alveoli match their function?

Alveoli have a thin, moist epithelium across which dissolved O_2 and CO_2 can easily diffuse into or out of the surrounding capillaries. The huge collective surface area of all the alveoli enables the passage of many gas molecules.

Transport of Gases in the Human Body

10 min

9.4 Blood transports respiratory gases

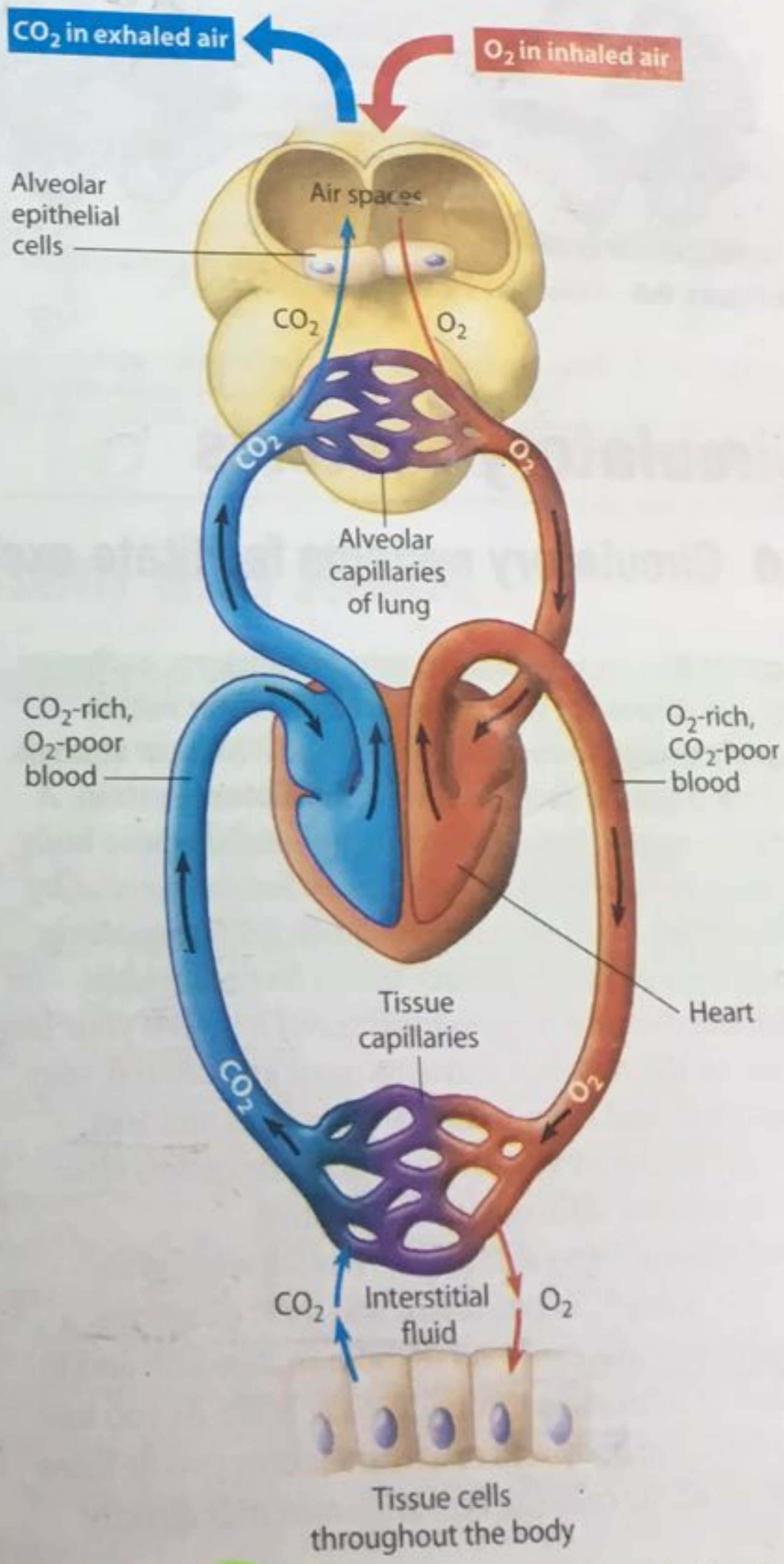
How does oxygen get from your lungs to all the other tissues in your body, and how does carbon dioxide travel from the tissues to your lungs? To answer these questions, we must look at the basic organization of the human circulatory system.

Figure 9.4 is a diagram showing the main components of your circulatory system and their roles in gas exchange. Let's start with the heart, in the middle of the diagram. One side of the heart handles oxygen-poor blood (colored blue). The other side handles oxygen-rich blood (red). As indicated in the lower left of the diagram, oxygen-poor blood returns to the heart from capillaries in body tissues. The heart pumps this blood to the alveolar capillaries in the lungs. Gases are exchanged between air in the alveoli and blood in the capillaries (top of diagram). Blood that has lost CO_2 and gained O_2 returns to the heart and is then pumped out to body tissues.

