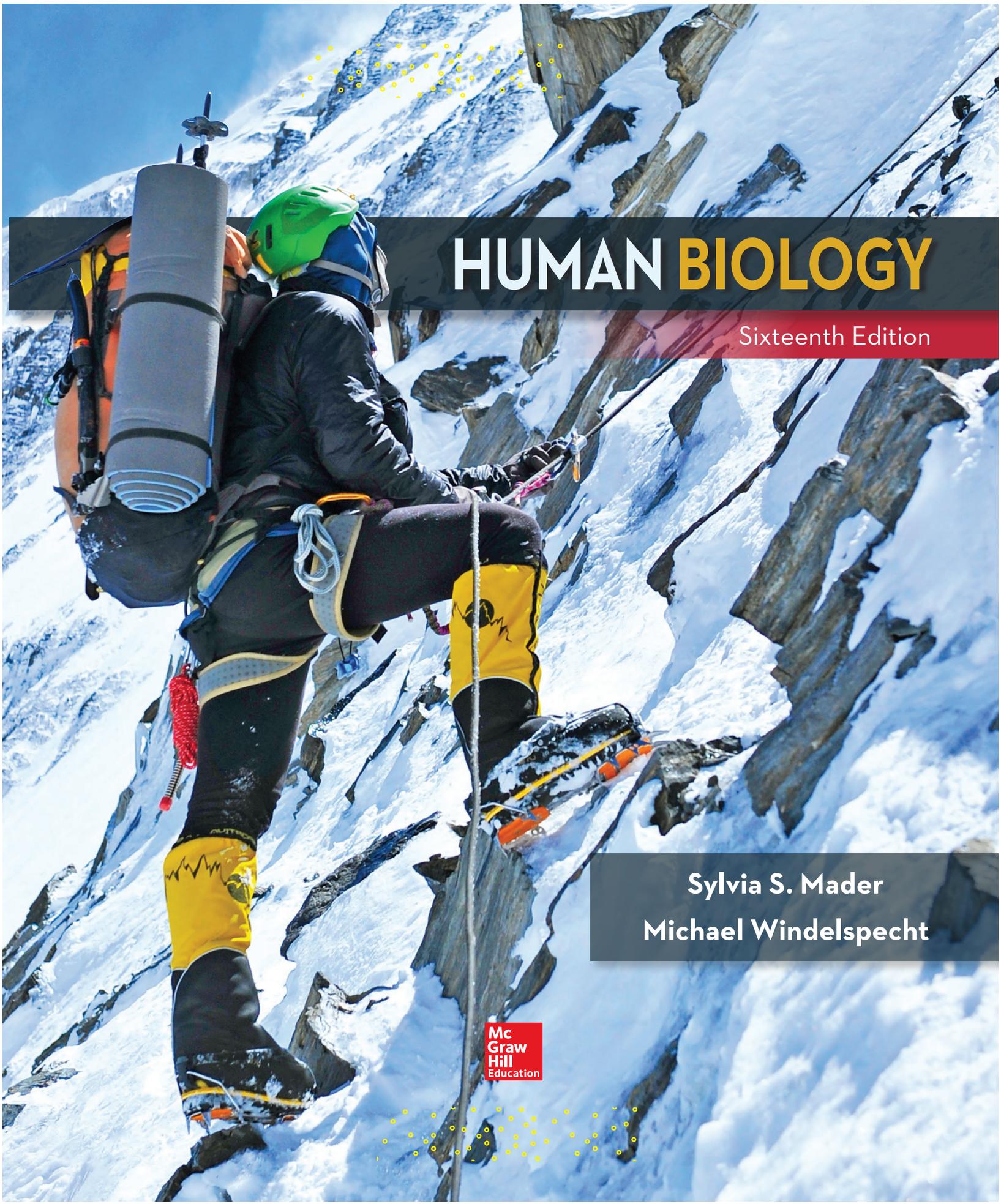

HUMAN BIOLOGY

Sixteenth Edition

Sylvia S. Mader
Michael Windelspecht

Mc Graw Hill Education

HUMAN BIOLOGY, SIXTEENTH EDITION

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Sylvia S. Mader

Sylvia S. Mader has authored several nationally recognized biology texts published by McGraw-Hill. Educated at Bryn Mawr College, Harvard University, Tufts University, and Nova Southeastern University, she holds degrees in both biology and education. Over the years she has taught at University of Massachusetts, Lowell; Massachusetts Bay Community College; Suffolk University; and Nathan Mayhew Seminars. Her ability to reach out to science-shy students led to the writing of her first text, *Inquiry into Life*. Highly acclaimed for her crisp and entertaining writing style, her books have become models for others who write in the field of biology.

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Michael Windelspecht

As an educator, Dr. Windelspecht has taught introductory biology, genetics, and human genetics in the online, traditional, and hybrid environments at community colleges, comprehensive universities, and military institutions. For over a decade he served as the Introductory Biology Coordinator at Appalachian State University, where he directed a program that enrolled over 4,500 students annually.

He received degrees from Michigan State University (BS, zoology-genetics) and the University of South Florida (PhD, evolutionary genetics) and has published papers in areas as diverse as science education, water quality, and the evolution of insecticide resistance. His current interests are in the analysis of data from digital learning platforms for the development of personalized microlearning assets and next-generation publication platforms. He is currently a member of the National Association of Science Writers and several science education associations. He has served as the keynote speaker on the development of multimedia resources for online and hybrid science classrooms. In 2015 he won the DevLearn HyperDrive competition for a strategy to integrate student data into the textbook revision process.

As an author and editor, Dr. Windelspecht has over 20 reference textbooks and multiple print and online lab manuals. He has founded several science communication companies, including Ricochet Creative Productions, which actively develops and assesses new technologies for the science classroom. You can learn more about Dr. Windelspecht by visiting his website at www.michaelwindelspecht.com

ACKNOWLEDGMENTS

Dr. Sylvia Mader is one of the icons of science education. Her dedication to her students, coupled with her clear, concise writing style, has benefited the education of thousands of students over the past four decades. As an educator, it is an honor to continue her legacy and to bring her message to the next generation of students.

As always, I had the privilege to work with a phenomenal group of people on this edition. I would especially like to thank you, the numerous instructors who have shared e-mails with me or have invited me into your classrooms, both physically and virtually, to discuss your needs as instructors and the needs of your students. You are all dedicated and talented teachers, and your energy and devotion to quality teaching is what drives a textbook revision.

Many dedicated and talented individuals assisted in the development of this edition of *Human Biology*. I am very grateful for the help of so many professionals at McGraw-Hill who were involved in bringing this book to fruition. Therefore, I would like to thank the following:

- My product developer, Anne Winch, for her patience and sometimes impossible ability to keep me focused.
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- Dawnelle Krouse, Michael McGee, and Sharon O'Donnell, who acted as my proofreaders and copyeditors for this edition.

As both an educator and an author, communicating the importance of science represents one of my greatest passions. Our modern society is based largely on advances in science and technology over the past few decades. As I present in this text, there are many challenges facing humans, and an understanding of how science can help analyze, and offer solutions to, these problems is critical to our species' health and survival.

I also want to acknowledge my family for all of their support. My wife, Sandy, has never wavered in her energy and support of my projects. The natural curiosity of my children, Devin and Kayla, has provided me with the motivation to make this world a better place for everyone.

Michael Windelspecht, PhD
Blowing Rock, NC

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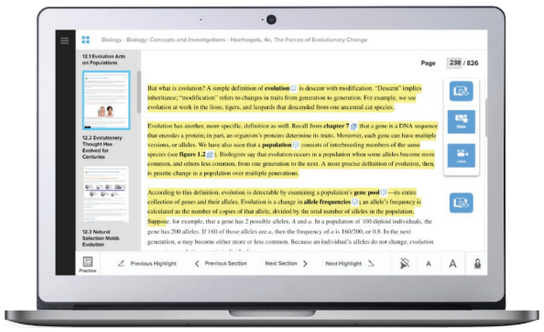

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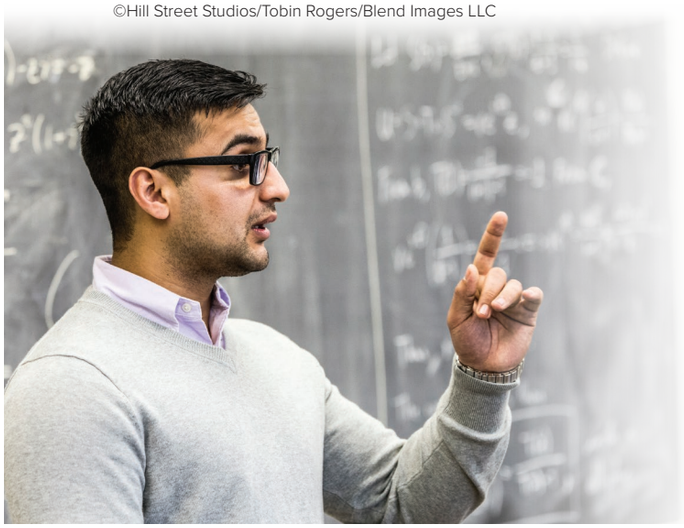

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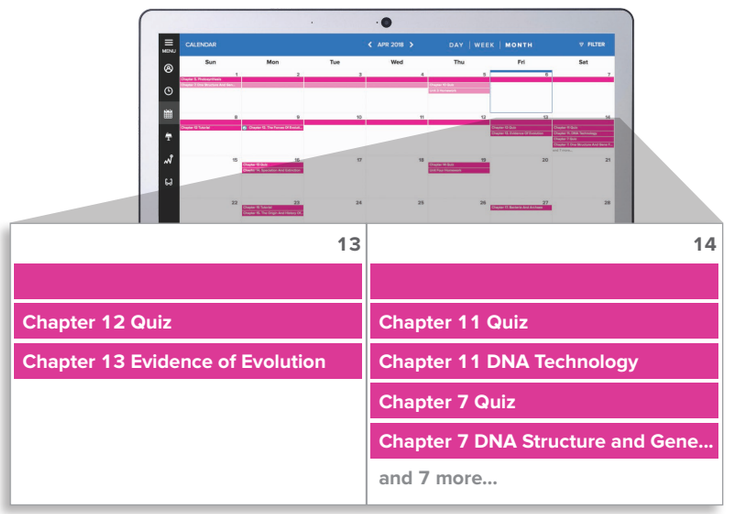

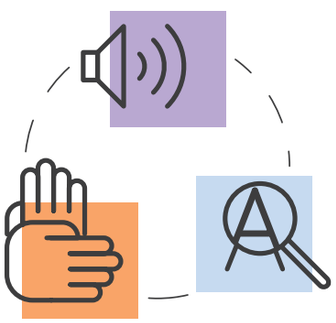

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PREFACE

Goals of the Sixteenth Edition

Humans are a naturally inquisitive species. As children, we become fascinated with our bodies, and life in general, at a very early age. We want to know how our bodies work, why there are differences, and similarities, between ourselves and the other children around us. In other words, at a very early age, we are all biologists.

In many ways, today's students in the science classroom face some of the same challenges their parents did decades ago. The abundance of new terms often overwhelms even the best prepared student, and the study of biological processes and methods of scientific thinking may convince some students that "science isn't their thing." The study of human biology creates an opportunity for teachers to instruct their students using the ultimate model organism—their own bodies. Whether this is their last science class or the first in a long career in allied health, the study of human biology is pertinent to everyone.

There are also challenges that are unique to the modern classroom. Today's students are being exposed, almost on a daily basis, to exciting new discoveries and insights that, in many cases, were beyond our predictions even a few short years ago. It is our task, as instructors, not only to make these findings available to our students, but to enlighten students as to why these discoveries are important to their lives and society. At the same time, we must provide students with a firm foundation in those core principles on which biology is founded, and in doing so, provide them with the background to keep up with the many discoveries still to come.

The author identified the following goals for the sixteenth edition of *Human Biology*:

- Updating of chapter openers, featured readings, and Connections content to focus on issues and topics important to this generation of students.
- Integrate more information on emerging diseases (such as Zika) and new technologies (for example, CRISPR).
- Update statistics, maps and tables to reflect changes in our scientific understanding of the various topics in the text.
- Assessment and redesign of art to better fit the digital learning environment.

Relevancy

The use of real-world examples to demonstrate the importance of biology in the lives of students is widely recognized as an effective teaching strategy for the introductory biology classroom. Students want to learn about the topics they are interested in. The development of relevancy-based resources is a major focus of the authors. Some examples of how we have increased the relevancy content of this edition include:

- A series of new chapter openers to introduce relevancy to the chapter. The authors chose topics that would be of interest to a nonscience major, and represent what would typically be found on a major news source.
- The inclusion of a series of the relevancy-based BioNow videos that offer relevant, applied classroom resources to allow students to feel that they can actually do and learn biology themselves.
- A website, RicochetScience.com, managed by Dr. Windelspecht, that provides updates on news and stories that are interesting to nonscience majors. The Biology101 project links these resources to the major topics of an introductory biology text. The site also features videos and tutorial animations to assist the students in recognizing the relevancy of what they are learning in the classroom.

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BRIEF CONTENTS

CONTENTS

Unit 7 Human Evolution and Ecology

READINGS

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CHAPTER

3

Cell Structure and Function

When Cells Malfunction

Mary and Kevin first noticed that something was wrong with their newborn about 4 months after birth. Whereas most newborns rapidly strengthen and develop the ability to hold their head up, as well as demonstrate hand-eye coordination, their baby seemed to be weakening. In addition, Mary began to sense that something was wrong when their baby started having trouble swallowing his formula. After consulting with their pediatrician, Mary and Kevin decided to take their child to a local pediatric research hospital to talk with physicians trained in newborn developmental disorders.

After a series of tests that included blood work and a complete physical examination, the specialists at the research center informed Kevin and Mary that the symptoms their newborn was exhibiting are characteristic of a condition called Tay-Sachs disease. This condition is a rare metabolic disorder that causes one of the internal components of the cell, the lysosome, to malfunction. Because of this malfunction, fatty acids were accumulating in the cells of their child. These accumulations were causing the neurons to degrade, producing the symptoms noted by the parents.

What puzzled the research team was the fact that neither Kevin nor Mary were of Eastern European descent. Populations from this area are known to have a higher rate of the mutation that causes Tay-Sachs disease. However, genetic testing of both Kevin and Mary indicated they were carriers for the trait, meaning that although they each had one normal copy of the gene associated with Tay-Sachs disease, each carried a defective copy as well. Only one good copy of the gene is needed for the lysosome to function correctly. Unfortunately, both had passed on a copy of the defective gene to their child.

Despite the poor prognosis for their child, both Kevin and Mary were determined to learn more about how this defect caused the lysosome to malfunction and learn about treatments being developed to prolong the life span of a child with Tay-Sachs disease.

As you read through the chapter, think about the following questions:

1. What organelle produces the lysosomes?
2. What is the role of the lysosome in a normally functioning cell?
3. Why would a malfunction in the lysosome cause an accumulation of fatty acids in the cell?

