CELLS AND HOW THEY WORK

3

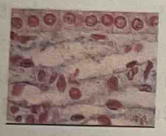
LINKS TO EARLIER CONCEPTS

The living cell is one of the first levels of organization in nature (1.2).

This chapter explains how lipids are organized to form cell membranes (2.10). You will learn where DNA and RNA are found in cells (2.13) and which cell parts build large molecules from carbohydrates and amino acids (2.9, 2.11, 2.12).

The chapter explains how water and solutes move into and out of cells (2.5). It also considers how cells make and use molecules of ATP to fuel their activities (2.13).

KEY CONCEPTS



Basic Cell Features

Cells have an outer plasma membrane, and they contain cytoplasm and DNA. Most cells can only be seen with a microscope. Cells of all complex organisms contain compartments called organelles. Sections 3.1–3.4

Cells and Their Parts

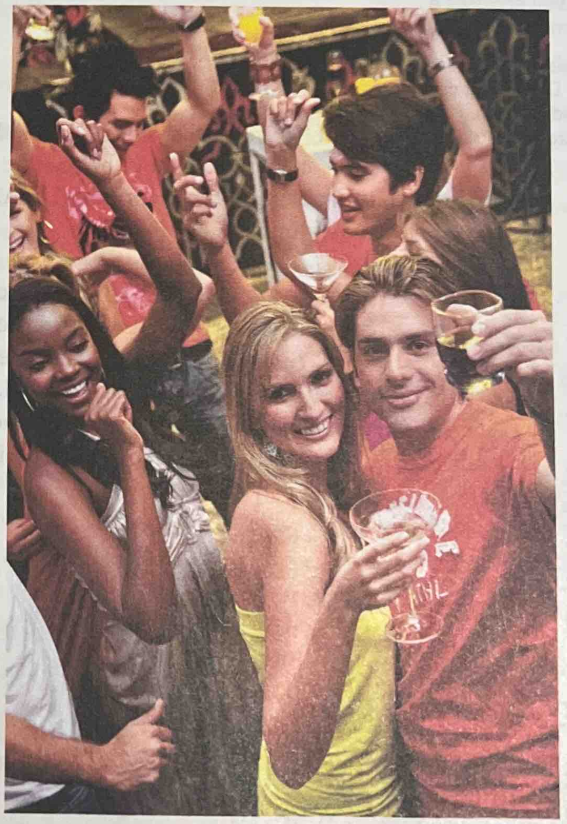
Cell organelles have specialized functions. The plasma membrane controls the movement of substances into and out of the cell. The nucleus is a control center that contains the cell's DNA. Sections 3.6–3.12

Energy for Cell Activities

Organelles called mitochondria use organic compounds to make ATP—a nucleotide that is the main fuel for cell activities. Sections 3.13–3.17

Top: G.L. Decker, Baylor College of Medicine; Middle: © Cengage Learning; Bottom: © Cengage Learning

Ethyl alcohol, the form in alcoholic drinks, is a powerful drug. For starters, it triggers the release of acid that irritates cells in the stomach lining. Even moderate drinkers may develop ulcers and be at higher risk for cancers of the mouth, throat, and esophagus. Alcohol also slows the operations of brain cells. Long-term, heavy use may damage a drinker's memory, reflexes, and other functions. Binge drinking—five or more drinks in a brief period—can be deadly because the flood of alcohol can stop the heart. Liver cells detoxify 95 percent of the alcohol a person drinks, but in the long run this "detox" may cause alcohol-related hepatitis and cirrhosis. Every day we make choices about what we eat and drink. And in one way or another, everything that enters the body affects the ability of our cells to carry out the tasks that keep us alive.



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Homeostasis Preview

This chapter discusses how cells bring in some substances, keep others out, and make and release still others. These activities constantly change the chemical and physical conditions in which cells operate.

3.1 What Is a Cell?

- From its size and shape to the structure of its parts, a cell is built to carry out life functions efficiently.
- Links to Life's characteristics 1.1, 1.2, Phospholipids 2.10

cell theory Scientific theory stating that cells are the smallest units of life, all organisms consist of one or more cells, and all cells come from pre-existing ones.

cytoplasm Contents of a cell between the outer plasma membrane and the nucleus.

cytosol Jellylike fluid portion of a cell's cytoplasm.

eukaryotic cell Cell that has a nucleus containing its DNA.

organelle Any of the compartments and sacs in a cell.

plasma membrane Covering that encloses a cell's internal parts.

prokaryotic cell Cell in which the DNA is not contained inside a nucleus; bacteria are prokaryotic cells.

There are trillions of cells in your body, and each one is a highly organized bit of life. A desire to understand cells led early biologists to develop the **cell theory**:

1. **Every organism is composed of one or more cells.**
2. **The cell is the smallest unit having the properties of life.**
3. **All cells come from pre-existing cells.**

Today we also know that chemical reactions occur in cells, and that cells contain and can pass on the hereditary material DNA.

All cells are alike in three ways

All living cells have three things in common. They have an outer **plasma membrane**, they contain DNA, and they contain cytoplasm.

The plasma membrane This outer covering encloses the cell's internal parts, so that cell activities can go on apart from events that may be taking place outside the cell. Substances can enter or leave the cells by moving across the membrane in ways described later in this chapter.

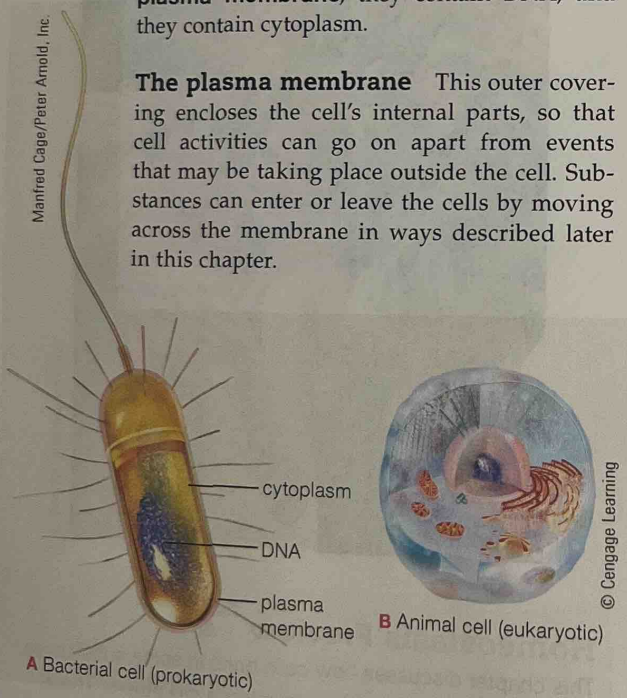


Figure 3.1 Animated! There are two basic types of cells. **A** A prokaryotic cell. **B** A eukaryotic cell, which has many types of organelles, including a nucleus.

TABLE 3.1 Eukaryotic and Prokaryotic Cells Compared

	Eukaryotic	Prokaryotic
Plasma membrane	yes	yes
Region that contains DNA	yes	yes
Cytoplasm	yes	yes
Nucleus inside a membrane	yes	no

DNA Cells contain DNA. Cells also contain molecules that can copy or "read" the genetic instructions DNA carries.

Cytoplasm **Cytoplasm** (SIGH-toe-plaz-um) is everything between the plasma membrane and the region of DNA. It consists of a thick, jellylike fluid called the **cytosol**, and various other components.

There are two basic kinds of cells

Cells are classified into two basic kinds, depending on how they are organized internally (Table 3.1). In a **prokaryotic cell** (pro-care-ee-AH-tik, meaning "before the nucleus") nothing separates the cell's DNA from other internal cell parts. Bacteria, like the one diagrammed in Figure 3.1A, are prokaryotic cells.

Cells that have their DNA inside a nucleus are called **eukaryotic cells** (YEW-care-ee-ah-tik, "true nucleus"). The nucleus is one of numerous **organelles** ("little organs") in eukaryotic cells (Figure 3.1B). Organelles are compartments or sacs. We will discuss them more fully in Section 3.2.

Most cells have a large surface area compared to their volume

A few cells—including the yolks of chicken eggs—can be seen with the unaided eye, but most cells are so small that they can only be seen with a microscope. For instance, a

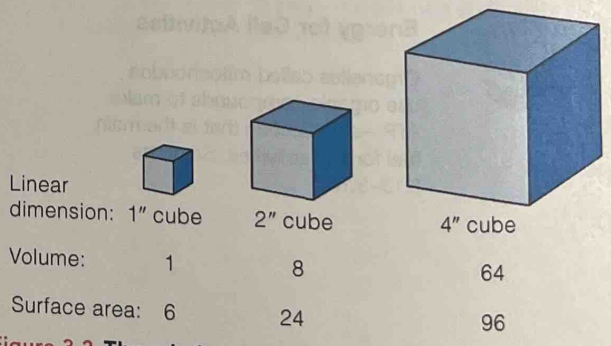
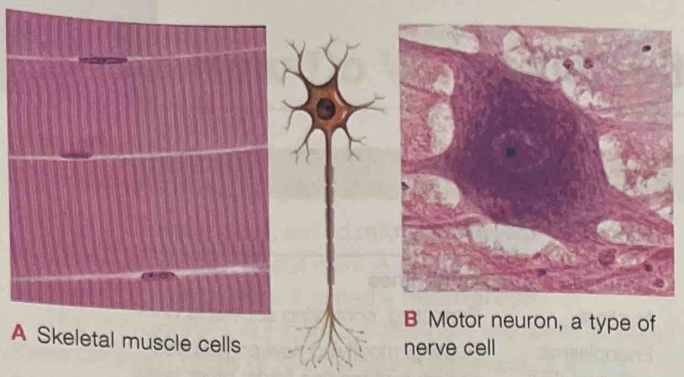
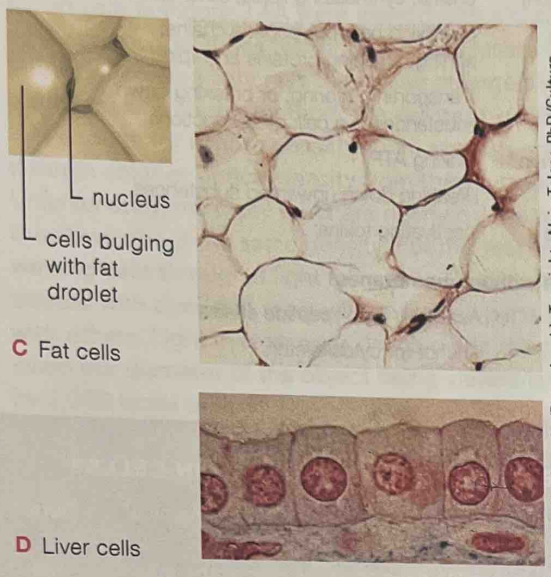


Figure 3.2 The relationship of surface to volume influences the size of cells. Here boxes represent cells. If the linear dimensions of a box double, the volume increases 8 times but the surface area increases only 4 times. As in the text example, if the linear dimensions increase by 4 times, the volume is 64 times greater but the surface area is only 16 times larger.



A Skeletal muscle cells

B Motor neuron, a type of nerve cell



C Fat cells

D Liver cells

Top left: Ed Reschke/Peter Arnold; Top right: Alvin Telser, PhD/Cultura RM/Alamy; Middle: © University of Cincinnati, Raymond Walters College, Biology; Bottom: G.L. Decker, Baylor College of Medicine

Figure 3.3 Human cells come in many shapes and sizes. **A Cells of skeletal muscles are long and slender.** **B A motor neuron, a type of nerve cell, has slender extensions.** **C The cells that make up body fat are rounded and contain whitish lipid molecules.** **D These boxy-looking liver cells are shown in cross section. Each cell's nucleus looks reddish because it has been stained with dye.**

human red blood cell is so tiny that you could line up 2,000 of them across your thumbnail.

The **surface-to-volume ratio** is responsible for the small size of cells. This ratio is a physical relationship. It dictates that as the linear dimensions of a three-dimensional object increase, the volume of the object increases faster than its surface area does (Figure 3.2). For instance, if a round cell grew like an inflating balloon so that its diameter increased to 4 times the starting girth, the volume inside the cell would be 64 times more than before, but the cell's surface would be just 16 times larger. The cell would not have enough surface area to allow nutrients to flow inward rapidly, or for wastes or cell products to move rapidly outward. A large, round cell also would have trouble moving materials through its cytoplasm. In short order the cell would die.

In small cells, though, random motions of molecules easily distribute materials. If a cell isn't small, it likely is long and thin or has folds that increase its surface area relative to its volume. The smaller or narrower or more frilly the cell, the more efficiently materials can cross its surface and disperse inside it. Figure 3.3 shows four of the many shapes

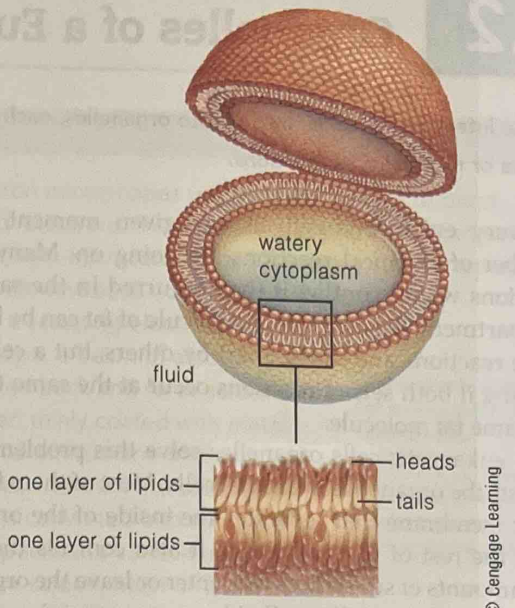


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Figure 3.4 Animated! In cell membranes, phospholipids are arranged in a bilayer.

of cells in your own body. Figure 3.3A depicts long, slender cells in a type of muscle called skeletal muscle. In the biceps of your upper arm they are many inches long—as long as the muscle itself.