The exchange of gases between capillaries and the cells around them occurs by the diffusion of gases down gradients of pressure. A mixture of gases, such as air, exerts pressure. You see evidence of gas pressure whenever you open a can of soda, releasing the pressure of the CO_2 it contains. Each kind of gas in a mixture accounts for a portion of the total pressure of the mixture. Thus, each gas has what is called a **partial pressure**. Molecules of each kind of gas will diffuse down a gradient of their own partial pressure independently of the other gases. At the bottom of the figure, for instance, O_2 moves from oxygen-rich blood, through the interstitial fluid, and into tissue cells because it diffuses from a region of higher partial pressure to a region of lower partial pressure. The tissue cells maintain this gradient as they consume O_2 in cellular respiration. The CO_2 produced as a waste product of cellular respiration diffuses down its own partial pressure gradient out of tissue cells and into the capillaries. Diffusion down partial pressure gradients also accounts for gas exchange in the alveoli.

? What is the physical process underlying gas exchange?

Diffusion of each gas down its partial pressure gradient.



▲ **Figure 9.4** Gas transport and exchange in the body

10 min

9.5 Hemoglobin carries O_2, helps transport CO_2, and buffers the blood

Oxygen is not highly soluble in water, and most animals transport O_2 bound to proteins called respiratory pigments. These molecules have distinctive colors, hence the name pigment. Many molluscs and arthropods use a blue, copper-containing pigment. Almost all vertebrates and many invertebrates use **hemoglobin**, an iron-containing pigment that turns red when it binds O_2.

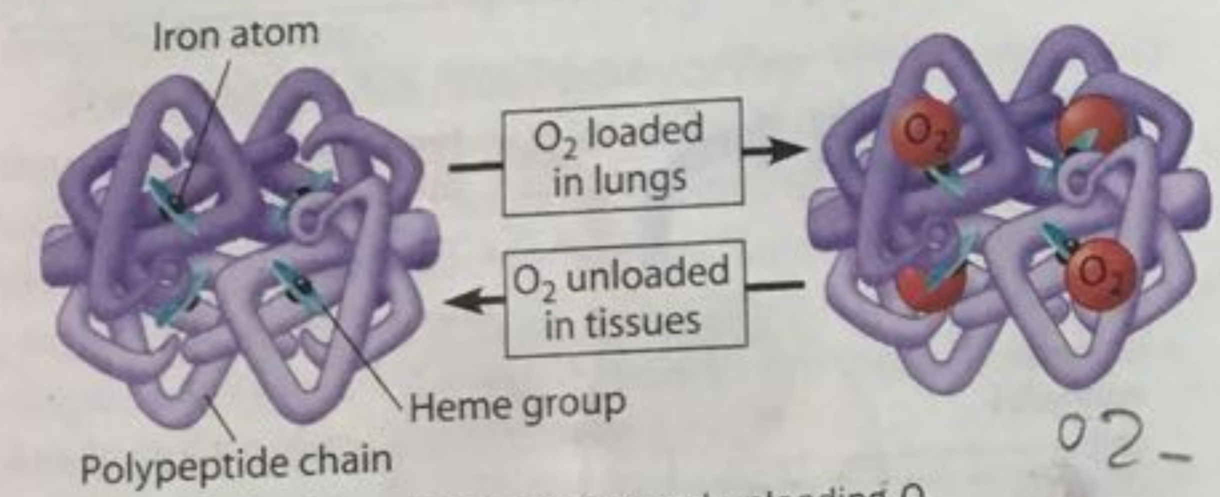
Each of your red blood cells is packed with about 250 million molecules of hemoglobin. A hemoglobin molecule consists of four polypeptide chains of two different types, depicted with two shades of purple in **Figure 9.5**. Attached to each polypeptide is a chemical group called a heme (colored blue in the figure), at the center of which is an iron atom (black). Each iron atom binds one O_2 molecule. Thus, every hemoglobin molecule can carry up to four O_2 molecules. Hemoglobin loads up with O_2 in the lungs and transports it to the body's tissues. There, hemoglobin unloads some or all of its cargo, depending on the O_2 needs of the cells. The partial pressure of O_2 in the tissue reflects how much O_2 the cells are using and determines how much O_2 is unloaded.

Hemoglobin is a multipurpose molecule. It also helps transport CO_2 and assists in buffering the blood. Most of the CO_2 that diffuses from tissue cells into a capillary enters red blood cells, where some of it combines with hemoglobin. The rest reacts with water, forming carbonic acid (H_2CO_3), which then breaks apart into a hydrogen ion (H^+) and a bicarbonate ion (HCO_3^-). This reversible reaction is shown below:

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Water}}{H_2O} \rightleftarrows \underset{\text{Carbonic acid}}{H_2CO_3} \rightleftarrows \underset{\text{Hydrogen ion}}{H^+} + \underset{\text{Bicarbonate ion}}{HCO_3^-}$$

Hemoglobin binds most of the H^+ produced by this reaction, minimizing the change in blood pH. The bicarbonate ions diffuse into the plasma, where they are carried to the lungs.