CHAPTER OUTLINE

BEFORE YOU BEGIN

Before beginning this chapter, take a few moments to review the following discussions:

Section 2.2 What properties of water make it a crucial molecule for life as we know it?

Sections 2.3 to **2.7** What are the basic roles of carbohydrates, fats, proteins, and nucleic acids in the cell?

Section 2.7 What is the role of ATP in a cell?

3.1 What Is a Cell?

LEARNING OUTCOMES

Upon completion of this section, you should be able to

1. State the basic principles of the cell theory.
2. Explain how the surface-area-to-volume ratio limits cell size.
3. Summarize the role of microscopy in the study of cells.

All organisms, including humans, are composed of cells. From single-celled bacteria to plants and complex animals such as ourselves, the cell is the fundamental unit of life. Despite their importance, most cells are small and can be seen only under a microscope. The small size of cells means they are measured using the smaller units of the metric system, such as the *micrometer* (μm). A micrometer is 1/1,000 millimeter (mm). The micrometer is the common unit of measurement for people who use microscopes professionally (see Appendix A for a complete list of metric units).

Most human cells are approximately 100 μm in diameter, about the width of a human hair. The internal contents of a cell are even smaller and, in most cases, may be viewed only using powerful microscopes. Because of this small size, the **cell theory,** one of the fundamental principles of modern biology, was not formulated until after the invention of the microscope in the seventeenth century.

The Cell Theory

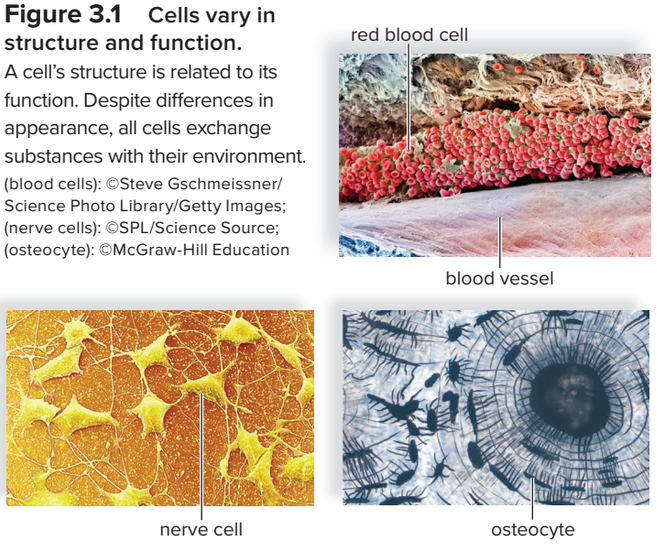
A cell is the basic unit of life. According to the cell theory, nothing smaller than a cell is considered to be alive. A single-celled organism exhibits the basic characteristics of life that were presented in Section 1.1. There is no smaller unit of life that is able to reproduce and grow, respond to stimuli, remain homeostatic, take in and use materials from the environment, and become adapted to the environment. In short, life has a cellular nature.

All living organisms are made up of cells. While many organisms, such as bacteria, are single-celled, other organisms, including humans and plants, are multicellular. In multicellular organisms, cells are often organized as tissues, such as nervous tissue and connective tissue. Even bone consists of cells (called osteocytes) surrounded by the material they have deposited. Cells may differ in their appearance, as shown in the comparison of several cell types in Figure 3.1. However, despite these differences, they all have certain structures in common. In general, it is important to recognize that the structure of a cell is directly related to its function.

New cells arise only from preexisting cells. Until the nineteenth century, most people believed in spontaneous generation: that nonliving objects could give rise to living organisms. For example, maggots were thought to arise from meat hung in the butcher shop. Maggots often appeared in meat to which flies had access. However, people did not realize that the living maggots did not spontaneously generate from the nonliving meat. A series of experiments by Francesco Redi in the seventeenth century demonstrated that meat that was placed within sealed containers did not generate maggots. In other words, life did not generate spontaneously. In 1864, the French scientist Louis Pasteur conducted a now-classic set of experiments using bacterial cells. His experiments proved conclusively that spontaneous generation of life from nonlife is not possible.

When animals, such as humans, reproduce, a sperm cell joins with an egg cell to form a zygote. By reproducing, parents pass a copy of their genetic information to their offspring. The zygote is the first cell of a new multicellular organism. Through the process of cell division, every cell in the new organism will contain a copy of the parents' genes.

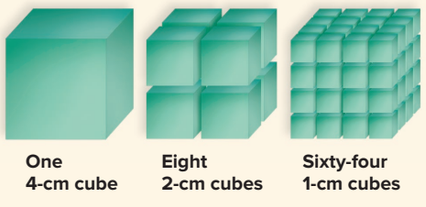
Figure 3.1 Cells vary in structure and function.
A cell's structure is related to its function. Despite differences in appearance, all cells exchange substances with their environment.
(blood cells): ©Steve Gschmeissner/Science Photo Library/Getty Images; (nerve cells): ©SPL/Science Source; (osteocyte): ©McGraw-Hill Education



Cell Size

A few cells, such as the egg of a chicken or frog, are large enough to be seen by the naked eye. In comparison, a human egg cell is around 100 μm in size, placing it right at the limit of what can be viewed by our eyes. However, most cells are much smaller. The small size of cells is explained by considering the *surface-area-to-volume ratio* of cells. Nutrients enter a cell—and waste exits a cell—at its surface. Therefore, the greater the amount of surface, the greater the ability to get material into and out of the cell. A large cell requires more nutrients and produces more waste than a small cell. However, as cells become smaller in volume, the proportionate amount of surface area actually increases. You can see this by comparing the cubes in Figure 3.2.

We would expect, then, that there would be a limit to how large an actively metabolizing cell can become. An example is a chicken's egg. Once a chicken's egg is fertilized and starts metabolizing, it divides repeatedly without increasing in size. This increases the amount of surface area needed for adequate exchange of materials in these rapidly dividing cells.



Total surface area (height × width × number of sides × number of cubes)	96 cm^2	192 cm^2	384 cm^2
Total volume (height × width × length × number of cubes)	64 cm^3	64 cm^3	64 cm^3
Surface area: Volume per cube (surface area ÷ volume)	1.5:1	3:1	6:1

Figure 3.2 **Surface-area-to-volume ratio limits cell size.**
As cell size decreases, the ratio of the surface area to volume increases.

Microscopy

Microscopes provide scientists with a deeper look into how cells function. There are many types of microscopes, from compound light microscopes to powerful electron microscopes. The *magnification,* or the ratio between the observed size of an image and its actual size, varies with the type of microscope. In addition, the resolution of the image varies between microscopes (Table 3.1). *Resolution* is the ability to distinguish between two adjacent points, and it represents the minimum distance between two objects that allows them to be seen as two different objects. Usually, the more powerful the microscope, the greater the resolution. Figure 3.3 illustrates images of a red blood cell taken by three different types of microscopes.

Table 3.1 **Resolving Power of the Eye and Common Microscopes**

	Magnification	Resolving Power
Eye	N/A	0.1 mm (100 μm)
Light microscope	1,000×	0.0001 mm (0.1 μm)
Transmission electron microscope	100,000× (or greater)	0.000001 mm (0.01 μm)

A *compound light microscope* (Fig. 3.3*a*) uses a set of glass lenses and light rays passing through the object to magnify objects. The image can be viewed directly by the human eye.

The *transmission electron microscope* makes use of a stream of electrons to produce magnified images (Fig. 3.3*b*). The human eye cannot see the image. Therefore, it is projected onto a fluorescent screen or photographic film to produce an image (called a *micrograph*) that can be viewed. The magnification and resolution produced by a transmission electron microscope is much higher than that of a light microscope. Therefore, this microscope has the ability to produce enlarged images with greater detail.

A *scanning electron microscope* provides a three-dimensional view of the surface of an object (Fig. 3.3*c*). A narrow beam of electrons is scanned over the surface of the specimen, which is coated with a thin layer of metal. The metal gives off secondary electrons, which are collected to produce a television-type picture of the specimen's surface on a screen.

In the laboratory, the light microscope is often used to view live specimens. However, this is not the case for electron microscopes. Because electrons cannot travel very far in air, a strong vacuum must be maintained along the entire path of the electron beam. Often, cells are treated before being viewed under a microscope. Because most cells are transparent, they are often stained with colored dyes before being viewed under a light microscope. Certain cellular components take up the dye more

Figure 3.3 **Micrographs of human red blood cells.**
a. Light micrograph (LM) of many cells in a large vessel (stained).
b. Transmission electron micrograph (TEM) of just three cells in a small vessel (colored).
c. Scanning electron micrograph (SEM) gives a three-dimensional view of cells and vessels (colored).
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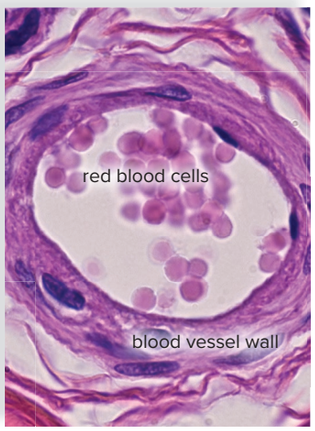
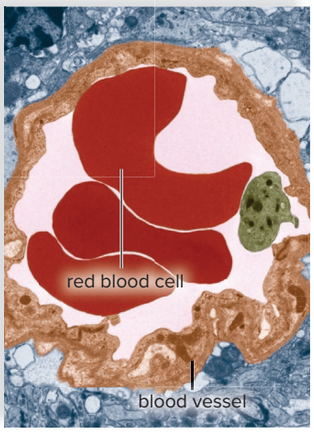


a. Light micrograph 250×



b. Transmission electron micrograph 4,000×

c. Scanning electron micrograph

BIOLOGY TODAY

Science

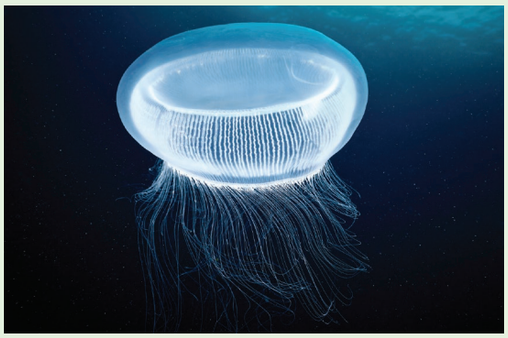
Green Fluorescent Proteins and Cells

Most cells lack any significant pigmentation. Thus, cell biologists frequently rely on dyes to produce enough contrast to resolve organelles and other cellular structures. The first of these dyes were developed in the nineteenth century from chemicals used to stain clothes in the textile industry. Since then, significant advances have occurred in the development of cellular stains.

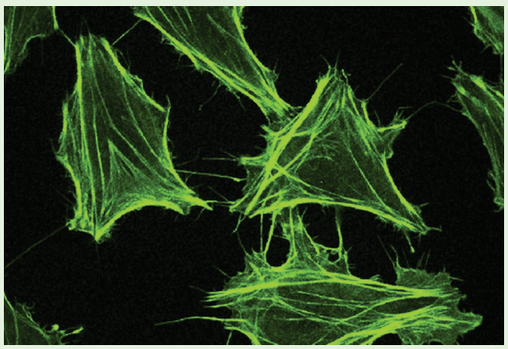
In 2008, three scientists—Martin Chalfie, Roger Y. Tsien, and Osamu Shimomura—earned the Nobel Prize in Chemistry or Medicine for their work with a protein called *green fluorescent protein,* or GFP. GFP is a bioluminescent protein found in the jellyfish *Aequorea victoria,* commonly called the crystal jelly (Fig. 3A*a*). The crystal jelly is a native of the West Coast of the United States. Normally, this jellyfish is transparent. When it is disturbed, though, special cells in the jellyfish release a fluorescent protein called aequorin. Aequorin fluoresces with a green color. The research teams of Chalfie, Tsien, and Shimomura were able to isolate the fluorescent protein from the jellyfish and develop it as a molecular tag. These tags can be generated for almost any protein within the cell, revealing not only its cellular location but also how its distribution within the cell may change as a result of a response to its environment. Figure 3A*b* shows how a GFP-labeled antibody can be used to identify the cellular location of the actin proteins in a human cell. Actin is one of the prime components of the cell's microfilaments, which in turn are part of the cytoskeleton of the cell. This image shows the distribution of actin in a human cell.

Questions to Consider

1. Discuss how a researcher might use a GFP-labeled protein in a study of a disease, such as cancer.
2. How do studies such as these support the idea that preserving the diversity of life on the planet is important?



a. Jellyfish



b. Actin filaments

Figure 3A GFP shows details of the interior of cells.
a. The jellyfish *Aequorea victoria* and **b.** the GFP stain of a human cell. This illustration shows a human cell tagged with a GFP-labeled antibody to the actin protein.
(a): ©Alexander Semenov/Getty Images; (b): ©Dr. Gopal Murti/Science Source

than other components, which enhances contrast. A similar approach is used in electron microscopy, except the sample is treated with electron-dense metals (such as gold) to provide contrast. The metals do not provide color, so electron micrographs may be colored after the micrograph is obtained. The expression "falsely colored" means the original micrograph was colored after it was produced. In addition, during electron microscopy, cells are treated so they do not decompose in the vacuum. Frequently, they are also embedded into a matrix, which allows a researcher to slice the cell into very thin pieces, providing cross-sections of the cell's interior.

These are just a few of the types of microscopes and techniques available to scientists and researchers who study cells (see the Science feature "Green Fluorescent Proteins and Cells"). Although microscope technology is evolving rapidly, it is still dependent on the principles of resolution and magnification.

CHECK YOUR PROGRESS 3.1

1. Summarize the cell theory and state its importance to the study of biology.
2. Explain how a cell's size relates to its function.
3. Compare and contrast the information that may be obtained from a light microscope and an electron microscope.

CONNECTING THE CONCEPTS

For more on the cells mentioned in this section, refer to the following discussions:

Section 6.2 discusses how red blood cells transport gases within the circulatory system.

Section 6.6 provides an overview of how red blood cells help maintain homeostasis in the body.

Section 18.1 examines the complex structure of a human egg cell.

3.2 How Cells Are Organized

LEARNING OUTCOMES

Upon completion of this section, you should be able to

1. Distinguish between the structure of a prokaryotic cell and that of a eukaryotic cell.
2. Identify the roles of the plasma membrane and the organelles of a cell.
3. Summarize how eukaryotic cells evolved from prokaryotic cells.