Membranes enclose cells and organelles

Membranes enclose a eukaryotic cell and its organelles. Most molecules in cell membranes are phospholipids (Section 2.10). You may remember that a phospholipid has a hydrophilic (water-loving) head and two fatty acid tails, which are hydrophobic (water-fearing). In cell membranes, phospholipids organize into two layers with all the hydrophobic tails sandwiched between all the heads (Figure 3.4). This heads-out, tails-in arrangement is called a **lipid bilayer**. All cell membranes have the lipid bilayer structure. The hydrophilic heads of the phospholipids are dissolved in the watery fluids inside and outside cells.

lipid bilayer Structure of the plasma membrane, in which two parallel layers of phospholipids form with their heads facing outward and their tails facing inward.

surface-to-volume ratio Physical relationship by which the volume of a growing three-dimensional object increases faster than its surface area does.

TAKE-HOME MESSAGE

WHAT BASIC COMPONENTS DO ALL LIVING CELLS SHARE?

- All living cells have an outer plasma membrane, cytoplasm inside the membrane, and the genetic material DNA.
- Eukaryotic cells make up complex organisms such as humans. A eukaryotic cell's DNA is contained in the nucleus, an organelle.
- Prokaryotic cells, such as bacteria, have DNA but no nucleus.
- The surface-to-volume ratio limits cell size.
- A cell's membranes consist mainly of phospholipids arranged in a lipid bilayer.

3.2 Organelles of a Eukaryotic Cell

■ **The interior of a cell is divided into organelles, each with one or more special functions.**

In every eukaryotic cell, at any given moment, a vast number of chemical reactions are going on. Many of the reactions would conflict if they occurred in the same cell compartment. For example, a molecule of fat can be built by some reactions and taken apart by others, but a cell gains nothing if both sets of reactions occur at the same time on the same fat molecule.

In eukaryotic cells organelles solve this problem. Table 3.2 lists the organelles in animal cells. Most of them have an outer membrane that separates the inside of the organelle from the rest of the cytoplasm. It also controls the types and amounts of substances that enter or leave the organelle. For example, organelles called lysosomes contain enzymes that break down various unwanted substances. If the enzymes escaped from the organelle, they could destroy the entire cell. A membrane is not present in the organelles called ribosomes and centrioles.

Organelles also may serve as "way stations" for operations that occur in steps. For example, proteins are assembled and modified in steps involving several organelles.

Figure 3.5 shows where organelles and some other structures might be located in a body cell. This is only a general picture of cells. There are major differences in the structures and functions of cells in different tissues.

TABLE 3.2 Organelles of Animal Cells

Name	Function
Organelles with membranes	
Nucleus	Protecting, controlling access to DNA
Endoplasmic reticulum (ER)	Routing, modifying new polypeptide chains; synthesizing lipids; other tasks
Golgi body	Modifying new polypeptide chains; sorting, shipping proteins and lipids
Vesicles	Transporting, storing, or breaking down substances in a cell; other functions
Mitochondrion	Making ATP
Lysosome	Breaking down unwanted substances
Peroxisome	Inactivating toxins
Organelles without membranes	
Ribosomes	Assembling polypeptide chains
Centriole	Anchor for cytoskeleton

TAKE-HOME MESSAGE

WHY ARE ORGANELLES IMPORTANT IN CELLS?

- Organelles isolate and physically organize chemical reactions in cells.
- Nearly all organelles have an outer membrane that separates the inside of the organelle from the cytosol and the rest of the cytoplasm.
- Organelles also provide separate locations for activities that occur in a sequence of steps.

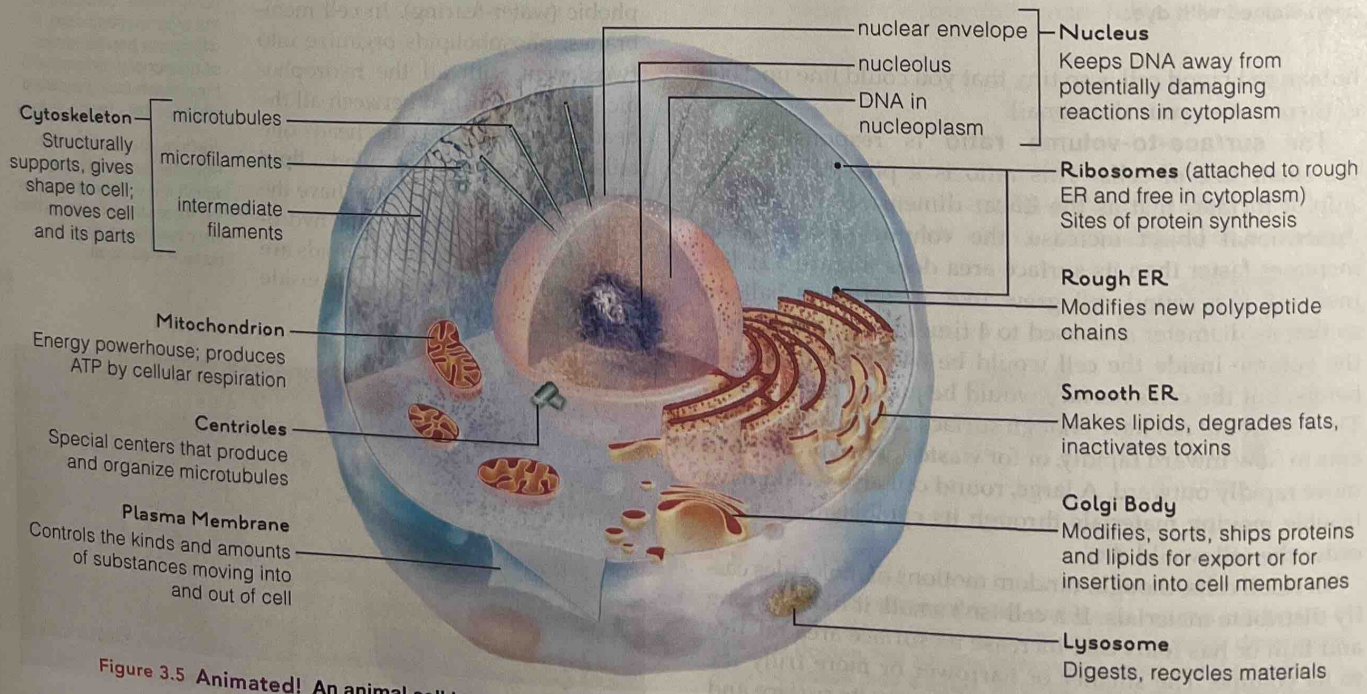


Figure 3.5 Animated! An animal cell has a variety of internal parts. (© Cengage Learning)

3.3 How Do We See Cells?

SCIENCE COMES TO LIFE

The use of microscopes, called **microscopy**, has allowed us to learn a great deal about cells. A photograph of an image formed by a microscope is called a **micrograph**.

The micrographs in Figure 3.6 compare the sorts of detail three different types of microscopes can reveal. The red blood cells in Figure 3.6A were viewed with a compound light microscope. It has two or more glass lenses that bend (refract) incoming light rays to form an enlarged image of a specimen. With this method, the cell must be small or thin enough for light to pass through, and its parts must differ in color or optical density from their surroundings. Unfortunately, most cell parts are nearly colorless and they have about the same density. For this reason, before viewing cells through a light microscope, cells often are treated with dyes that react with some cell parts but not with others. Light microscopes only provide sharp images when the diameter of the object being viewed is magnified by 2,000 times or less.

Electron microscopes use magnetic lenses to bend beams of electrons. They reveal smaller details than even the best light microscopes can. There are several types, with new innovations occurring often.

With a scanning electron microscope, a beam of electrons is directed back and forth across a specimen thinly coated with metal. The metal emits some of its own electrons, and then the electron energy is converted into an image of the specimen's surface on a television screen. Most of the images have fantastic depth (Figure 3.6B).

micrograph Photograph of an image formed by a microscope.

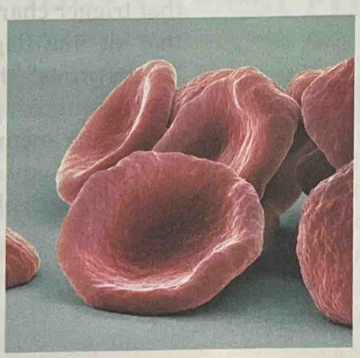
microscopy Use of a microscope to view objects including cells, that are not visible to the unaided eye.

A transmission electron microscope (Figure 3.6C) uses a magnetic field as the "lens" that bends a stream of electrons and focuses it into an image.

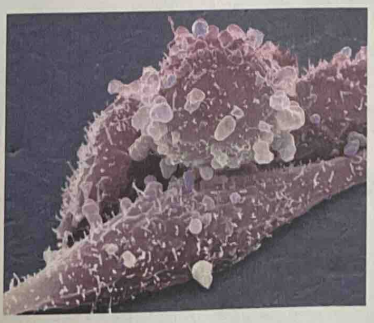
A Compound light microscope

This image shows red blood cells inside a small blood vessel, as revealed by a light microscope. You may use this type of microscope in your biology class laboratory.

B Scanning electron micrographs

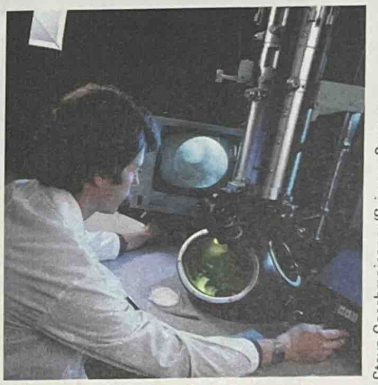


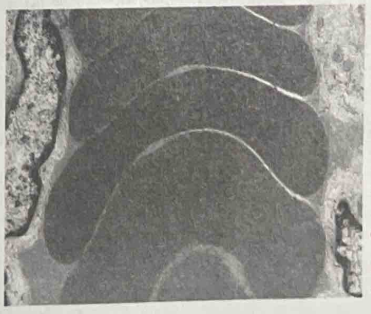
This scanning electron micrograph (SEM) with color added shows the "doughnut without a hole" shape of red blood cells.



This colored SEM shows lung cancer cells.

C Transmission electron microscope





In this transmission electron micrograph (TEM) we see hemoglobin packed inside red blood cells. Hemoglobin is a protein that carries oxygen in the blood.

A, top: © Jupiterimages; A, bottom: Science Source; B, top: Steve Geschmeissner/Science Source; B, bottom: Steve Geschmeissner/Science Source; C, top: R. Maisonneuve/Science Source; C, bottom: David M. Phillips/Science Source

Figure 3.6 Different types of microscopes reveal different kinds of details about cells or their parts.

3.4 The Plasma Membrane: A Double Layer of Lipids

- The plasma membrane encloses the cell and controls the movement of substances into and out of it.
- Links to Polar molecules 2.4, Enzymes 2.8, Phospholipids 2.10

The plasma membrane is a mix of lipids and proteins

The plasma membrane encloses a cell, but it isn't a solid wall between a cell's cytoplasm and the fluid outside. If it were, needed substances couldn't enter the cell and wastes couldn't leave it. Instead, the plasma membrane has a fluid quality, something like cooking oil. The membrane also is extremely thin. A thousand stacked like pancakes would be about as thick as this page.

In Figure 3.4 you've already seen a simple picture of a plasma membrane lipid bilayer with its "sandwich" of phospholipids. This structure often is described as a "mosaic" of proteins and different kinds of lipids. These include phospholipids, glycolipids, and, in the cells of humans and other animals, the lipid we call cholesterol. Plasma membrane proteins are embedded in the bilayer or attach to its outer or inner surface.

What makes the membrane fluid? A key factor is the movement of the molecules in it. Most phospholipids can spin on their long axis like a chicken on a rotisserie. They also move sideways and their tails flex. These movements help keep neighboring molecules from packing into a solid layer.

Proteins in cell membranes carry out many functions

The proteins that are embedded in or attached to a lipid bilayer carry out most of a cell membrane's functions (Figure 3.7). Many of these proteins are enzymes; you may recall from Chapter 2 that enzymes speed chemical reactions in cells. Other membrane proteins are receptors; they are like docks for signaling molecules, such as hormones, that trigger changes in cell activities. Recognition proteins that sit like flags on the surface of a cell are chemical "fingerprints" that identify the cell as being of a specific type. Transport proteins allow specific substances to move across the membrane. Some are open channels through which substances move on their own, while others use energy to actively move substances across.