As blood flows through capillaries in the lungs, the reaction is reversed. Bicarbonate ions combine with H^+ to form carbonic acid; carbonic acid is converted to CO_2 and water; and CO_2 diffuses from the blood to the alveoli and leaves the body in exhaled air.



▲ **Figure 9.5** Hemoglobin loading and unloading O_2

? O_2 in the blood is transported bound to ______ within ______ ______ cells, and CO_2 is mainly transported as ______ ions within the plasma.

hemoglobin . . . red blood . . . bicarbonate

O2 - 104 mmHg - in Alveoli → reach Tissue as 100 mmHg.
O2 - 40 mmHg in Tissue
تركيز CO2 - 45 mmHg - in Tissue
CO2 - 40 mmHg - in lung (alveoli)

Circulatory Systems

9.6 Circulatory systems facilitate exchange with all body tissues

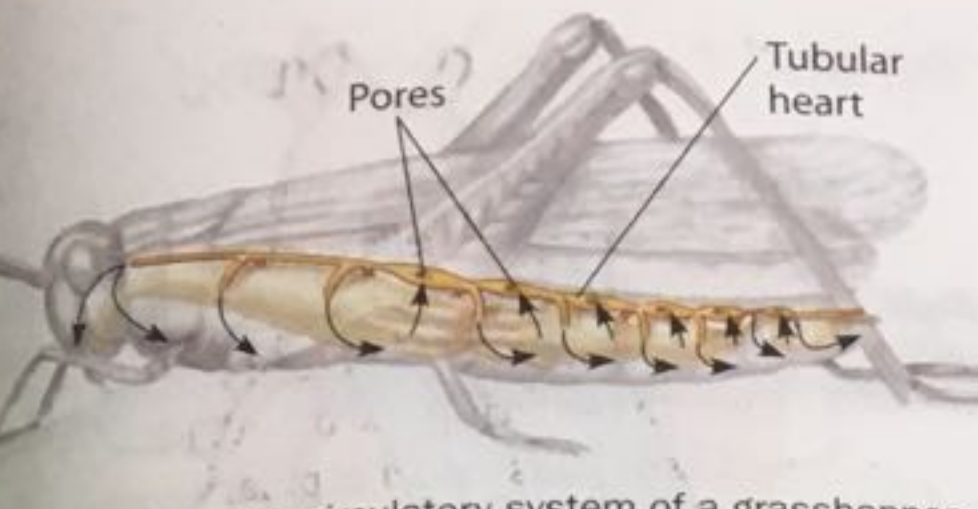
To sustain life, an animal must acquire nutrients, exchange gases, and dispose of waste products, and these needs ultimately extend to every cell in the body. In most animals, these functions are facilitated by a **circulatory system**. A circulatory system is necessary in any animal whose body is too large or too complex for such exchange to occur by diffusion alone. Diffusion is inadequate for transporting materials over distances greater than a few cell widths—far less than the distance oxygen must travel between your lungs and brain or the distance nutrients must go between your small intestine and the muscles in your arms and legs. An internal transport system must bring resources close enough to cells for diffusion to be effective.

Several types of internal transport have developed in animals. For example, in cnidarians and most flatworms, a central gastrovascular cavity serves both in digestion and in distribution of substances throughout the body. As you saw in Figure 8.3A, the body wall of a hydra is only two or three cells thick, so all the cells can exchange materials directly with the water surrounding the animal or with the fluid in its gastrovascular cavity. Nutrients and other materials have only a short distance to diffuse between cell layers.

A gastrovascular cavity is not adequate for animals with thick, multiple layers of cells. Such animals require a true circulatory system, which consists of a muscular pump (heart), a circulatory fluid, and a set of tubes (vessels) to carry the circulatory fluid.

الاوعية

Two basic types of circulatory systems have developed in animals. Many invertebrates, including most molluscs and all arthropods, have an **open circulatory system**. The system is called "open" because fluid is pumped through open-ended vessels and flows out among the tissues; there is no distinction between the circulatory fluid and interstitial fluid. In an insect such as the grasshopper (**Figure 9.6A**), pumping of the tubular heart drives body fluid into the head and the rest of the body (black arrows). Body movements help circulate the fluid as materials are exchanged with body cells. When the heart relaxes, fluid enters through several pores. Each pore has a valve