Biologists classify cells into two broad categories—the prokaryotes and eukaryotes. The primary difference between a prokaryotic cell and a eukaryotic cell is the presence or absence of a nucleus, a membrane-bound structure that houses the DNA. **Prokaryotic cells** lack a nucleus, whereas **eukaryotic cells** (Fig. 3.4) possess a nucleus. The prokaryotic group includes two groups of bacteria: the

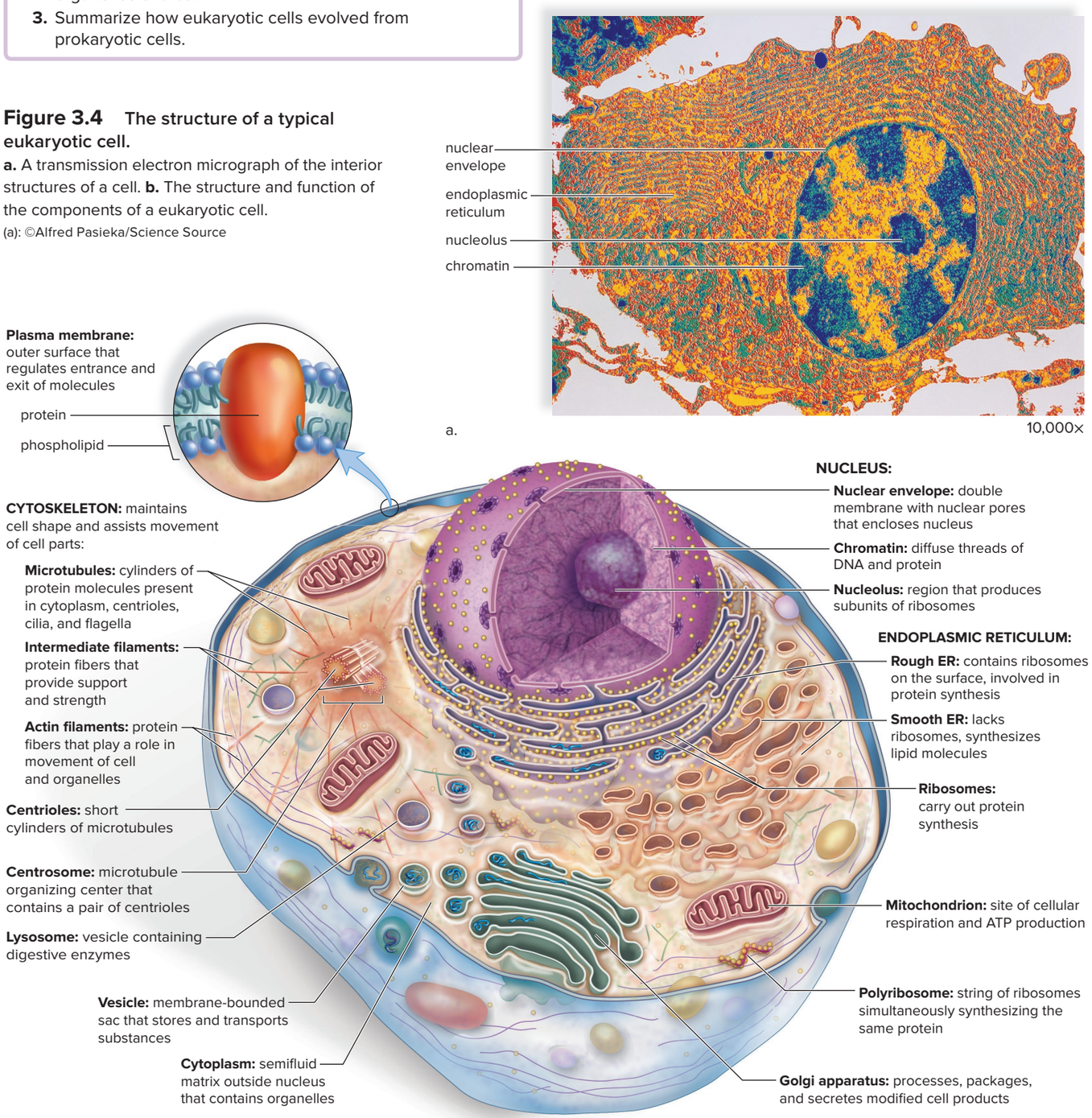


Figure 3.4 **The structure of a typical eukaryotic cell.**
a. A transmission electron micrograph of the interior structures of a cell. **b.** The structure and function of the components of a eukaryotic cell.
(a): ©Alfred Pasieka/Science Source

eubacteria and the archaebacteria. We will take a look at their structure in more detail in Section 8.1. Within the eukaryotic group are the animals, plants, and fungi, as well as some single-celled organisms called protists.

Despite their differences, both types of cells have a **plasma membrane,** an outer membrane that regulates what enters and exits a cell. The plasma membrane is a phospholipid bilayer—a "sandwich" made of two layers of phospholipids. Their polar phosphate molecules form the top and bottom surfaces of the bilayer, and the nonpolar lipid lies in between. The phospholipid bilayer is **selectively permeable,** which means it allows certain molecules—but not others—to enter the cell. Proteins scattered throughout the plasma membrane play important roles in allowing substances to enter the cell. All types of cells also contain **cytoplasm,** which is a semifluid medium containing *cytosol*, a mixture of water and various types of molecules, and organelles. The presence of proteins accounts for the semifluid nature of the cytoplasm.

The cytoplasm of a eukaryotic cell contains **organelles,** internal compartments that have specialized functions. Originally, the term *organelle* referred to only membranous structures, but we will use it to include any well-defined subcellular structure. Eukaryotic cells have many types of organelles (Fig. 3.4). Organelles allow for the compartmentalization of the cell. This keeps the various cellular activities separated from one another.

Evolutionary History of the Eukaryotic Cell

The first cells on Earth were prokaryotic cells. Today these cells are represented by bacteria and archaea, which differ mainly by their chemistry.

Early prokaryotic organisms, such as archaea, were well adapted to life on early Earth. The environment they evolved in contained conditions that would be instantly lethal to life today: The atmosphere contained no oxygen; instead it was filled with carbon monoxide and other poisonous gases; the temperature of the planet was above 200°F, and there was no ozone layer to protect organisms from damaging radiation from the sun.

Despite these conditions, prokaryotic life survived, and in doing so gradually adapted to Earth's environment. In the process, most of the archaebacteria went extinct. However, we now know that some are still around and can be found in some of the most inhospitable places on the planet, such as thermal vents and salty seas. The study of these ancient bacteria is still shedding light on the early origins of life.

Evidence widely supports the hypothesis that eukaryotic cells evolved from archaea. The internal structure of eukaryotic cells is believed to have evolved as the series of events shown in Figure 3.5. The nucleus could have formed by invagination of the plasma membrane, a process whereby a pocket is formed in the plasma membrane. The pocket would have enclosed the DNA of the cell, thus forming its nucleus. Surprisingly, some of the organelles in eukaryotic cells may have arisen by engulfing prokaryotic cells. The engulfed prokaryotic cells were not digested; rather, they then evolved into different organelles. One of these events would have given the eukaryotic cell a mitochondrion. Mitochondria are organelles that carry on cellular respiration.

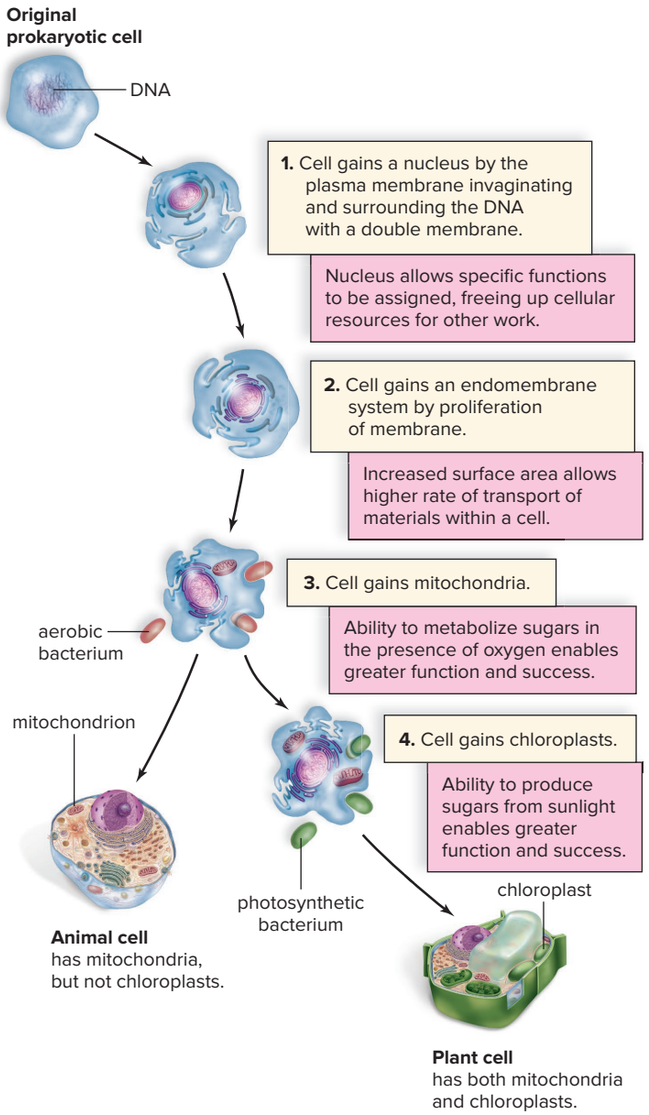


Figure 3.5 **The evolution of eukaryotic cells.**
Invagination of the plasma membrane of a prokaryotic cell could have created the nucleus. Later, the cell gained organelles, some of which may have been independent prokaryotes.

Another such event may have produced the chloroplast. Chloroplasts are found in cells that carry out photosynthesis. This process is often called *endosymbiosis.*

CHECK YOUR PROGRESS 3.2

1. Summarize the role of the plasma membrane in a cell.
2. Describe the main differences between a eukaryotic and a prokaryotic cell.
3. Describe the possible evolution of the nucleus, mitochondria, and chloroplast.

CONNECTING THE CONCEPTS

The material in this section summarizes some previous concepts of eukaryotic and prokaryotic cells and the role of phospholipids in the plasma membrane. For more information, refer to the following discussions:

Section 1.2 examines the difference in the classification of eukaryotic and prokaryotic organisms.

Section 8.1 provides more information on the structure of bacterial cells.

3.3 The Plasma Membrane and How Substances Cross It

LEARNING OUTCOMES

Upon completion of this section, you should be able to

1. Describe the structure of the plasma membrane and list the type of molecules found in the membrane.
2. Distinguish between the processes of diffusion, osmosis, and facilitated transport.
3. Explain how tonicity relates to the direction of water movement across a membrane.
4. Compare passive-transport and active-transport mechanisms.
5. Summarize how eukaryotic cells move large molecules across membranes.

Like all cells, a human cell is surrounded by an outer plasma membrane (Fig. 3.6). The plasma membrane marks the boundary between the outside and the inside of the cell. The integrity and function of the plasma membrane are necessary to the life of the cell.

The plasma membrane is a phospholipid bilayer with attached or embedded proteins. A phospholipid molecule has a polar head and nonpolar tails (see Fig. 2.19). When phospholipids are placed in water, they naturally form a spherical bilayer. The polar heads, being charged, are *hydrophilic* (attracted to water). They position themselves to face toward the watery environment outside and inside the cell. The nonpolar tails are *hydrophobic* (not attracted to water). They turn inward toward one another, where there is no water.

At body temperature, the phospholipid bilayer is a liquid. It has the consistency of olive oil. The proteins are able to change their position by moving laterally. The **fluid-mosaic model** is a working description of membrane structure. It states that the protein molecules form a shifting pattern within the fluid phospholipid bilayer. Cholesterol lends support to the membrane.

Short chains of sugars (carbohydrates) are attached to the outer surface of some protein and lipid molecules. The attachment of a sugar produces a *glycoprotein*, while the attachment of a sugar to a lipid molecule creates a *glycolipid*. These molecules help mark the cell as belonging to a particular individual. This identification is called "self" and helps the body identify foreign cells that may cause infections. They also account for why people have different blood types.

Some plasma membrane proteins form channels through which certain substances can enter cells. Others are either enzymes that catalyze reactions or are carriers involved in the passage of molecules through the membrane.

Plasma Membrane Functions

The plasma membrane isolates the interior of the cell from the external environment. In doing so, it allows only certain molecules and ions to enter and exit the cytoplasm freely. Therefore, the plasma membrane is said to be selectively permeable (Fig. 3.7). Small, lipid-soluble molecules, such as oxygen and carbon dioxide, can pass through the membrane easily. The small size of water molecules allows them to freely cross the membrane by using protein channels called *aquaporins*. Ions and large molecules cannot cross the membrane without more direct assistance, which will be discussed later.

Diffusion

Diffusion is the random movement of molecules from an area of higher concentration to an area of lower concentration, until they are equally distributed. Diffusion is a passive way for molecules to enter or exit a cell. No cellular energy is needed to bring it about.

Certain molecules can freely cross the plasma membrane by diffusion. When molecules can cross a plasma membrane, which way will they go? The molecules will move in both directions. But the *net movement* will be from the region of higher concentration to the region of lower concentration, until equilibrium is achieved. At equilibrium, just as many molecules of the substance will be entering as leaving the cell (Fig. 3.8). Oxygen diffuses across the plasma membrane, and the net movement is toward the inside of the cell. As the cell produces ATP, it uses oxygen, so the concentration of oxygen is lower on the inside of the cell compared to the exterior environment.

Osmosis

Osmosis is the net movement of water across a selectively permeable membrane. The direction by which water will diffuse is determined by the tonicity of the solutions inside and outside the cell. Tonicity is based on dissolved particles, called solutes, within a solution. The higher the concentration of solutes in a solution, the lower the concentration of water, and vice versa. Typically, water will diffuse from the area that has less solute (low tonicity, and therefore more water) to the area with more solute (high tonicity, and therefore less water).

Normally, body fluids are *isotonic* to cells (Fig. 3.9*a*). There is the same concentration of nondiffusible solutes and water on both sides of the plasma membrane. Therefore, cells maintain their normal size and shape. Intravenous solutions given in medical situations are usually isotonic.