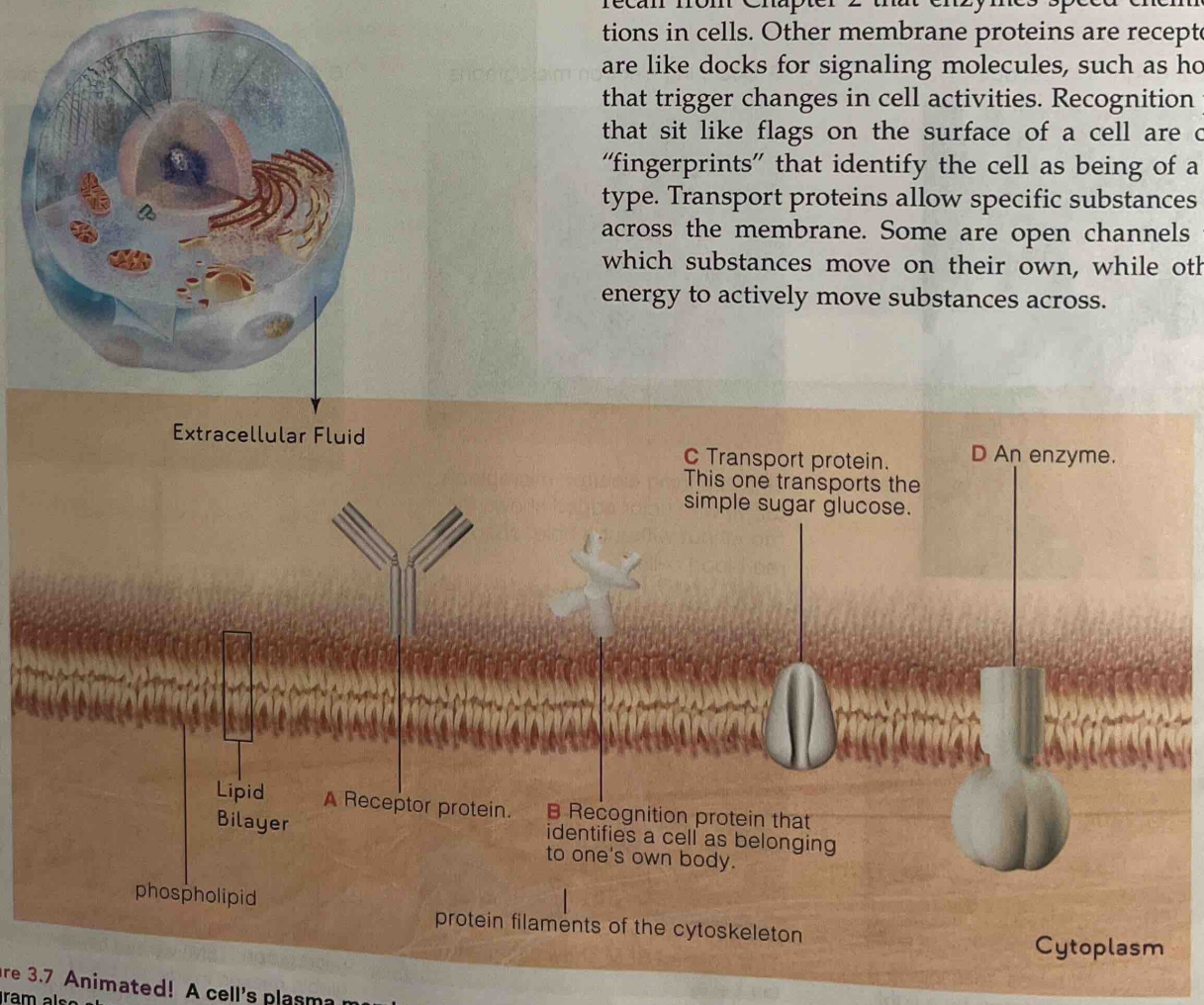


Figure 3.7 Animated! A cell's plasma membrane consists of lipids and proteins. Most of the lipids are phospholipids. This diagram also shows examples of membrane proteins. Biologists refer to the membrane's mix of lipids and proteins as a "mosaic." (© Cengage Learning)

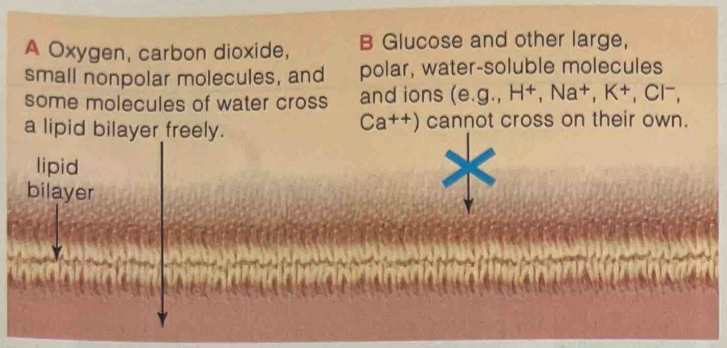


Figure 3.8 Animated! Cell membranes are selectively permeable. (© Cengage Learning)

The plasma membrane is "selective"

You have just read that a cell's plasma membrane is a bilayer containing lipids and proteins. These molecules give the membrane **selective permeability**. They allow some substances but not others to enter and leave a cell (Figure 3.8). They also control *when* a substance can cross and how much crosses at a given time. Lipids in the bilayer are mostly nonpolar, so they let small, nonpolar molecules such as carbon dioxide and oxygen slip across. Water molecules are polar, but some can move through gaps that briefly open up in the bilayer. Ions and large polar molecules (such as the blood sugar glucose) cross the bilayer through the interior of transport proteins. We'll look again at this topic in Section 3.10.

selective permeability
A property of the cell plasma membrane, in which the membrane allows only certain substances to cross it.

TAKE-HOME MESSAGE

HOW DOES THE PLASMA MEMBRANE'S STRUCTURE RELATE TO ITS FUNCTION?

- The plasma membrane is a lipid bilayer. It is a mix of various lipids and proteins and has a fluid quality.
- Proteins of the bilayer carry out many of the membrane's functions.
- The structure of the plasma membrane makes it selectively permeable. Some substances can cross it but others cannot.

3.5 100 Trillion of Your Closest Friends

SCIENCE COMES TO LIFE

You may be surprised to learn that only about 10 percent of your cells are human. The other 90 percent, roughly 100 trillion cells that account for several pounds of your body weight, are bacteria that live in your digestive system and on your skin (Figure 3.9). The bacterial cells are much smaller than any human cells, but there are many thousands of separate species. According to biologists who study this "microbiome" in the human body, only a relative few of the resident bacteria are types likely to cause illness if our defenses don't keep them in check. The rest are helpful or harmless.

Bacteria begin to colonize us at birth. Over time, each person becomes "home" to a particular assortment of microbes. It seems that no two people have exactly the same array, in part because the mix depends on your diet and age, your physical surroundings, health issues, and other factors.

Some bacteria prefer moist places, like your armpits, eyelids, and the folds behind your ears. Others thrive in the "wide open spaces" on your back, buttocks, and forearms. In a project dubbed the Belly Button Biodiversity Project, researchers in North Carolina are studying the 4,000-plus species of bacteria they have collected from swabs of volunteers' navels.

Learning about the bacteria that live on and in us is leading to medical insights. For example, wounds are often slow to heal in people with diabetes. Recent evidence suggests that slowed healing results when the mix of skin bacteria changes in response to a diabetic's high blood sugar. It may be possible to develop treatments that restore normal healing by spurring the growth of more favorable microbes.

Ken Cavanagh/Science Source

Figure 3.9 Bacteria from human skin growing in a glass laboratory dish.

3.6 The Nucleus

■ **Like a master control center, the nucleus contains and protects the cell's DNA, the genetic material.**

chromatin DNA molecules and proteins attached to them.

chromosome An individual DNA molecule and attached proteins.

nuclear envelope Double membrane that separates the inside of the nucleus from the cytoplasm. It has many pores.

nucleolus Cluster of the RNA and proteins used to assemble ribosomes from their subunits.

nucleus Organelle that encloses a eukaryotic cell's DNA.

The **nucleus** encloses the DNA of a eukaryotic cell. DNA contains instructions for building a cell's proteins. Those proteins in turn determine a cell's structure and function. In a human cell there are forty-six DNA molecules that together would be more than 6 feet long if they were stretched out end to end.

Figure 3.10 shows the basic structure of the nucleus. The nucleus has several key functions. To begin with, it prevents DNA from getting tangled up with structures in the cytoplasm. When a cell divides, its DNA molecules must be copied so that each new cell receives a full set. If the DNA is separate, it is easier to copy and organize these hereditary instructions. Also, outer membranes of the nucleus are a boundary where the movement of substances to and from the cytoplasm can be controlled.

A nuclear envelope encloses the nucleus

Unlike the cell itself, the nucleus has two outer lipid bilayers, one pressed against the other. This double-membrane system is called a **nuclear envelope** (Figure 3.11). The envelope surrounds the fluid part of the nucleus (the nucleoplasm), and many proteins are embedded in its layers. The outer portion of the nuclear envelope merges with the membrane of ER, an organelle in the cytoplasm that Section 3.7 describes.

Threadlike bits of protein attach to the inner surface of the nuclear envelope. They anchor DNA molecules to the envelope and help keep them organized.

Proteins that span both bilayers have a wide variety of functions. Some are receptors or transporters. Others form pores, as you can see in Figure 3.11. The pores are passageways. They allow small ions and molecules dissolved in the watery fluid inside and outside the nucleus to cross the nuclear membrane.

The nucleolus is where cells make the parts of ribosomes

As a cell grows, one or more dense masses appear inside its nucleus. Each mass is a **nucleolus** (noo-KLEE-oh-luhs), a construction site where some proteins and RNAs are combined to make the parts of ribosomes. These subunits eventually will cross through nuclear pores to the cytoplasm. There, they will briefly join up to form ribosomes. These organelles are "workbenches" where amino acids are assembled into proteins.

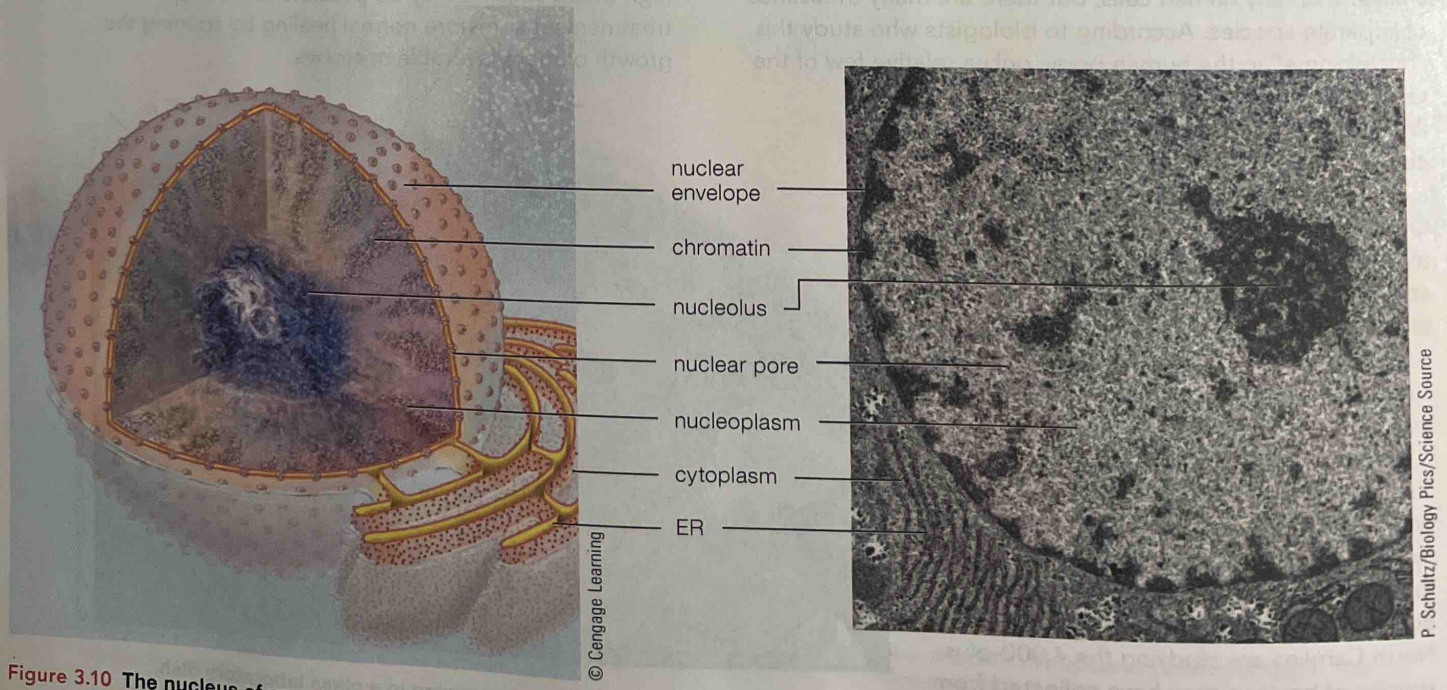


Figure 3.10 The nucleus of an animal cell contains the cell's DNA. The microscope image on the right shows the nucleus of a liver cell.

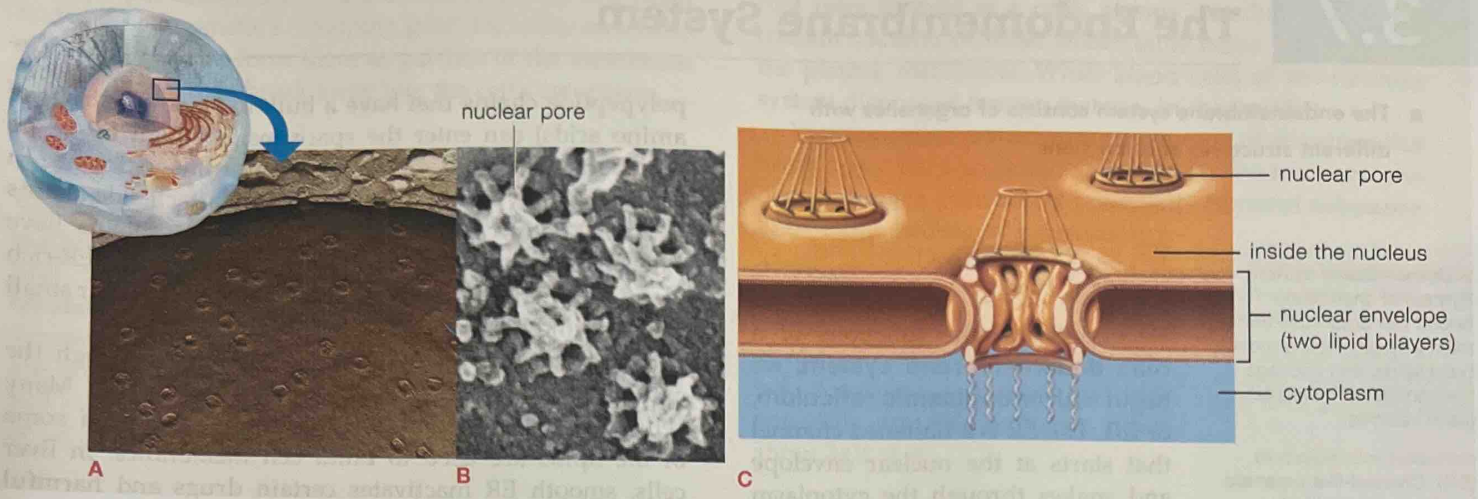


Figure 3.11 Animated! The nuclear envelope is a double membrane with pores. A This view of a cell's nuclear envelope shows pores that form channels through it. B This micrograph image reveals that each pore is a cluster of membrane proteins. They selectively allow certain substances to move into and out of the nucleus. The sketch of the nuclear envelope in C shows the envelope's structure. (A: Don W. Fawcett/Science Source; B: A.C. Faberge, *Cell and Tissue Research*, 151:403–415, 1974; C: © Cengage Learning)

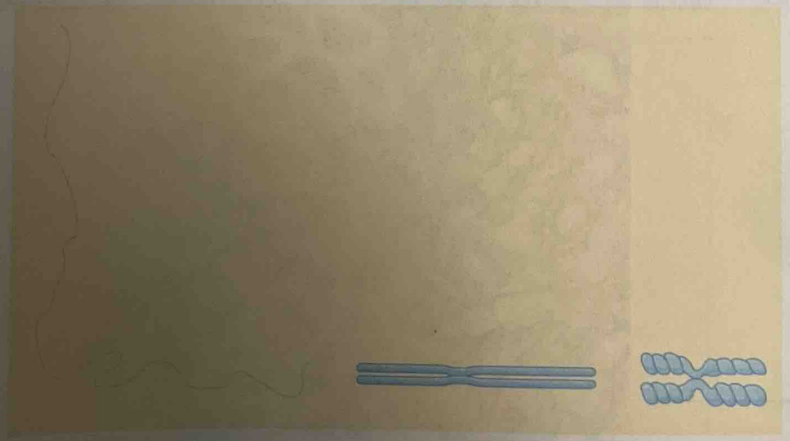
DNA is organized in chromosomes

When a eukaryotic cell is not dividing, you can't see individual DNA molecules. Neither can you see that each consists of two strands twisted together. The nucleus just looks grainy, as in Figure 3.10. When a cell is preparing to divide, however, it copies its DNA so that each new cell will get all the required hereditary instructions. Soon the duplicated DNA molecules are visible as long threads. They then fold and twist into a compact structure (Figure 3.12).