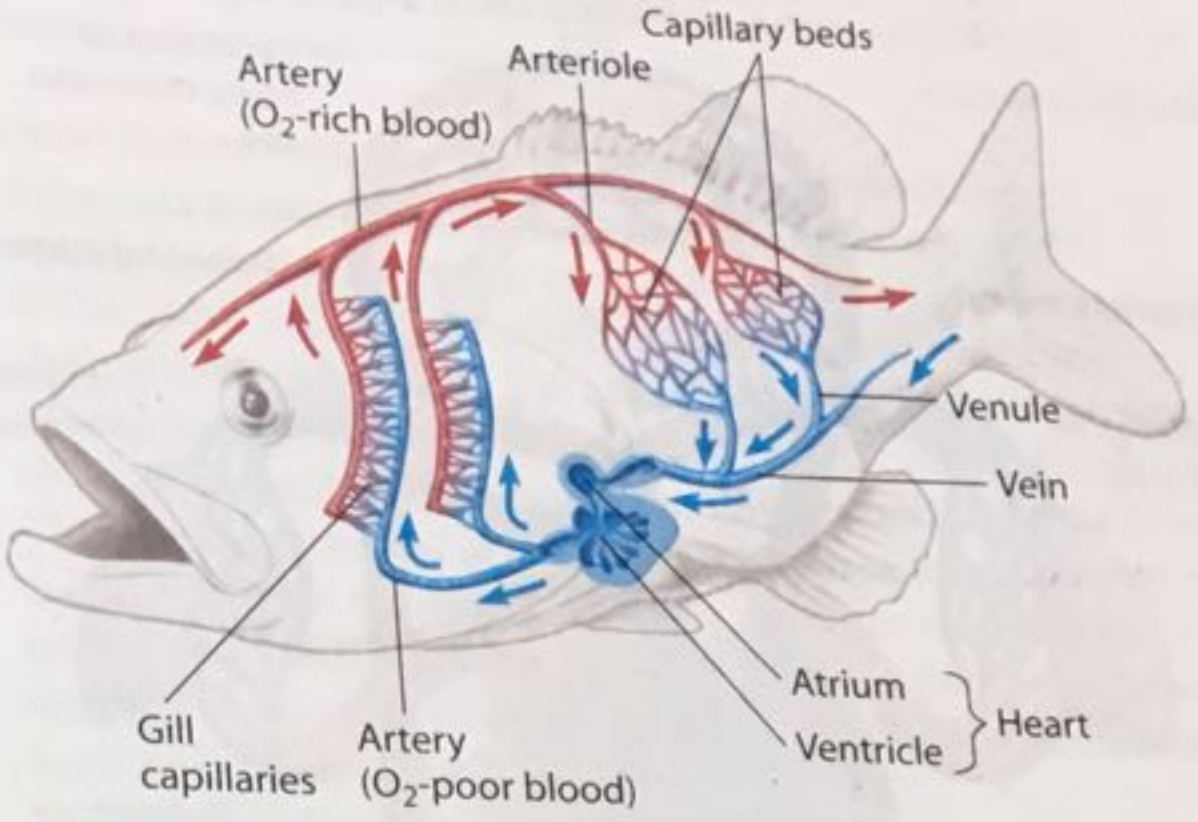


▲ **Figure 9.6A** The open circulatory system of a grasshopper

that closes when the heart contracts, preventing backflow of the circulating fluid. In insects, respiratory gases are conveyed to and from body cells by the tracheal system (not shown here), not by the circulatory system.

Earthworms, squids, octopuses, and vertebrates (such as ourselves and giraffes) all have a **closed circulatory system**. It is called "closed" because the circulatory fluid, **blood**, is confined to vessels, keeping it distinct from the interstitial fluid. There are three kinds of vessels: **Arteries** carry blood away from the heart to body organs and tissues; **veins** return blood to the heart; and **capillaries** convey blood between arteries and veins within each tissue. The vertebrate circulatory system is often called a **cardiovascular system** (from the Greek *kardia*, heart, and Latin *vas*, vessel). How extensive are the vessels in your cardiovascular system? If all your blood vessels were lined up end to end, they would circle Earth's equator twice.

The cardiovascular system of a fish **(Figure 9.6B)** illustrates some key features of a closed circulatory system. The heart of a fish has two main chambers. The **atrium** (plural, *atria*) receives blood from the veins, and the **ventricle** pumps blood to the gills via large arteries. As in all figures depicting closed circulatory systems in this book, red represents oxygen-rich blood and blue represents oxygen-poor blood. After passing through the gill capillaries, the blood, now oxygen-rich, flows into large arteries that carry it to all other parts of the body. The large arteries branch into **arterioles**, small vessels that give rise to capillaries. Networks of capillaries called **capillary beds** infiltrate every organ and tissue in the body. The thin walls of the capillaries allow chemical exchange between the blood and the interstitial fluid. The capillaries converge into **venules**, which in turn converge into larger veins that return blood to the heart.