Solutions that cause cells to swell or even burst due to an intake of water are said to be *hypotonic*. A hypotonic solution has a lower concentration of solute and a higher concentration of water than the cells. If red blood cells are placed in a hypotonic solution,

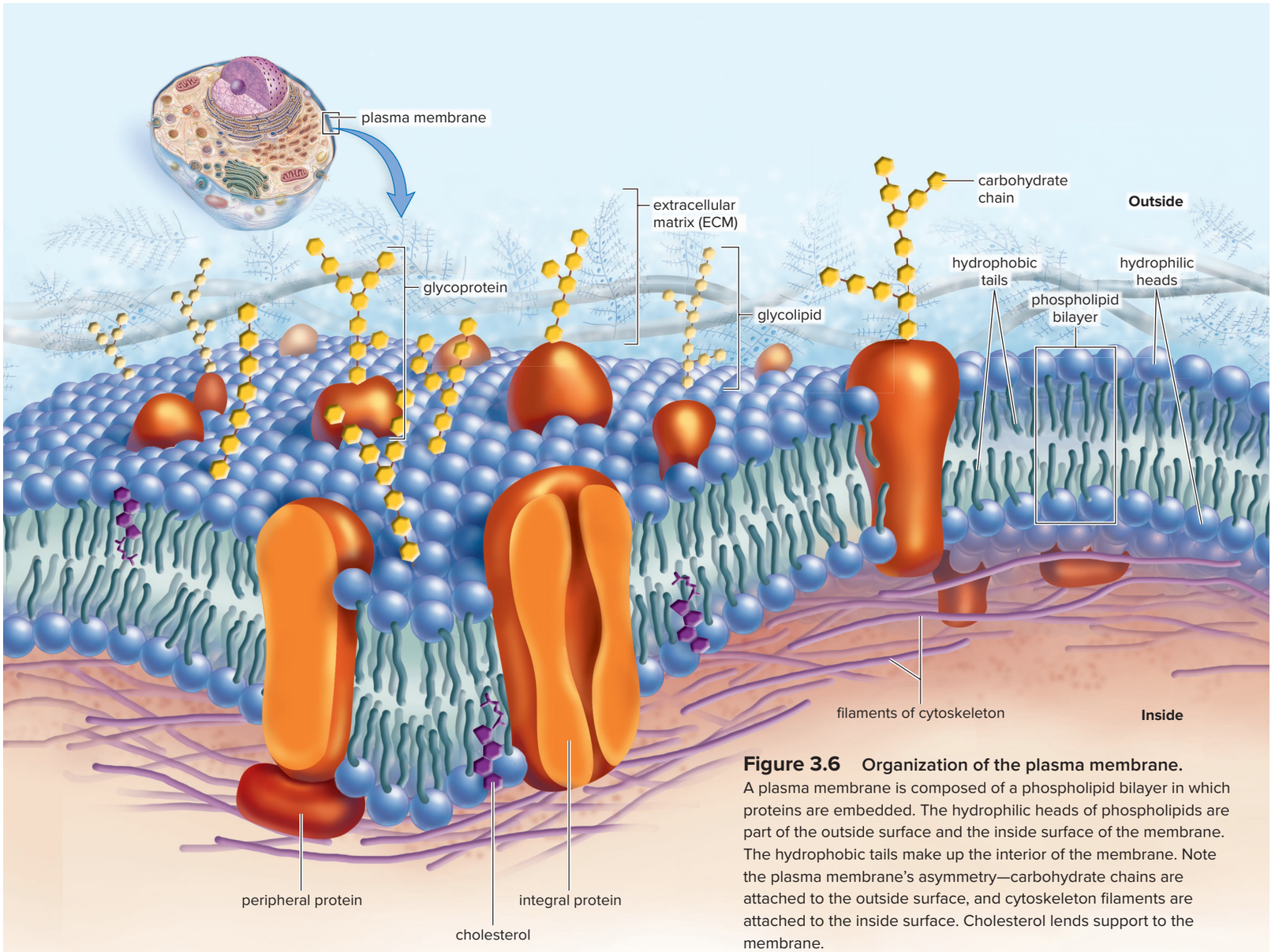


Figure 3.6 **Organization of the plasma membrane.**
A plasma membrane is composed of a phospholipid bilayer in which proteins are embedded. The hydrophilic heads of phospholipids are part of the outside surface and the inside surface of the membrane. The hydrophobic tails make up the interior of the membrane. Note the plasma membrane's asymmetry—carbohydrate chains are attached to the outside surface, and cytoskeleton filaments are attached to the inside surface. Cholesterol lends support to the membrane.

water enters the cells. They swell to bursting (Fig. 3.9*b*). *Lysis* is used to refer to the process of bursting cells. Bursting of red blood cells is termed *hemolysis.*

Solutions that cause cells to shrink or shrivel due to loss of water are said to be *hypertonic.* A hypertonic solution has a higher concentration of solute and a lower concentration of water than do the cells. If red blood cells are placed in a hypertonic solution, water leaves the cells; they shrink (Fig. 3.9*c*). The term *crenation* refers to red blood cells in this condition. These changes have occurred due to osmotic pressure. **Osmotic pressure** controls water movement in our bodies. For example, in the small and large intestines, osmotic

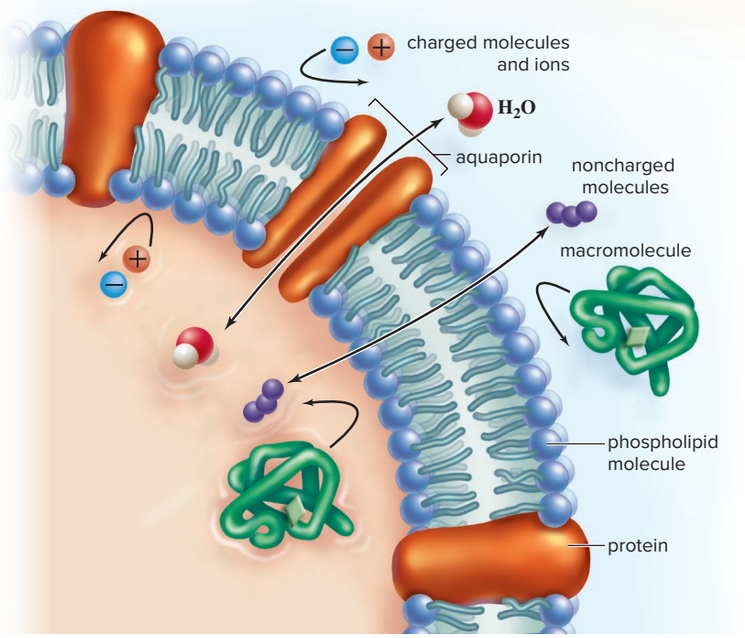


Figure 3.7 **Selective permeability of the plasma membrane.**
Small, uncharged molecules are able to cross the membrane, whereas large or charged molecules cannot. Water travels freely across membranes through aquaporins.

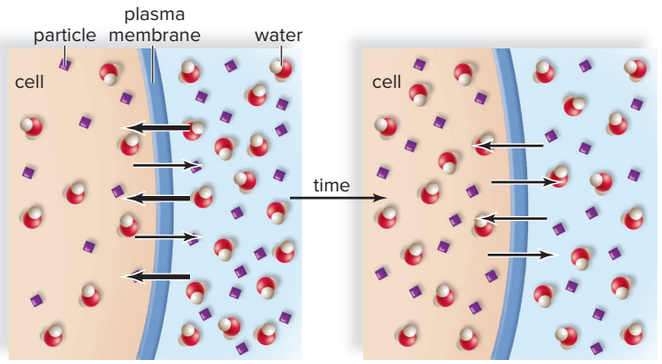


Figure 3.8 Diffusion across the plasma membrane.
a. When a substance can diffuse across the plasma membrane, it will move back and forth across the membrane, but the net movement will be toward the region of lower concentration. **b.** At equilibrium, equal numbers of particles and water cross in both directions, and there is no net movement.

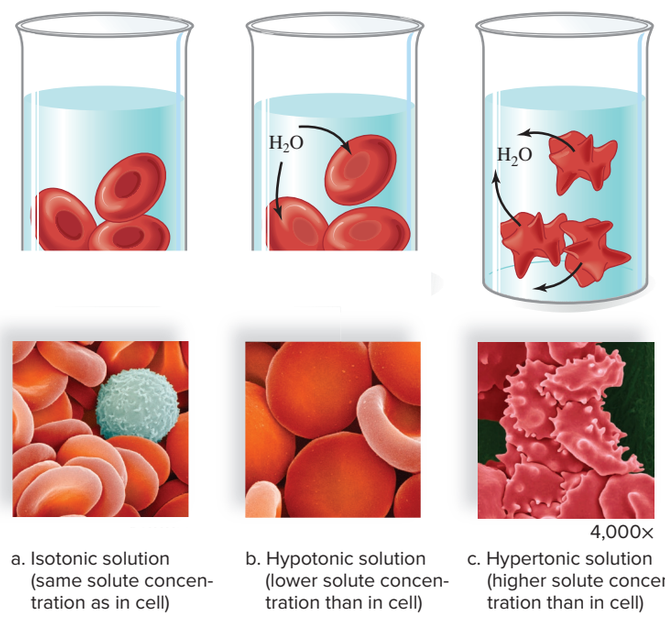


Figure 3.9 Effects of changes in tonicity on red blood cells.
a. In an isotonic solution, cells remain the same. **b.** In a hypotonic solution, cells gain water and may burst (lysis). **c.** In a hypertonic solution, cells lose water and shrink (crenation).
(photos) (a–b): ©Power and Syred/Science Photo Library/Getty Images; (c): ©Steve Gschmeissner/Science Photo Library/Getty Images

pressure allows us to absorb the water in food and drink. In the kidneys, osmotic pressure controls water absorption as well.

Facilitated Transport

Many solutes do not simply diffuse across a plasma membrane. They are transported by means of protein carriers within the membrane. During **facilitated transport,** a molecule is transported across the plasma membrane from the side of higher concentration to the side of lower concentration (Fig. 3.10). This is a passive means of transport, because the cell does not need to expend energy to move a substance down its concentration gradient. Each protein carrier, sometimes called a *transporter,* binds only to a specific molecule. For example, a glucose transporter will only move glucose molecules across the membrane. Type 2 diabetes results when cells lack a sufficient number of glucose transporters.

SCIENCE IN YOUR LIFE

Can you drink seawater?

Seawater is hypertonic to our cells. Seawater contains approximately 3.5% salt, whereas our cells contain 0.9%. Once salt has entered the blood, your cells would shrivel up and die as they lost water trying to dilute the excess salt. Your kidneys can only produce urine that is slightly less salty than seawater, so you would dehydrate providing the amount of water necessary to rid your body of the salt. In addition, salt water contains high levels of magnesium ions, which cause diarrhea and further dehydration.

SCIENCE IN YOUR LIFE

What causes cystic fibrosis?

In 1989, scientists determined that defects in a gene on chromosome 7 are the cause of cystic fibrosis (CF). This gene, called *CFTR* (cystic fibrosis conductance transmembrane regulator), codes for a protein that is responsible for the movement of chloride ions across the membranes of cells that produce mucus, sweat, and saliva. Defects in this gene cause an improper water-salt balance in the excretions of these cells, which in turn leads to the symptoms of CF. To date, there are over 1,800 known mutations in the CF gene. This tremendous amount of variation in this gene accounts for the differences in the severity of the disease in CF patients.

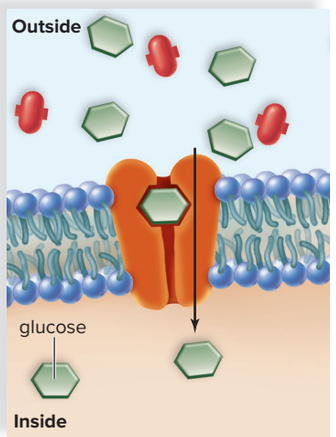


Figure 3.10 Facilitated transport across a plasma membrane.
This is a passive form of transport in which substances move down their concentration gradient through a protein carrier. In this example, glucose (green) moves into the cell by facilitated transport. The end result will be an equal distribution of glucose on both sides of the membrane.

Active Transport

During **active transport,** a molecule is moving from an area of *lower* concentration to one of *higher* concentration. Active transport in involved in a number of functions in the body, from the movement of iodine ions into the cells of the thyroid gland to the transport of sugar into the cells lining the small intestine. All active transport mechanisms require a protein carrier and the use of cellular energy obtained from the breakdown of ATP. When ATP is broken down, energy is released. In this case, the energy is used to carry out active transport.

Proteins involved in active transport often are called *pumps.* Just as a water pump uses energy to move water against the force of gravity, energy is used to move substances against their concentration gradients. One type of pump, called the **sodium–potassium pump,** is active in all the cells of the body for the movement of sodium ions (Na^+) outside, and potassium ions (K^+) inside, the cell (Fig. 3.11). This type of pump is associated especially with nerve and muscle cells.

The passage of salt (NaCl) across a plasma membrane is of primary importance in cells. First, sodium ions are pumped across a membrane. Then, chloride ions diffuse through channels that allow their passage. In cystic fibrosis, a mutation in these chloride ion channels causes them to malfunction. This leads to the symptoms of this inherited (genetic) disorder.

Bulk Transport

Cells use bulk transport to move large molecules, such as polysaccharides or polypeptides, across the membrane. These processes use vesicles rather than channel or transport proteins. During *endocytosis,* a portion of the plasma membrane invaginates, or forms a pouch, to envelop a substance and fluid. Then, the membrane pinches off to form an endocytic vesicle inside the cell (Fig. 3.12*a*). Some white blood cells are able to take up pathogens (disease-causing agents) by endocytosis. This process is given a special name: *phagocytosis.* If small molecules and fluid are being imported, then the process is called *pinocytosis* (Fig. 3.12*b*).

During *exocytosis,* a vesicle fuses with the plasma membrane as secretion occurs. Later in this chapter, we will see that a steady

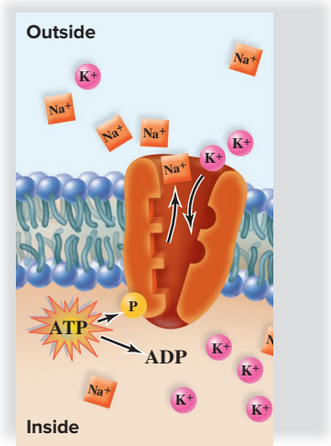


Figure 3.11 Active transport and the sodium–potassium pump.
This is a form of transport in which a molecule moves from low concentration to high concentration. It requires a protein carrier and energy. Na^+ exits, and K^+ enters, the cell by active transport, so Na^+ will be concentrated outside the cell and K^+ will be concentrated inside it.