Early microscopists named the grainy-looking substance in the nucleus *chromatin*, and they called the compact structures *chromosomes* ("colored bodies"). Today we define **chromatin** as the cell's DNA along with the proteins associated with it. Sections of chromatin make up each **chromosome**—a double-stranded DNA molecule that carries genetic information. A chromosome looks grainy or compact depending on whether the cell is dividing or is in another part of its life cycle.

Events that begin in the nucleus continue in the cell cytoplasm

Outside the nucleus, new polypeptide chains for proteins are assembled on ribosomes. Many of the chains are used right away or stockpiled in the cytoplasm. Others move into the endomembrane system. As you'll read in the next section, this system includes various structures. It is where many proteins get their final form and where lipids are assembled and packaged.



a grainy, threadlike molecule of DNA (two strands, with proteins)

a chromosome that has been duplicated (two DNA molecules with proteins)

a chromosome that has been duplicated, then twisted and folded

Figure 3.12 The physical organization of a DNA differs at different times in a cell's life cycle. (© Cengage Learning)

TAKE-HOME MESSAGE

WHAT IS THE CELL NUCLEUS?

- The nucleus is the organelle that contains and protects a cell's DNA.
- DNA is organized into chromosomes. Each chromosome is one double-stranded DNA molecule.
- Because the DNA is separate from other cell parts, it is easier to keep the DNA's organization and to copy it before a cell divides.
- The nuclear envelope encloses the fluid part of the nucleus. Proteins embedded in the envelope's two bilayers control the passage of molecules between the nucleus and the cytoplasm.
- The nucleolus is where the parts of ribosomes form before passing into the cell's cytoplasm.

3.7 The Endomembrane System

- The endomembrane system consists of organelles with different structures and functions.

endomembrane system System of membrane-bound cell organelles that mainly modify new proteins, build lipids, and package the completed molecules (as in vesicles).

endoplasmic reticulum (ER) Channel-like organelle. Lipids are assembled in smooth ER. In rough ER, side chains are added to newly formed polypeptides.

Golgi body Series of flattened saclike organelles in which new lipids and polypeptide chains are processed into their final form.

ribosome Organelle where protein polypeptide chains are built.

vesicle A small, membrane-bound sac in cells. Some vesicles transport substances, others contain digestive enzymes.

ER is a protein and lipid assembly line

To understand the functions of a cell's **endomembrane system**, we begin with **endoplasmic reticulum**, or **ER**. The ER is a flattened channel that starts at the nuclear envelope and snakes through the cytoplasm (Figure 3.13). At certain points inside the channel, lipids are assembled and "raw" polypeptide chains are processed into final proteins. In different places the ER looks rough or smooth, depending mainly on whether the organelles called ribosomes are attached to the side of the membrane that faces the cytoplasm. A **ribosome** is a platform for building a cell's proteins. Its parts were synthesized in the nucleolus, as described in Section 3.6.

Rough ER is studded with ribosomes (Figure 3.13A). Newly forming polypeptide chains that have a built-in signal (a string of amino acids) can enter the space inside rough ER or be incorporated into ER membranes. Once the chains are in rough ER, enzymes in the channel may attach side chains to them. Body cells that secrete finished proteins have extensive rough ER. For example, in your pancreas, ER-rich gland cells make and secrete enzymes that enter your small intestine and help you digest the food you eat.

Smooth ER has no ribosomes and curves through the cytoplasm like flat connecting pipes (Figure 3.13B). Many cells assemble most lipids inside these pipes, and some of the lipids are used to build cell membranes. In liver cells, smooth ER inactivates certain drugs and harmful by-products of metabolism. In skeletal muscle cells a type of smooth ER called sarcoplasmic reticulum stores and releases calcium ions essential for muscles to contract.

Golgi bodies "finish, pack, and ship"

A **Golgi body** is a series of flattened sacs that are often compared to a stack of cupped pancakes (Figure 3.13C). Enzymes in the sacs put the finishing touches on proteins and lipids, then package the completed molecules in vesicles for shipment to specific locations. A **vesicle** is a tiny sac that moves through the cytoplasm or takes up positions in it. For example, an enzyme in one Golgi region might attach a phosphate group to a new protein and then "pack" the protein into a vesicle, thereby giving it a "mailing tag"

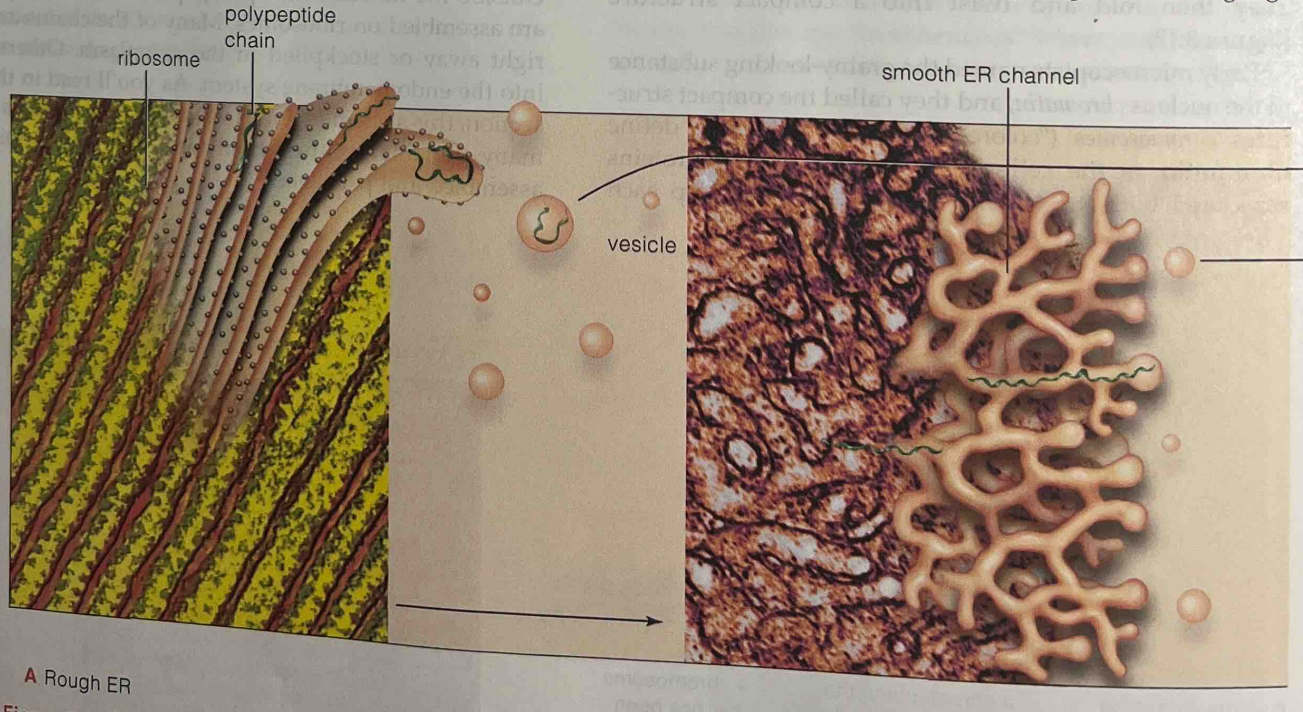


Figure 3.13 The endomembrane system builds lipids and modifies many cell proteins. These molecules are sorted and shipped to other cell parts or to the plasma membrane to be exported out of the cell. (© Cengage Learning ; A: Don W. Fawcett/Science Source; B: Don W. Fawcett/Mary Martin/Science Source)

to its proper destination. The pancake at the top of a Golgi body is the organelle's "shipping gate" for molecules to be exported. Vesicles form there as patches of the membrane bulge out and then break away into the cell's cytoplasm.

Vesicles have a range of roles in cells

Vesicles may have other specialized roles in cells. An example is the lysosome, a type of vesicle that buds from the membranes of Golgi bodies (Figure 3.13D). A **lysosome**'s function is to chemically digest (break down) substances. It contains a potent stew of enzymes that speed the breakdown of proteins, some lipids, complex sugars, and nucleic acids. Lysosomes may even digest whole cells or cell parts. Often, lysosomes fuse with other vesicles that have formed at a cell's plasma membrane and that contain bacteria or other undesirable items that attach to the plasma membrane. White blood cells of the immune system dispose of foreign material in the vesicles.

Vesicles called **peroxisomes** are sacs of enzymes that break down fatty acids and amino acids. The reactions produce hydrogen peroxide, a potentially harmful substance. But before hydrogen peroxide can injure the cell, another enzyme in peroxisomes converts it to water and oxygen or uses it to break down alcohol. When someone drinks alcohol, peroxisomes of liver and kidney cells are able to break down about half of it.

lysosome Vesicle in which enzymes break down unwanted molecules.

peroxisome Vesicle in which enzymes break down fatty acids and amino acids.

THINK OUTSIDE THE BOOK

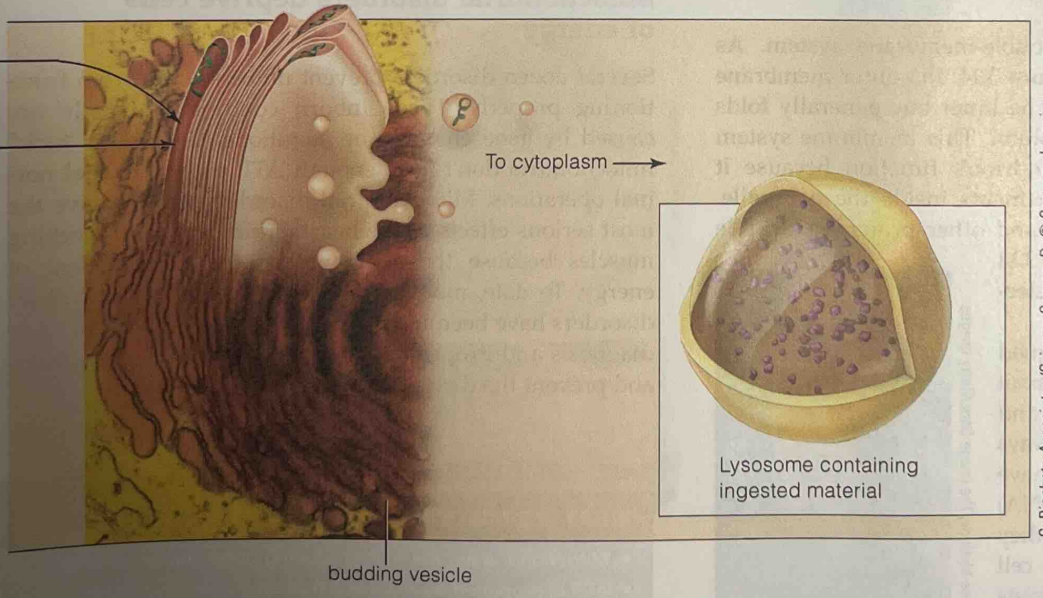
In genetic conditions called lysosomal storage diseases, an enzyme is missing from cell lysosomes. The substance the missing enzyme would break down builds up instead. As it accumulates, it interferes with cell activities. Briefly research this topic. What is the most common lysosomal storage disease in humans? How does the disease affect a person who is born with it?

One good information source is the Lysosomal Storage Disease Center at the University of California San Francisco Children's Hospital (www.ucsfhealth.org/clinics/lysosomal_storage_disease_center/index.html).

TAKE-HOME MESSAGE

WHAT DO ENDOMEMBRANE SYSTEM ORGANELLES DO?

- Ribosomes on rough endoplasmic reticulum (ER) build new cell proteins.
- In the smooth ER and Golgi bodies, lipids are assembled and many proteins are modified into their final form.
- Some vesicles move substances into or around cells or transport them to the outside.
- The vesicles called lysosomes and peroxisomes break down unwanted material.



C Golgi body

D A lysosome

C: Biophoto Associates/Science Source; D: © Cengage Learning

3.8 Mitochondria: The Cell's Energy Factories

- The energy for cell activities comes from ATP made in the cell's mitochondria.
- Link to ATP 2.13

Mitochondria make ATP

Section 2.13 introduced ATP, the main energy carrier in cells. Because ATP can deliver energy to nearly all the sites where chemical reactions occur in a cell, ATP is the fuel for most cell activities. ATP forms during reactions that break down organic compounds to carbon dioxide and water. These reactions occur in a **mitochondrion** (my-toe-KON-dree-ahn; plural: mitochondria).

Only eukaryotic cells contain mitochondria. The one shown in Figure 3.14 gives you an idea of their structure. The ATP-forming reactions that occur in mitochondria extract far more energy from organic compounds than can be obtained any other way. The reactions can't be completed without an ample supply of oxygen. Every time you inhale, you are taking in oxygen mainly for the mitochondria in your cells.

mitochondrion Organelle that produces ATP, the main cell fuel.