▲ **Figure 9.6B** The closed circulatory system of a fish

? **What are the key differences between an open circulatory system and a closed circulatory system?**

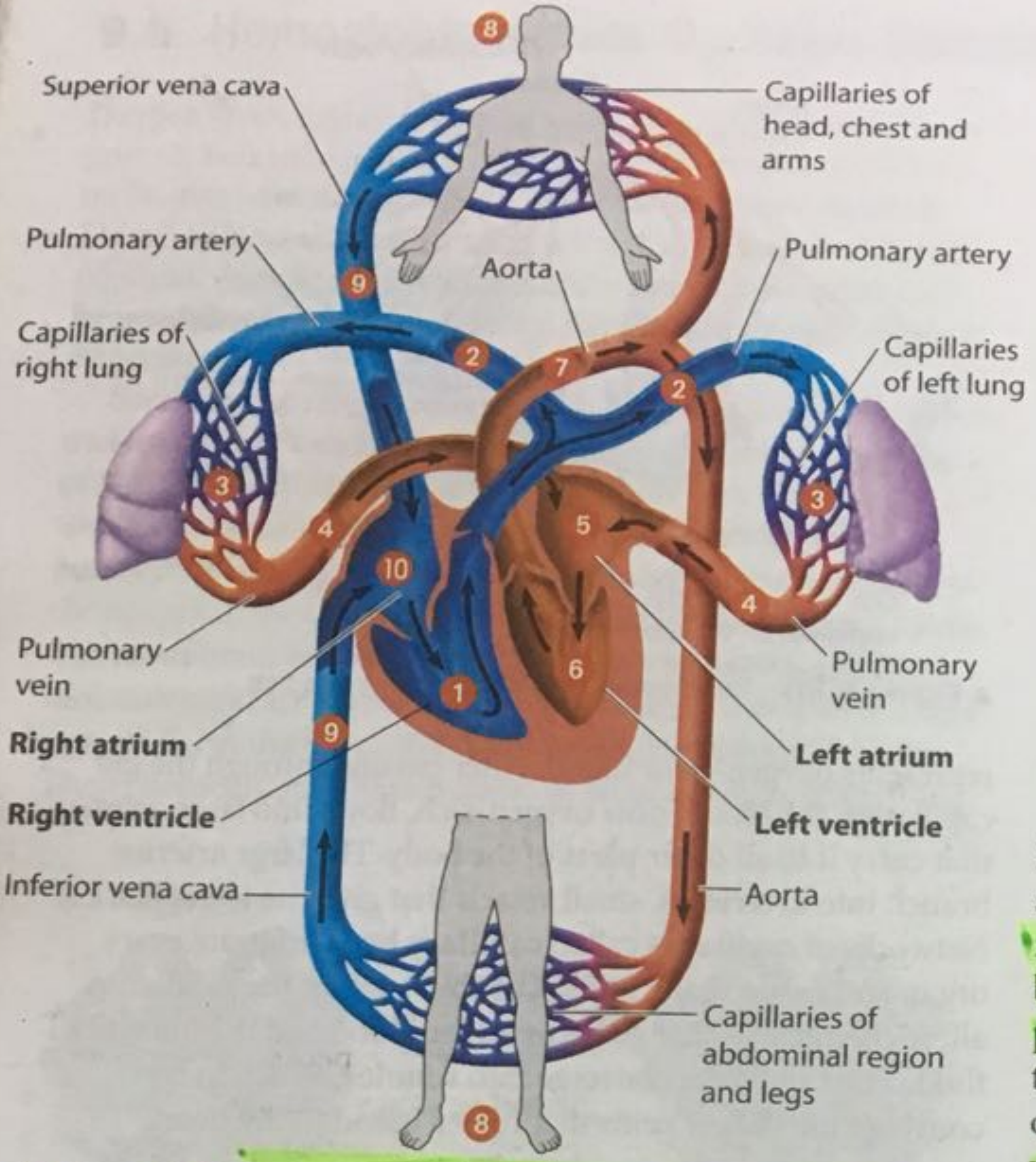
The Human Cardiovascular System and Heart

9.7 The human cardiovascular system illustrates the double circulation of mammals

Let's follow the flow of blood through the human circulatory system. Starting in the right ventricle in **Figure 9.7A**, we trace the pulmonary circuit first. ① The right ventricle pumps oxygen-poor blood to the lungs via ② the **pulmonary arteries**. As blood flows through ③ capillaries in the lungs, it takes up O_2 and unloads CO_2. Oxygen-rich blood flows back through ④ the **pulmonary veins** to ⑤ the left atrium. Next, the oxygen-rich blood flows from the left atrium into ⑥ the left ventricle.