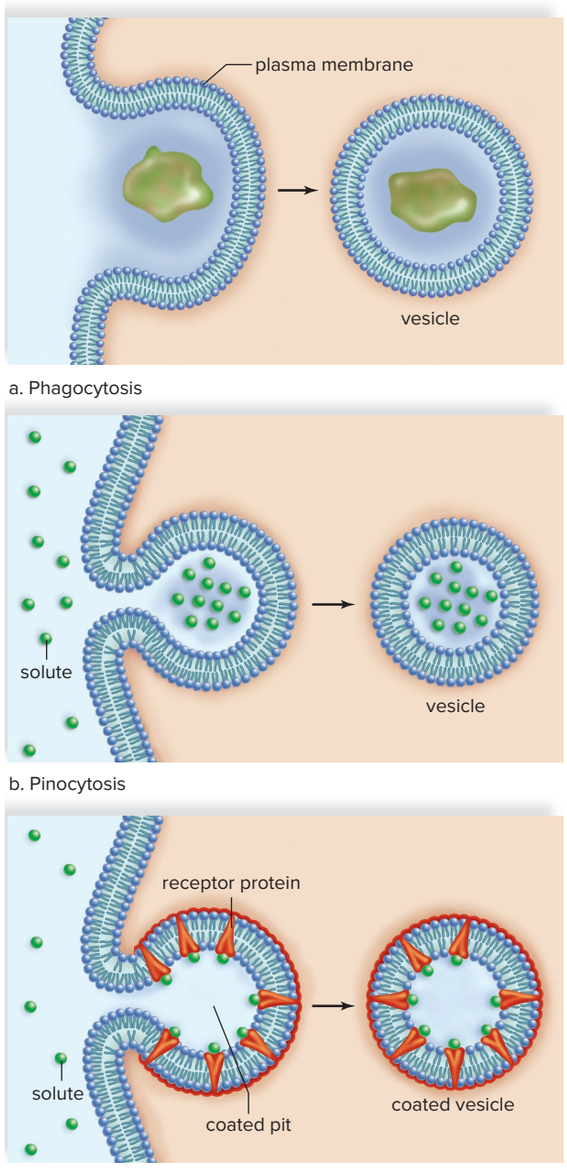


Figure 3.12 Examples of endocytosis.
a. Large substances enter a cell by phagocytosis. **b.** Small molecules and fluids enter a cell by pinocytosis. **c.** In receptor-mediated endocytosis, molecules first bind to specific receptors and are then brought into the cell by endocytosis.

stream of vesicles moves between certain organelles, before finally fusing with the plasma membrane. This is the way that signaling molecules, called *neurotransmitters,* leave one nerve cell to excite the next nerve cell or a muscle cell.

One form of endocytosis uses a receptor, a form of membrane protein, on the surface of the cell to concentrate specific molecules of interest for endocytosis. This process is called *receptor-mediated endocytosis* (Fig. 3.12*c*). An inherited form of cardiovascular disease occurs when cells fail to take up a combined lipoprotein and cholesterol molecule from the blood by receptor-mediated endocytosis.

CHECK YOUR PROGRESS 3.3

1. Summarize how the fluid-mosaic model describes the structure of the plasma membrane.
2. Compare and contrast diffusion, osmosis, facilitated transport, and active transport.
3. Discuss the various ways cells can move materials in bulk into and out of the cell.

CONNECTING THE CONCEPTS

The movement of materials across a plasma membrane is crucial to the maintenance of homeostasis for many organ systems in humans. For some examples, refer to the following discussions:

Section 9.3 examines how nutrients, including glucose, are moved into the cells of the digestive system.

Section 11.4 investigates how the movement of salts by the urinary system maintains blood homeostasis.

Section 21.2 explains the patterns of inheritance associated with cystic fibrosis.

3.4 The Nucleus and Endomembrane System

LEARNING OUTCOMES

Upon completion of this section, you should be able to

1. Describe the structure of the nucleus and explain its role as the storage place of genetic information.
2. Summarize the functions of the organelles of the endomembrane system.
3. Explain the role and location of the ribosomes.

The nucleus contains the genetic instructions necessary for the manufacture of the proteins involved in most cellular functions. The endomembrane system is a series of membranous organelles that function in the processing of materials for the cell.

The Nucleus

The presence of a nucleus is a defining characteristic of eukaryotic cells (Fig. 3.13). The function of the nucleus is to store the genetic information as long chains of DNA.

Within the nucleus is **chromatin,** a combination of the DNA molecules and proteins. The chromatin is surrounded by a semifluid medium called the *nucleoplasm,* which differs in pH and composition from the cytoplasm outside the nucleus. During cell division, chromatin can coil tightly to form visible long linear structures called **chromosomes.** While uncoiled, the individual chromosomes cannot be distinguished; the chromatin appears grainy in electron micrographs of the nucleus. As we will see in Section 19.1, the chromosomes are responsible for transmitting genetic information from one generation to the next.

Located on the chromosome are collections of **genes,** which are segments of DNA that contain information for the production of specific proteins. These proteins have many functions in cells, and they help determine a cell's specificity. While every cell in the body contains the same genes, cells vary in which genes are turned on and off, and this enables them to perform their function in the tissue or organism.

Micrographs of a nucleus often show a dark region (or sometimes more than one) of chromatin. This is the **nucleolus,** where ribosomal RNA (rRNA) is produced. This is also where rRNA joins with proteins to form the subunits of ribosomes.

The nucleus is separated from the cytoplasm by a double membrane known as the **nuclear envelope.** This is continuous with the endoplasmic reticulum (ER), a membranous system of membranous saccules and channels, discussed a little later in this section. The nuclear envelope has **nuclear pores** of sufficient size to permit the passage of ribosomal subunits out of the nucleus and proteins into the nucleus.

Ribosomes

Ribosomes are organelles composed of proteins and rRNA. Protein synthesis occurs at the ribosomes. Ribosomes are often attached to the endoplasmic reticulum, but they also may occur free within the cytoplasm, either singly or in groups called *polyribosomes.* Proteins synthesized at ribosomes attached to the endoplasmic reticulum have a different destination from that of proteins manufactured at ribosomes free in the cytoplasm.

The Endomembrane System

The **endomembrane system** consists of the nuclear envelope, the endoplasmic reticulum, the Golgi apparatus, lysosomes, and **vesicles** (tiny membranous sacs) (Fig. 3.14). This system compartmentalizes the cell so that chemical reactions are restricted to specific regions. The vesicles transport molecules from one part of the system to another.

The Endoplasmic Reticulum

The **endoplasmic reticulum (ER)** has two portions. *Rough ER* is studded with ribosomes on the side of the membrane that faces the

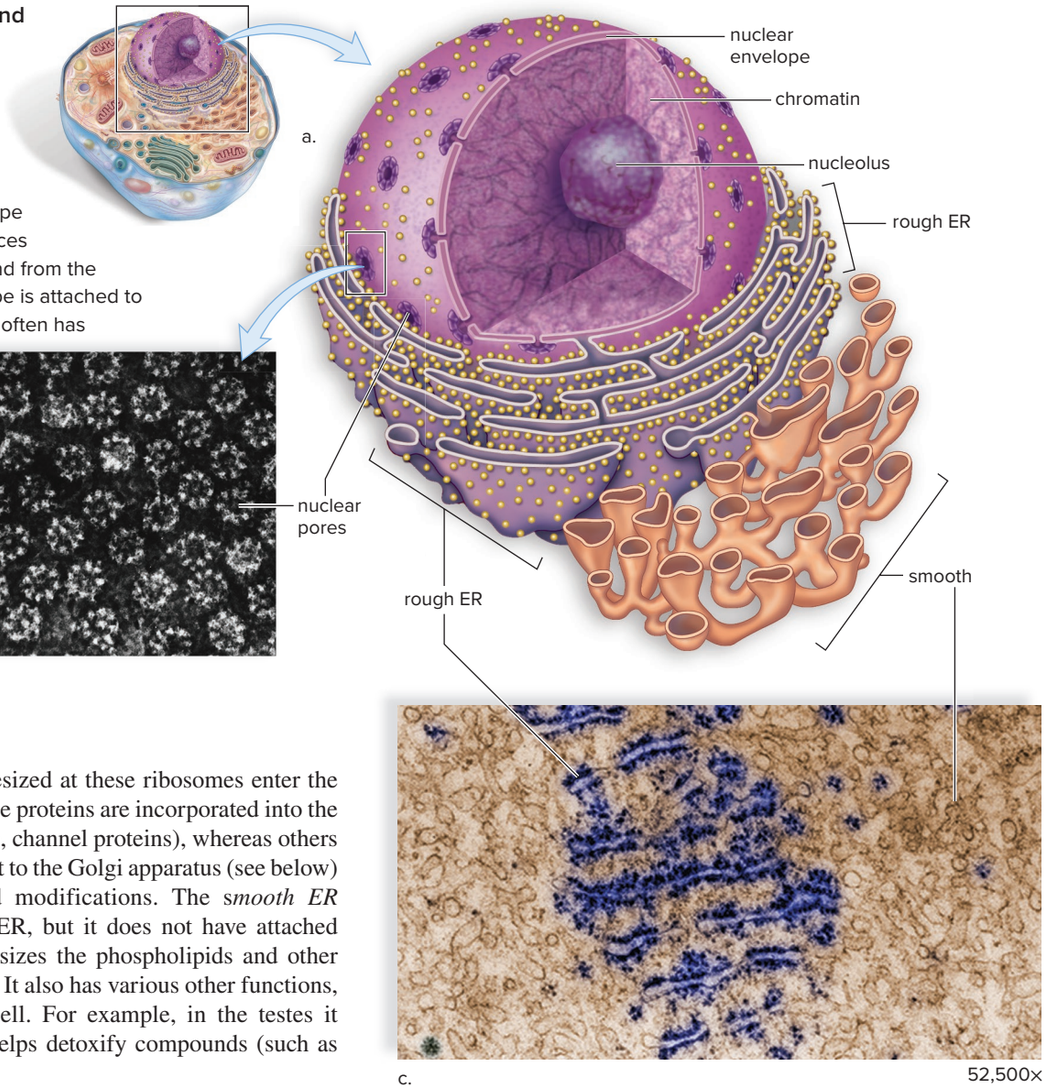


Figure 3.13 **The nucleus and endoplasmic reticulum.** **a.** The nucleus contains chromatin. Chromatin has a region called the nucleolus, where rRNA is produced and ribosome subunits are assembled. **b.** The nuclear envelope contains pores that allow substances to enter and exit the nucleus to and from the cytoplasm. **c.** The nuclear envelope is attached to the endoplasmic reticulum, which often has attached ribosomes, where protein synthesis occurs.

(photos) (b): ©Don W. Fawcett/Science Source; (c): ©Martin M. Rotker/Science Source

cytoplasm. The proteins synthesized at these ribosomes enter the interior of the ER. Some of these proteins are incorporated into the plasma membrane (for example, channel proteins), whereas others are packed into vesicles and sent to the Golgi apparatus (see below) for additional processing and modifications. The s*mooth ER* is continuous with the rough ER, but it does not have attached ribosomes. Smooth ER synthesizes the phospholipids and other lipids that occur in membranes. It also has various other functions, depending on the particular cell. For example, in the testes it produces testosterone, and it helps detoxify compounds (such as drugs) in the liver.

The ER forms transport vesicles in which large molecules are transported to other parts of the cell. Often, these vesicles are on their way to the plasma membrane or the Golgi apparatus.

The Golgi Apparatus

The **Golgi apparatus** is named for Camillo Golgi who discovered its presence in cells in the late nineteenth century. The Golgi apparatus consists of a stack of slightly curved saccules whose appearance can be compared to a stack of pancakes. Here, proteins and lipids received from the ER are modified. For example, a chain of sugars (carbohydrates) may be added to them, forming glycoproteins and glycolipids. These are then incorporated into the plasma membrane where they serve in the process of cellular identification.

The vesicles that leave the Golgi apparatus move to other parts of the cell. Some vesicles proceed to the plasma membrane where they discharge their contents. In all, the Golgi apparatus is involved in processing, packaging, and secretion.

Lysosomes

Lysosomes, membranous sacs produced by the Golgi apparatus, contain hydrolytic enzymes. Lysosomes are found in all cells of the body but are particularly numerous in white blood cells that engulf disease-causing microbes. When a lysosome fuses with such an endocytic vesicle, its contents are digested by hydrolytic enzymes into simpler subunits, which then enter the cytoplasm. In a process called autodigestion, parts of a cell may be broken down by the lysosomes. Some human diseases are caused by the lack of a particular enzyme in the lysosome. Tay-Sachs disease, as discussed in the chapter opener, occurs when an undigested substance collects in nerve cells, leading to developmental problems and death in early childhood.

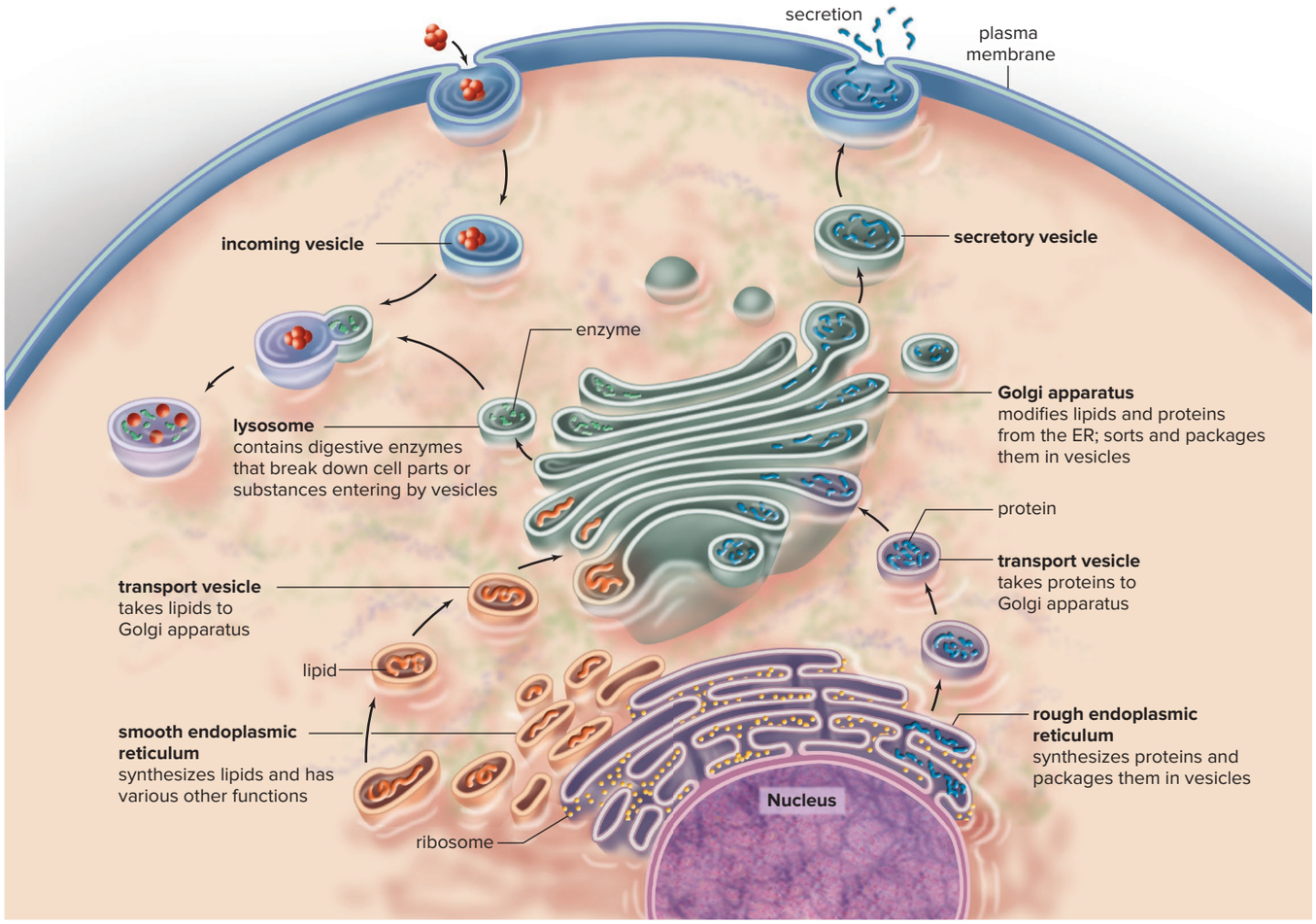


Figure 3.14 The endomembrane system.
The organelles in the endomembrane system work together to produce, modify, and secrete products for the cell. Some of these may be loaded into vesicles to produce lysosomes to digest incoming materials.