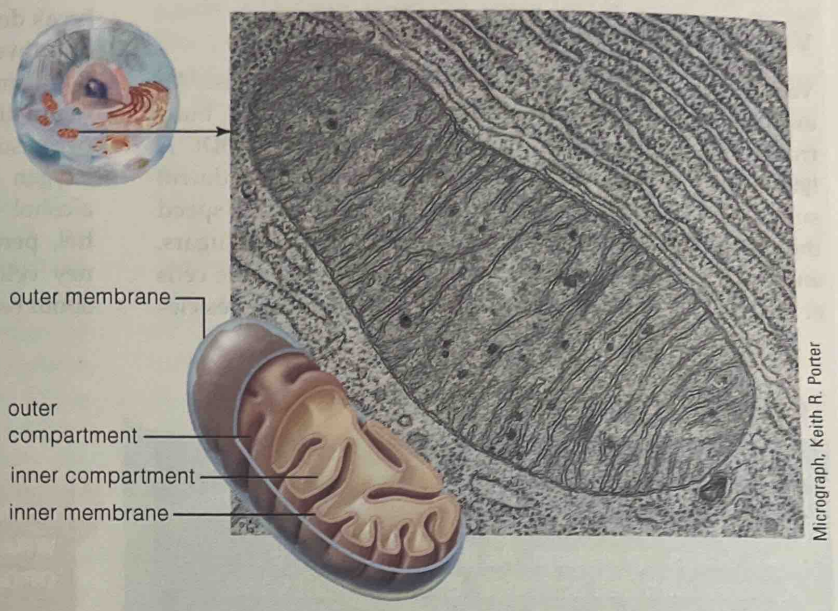


Figure 3.14 Animated! Mitochondria form ATP. Sketch and transmission electron micrograph of a mitochondrion. Reactions inside mitochondria produce ATP, the major energy carrier in cells. (© Cengage Learning)

ATP forms in an inner compartment of the mitochondrion

A mitochondrion has a double-membrane system. As shown in the sketch in Figure 3.14, the outer membrane faces the cell's cytoplasm. The inner one generally folds back on itself, accordion-fashion. This membrane system is the key to the mitochondrion's function because it forms two separate compartments inside the organelle. In the outer one, enzymes and other proteins stockpile hydrogen ions. As Section 3.14 will explain, energy from electrons fuels this process.


Joe McBride/The Image Bank/Getty Images

Mitochondria have intrigued biologists because they are about the same size as bacteria and function like them in many ways as well. Mitochondria even have their own DNA (called mtDNA) and some ribosomes, and they divide independently of the cell they are in. Many biologists believe mitochondria evolved from ancient bacteria that were consumed by another ancient cell, yet did not die. If they became protected, permanent residents in the host cell, they might have lost structures and functions required for independent life while they were evolving into mitochondria, the ATP-producing organelles without which we humans could not survive.

Mitochondrial disorders deprive cells of energy

Several dozen disorders prevent mitochondria from functioning properly. These inborn conditions usually are caused by gene changes, or mutations. Cells with "sick" mitochondria don't have enough ATP energy to fuel normal operations. Mitochondrial disorders tend to have the most serious effects in the heart, brain, and hard-working muscles because those organs require a great deal of energy. To date, more than forty different mitochondrial disorders have been identified. None are curable, but early diagnosis and proper treatment may help curb symptoms and prevent the disease from progressing.

TAKE-HOME MESSAGE

WHAT DO MITOCHONDRIA DO?

- Mitochondria are the ATP-producing powerhouses of cells.
- ATP is produced by reactions that take place in the inner compartment formed by a mitochondrion's double-membrane system.
- Reactions that form ATP in mitochondria require oxygen.

3.9 The Cell's Skeleton

- **A cell's structural framework is called the cytoskeleton. The cytoskeleton's elements assemble and disassemble as needed for cell activities.**

The **cytoskeleton** is a system of interconnected fibers, threads, and lattices in the cytosol (Figure 3.15A). Different proteins form these parts, which collectively give cells their shape, organization, and ability to move.

centrioles Cell structures that give rise to microtubules.

cilia Short, bendable structures built of microtubules.

cytoskeleton The cell's internal structural framework.

flagella Whiplike structures built of microtubules.

intermediate filaments Cytoskeleton filaments that anchor proteins (actin and myosin) in the cytosol and add strength to it.

microfilaments Filaments in the cytoskeleton that reinforce or anchor cell parts.

microtubules Largest elements of the cytoskeleton.

Microtubules are the largest cytoskeleton elements. They spatially organize the interior of the cell, and also help move cell parts. **Microfilaments** often reinforce some part of a cell, such as the plasma membrane. They also anchor some membrane proteins.

Some kinds of cells also have **intermediate filaments** that add strength much as steel rods strengthen concrete pillars. Intermediate filaments also anchor the filaments of two proteins, called actin and myosin, which interact in muscle cells and enable the muscle to contract. Chapter 6 explains how they function.

Some types of cells move about by **flagella** (singular: flagellum) or have moving **cilia** (singular: cilium) (Figure 3.15B and 3.15C). In both structures nine pairs of microtubules ring a central pair. A system of spokes and links holds this "9 + 2 array" together (Figure 3.16). The flagellum or cilium bends when microtubules in the ring slide over each other. Whiplike flagella propel human sperm.

Cilia are shorter than flagella, and there may be more of them per cell. In your respiratory tract, thousands of ciliated cells whisk out mucus laden with dust or other undesirable material. The microtubules of cilia and flagella arise from **centrioles**, which remain at the base of the completed structure as a "basal body." Centrioles also have a major role to play when a cell divides.

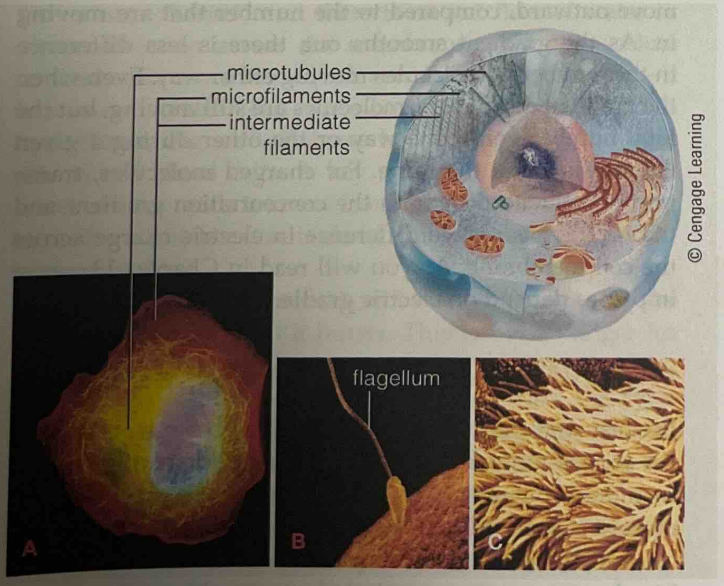


Figure 3.15 Animated! Microtubules and filaments make up the cytoskeleton. A The cytoskeleton of a pancreas cell. B The flagellum of a sperm cell. C Cilia in an airway in the lungs.
(Left: Jennifer C. Waters/Science Source; Center: Don W. Fawcett/Science Source; Right: J.W. Shuler/Science Source)

TAKE-HOME MESSAGE

WHAT IS THE ROLE OF THE CYTOSKELETON?

- The cytoskeleton gives a cell its shape, internal structure, and capacity for movement.
- The main elements of the cytoskeleton are microtubules, microfilaments, and intermediate filaments.
- Some types of cells have flagella or cilia, which move by way of microtubules.

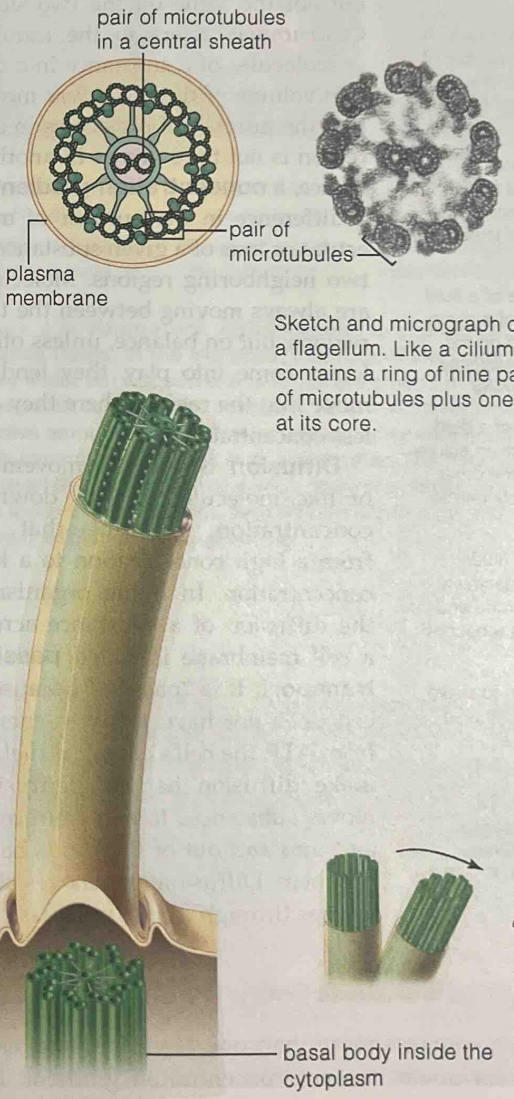


Figure 3.16 Microtubules allow cilia and flagella to move.

3.10 How Diffusion and Osmosis Move Substances across Membranes

- A cell takes in and expels substances across its plasma membrane. Diffusion and osmosis are the major means for accomplishing these tasks.
- Phospholipids 2.10, Protein function 2.12

As you now know, a cell's plasma membrane is selectively permeable. It allows only certain kinds of substances to enter and leave the cell. Why does a solute move one way or another at any given time? The answer starts with concentration gradients.

In diffusion, a dissolved molecule or ion moves down a concentration gradient

There is fluid on both sides of a cell's plasma membrane, but the kinds and amounts of dissolved substances in the fluid are not the same on the two sides. *Concentration* refers to the number of molecules of a substance in a certain volume of fluid. *Gradient* means that the number of molecules in one region is not the same as in another. Hence, a **concentration gradient** is a difference in the number of molecules or ions of a given substance in two neighboring regions. Molecules are always moving between the two regions, but on balance, unless other forces come into play, they tend to move into the region where they are less concentrated.

concentration gradient A difference in the number of molecules or ions of a substance in two neighboring regions.

diffusion Movement of molecules or ions from a region of higher concentration to a region of lower concentration.

hypertonic State of a fluid containing more of a given solute than a fluid on the other side of a selectively permeable membrane.

hypotonic State of a fluid having less of a given solute than the fluid on the other side of a selectively permeable membrane.

isotonic State of fluids separated by a selectively permeable membrane and that contain equal amounts of a given solute.

osmosis Diffusion (passive transport) of water across a selectively permeable membrane.

passive transport The diffusion of a substance across a cell membrane; does not require ATP energy.

Diffusion is the net movement of like molecules or ions down a concentration gradient—that is, from a high concentration to a low concentration. In living organisms, the diffusion of a substance across a cell membrane is called **passive transport**. It is "passive" because a cell does not have to draw energy from ATP, the cell's chemical fuel, to make diffusion happen. Diffusion moves substances to and from cells, and into and out of the fluids bathing them. Diffusion also moves substances through a cell's cytoplasm.

Each type of solute follows its own gradient

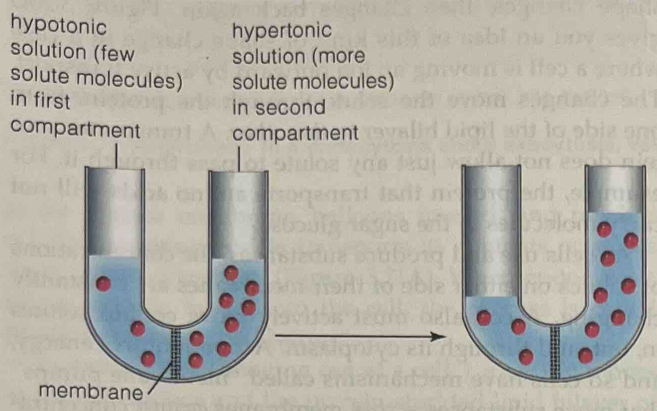
If a solution contains more than one kind of solute, each kind diffuses down its own concentration gradient. For example, if you put a drop of dye in one side of a bowl of water, the dye molecules diffuse to the region where they are less concentrated. Likewise, the water molecules move in the opposite direction, to the region where *they* are less concentrated (Figure 3.17).

Figure 3.17 Substances diffuse down a concentration gradient. A A drop of dye enters a bowl of water. Gradually the dye molecules disperse evenly through the molecules of water. **B** The same thing happens with the water molecules. If red dye and yellow dye are added to the same bowl, each substance will move (diffuse) down its own concentration gradient.

Molecules diffuse faster when the gradient is steep. Where molecules are most concentrated, more of them move outward, compared to the number that are moving in. As the gradient smooths out, there is less difference in the number of molecules moving either way. Even when the gradient disappears, molecules are still moving, but the total number going one way or the other during a given interval is about the same. For charged molecules, transport is influenced by both the concentration gradient and the *electric gradient*—a difference in electric charge across the cell membrane. As you will read in Chapter 13, nerve impulses depend on electric gradients.

Water crosses membranes by osmosis

Because the plasma membrane is selectively permeable, the concentration of a solute can increase on one side of the membrane but not on the other. For example, the cytoplasm of most cells usually contains solutes (such as proteins) that cannot diffuse across the plasma membrane. When solutes become more concentrated on one side of the plasma membrane, the resulting solute concentration gradients affect how water diffuses across the membrane. **Osmosis**



A Initially, the two compartments have equal volumes of fluid, but the solute concentration across the membrane differs.

B The fluid volume rises in the second compartment as water follows its concentration gradient and diffuses into it.