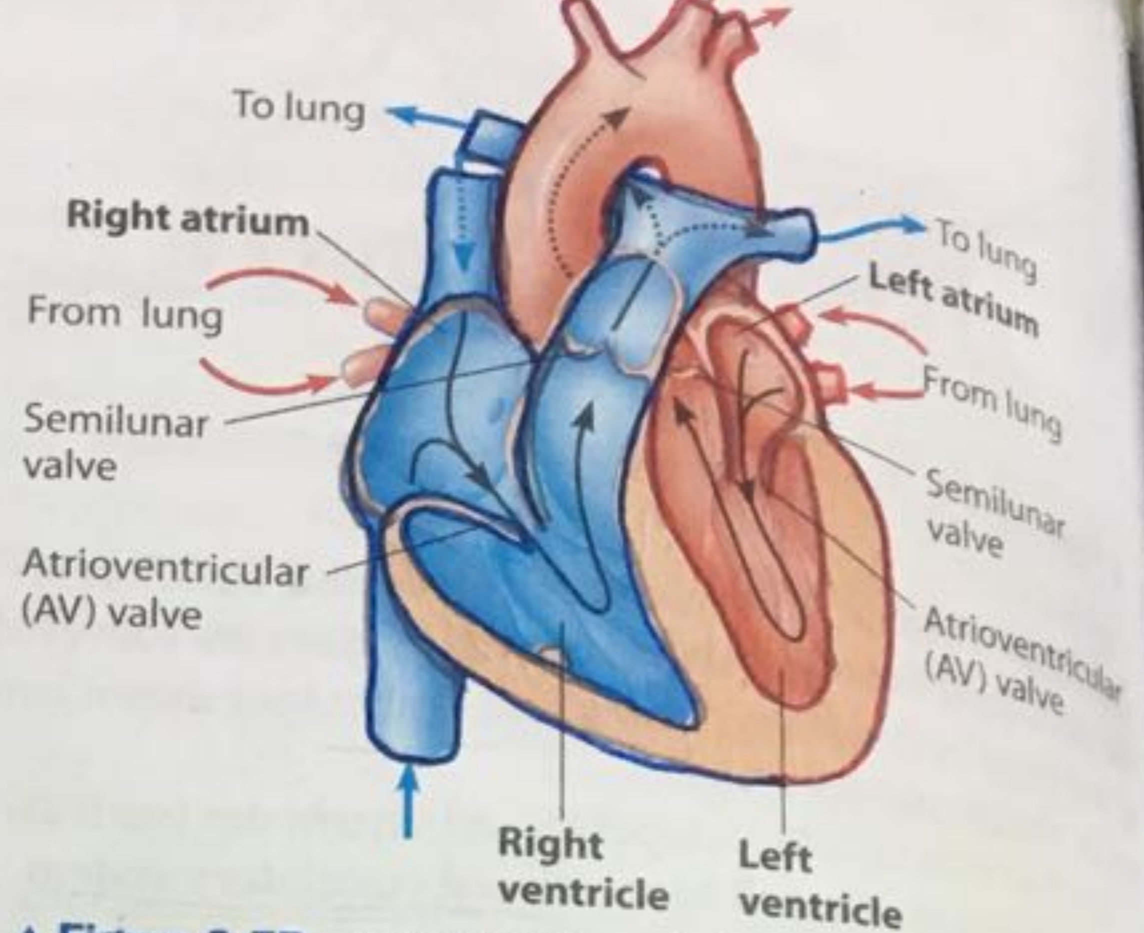
Now let's trace the systemic circuit. As Figure 9.7A shows, the left ventricle pumps oxygen-rich blood into ⑦ the **aorta**. The aorta is our largest blood vessel, with a diameter of about 2.5 cm, roughly equal to the diameter of a quarter. The first branches from the aorta are the coronary arteries (not shown), which supply blood to the heart muscle itself. Next there are large branches leading to ⑧ the head, chest, and arms, and the abdominal regions and legs. For simplicity, Figure 9.7A does not show the individual organs, but within each organ, arteries lead to arterioles t branch into capillaries. The capillaries rejoin as venules, which lead to veins. ⑨ Oxygen-poor blood from the up part of the body is channeled into a large vein called the **superior vena cava**, and from the lower part of the bod flows through the **inferior vena cava**. The two venae ca empty into ⑩ the right atrium. As the blood flows fron the right atrium into the right ventricle, we complete o journey, only to start the pulmonary circuit again at th right ventricle.

Remember that the path of any single red blood cel always heart to lung capillaries to heart to body tissue



▲ **Figure 9.7A** Blood flow through the double circulation of the human cardiovascular system

capillaries and back to heart. In one systemic circuit, a blood cell may travel to the brain; in the next (after a pulmonary circuit), it may travel to the legs. A red blood cell never travels from the brain to the legs without first returning to the heart and being pumped to the lungs to be recharged with oxygen.



▲ **Figure 9.7B** Blood flow through the human heart

Figure 9.7B shows the path of blood through the human heart. About the size of a clenched fist, your heart is enclosed in a sac just under the sternum (breastbone). The heart is formed mostly of cardiac muscle tissue. Its thin-walled atria collect blood returning to the heart. The thicker-walled ventricles pump blood to the lungs and to all other body tissues. Notice that the left ventricle walls are thicker than the right, a reflection of how much farther it pumps blood in the body. Flap-like valves between the atria and ventricles and at the openings to the pulmonary artery and the aorta regulate the direction of blood flow. We'll look at these valves and the functioning of the heart in the next module.

? Why does blood in the pulmonary veins have more O_2 than blood in the venae cavae, which are also veins?