CHECK YOUR PROGRESS 3.4

1. Describe the functions of the following organelles: endoplasmic reticulum, Golgi apparatus, and lysosomes.
2. Explain how the nucleus, ribosomes, and rough endoplasmic reticulum contribute to protein synthesis.
3. Describe the organelles of the endomembrane system involved in the export of a protein from the cell.

CONNECTING THE CONCEPTS

For a more detailed look at how the organelles of the endomembrane system function, refer to the following discussions:

Section 18.5 contains information on how aging is related to the breakdown of cellular organelles.

Section 21.2 explores the patterns of inheritance associated with Tay-Sachs disease.

Section 22.2 provides a more detailed look at how ribosomes produce proteins.

3.5 The Cytoskeleton, Cell Movement, and Cell Junctions

LEARNING OUTCOMES

Upon completion of this section, you should be able to

1. Explain the role of the cytoskeleton in the cell.
2. Summarize the major protein fibers in the cytoskeleton.
3. Describe the role of flagella and cilia in human cells.
4. Compare the functions of adhesion junctions, gap junctions, and tight junctions in human cells.

It took a high-powered electron microscope to discover that the cytoplasm of the cell is crisscrossed by several types of protein fibers, collectively called the **cytoskeleton** (see Fig. 3.4). The cytoskeleton helps maintain a cell's shape and either anchors the organelles or assists in their movement, as appropriate.

In the cytoskeleton, **microtubules** are cylinders that contain rows of a protein called tubulin. The regulation of microtubule assembly is under the control of a microtubule organizing center called the **centrosome** (see Fig. 3.4). Microtubules help maintain the shape of the cell and act as tracks along which organelles move. During cell division, microtubules form spindle fibers, which assist in the movement of chromosomes. **Actin filaments,** made of a protein called actin, are long, extremely thin fibers that usually occur in bundles or other groupings. Actin filaments are involved in movement. Microvilli, which project from certain cells and can shorten and extend, contain actin filaments. **Intermediate filaments,** as their name implies, are intermediate in size between microtubules and actin filaments. Their structures and functions differ according to the type of cell.

Cilia and Flagella

Cilia (*sing***., cilium)** and **flagella (***sing***., flagellum)** are involved in movement. The ciliated cells that line our respiratory tract sweep back up the throat the debris trapped within mucus. This helps keep the lungs clean. Similarly, ciliated cells move an egg along the uterine tube, where it may be fertilized by a flagellated sperm cell (Fig. 3.15). Motor molecules, powered by ATP, allow the microtubules in cilia and flagella to interact and bend and, thereby, move.

The importance of normal cilia and flagella is illustrated by the occurrence of a genetic disorder called ciliary dyskinesia. This is a recessive disorder (see Section 21.3) in which one of the genes associated with the production of a protein found in the microtubules of cilia and flagella is not formed correctly. The result is cilia and flagella that will not bend. Not surprisingly, these individuals suffer from recurrent and severe respiratory infections. The ciliated cells lining respiratory passages fail to keep their lungs clean. They are also unable to reproduce naturally due to the lack of ciliary action to move the egg in a female or the lack of flagella action by sperm in a male.

SCIENCE IN YOUR LIFE

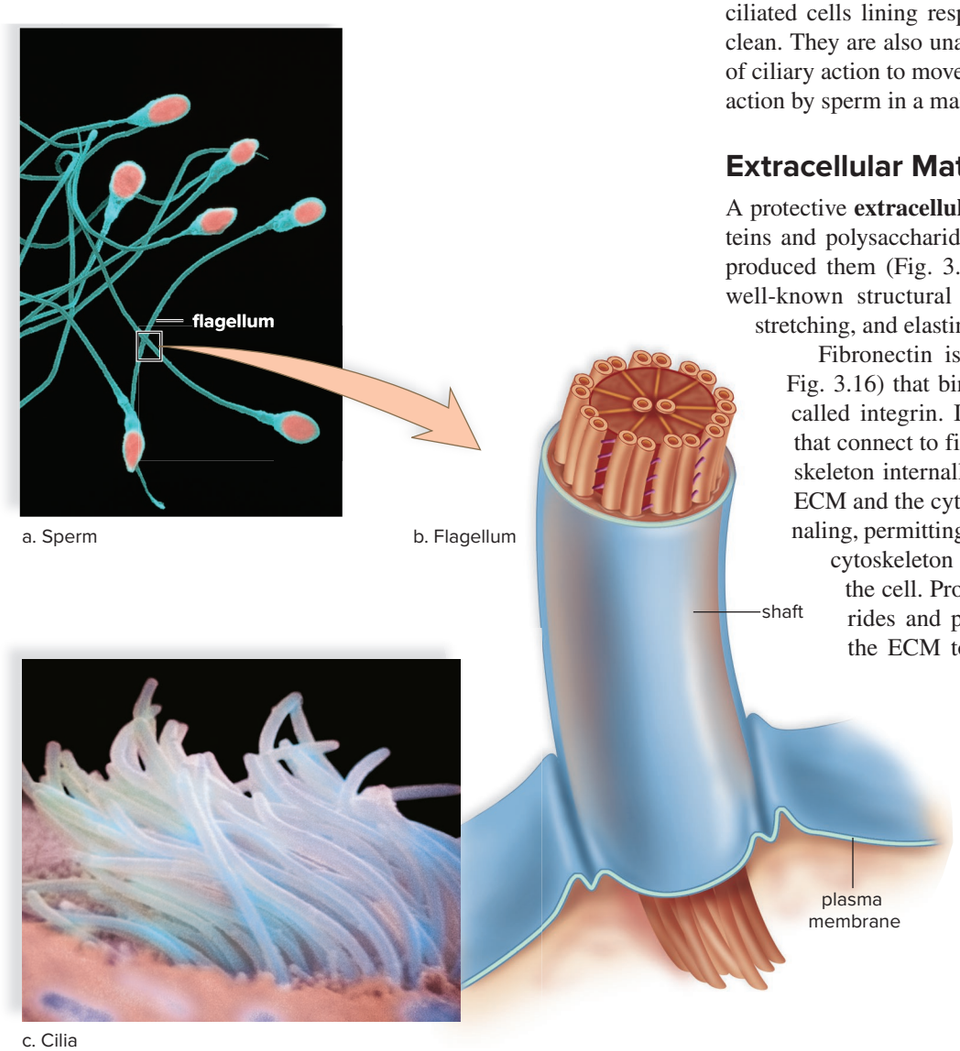
How fast does a human sperm swim?

Individual sperm speeds vary considerably and are greatly influenced by environmental conditions. However, in recent studies, researchers found that some human sperm could travel at top speeds of approximately 20 centimeters (cm) per hour. This means these sperm could reach the female ovum in less than an hour. Scientists are interested in sperm speed so they can design new contraceptive methods.

Extracellular Matrix

A protective **extracellular matrix (ECM)** is a meshwork of proteins and polysaccharides in close association with the cell that produced them (Fig. 3.16). Collagen and elastin fibers are two well-known structural proteins in the ECM; collagen resists stretching, and elastin gives the ECM resilience.

Fibronectin is an adhesive protein (colored green in Fig. 3.16) that binds to a protein in the plasma membrane called integrin. Integrins are integral membrane proteins that connect to fibronectin externally and to the actin cytoskeleton internally. Through its connections with both the ECM and the cytoskeleton, integrin plays a role in cell signaling, permitting the ECM to influence the activities of the cytoskeleton and, therefore, the shape and activities of the cell. Proteoglycans (a combination of polysaccharides and proteins) interact with polysaccharides in the ECM to resist compression. Proteoglycans also



a. Sperm b. Flagellum c. Cilia

Figure 3.15 **Structure and function of the flagella and cilia.**
a. Sperm are an example of a human cell with flagella. **b.** The structure of a flagellum (or cilium) contains microtubules. **c.** Cilia cover the surface of the cells of the respiratory system, where they beat upward to remove foreign matter.
(photos) (a): ©Dr. Tony Brain/Science Photo Library/Getty Images; (c): ©Dr. G. Moscoso/Science Source

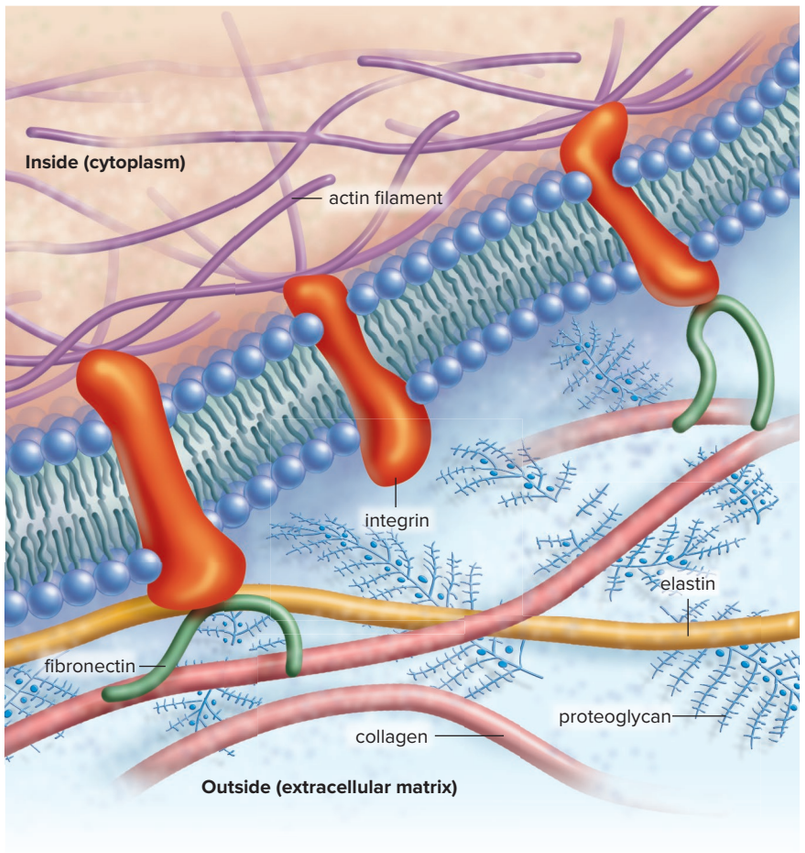


Figure 3.16 **Extracellular matrix.**
In the extracellular matrix (ECM), collagen and elastin have a support function, whereas fibronectins bind to integrin, thus assisting communication between the ECM and the cytoskeleton.

influence the process of cell signaling by regulating the passage of molecules through the ECM to the plasma membrane, where receptors are located.

In Section 4.2, during the discussion of connective tissue, we will explore how the extracellular matrix varies in quantity and consistency: being quite flexible, as in loose connective tissue; semiflexible, as in cartilage; and rock solid, as in bone. The extracellular matrix of bone is hard because, in addition to the components mentioned, mineral salts, notably calcium salts, are deposited outside the cell.

Junctions Between Cells

As we will see in Section 4.1, human tissues are known to have junctions between their cells that allow them to function in a coordinated manner. Figure 3.17 illustrates the three main types of cell junctions in human cells.

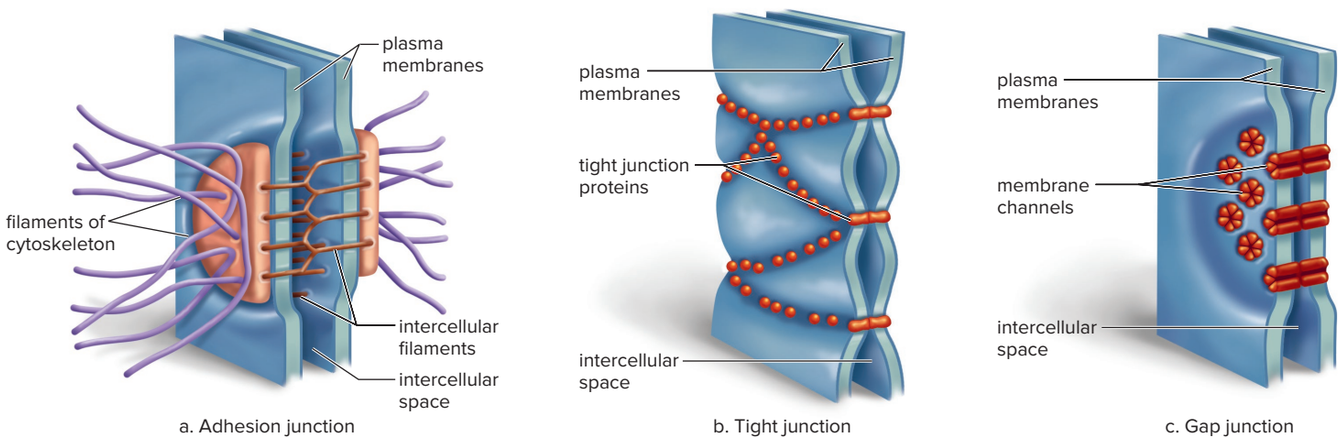


Figure 3.17 **Junctions between cells.**
a. Adhesion junctions mechanically connect cells. **b.** Tight junctions form barriers with the external environment. **c.** Gap junctions allow for communication between cells.

Adhesion junctions mechanically attach adjacent cells. In these junctions, the cytoskeletons of two adjacent cells are interconnected. They are a common type of junction between skin cells. In *tight junctions,* connections between the plasma membrane proteins of neighboring cells produce a zipperlike barrier. These types of junctions are common in the digestive system and the kidney where it is necessary to contain fluids (digestive juices and urine) within a specific area. *Gap junctions* serve as communication portals between cells. In these junctions, channel proteins of the plasma membrane fuse, allowing easy movement between adjacent cells.

CHECK YOUR PROGRESS 3.5

1. List the three types of fibers in the cytoskeleton.
2. Describe the structure of cilia and flagella, and state the function of each.
3. List the types of junctions found between animal cells, and state a function for each.

CONNECTING THE CONCEPTS

The cytoskeleton of the cell plays an important role in many aspects of our physiology. To explore this further, refer to the following discussions:

Section 10.1 investigates how the ciliated cells of the respiratory system function.

Section 17.2 explains the role of the flagellated sperm cell in reproduction.

Section 19.3 explores how the cytoskeleton is involved in cell division.