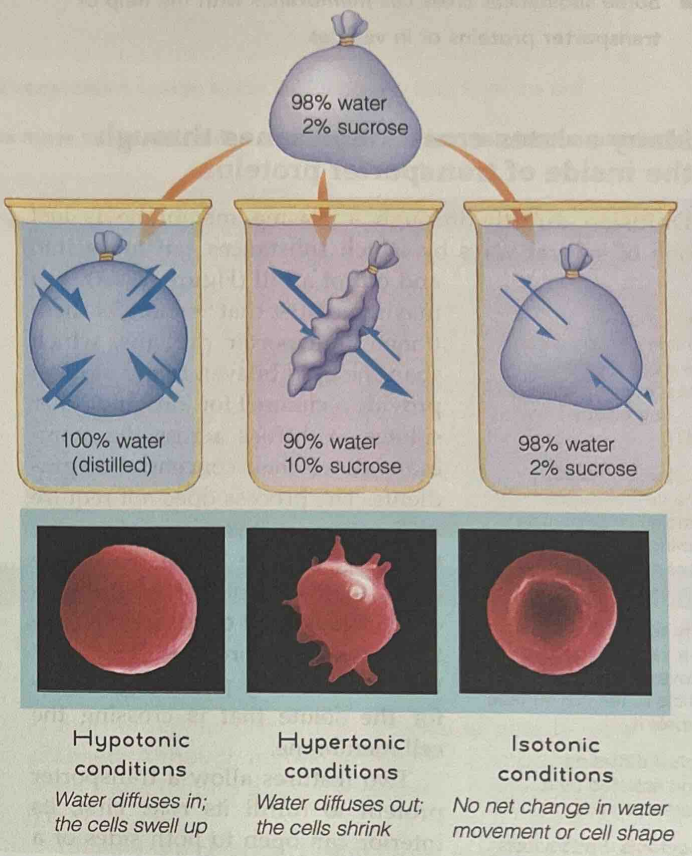
Figure 3.18 Animated! The concentration of a solute affects the movement of water by osmosis. A Distribution of water before osmosis occurs. B Redistribution of water due to osmosis. (© Cengage Learning)

(oss-MOE-sis) is the name for the diffusion of water across a selectively permeable membrane in response to solute concentration gradients. Figure 3.18 is a simple diagram of this process.

Tonicity is the concentration of solutes in a solution. When solute concentrations in the fluids on either side of a cell membrane are the same, the fluids are **isotonic** (*iso-* means "same") and there is no net flow of water in either direction across the membrane. When the solute concentrations are not equal, one fluid is **hypotonic**—it has fewer solutes. The other has more solutes and it is **hypertonic**. Figure 3.19 shows how the tonicity of a fluid affects red blood cells. A key point to remember is that water always tends to move from a hypotonic solution to a hypertonic one because it always moves down its concentration gradient.

If too much water enters a cell by osmosis, in theory the cell will swell up until it bursts. This is not a danger for most body cells because they can selectively move solutes out—and as solutes leave, so does water. Also, the cytoplasm exerts pressure against the plasma membrane. When this pressure counterbalances the tendency of water to follow its concentration gradient, osmosis stops.

Every moment, cell activities and other events change the factors that affect the solute concentrations of body fluids and water movements between them. Chapter 12 explains how osmotic water movements help maintain the body's water balance.



All three images: David M. Phillips/Science Source

Figure 3.19 Animated! Cells respond to changes in tonicity of body fluids. In the sketches, membrane-like bags that allow water but not sucrose to cross are placed in hypotonic, hypertonic, and isotonic solutions. Arrow width represents the relative amount of water movement in each container. Red blood cells cannot actively take in or expel water. The micrographs show what happens to them when they are placed in solutions like those in the sketches. Red blood cells in a hypotonic solution quickly explode. (© Cengage Learning)

TAKE-HOME MESSAGE

WHY ARE DIFFUSION AND OSMOSIS IMPORTANT IN THE FUNCTIONING OF A CELL?

- Diffusion and osmosis are the main ways substances enter and leave cells.
- Many substances, including water, diffuse into and out of cells down a concentration gradient. The diffusion of water is called osmosis.
- This diffusion is a passive process—it does not require ATP energy.
- Most body cells have mechanisms for adjusting the movement of water and solutes into and out of the cell.

3.11 Other Ways Substances Cross Cell Membranes

- Some substances cross cell membranes with the help of transporter proteins or in vesicles.

Many solutes cross membranes through the inside of transporter proteins

Diffusion directly through a plasma membrane is just one of several ways by which substances can move into and out of a cell (Figure 3.20A). You may remember that Section 3.4 mentioned transporter proteins, which span the lipid bilayer. Many of them provide a channel for ions and other solutes to diffuse across the membrane down their concentration gradients. The process does not require ATP energy, so it is a form of passive transport (Figure 3.20B). This type of passive transport sometimes is called **facilitated diffusion** because the transporter proteins "facilitate" the movement by providing a route for the solute that is crossing the cell membrane.

Two features allow a transporter protein to fulfill its role. First, its interior can open to both sides of a cell membrane. Second, when the protein interacts with a solute, its shape changes, then changes back again. Figure 3.20D gives you an idea of this kind of shape change in a case where a cell is moving an ion outward by active transport. The changes move the solute through the protein, from one side of the lipid bilayer to the other. A transporter protein does not allow just any solute to pass through it. For example, the protein that transports amino acids will not carry molecules of the sugar glucose.

As cells use and produce substances, the concentrations of solutes on either side of their membranes are constantly changing. A cell also must actively move certain solutes in, out, and through its cytoplasm. Action requires energy, and so cells have mechanisms called "membrane pumps" that move substances across membranes *against* concentration gradients. This pumping is called **active transport** (Figure 3.20C). ATP provides most of the energy for active transport, and membrane pumps can continue working until the solute is *more* concentrated on the side of the membrane where it is being pumped. This difference lays the chemical foundation for vital processes such as the contraction of your muscles.

active transport Movement of substances across a cell membrane against a concentration gradient, using energy from ATP.

endocytosis Process by which a cell takes in a large molecule or particle by forming a vesicle that encloses it and moves it into the cell cytoplasm.

exocytosis Process in which a vesicle encloses and moves a large molecule or particle to the cell surface and expels it.

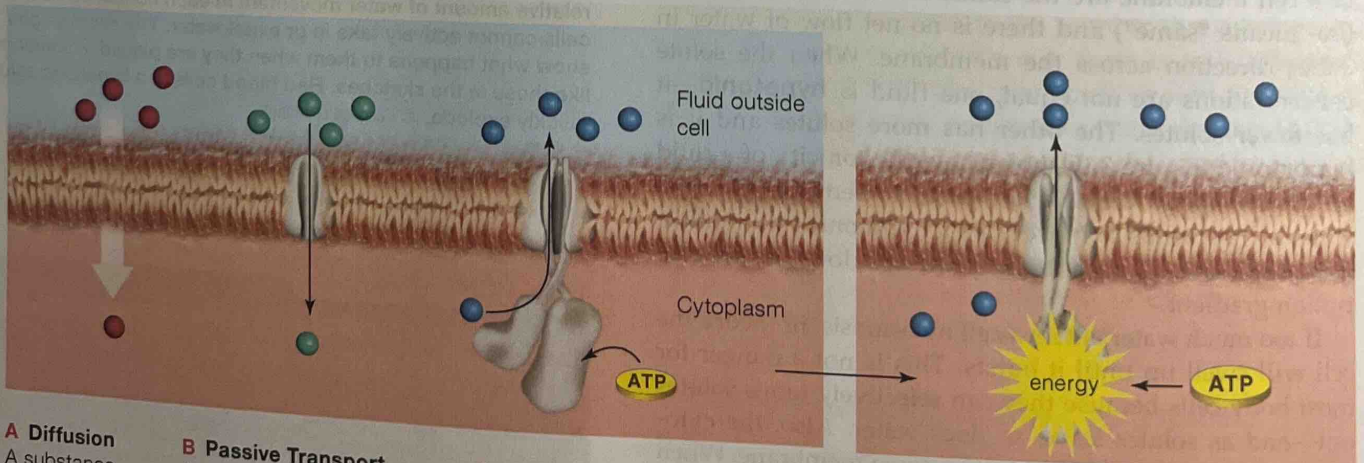
facilitated diffusion Diffusion assisted by a transporter protein.

phagocytosis Endocytosis of a cell or other organic matter.

Vesicles transport large solutes

Transporter proteins can only move small molecules and ions into or out of cells. To bring in or expel larger molecules or particles, cells use vesicles that form through endocytosis and exocytosis (Figure 3.21).

In **endocytosis** ("coming inside a cell"), a cell takes in substances next to its surface. A small indentation forms



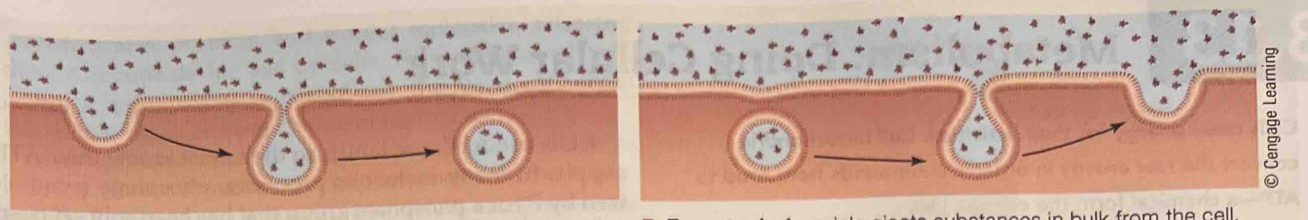
A Diffusion A substance simply diffuses across lipid bilayer.

B Passive Transport A solute moves across bilayer through interior of passive transporter; movement is driven by concentration gradient.

C Active Transport Active transporter uses energy (often, ATP) to pump a solute through bilayer against its concentration gradient.

D Solute pumped out against its concentration gradient.

Figure 3.20 Animated! Substances cross cell membranes in a variety of ways. Notice that A diffusion and B passive transport do not require the cell to invest energy. C Active transport uses ATP energy, whether a cell is moving a needed substance inward or D releasing a substance to the outside. (© Cengage Learning)



A **Endocytosis** A vesicle brings substances in bulk into the cell. B **Exocytosis** A vesicle ejects substances in bulk from the cell.

© Cengage Learning

Figure 3.21 Animated! In A endocytosis and B exocytosis, vesicles move large molecules or particles across the plasma membrane.

at the plasma membrane, balloons inward, and pinches off. The resulting vesicle transports its contents or stores them in the cytoplasm (Figure 3.21A). When endocytosis brings organic matter into the cell, the process is called **phagocytosis**, or "cell eating."

In **exocytosis** ("moving out of a cell"), a vesicle moves to the cell surface and the protein-studded lipid bilayer of its membrane fuses with the plasma membrane (Figure 3.21B). Its contents are then released to the outside.

TAKE-HOME MESSAGE

HOW DO TRANSPORTER PROTEINS OR VESICLES MOVE SUBSTANCES ACROSS CELL MEMBRANES?

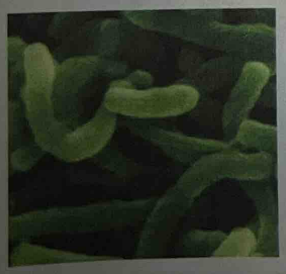
- Some substances that cannot cross the plasma membrane by simple diffusion cross instead through transporter proteins. This type of passive transport is called facilitated diffusion.
- In active transport, protein pumps in the plasma membrane move solutes against their gradient. ATP provides much of the needed energy.
- Endocytosis and exocytosis move large molecules or particles across the membrane.

FOCUS ON HUMAN IMPACT

3.12 A Watery Disaster for Cells

Soon after the massive earthquake that devastated the island nation of Haiti in 2010, health officials called upon to help cope with the disaster began worrying about water. Specifically, they were concerned about waterborne diseases, which can pose serious problems in places where public sanitation is poor or previously safe water supplies become contaminated. One such disease, cholera, is caused by a bacterium, *Vibrio cholerae*. It produces a toxin that affects transport proteins in the plasma membranes of cells in the small intestine. The toxin causes cells to pump out various ions, and other dissolved substances follow. As these substances leave, cells lose their water by osmosis, a process that is described in Section 3.10.

Cholera's main symptom is massive watery diarrhea. In severe cases it can literally drain a person's body of water in less than a day. Treatment—if it comes in time—involves quickly rehydrating the patient with fluids that replenish both lost water and electrolytes, followed by a course of antibiotics. Mildly infected people who don't show symptoms may receive antibiotics, but they still can pass infectious bacteria in their feces for as long as 10 days.



Vibrio cholerae bacteria, which cause cholera. This image is a scanning electron micrograph with color added. (Callista Images/Collection Mix: Subjects/Getty Images)

Not long after the Haitian quake, cases of cholera began turning up in Haiti—first by the dozens, then by the thousands. In short order, hundreds of thousands of people were sickened. Although authorities rushed in supplies of clean water (Figure 3.22), the disease killed more than 8,000 people.

Cholera is a common health threat in parts of South America, Africa, Asia, and the Indian subcontinent, including Nepal. Until the quake, however, it hadn't been a major problem in Haiti. Eventually the outbreak was traced to a leaky sewage system servicing a base where United Nations peacekeepers from Nepal were stationed to help keep order in the ravaged county. The tragic episode underscored how easy it is to spread disease in a time when it takes only hours for individuals—and microbes they host—to travel halfway around the globe.

UN Photo/Marco Dormino

Figure 3.22 Getting clean drinking water to Haiti earthquake survivors was an urgent priority in order to prevent disease.

3.13 Metabolism: Doing Cellular Work

- Cells need energy for their activities. Cell mitochondria convert the raw energy in organic compounds from food to ATP—a chemical form the cell can use.
- Links to Organic compounds 2.8, Energy carriers 2.13

ATP is the cell's energy currency

The chemical reactions in cells are called **metabolism**. Some reactions release energy and others require it. ATP links the two kinds of reactions, carrying energy from one reaction to another. You may remember from Section 2.13 that ATP is short for adenosine triphosphate, one of the nucleotides. A molecule of ATP consists of the five-carbon sugar ribose to which adenine (a nucleotide base) and three phosphate groups are attached (Figure 3.23A). ATP's stored energy is contained in the bond between the second and third phosphate groups.

active site Area on the surface of an enzyme where the enzyme and its substrate can interact.

anabolism Metabolic activity that builds large molecules from smaller ones.