● Pulmonary veins carry blood from the lungs, where it picks up O_2, to the heart. The venae cavae carry blood returning to the heart after delivering O_2 to body tissues.

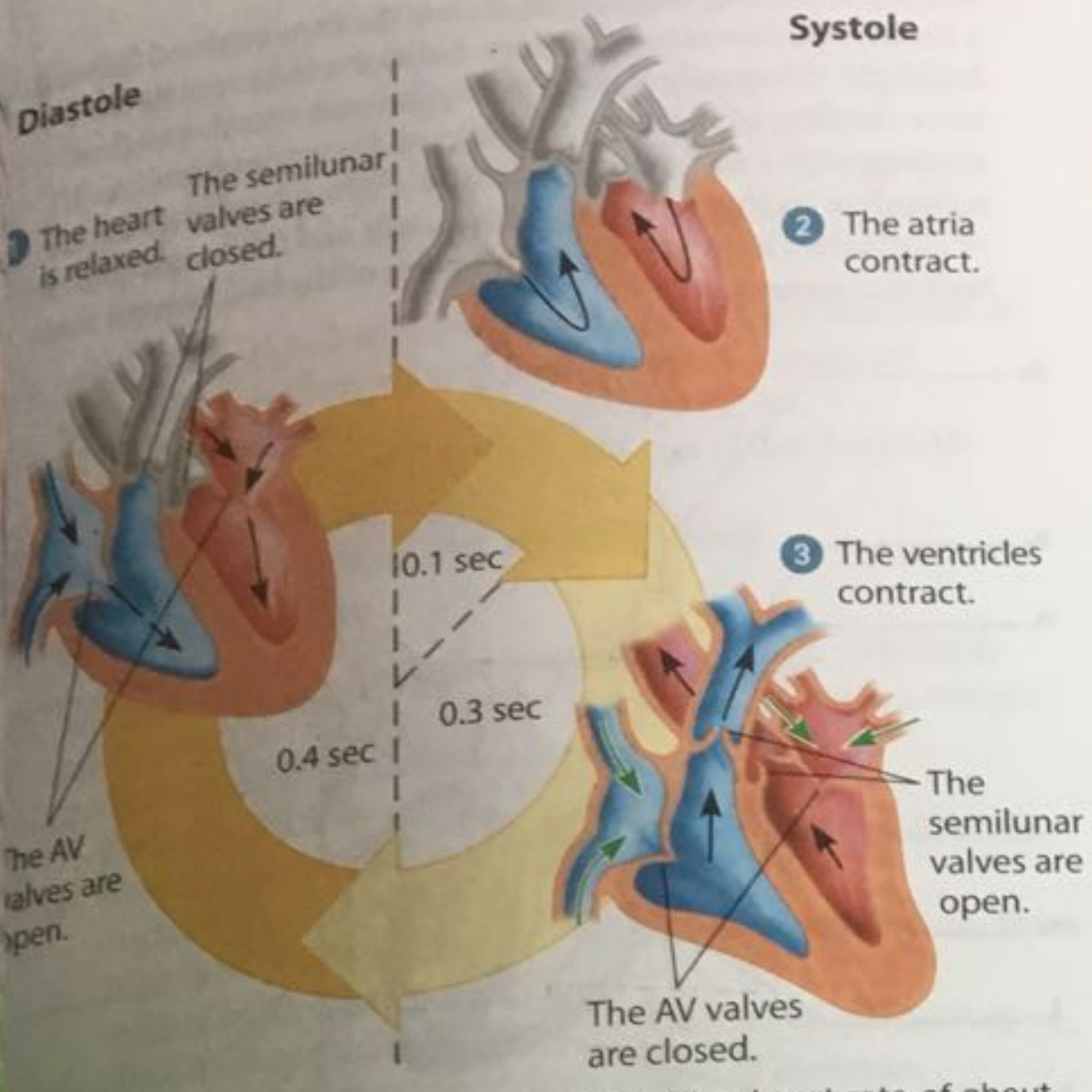
9.8 The heart contracts and relaxes rhythmically

The four-chambered heart is the hub of the circulatory system. It separately but simultaneously pumps oxygen-poor blood to the lungs and oxygen-rich blood to the body. Its pumping action occurs as a rhythmic sequence of contraction and relaxation, called the **cardiac cycle.** When the heart contracts, it pumps blood; when it relaxes, blood fills its chambers.

The Cardiac Cycle How long does a cardiac cycle take? If you have a heart rate of 72 beats per minute, your cardiac cycle takes about 0.8 second. **Figure 9.8** shows that when the heart is relaxed, in the phase called ① **diastole,** blood flows into all four of its chambers. Blood enters the right atrium from the venae cavae and the left atrium from the pulmonary veins (see Figure 9.7A). The valves between the atria and the ventricles (atrioventricular, or AV, valves) are open. The valves leading from the ventricles to the aorta or pulmonary artery (semilunar valves) are closed. Diastole lasts about 0.4 second, during which the ventricles nearly fill with blood.