3.6 Metabolism and the Energy Reactions

LEARNING OUTCOMES

Upon completion of this section, you should be able to

1. Understand the relationship of products and reactants in a metabolic reaction.
2. Identify the role of an enzyme in a metabolic reaction.
3. Summarize the roles of the anaerobic and aerobic pathways in energy generation.
4. Illustrate the stages of the ATP cycle.

Metabolic Pathways

Metabolism is the sum of all the chemical reactions that occur within the body. The reactions, such as cellular respiration, occur at the cellular level and often involve metabolic pathways that are carried out by enzymes sequentially arranged in cells:

$$A \xrightarrow{1} B \xrightarrow{2} C \xrightarrow{3} D \xrightarrow{4} E \xrightarrow{5} F \xrightarrow{6} G$$

The letters, except *A* and *G,* are **products** of the previous reaction and the **reactants** for the next reaction. *A* represents the beginning reactant, and *G* represents the final product. The numbers in the pathway refer to different enzymes. *Each reaction in a metabolic pathway requires a specific enzyme.* The mechanism of action of enzymes has been studied extensively, because of their importance in metabolism.

Metabolic pathways are highly regulated by the cell. One type of regulation is *feedback inhibition.* In feedback inhibition, one of the end products of the metabolic pathway interacts with an enzyme early in the pathway. In most cases, this feedback slows down the pathway so that the cell does not produce more product than it needs.

Enzymes

Enzymes are metabolic assistants that speed up the rate of a chemical reaction. The reactant(s) that participate(s) in the reaction is/are called the enzyme's **substrate(s).** Enzymes are often named for their substrates. For example, lipids are broken down by lipase, maltose by maltase, and lactose by lactase.

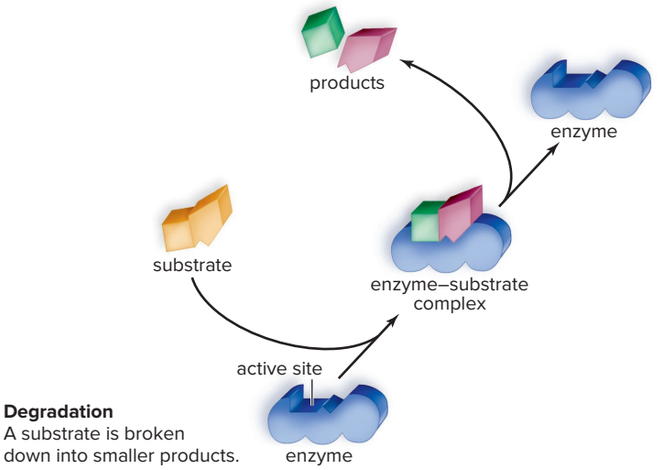
Enzymes have a specific region, called an **active site,** where the substrates are brought together so they can react. An enzyme's specificity is caused by the shape of the active site. Here, the enzyme and its substrate(s) fit together in a specific way, much as the pieces of a jigsaw puzzle fit together (Fig. 3.18). After one reaction is complete, the product or products are released. The enzyme is ready to be used again. Therefore, a cell requires only a small amount of a particular enzyme to carry out a reaction. A chemical reaction can be summarized in the following manner:

$$E + S \longrightarrow ES \longrightarrow E + P$$

where E = enzyme, S = substrate, ES = enzyme–substrate complex, and P = product. Enzymes are not destroyed in a chemical reaction, and therefore can be used over and over again.

Molecules frequently do not react with one another unless they are activated in some way. In the lab, for example, in the absence of an enzyme, activation is very often achieved by heating a reaction flask to increase the number of effective collisions between molecules. The energy that must be added to cause molecules to react with one another is called the **energy of activation (E_a)** (Fig. 3.19). Even though the reaction will proceed, the energy of activation must be overcome. The burning of firewood releases a tremendous amount of energy, but firewood in a pile does not spontaneously combust. The input of some energy, perhaps a lit match, is required to overcome the energy of activation.

Figure 3.19 shows E_a when an enzyme is not present compared to when an enzyme is present, illustrating that enzymes lower the amount of energy required for activation to occur. Nevertheless, the addition of the enzyme does not change the end result of the reaction. Notice that the energy of the products is less than the energy of the reactants. This indicates that the reaction will occur, but not until the energy of activation is overcome. Without the enzyme, the reaction rate will be very slow.



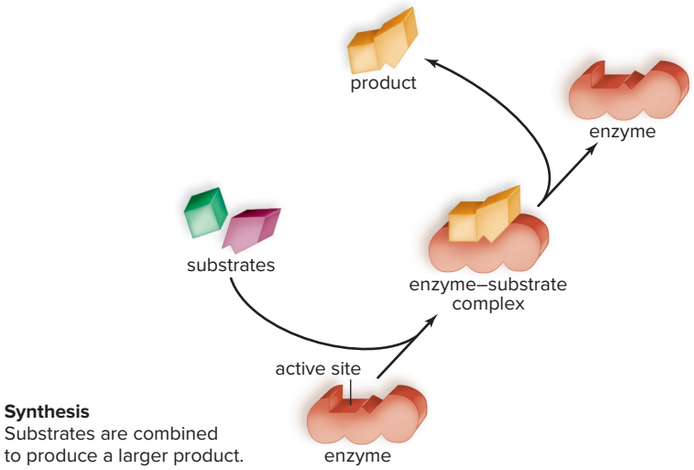


Figure 3.18 Action of an enzyme.
An enzyme has an active site, where the substrates and enzyme fit together in such a way that the substrates are oriented to react. Following the reaction, the products are released and the enzyme is free to act again. **a.** Some enzymes carry out degradation, in which the substrate is broken down into smaller products. **b.** Other enzymes carry out synthesis, in which the substrates are combined to produce a larger product.

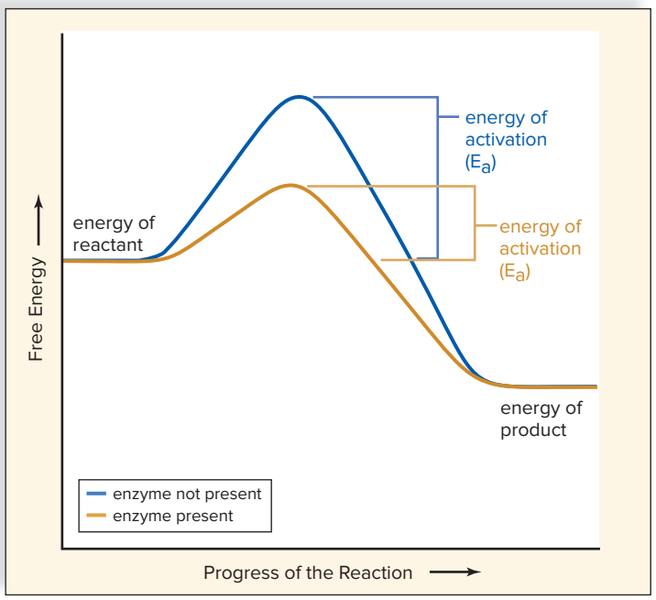


Figure 3.19 Energy of activation.
Enzymes accelerate the rate of a metabolic reaction by lowering the amount of energy of activation needed to start the reaction.

By lowering the energy of activation, the enzyme increases the rate of the reaction.

Coenzymes are nonprotein molecules that assist the activity of an enzyme and may even accept or contribute atoms to the reaction. It is interesting that vitamins are often components of coenzymes. The vitamin niacin is a part of the coenzyme **NAD^+ (nicotinamide adenine dinucleotide),** which carries hydrogen (H) and electrons.

Mitochondria and Cellular Respiration

Mitochondria (*sing.,* mitochondrion) are often called the powerhouses of the cell. Just as a powerhouse burns fuel to produce electricity, the mitochondria convert the chemical energy of glucose products into the chemical energy of ATP molecules. In the process, mitochondria use up oxygen and give off carbon dioxide. Therefore, the process of producing ATP is called **cellular respiration.** The structure of mitochondria is appropriate to the task. Mitochondria are double-membrane organelles, with an outer plasma membrane and an inner membrane that is folded to form little shelves called *cristae*. These project into the matrix, an inner space filled with a gel-like fluid (Fig. 3.20). The matrix of a mitochondrion contains enzymes for breaking down glucose products. ATP production then occurs at the cristae. Protein complexes that aid in the conversion of energy are located in an assembly-line fashion on these membranous shelves.

The structure of a mitochondrion supports the hypothesis that mitochondria were originally prokaryotes that became engulfed by a cell (see Fig. 3.5). Mitochondria are bound by a double membrane, as a prokaryote would be if it were taken into a cell by endocytosis. Even more interesting is the observation that mitochondria have their own genes—and they reproduce themselves!

ATP–ADP Cycle

ATP is the energy currency of the cell and is involved in a variety of cellular processes. The ATP (Fig. 3.21) resembles that of a rechargeable battery. The breakdown of glucose during cellular respiration is used to produce ATP from ADP and inorganic phosphate Ⓟ. This ATP is then used for the metabolic work of the cell. Muscle cells use ATP for contraction, and nerve cells use it for conduction of nerve impulses. ATP breakdown releases heat, ADP, and phosphate Ⓟ.

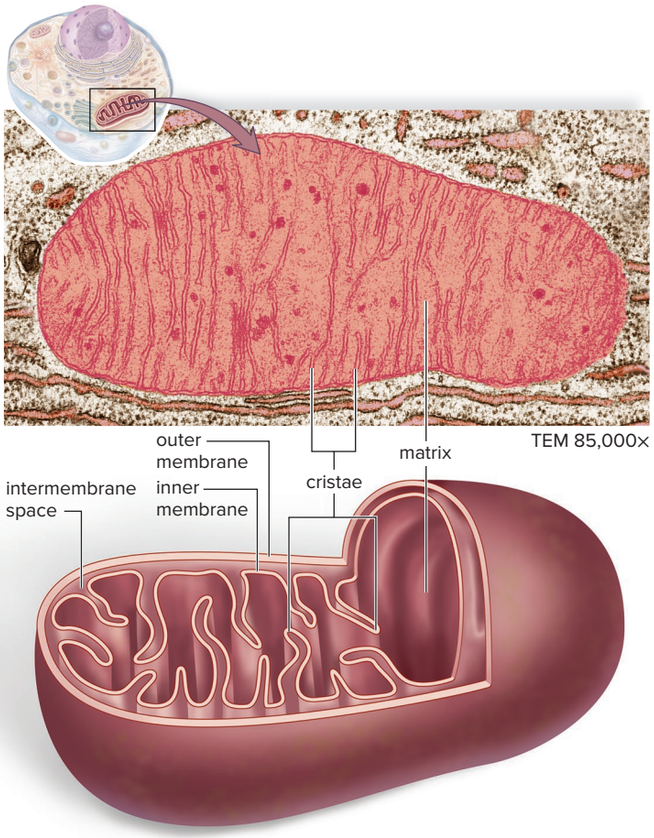


Figure 3.20 The structure of a mitochondrion.
A mitochondrion is bound by a double membrane, and the inner membrane folds into projections called cristae. The cristae project into a semifluid matrix that contains many enzymes.
(photo): ©Keith R. Porter/Science Source

Cellular Respiration

After blood transports glucose and oxygen to cells, cellular respiration begins. Cellular respiration breaks down glucose to carbon dioxide and water. Three pathways are involved in the breakdown of glucose—glycolysis, the citric acid cycle, and the electron transport chain (Fig. 3.22). These metabolic pathways allow the energy in a glucose molecule to be slowly released, so that ATP can be gradually produced. Cells would lose a tremendous amount of energy, in the form of heat, if glucose breakdown occurred all at once. When humans burn wood or coal, the energy escapes all at once as heat. But a cell "burns" glucose gradually, and energy is captured as ATP.

Glycolysis **Glycolysis** means "sugar splitting." During glycolysis, glucose, a 6-carbon (C_6) molecule, is split so that the result is two 3-carbon (C_3) molecules of *pyruvate.* Glycolysis, which occurs in the cytoplasm, is found in most every type of cell. Therefore, this pathway is believed to have evolved early in the history of life.

Glycolysis is an **anaerobic** pathway because it does not require oxygen. This pathway can occur in microbes that live in bogs or swamps or in our intestinal tract where there is no oxygen. During glycolysis, hydrogens and electrons are removed from glucose, and NADH results. The breaking of bonds releases enough energy for a net yield of two ATP molecules.

Preparatory Reaction Pyruvate is a pivotal molecule in cellular respiration. When oxygen is available, the molecule enters the preparatory (prep) reaction, named because it prepares the outputs of glycolysis (pyruvate molecules) for use in the citric acid cycle mitochondria so they may be completely broken down. A small amount of NADH is produced per glucose. As we will discuss later in this section, fermentation occurs when oxygen is not available.

Citric Acid Cycle Each of the pyruvate molecules, after a brief modification, enters the citric acid cycle as acetyl CoA. The **citric acid cycle,** also called the *Krebs cycle,* is a cyclical series of enzymatic reactions that occurs in the matrix of mitochondria.

The purpose of this pathway is to complete the breakdown of glucose by breaking the remaining C—C bonds. As the reactions progress, carbon dioxide is released, a small amount of ATP (two per glucose) is produced, and the remaining hydrogen and electrons are carried away by NADH and a similar molecule called $FADH_2$.

The cellular respiration pathways have the ability to use organic molecules other than carbohydrates as an energy source. Both fats and proteins may be converted to compounds that enter the citric acid cycle. More information on these processes is provided in the Health feature "The Metabolic Fate of Pizza" later in this section.

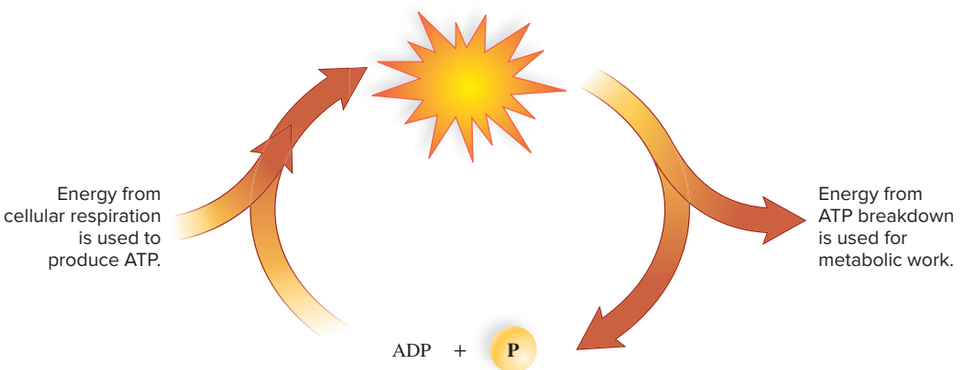


Figure 3.21 The ATP cycle.
The breakdown of organic nutrients, such as glucose, by cellular respiration transfers energy to form ATP. ATP is used for energy-requiring reactions, such as muscle contraction. ATP breakdown also gives off heat. Additional food energy rejoins ADP and Ⓟ to form ATP again.