ATP/ADP cycle A cycle in which a phosphate attaches to ADP, forming ATP, which then transfers a phosphate elsewhere, becoming ADP again.

catabolism Metabolic activity that breaks down large molecules into smaller ones.

metabolism The chemical reactions in cells.

substrate The particular kind of molecule that interacts with a given enzyme.

Enzymes can break the bond between the second and third phosphate groups of the ATP molecule. The enzymes then can attach the released phosphate group to another molecule. When a phosphate group is moved from one molecule to another, stored energy goes with it.

Cells use ATP constantly, so they must renew their ATP supply. In many metabolic processes, phosphate (symbolized by P_i) or a phosphate group that has been split off from some substance is attached to ADP, adenosine diphosphate (the prefix *di-* indicates that *two* phosphate groups are present). Now the molecule, with three phosphates, is ATP. And when ATP transfers a phosphate group elsewhere, it reverts to ADP. In this way it completes the **ATP/ADP cycle** (Figure 3.23B).

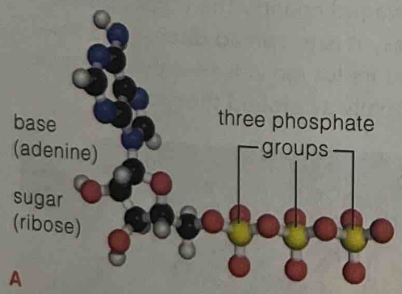
Like money earned at a job and then spent to pay your expenses, ATP is earned in reactions that produce energy and spent in reactions that require it. That is why textbooks often use a cartoon coin to symbolize ATP.

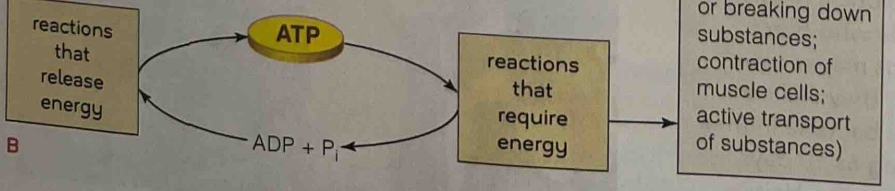
There are two main types of metabolic pathways

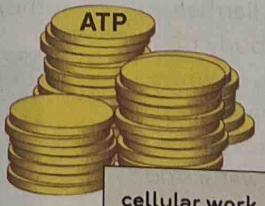
At this moment thousands of reactions are transforming thousands of substances inside each of your cells. Most of these reactions are part of metabolic pathways, steps in which reactions take place one after another. There are two main types of metabolic pathways, called anabolism and catabolism.

In **anabolism**, small molecules are put together into larger ones. In these larger molecules, the chemical bonds hold more energy. Anabolic pathways assemble complex carbohydrates, proteins, and other large molecules. The energy stored in their bonds is a major reason why we can use these substances as food.

In **catabolism**, large molecules are broken down to simpler ones. Catabolic reactions disassemble complex







cellular work (such as making or breaking down substances; contraction of muscle cells; active transport of substances)

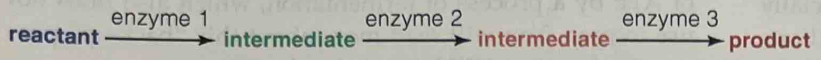
Martin Barraud/Stone/Getty Images

Figure 3.23 ATP provides energy for cell activities. A Structure of ATP. B ATP connects energy-releasing reactions with energy-requiring ones. In the ATP/ADP cycle, the transfer of a phosphate group turns ATP into ADP, then back again to ATP. (© Cengage Learning)

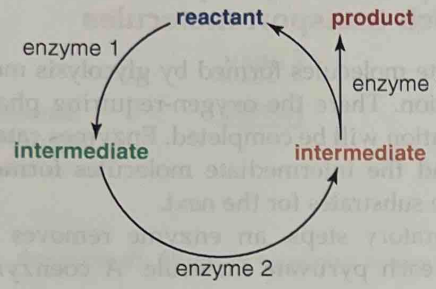
carbohydrates, proteins, and similar molecules, releasing their components for use by cells. For example, when a complex carbohydrate is catabolized, the reactions release the simple sugar glucose, the main fuel for cells.

Any substance that is part of a metabolic reaction is called a *reactant*. A substance that forms between the beginning and the end of a metabolic pathway is an *intermediate*. Substances present at the end of a reaction or a pathway are the *products*.

Many metabolic pathways advance step by step from reactants to products:



In other pathways the steps occur in a cycle, with the products serving as reactants to start things over.



Enzymes are essential in metabolism

Metabolic reactions require *enzymes*, which you first read about in Section 2.8. Most enzymes are proteins, and all are catalysts: They speed up chemical reactions. In fact, enzymes generally make reactions occur hundreds to millions of times faster than would be possible otherwise. Enzymes are not used up in reactions, so a given enzyme molecule can be used over and over.

Each kind of enzyme can only interact with specific kinds of molecules, which are called its **substrates**. The enzyme can chemically recognize a substrate, bind it, and change it in some way. An example is thrombin, one of the enzymes required to clot blood. It only recognizes a side-by-side set of two particular amino acids in a protein. When thrombin "sees" this arrangement, it breaks the peptide bond between the amino acids.

An enzyme and its substrate interact at a surface crevice on the enzyme. This area is called an **active site**. Figure 3.24 shows how enzyme action can combine two substrate molecules into a new, larger product molecule.

Powerful as they are, enzymes only work well within a certain temperature range. For example, if a person's body temperature rises too high, the increased heat energy breaks bonds holding an enzyme in its three-dimensional shape. The shape changes, substrates can't bind to the active site as usual, and chemical reactions do not occur as normal. For this reason people usually die if their internal temperature reaches 44°C (112°F).

Enzymes also function best within a certain pH range—in the body, from pH 7.35 to 7.4. Above or below this range most enzymes cannot operate normally.

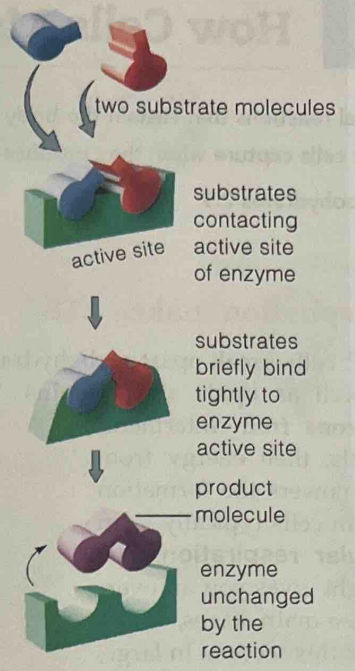


Figure 3.24 Animated! Enzymes and substrates fit together physically. When substrate molecules contact an enzyme's active site, they bind to the site for a brief time and a product molecule forms. When the product molecule is released, the enzyme goes back to its previous shape. The reaction it catalyzed does not change the enzyme in any way.

Section 2.13 mentioned that organic molecules called *coenzymes* assist with many reactions. Many coenzymes are derived from vitamins, which is one reason why vitamins are important in the diet.

The body controls the activity of enzymes

Controls may boost the action of enzymes, slow it down, or adjust how fast new enzyme molecules are made—and thus how many are available for a given metabolic pathway. For example, when you eat, food entering your stomach causes gland cells there to secrete the hormone gastrin into your bloodstream. Stomach cells with receptors for gastrin respond in a variety of ways, such as secreting the ingredients of "gastric juice"—including enzymes that break down food proteins.

TAKE-HOME MESSAGE

WHAT ARE METABOLIC PATHWAYS?

- Metabolic pathways are sequences of chemical reactions that build or dismantle molecules in cells.
- Pathways of anabolism require ATP energy to build large molecules from smaller ones. Pathways of catabolism release ATP energy as large molecules are broken down to smaller ones.
- Enzymes speed the rate of chemical reactions. Each type acts only on specific substrates.
- All enzymes function best within certain ranges of temperature and pH.

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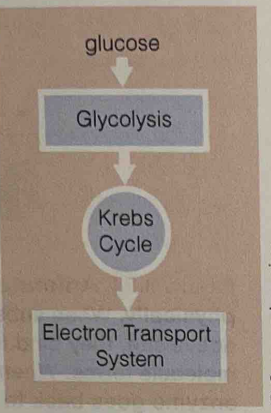
3.14 How Cells Make ATP

- The chemical reactions that sustain the body depend on energy that cells capture when they produce ATP.
- Link to Carbohydrates 2.9

Cellular respiration makes ATP

To make ATP, cells break apart carbohydrates, especially glucose, as well as lipids and proteins. The reactions remove electrons from intermediate compounds, then energy from the electrons powers the formation of ATP. Human cells typically form ATP by **cellular respiration**. The diagram at right gives you an overview of its three main stages, which are the topic of this section. In large, complex organisms like ourselves, all but the first stage of this process usually is aerobic—it uses oxygen. Glucose is the most common raw material for cellular respiration, so it will be our example here.



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cellular respiration The overall aerobic (oxygen-using) process by which cells break down organic molecules to make ATP.

electron transport system Chain of reactions in mitochondria that use energy from electrons to generate many ATP molecules.

glycolysis Process that breaks apart glucose molecules, forming pyruvate, in the first stage of cellular respiration.

Krebs cycle Process that produces energy-rich compounds ($NADH$ and $FADH_2$) that deliver electrons to electron transport systems in mitochondria. The cycle also produces a small amount of ATP.

phosphorylation Transfer of a phosphate group to a molecule.

Step 1: Glycolysis breaks glucose down to pyruvate

Cellular respiration starts in the cell's cytoplasm, in a set of reactions called **glycolysis**—literally, "splitting sugar." You may recall that glucose is a simple sugar. Each glucose molecule consists of six carbon atoms, twelve hydrogens, and six oxygens, all joined by covalent bonds. During glycolysis, a glucose molecule is broken into two molecules of a compound called pyruvate. As shown in Figure 3.25, each pyruvate molecule has three carbons.

When glycolysis begins, two ATPs each transfer a phosphate group to glucose, donating energy to it. This kind of transfer is called **phosphorylation**. It adds enough energy to glucose to begin the energy-releasing steps of glycolysis.

The first energy-releasing step breaks the glucose into two molecules of PGAL (for phosphoglyceraldehyde), which are converted to intermediates. These molecules then each donate a phosphate group to ADP, forming ATP. The same thing happens with the next intermediate in the sequence, and the end result is two molecules of pyruvate and four ATP. However, because two ATP were invested to start the reactions, the final, *net* energy yield is only two ATP.

Notice that glycolysis does not use oxygen. If oxygen is not available for the following aerobic steps of cellular respiration, for a short time a cell can still form a small amount of ATP by a process of fermentation, which also does not use oxygen. You will read more about this "back-up" process for forming ATP later in the chapter.

Step 2: The Krebs cycle produces energy-rich transport molecules

The pyruvate molecules formed by glycolysis move into a mitochondrion. There the oxygen-requiring phase of cellular respiration will be completed. Enzymes catalyze each reaction, and the intermediate molecules formed at one step become substrates for the next.

In preparatory steps, an enzyme removes a carbon atom from each pyruvate molecule. A coenzyme called coenzyme A combines with the remaining two-carbon fragment and becomes a compound called acetyl-CoA.

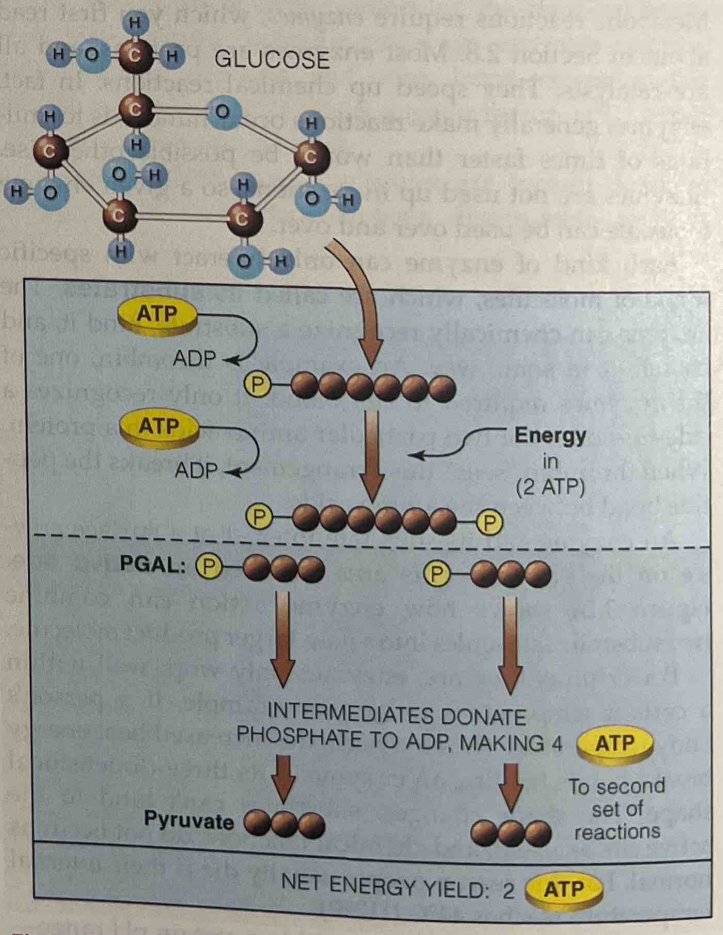
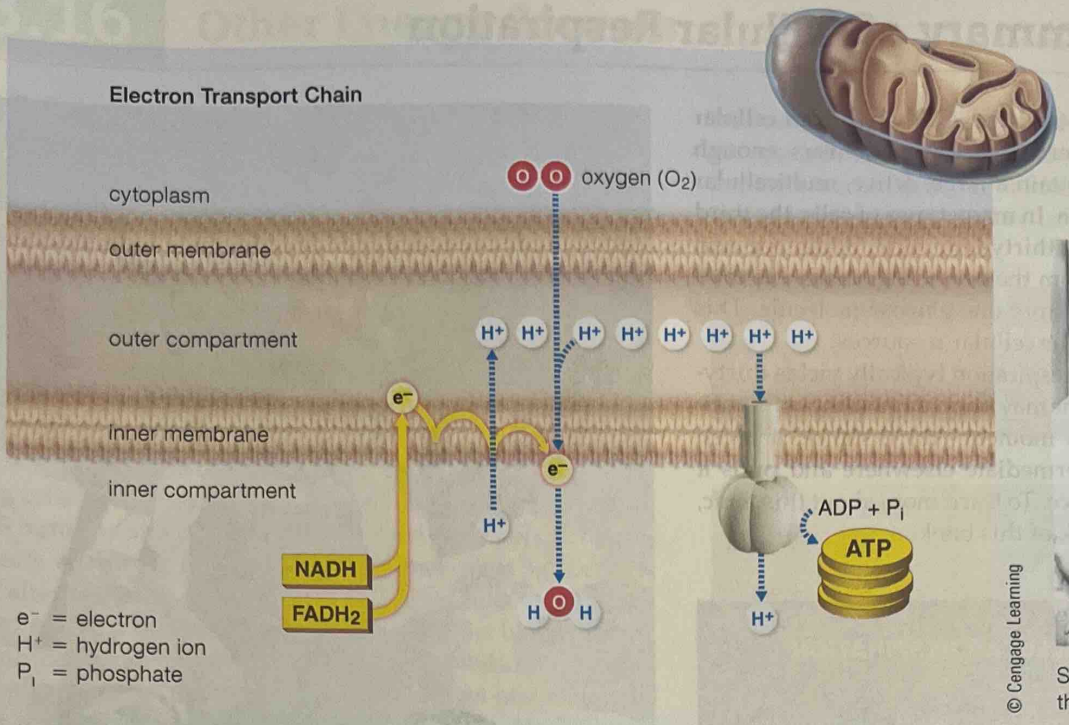
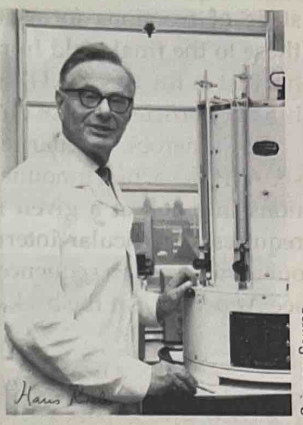