The contraction phase of the cardiac cycle is called systole. ② Systole begins with a very brief (0.1-second) contraction of the atria that completely fills the ventricles with blood (atrial systole). ③ Then the ventricles contract for about 0.3 second (ventricular systole). The force of their contraction closes the AV valves, opens the semilunar valves located at the exit from each ventricle, and pumps blood into the large arteries. Blood flows into the relaxed atria during the second part of systole, as the green arrows in step 3 indicate.

Because it pumps blood to your whole body, the left ventricle contracts with greater force than the right. Both ventricles, however, pump the same volume of blood. The volume of blood that each ventricle pumps per minute is called **cardiac output.** This volume is equal to the amount of blood pumped each time a ventricle contracts (about 70 mL, or a little more than $\frac{1}{4}$ cup, for the average person) times the **heart rate** (number of beats per minute). At an average resting heart rate of 72 beats per minute, cardiac output would be



▲ **Figure 9.8** A cardiac cycle in a human with a heart rate of about 72 beats a minute

calculated as 70 mL/beat × 72 beats/min = about 5 L/min, roughly equivalent to the total volume of blood in your body. Thus, a drop of blood can travel the entire systemic circuit in just 1 minute.

Heart rate and cardiac output vary, depending on age, fitness, and other factors. Both increase, for instance, during heavy exercise, in which cardiac output can increase fivefold, enabling the circulatory system to provide the additional oxygen needed by hardworking muscles. A well-trained athlete's heart may strengthen and enlarge with a resulting increase in the volume of blood a ventricle pumps. Thus, a resting heart rate of an athlete may be as low as 40 beats/min and still produce a normal cardiac output of about 5 L/min. During competition, a trained athlete's cardiac output may increase sevenfold.

Heart Valves Notice again in Figure 9.8 how the heart valves act as one-way doors at the exits of the atria and ventricles during a cardiac cycle. Made of flaps of connective tissue, these valves open when pushed from one side and close when pushed from the other. The powerful contraction of the ventricles forces blood against the AV valves, which closes them and keeps blood from flowing back into the atria. The semilunar valves are pushed open when the ventricles contract. When the ventricles relax, blood in the arteries starts to flow back toward the heart, causing the flaps of the semilunar valves to close and preventing blood from flowing back into the ventricles.

You can follow the closing of the two sets of heart valves either with a stethoscope or by pressing your ear tightly against the chest of a friend. The sound pattern is "lub-dup, lub-dup, lub-dup." The "lub" sound comes from the recoil of blood against the closed AV valves. The "dup" is produced by the recoil of blood against the closed semilunar valves.

Someone who is trained can detect the hissing sound of a **heart murmur**, which may indicate a defect in one or more of the heart valves. A murmur occurs when a stream of blood squirts backward through a valve. Some people are born with murmurs, while others have their valves damaged by infection (from rheumatic fever, for instance). Most valve defects do not reduce the efficiency of blood flow enough to warrant surgery. Those that do can be corrected by replacing the damaged valves with synthetic ones or with valves taken from an organ donor (human or other animal).

? During a cardiac cycle of 0.8 second, the atria are generally relaxed for ______ second.

● 0.7

CHAPTER 9 REVIEW

Reviewing the Concepts

Mechanisms of Gas Exchange (9.1–9.2)

9.1 Overview: Gas exchange in humans involves breathing, transport of gases, and exchange with body cells. Gas exchange, the interchange of O_2 and CO_2 between an organism and its environment, provides O_2 for cellular respiration and removes its waste product, CO_2.

9.2 Animals exchange O_2 and CO_2 across moist body surfaces. Respiratory surfaces must be thin and moist for diffusion of O_2 and CO_2 to occur. Some animals use their entire skin as a gas exchange organ. In most animals, gills, a tracheal system, or lungs provide large respiratory surfaces for gas exchange.

The Human Respiratory System (9.3)

9.3 In mammals, branching tubes convey air to lungs located in the chest cavity. Inhaled air passes through the pharynx and larynx into the trachea, bronchi, and bronchioles to the alveoli. Mucus and cilia in the respiratory passages protect the lungs.

Transport of Gases in the Human Body (9.4–9.5)

9.4 Blood transports respiratory gases. The heart pumps oxygen-poor blood to the lungs, where it picks up O_2 and drops off CO_2. Oxygen-rich blood returns to the heart and is pumped to body cells, where it drops off O_2 and picks up CO_2.

9.5 Hemoglobin carries O_2, helps transport CO_2, and buffers the blood.

Circulatory Systems (9.6)

9.6 Circulatory systems facilitate exchange with all body tissues. Gastrovascular cavities function in both digestion and transport. In open circulatory systems, a heart pumps fluid through open-ended vessels to bathe tissue cells directly.In closed circulatory systems, a heart pumps blood, whichtravels through arteries to capillaries to veins and back tothe heart.