Figure 3.25 Animated! Glycolysis splits glucose molecules and forms a small amount of ATP. (© Cengage Learning)





Sir Hans Krebs discovered the Krebs cycle.

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Figure 3.26 Animated! Electron transport forms large amounts of ATP.

This substance enters the **Krebs cycle**. For each turn of the cycle, six carbons, three from each pyruvate, enter and six also leave, in the form of carbon dioxide. The bloodstream then transports this CO_2 to the lungs where it is exhaled.

Reactions in mitochondria before and during the Krebs cycle have three important functions. First, they produce two molecules of ATP. Second, they regenerate intermediate compounds required to keep the Krebs cycle going. And in a third, crucial step, a large number of the coenzymes called NAD^+ and FAD pick up H^+ and electrons, in the process becoming NADH and $FADH_2$. Loaded with energy, NADH and $FADH_2$ will now move to the site of the third and final stage of reactions that make ATP.

Step 3: Electron transport produces many ATP molecules

ATP production increases during the last stage of cellular respiration. Now, chains of reactions capture and use energy released by electrons. Each chain is called an **electron transport system**. It includes enzymes inside the membrane that divides the mitochondrion into two compartments (Figure 3.26). As electrons flow through the system, each step transfers a small amount of energy to a molecule that briefly stores it. This gradual releasing of energy reduces the amount of energy that is lost (as heat) while a cell is making ATP.

As shown at the lower left of Figure 3.26, an electron transport system uses electrons and hydrogen ions that are provided by NADH and $FADH_2$. The electrons are transferred from one molecule of the transport system to the next in line. The yellow "bouncing" line in Figure 3.26 represents this process. When molecules in the chain accept electrons and then donate them, they also pick up hydrogen ions in the inner compartment, then release them to the outer compartment. At the end of an electron transport system, oxygen accepts electrons in a reaction that forms water (H_2O).

As the system moves hydrogen ions into the outer compartment of a mitochondrion, an H^+ concentration gradient develops. As the ions become more concentrated in the outer compartment, they follow the gradient back into the inner compartment, crossing the inner membrane through the interior of enzymes that can catalyze the formation of ATP from ADP and phosphate (P_i). This step is shown at the far right of Figure 3.26.

TAKE-HOME MESSAGE

HOW DOES CELLULAR RESPIRATION MAKE ATP?

- ATP forms as the stages of cellular respiration take place in the cell cytoplasm and mitochondria.
- Glycolysis occurs in the cytoplasm and does not require oxygen. Glycolysis breaks down a carbohydrate such as glucose, with a net yield of two ATP molecules.
- A second set of reaction steps, now in mitochondria, require oxygen. Enzymes acting on pyruvate molecules from glycolysis strip away carbon atoms that end up in carbon dioxide. The rest of the molecule enters the Krebs cycle, which produces two more ATP.
- Much more ATP forms in mitochondria as electrons and H^+ move through transport systems in which enzymes add a phosphate group to ADP.

3.15 Summary of Cellular Respiration

Figure 3.27 reviews the steps and ATP yield from cellular respiration. Only this aerobic pathway delivers enough energy to build and maintain a large, active, multicellular organism such as a human. In many types of cells, the third stage of reactions forms thirty-two ATP. When we add these to the final yield from the preceding stages, the total harvest is thirty-six ATP from one glucose molecule. This is a very efficient use of our cellular resources!

While aerobic cellular respiration typically yields thirty-six ATP, the actual amount may vary, depending on conditions in a cell at a given moment—for instance, if a cell requires a particular intermediate elsewhere and pulls it out of the reaction sequence. To learn more about this topic, see Appendix I at the back of this book.

TAKE-HOME MESSAGE

HOW MUCH ATP DOES CELLULAR RESPIRATION PRODUCE?

- From start to finish, cellular respiration typically nets thirty-six ATP for every glucose molecule.
- By far the most ATP is produced during the aerobic pathway that occurs in a cell's mitochondria.

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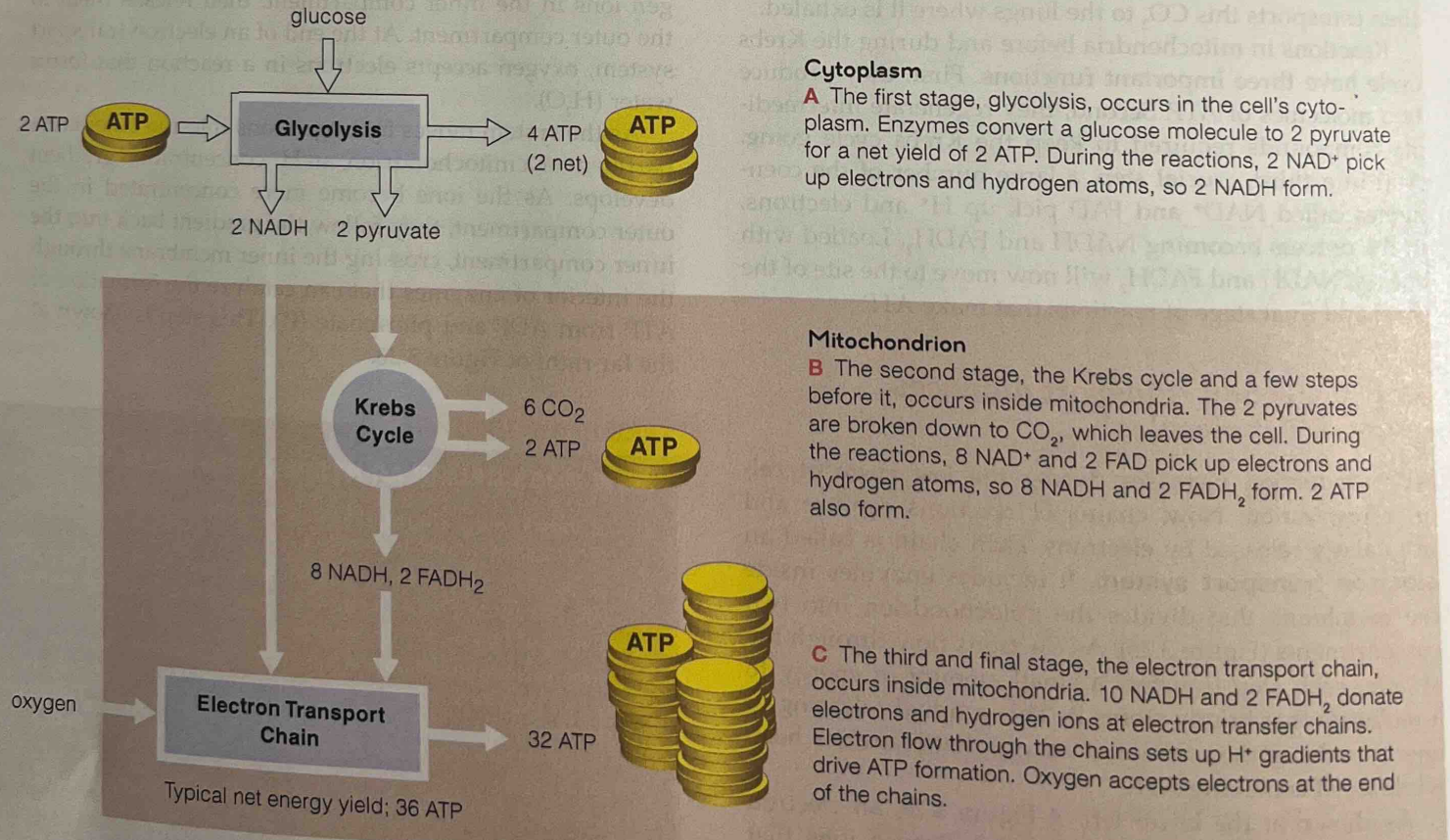

Cytoplasm

A The first stage, glycolysis, occurs in the cell's cytoplasm. Enzymes convert a glucose molecule to 2 pyruvate for a net yield of 2 ATP. During the reactions, 2 NAD^+ pick up electrons and hydrogen atoms, so 2 NADH form.

Mitochondrion

B The second stage, the Krebs cycle and a few steps before it, occurs inside mitochondria. The 2 pyruvates are broken down to CO_2, which leaves the cell. During the reactions, 8 NAD^+ and 2 FAD pick up electrons and hydrogen atoms, so 8 NADH and 2 $FADH_2$ form. 2 ATP also form.

C The third and final stage, the electron transport chain, occurs inside mitochondria. 10 NADH and 2 $FADH_2$ donate electrons and hydrogen ions at electron transfer chains. Electron flow through the chains sets up H^+ gradients that drive ATP formation. Oxygen accepts electrons at the end of the chains.

Figure 3.27 Animated! This diagram summarizes aerobic cellular respiration. (© Cengage Learning)

3.16 Other Energy Sources

- **Carbohydrates, fats, and proteins all can supply needed raw materials for making ATP.**

Glucose from carbohydrates is the body's main energy source, but fats and proteins also can supply this sugar. If you consume more glucose than your cells need for the moment, an intermediate of glycolysis is diverted into an anabolic pathway that makes a storage sugar called glycogen. This switch occurs often in muscle and liver cells, which store most of the body's glycogen.

Other kinds of cells tend to store excess glucose as fat, mostly in the form of triglycerides. These lipids build up in the cells of body fat (called *adipose tissue*), which occurs in the buttocks and other locations beneath the skin. Between meals or during exercise, the body may tap triglycerides as alternatives to glucose. Enzymes in fat cells break them into glycerol and fatty acids, which enter the bloodstream. Both can enter pathways of cellular respiration—glycerol in glycolysis (in the liver), and fatty acids as raw materials for the Krebs cycle.

The body doesn't store excess proteins but dismantles them into amino acids. A cell may use leftover carbons to make fats or carbohydrates. Alternatively, electrons removed from them may be used to help make ATP in the electron transport systems of the cell's mitochondria.

Sudden, strenuous exercise may call on cells in skeletal muscles (which attach to bones) that use an ATP-forming mechanism called *lactate fermentation* (Figure 3.28). The process converts pyruvate from glycolysis to lactic acid. It does not use oxygen and produces ATP quickly but not for long. Muscles feel sore when lactic acid builds up in them.

TAKE-HOME MESSAGE

WHAT NONCARBOHYDRATES CAN PROVIDE ENERGY FOR CELLS?

- If need be, cells also can use fats and proteins to make ATP.

David Turnley/Corbis

Figure 3.28 A gymnast's muscle cells can briefly make ATP by lactate fermentation.

FOCUS ON OUR ENVIRONMENT

3.17 A Way with Arsenic

The element arsenic is a powerful poison. When arsenic atoms enter cells, they disrupt the Krebs cycle and electron transport chain. ATP production stops cold, and the affected cell then dies. This effect has made arsenic a useful ingredient (in carefully regulated amounts) in some anticancer drugs, wood preservatives, and insecticides. On the other hand, murderers have used killer doses of arsenic to dispatch their victims for thousands of years. More often, people are exposed to low doses of arsenic in tainted food, water, or industrial emissions.

Arsenic occurs naturally in soil and rock in many areas of the world, including parts of the western United States and in Bangladesh, where some 19 million people drink arsenic-laced well water. With enough exposure, arsenic can cause cancer, disfiguring skin disorders, and severe damage to many internal organs.

Dr. Abul Hussam, a chemist at George Mason University in Virginia, was born in Bangladesh. When he learned that his own family's well was contaminated with naturally occurring arsenic, he and his brothers built a device that costs about $35 and that can filter the arsenic from roughly 130 gallons of water per day—enough to meet the needs of several families (Figure 3.29). In 2008 the National Academy of Engineering awarded Dr. Hussam a $1 million prize for his work. He pledged $250,000 to help fund more arsenic research. Nearly all the remaining prize money will go to buy filters for poor Bangladeshi families.

Because arsenic is a problem in the United States as well, the Environmental Protection Agency recently announced it will sponsor research on improved technologies for limiting arsenic pollution of water and soil.

George Mason University

Figure 3.29 Dr. Abul Hussam's low-cost water filtering device effectively removes arsenic from drinking water.