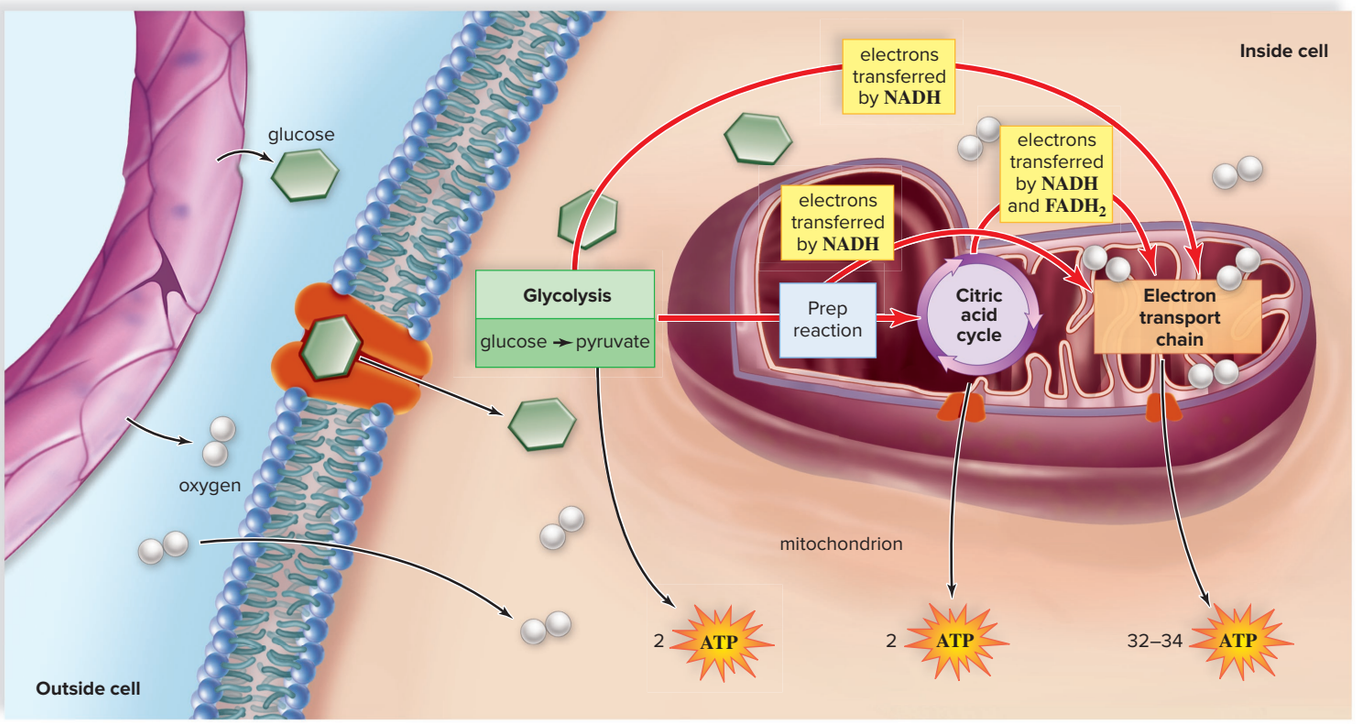


Figure 3.22 Production of ATP.
Glucose enters a cell from the bloodstream by facilitated transport. The three main pathways of cellular respiration (glycolysis, citric acid cycle, and electron transport chain) all produce ATP, but most is produced by the electron transport chain. NADH carries electrons to the electron transport chain from glycolysis and the citric acid cycle. ATP exits a mitochondrion by facilitated transport.

Electron Transport Chain NADH molecules from glycolysis and the citric acid cycle deliver electrons to the **electron transport chain.** The members of the electron transport chain are carrier proteins grouped into complexes. These complexes are embedded in the cristae of a mitochondrion. Each carrier of the electron transport chain accepts two electrons and passes them on to the next carrier. The hydrogens carried by NADH molecules will be used later.

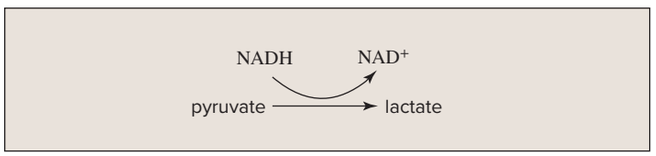
High-energy electrons enter the chain, and as they are passed from carrier to carrier, the electrons lose energy. Low-energy electrons emerge from the chain. Oxygen serves as the final acceptor of the electrons at the end of the chain. After oxygen receives the electrons, it combines with hydrogens and becomes water.

The presence of oxygen makes the electron transport chain **aerobic.** Oxygen does not combine with any substrates during cellular respiration. Breathing is necessary to our existence, and the sole purpose of oxygen is to receive electrons at the end of the electron transport chain.

The energy, released as electrons that pass from carrier to carrier, is used for ATP production. It took many years for investigators to determine exactly how this occurs, and the details are beyond the scope of this text. Suffice it to say that the inner mitochondrial membrane contains an ATP–synthase complex that combines ADP + Ⓟ to produce ATP. The ATP–synthase complex produces about 32 ATP per glucose molecule. Overall, the reactions of cellular respiration produce 36 to 38 ATP molecules.

Fermentation

Fermentation is an anaerobic process, meaning it does not require oxygen. When oxygen is not available to cells, the electron transport chain soon becomes inoperative. This is because oxygen is not present to accept electrons. In this case, most cells have a safety valve so that some ATP can still be produced. Glycolysis operates as long as it is supplied with "free" NAD^+ that is available to pick up hydrogens and electrons. Normally, NADH takes electrons to the electron transport chain and, thereby, is recycled to become NAD^+. However, if the system is not working due to a lack of oxygen, NADH passes its hydrogens and electrons to pyruvate molecules, as shown in the following reaction:



This means the citric acid cycle and electron transport chain do not function as part of fermentation. When oxygen is available again, lactate can be converted back to pyruvate and thus metabolism can proceed as usual.

Fermentation can give us a burst of energy for a short time, but it produces only two ATP per glucose molecule. Also, fermentation results in the buildup of lactate. While lactic acid is toxic to

BIOLOGY TODAY

Health

The Metabolic Fate of Pizza

Obviously, our diets do not consist solely of carbohydrates. Because fats and proteins are also organic nutrients, it makes sense that our bodies can utilize the energy found in the bonds of these molecules. In fact, the metabolic pathways we have discussed in this chapter are more than capable of accessing the energy of fats and proteins. For example, let's trace the fate of a pepperoni pizza, which contains carbohydrates (crust), fats (cheese), and protein (pepperoni).

We already know that the glucose in the carbohydrate crust is broken down during cellular respiration. When the cheese in the pizza (a fat) is used as an energy source, it breaks down into glycerol and three fatty acids. As Figure 3B indicates, glycerol can be converted to pyruvate and enter glycolysis. The fatty acids are converted to an intermediate that enters the citric acid cycle. An 18-carbon fatty acid results in nine acetyl CoA molecules. Calculation shows that respiration of these can produce a total of 108 ATP molecules. This is why fats are an efficient form of stored energy—the three long fatty acid chains per fat molecule can produce considerable ATP when needed.

Proteins are less frequently used as an energy source, but are available if necessary. The carbon skeleton of amino acids can enter glycolysis, be converted to acetyl groups, or enter the citric acid cycle at another point. The carbon skeleton is produced in the liver when the amino group is removed from the amino acid, a process called deamination. The amino group becomes ammonia (NH_3), which enters the urea cycle and becomes part of urea, the primary excretory product of humans.

In Section 9.6 we will take a more detailed look at the nutritional needs of humans, and will include discussions on how vitamins and minerals interact with metabolic pathways, as well as the dietary guidelines for proteins, fats, and carbohydrates.

Questions to Consider

1. How might a meal of a cheeseburger and fries be processed by the cellular respiration pathways?
2. Even though Figure 3B does not indicate the need for water, it is an important component of our diet. Where would water interact with these pathways?

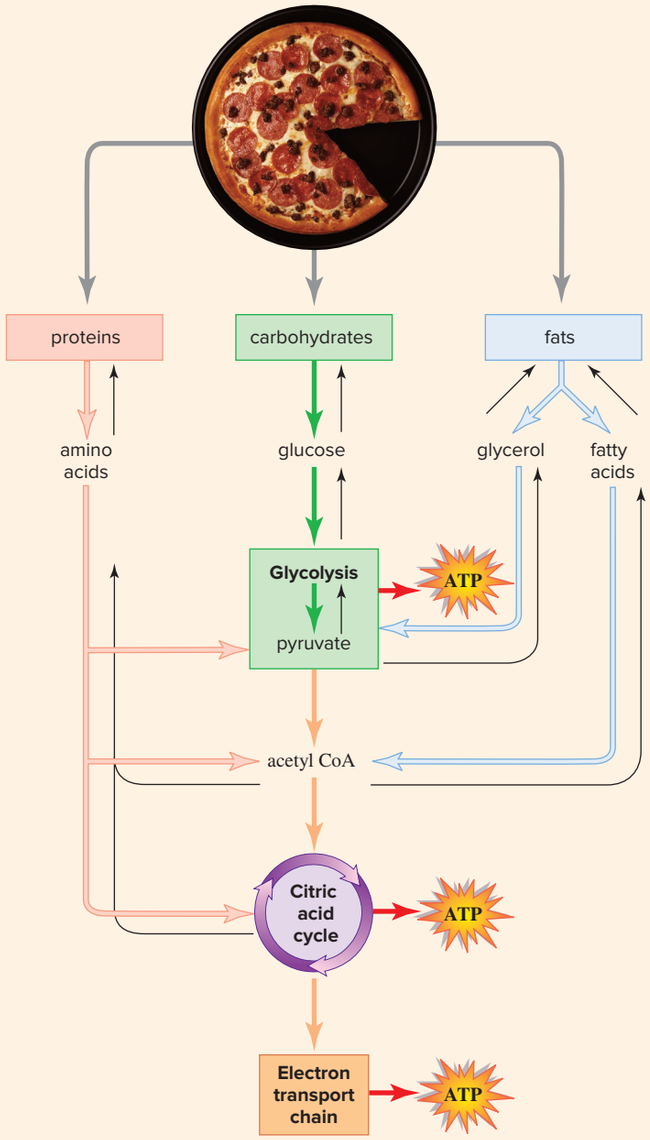


Figure 3B The use of fats and proteins for energy.
Carbohydrates, fats, and proteins can be used as energy sources, and their monomers (carbohydrates and proteins) or subunits (fats) enter degradative pathways at specific points.
(photo): ©C Squared Studios/Getty Images

cells and may cause damage over time, it is quickly removed by the circulatory system once aerobic conditions return. Although it may cause muscles to cramp and fatigue, the majority of the soreness that occurs following exercise is due to damage to the small capillaries servicing the muscle tissue.

Fermentation takes its name from yeast fermentation. Yeast fermentation produces alcohol and carbon dioxide (instead of lactate). When yeast is used to leaven bread, carbon dioxide production makes the bread rise. When yeast is used to produce alcoholic beverages, it is the alcohol that humans make use of.

CHECK YOUR PROGRESS 3.6

1. Summarize the roles of enzymes in chemical reactions.
2. Describe the basic steps required to break down glucose by cellular respiration.
3. Explain why the ATP cycle resembles that of a rechargeable battery.
4. Explain the differences between cellular respiration and fermentation.

CONNECTING THE CONCEPTS

For additional information on the processing of nutrients for energy, refer to the following discussions:

Sections 2.3 to **2.5** provide a more detailed look at carbohydrates and other energy nutrients.

Section 9.3 explores how the small intestine processes nutrients for absorption.

Section 9.6 describes the importance of carbohydrates, fats, and proteins in the diet.

CONCLUSION

Over the next few months, both Kevin and Mary dedicated hours to understanding the causes of and treatments for Tay-Sachs disease. They learned that the disease is caused by a recessive mutation that limits the production of an enzyme called beta-hexosaminidase A. This enzyme is loaded into a newly formed lysosome by the Golgi apparatus. The enzyme's function is to break down a specific type of fatty acid chain called *gangliosides*. Gangliosides play an important role in the early formation of the neurons in the brain. Tay-Sachs disease occurs when the gangliosides overaccumulate in the neurons.

Though the prognosis for their child was initially poor—very few children with Tay-Sachs live beyond the age of 4—the parents were encouraged to explore how recent advances in a form of medicine called gene therapy might be able to prolong the life of their child. In gene therapy, a correct version of the gene is introduced into specific cells in an attempt to regain lost function. Some initial studies using mice as a model had demonstrated an ability to reduce ganglioside concentrations by providing a working version of the gene that produced beta-hexosaminidase A to the neurons of the brain. Though research was still ongoing, it was a promising piece of information for both Kevin and Mary.

SUMMARIZE

3.1 What Is a Cell?

The **cell theory** states that cells are the basic units of life and that all life comes from preexisting cells. Microscopes are used to view cells, which must remain small to have a favorable surface-area-to-volume ratio.

3.2 How Cells Are Organized

The human cell is a **eukaryotic cell** with a **nucleus** that contains the genetic material. **Prokaryotic cells,** such as bacteria, are smaller than eukaryotic cells and lack a nucleus.

The cell is surrounded by a **plasma membrane,** a **selectively permeable** barrier that limits the movement of materials into and out of the cell. Between the plasma membrane and the nucleus is the **cytoplasm.** In eukaryotic cells, the cytoplasm contains various **organelles,** each with specific functions.

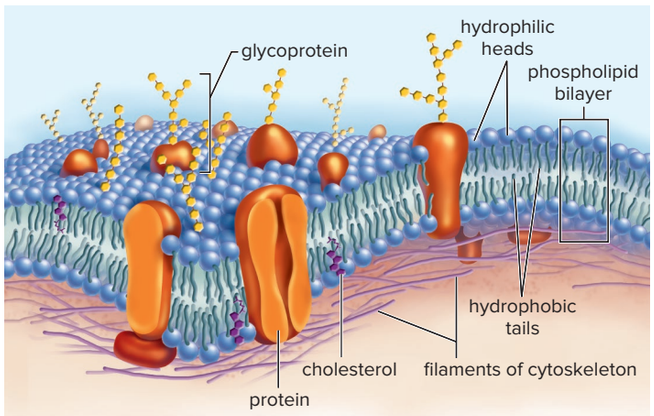
3.3 The Plasma Membrane and How Substances Cross It

The **fluid-mosaic model** describes the structure of the plasma membrane. The plasma membrane contains

- A phospholipid bilayer that selectively regulates the passage of molecules and ions into and out of the cell.
- Embedded proteins, which allow certain substances to cross the plasma membrane.

Passage of molecules into or out of cells can be passive or active.

- Passive mechanisms do not require energy. Examples are **diffusion, osmosis,** and **facilitated transport. Tonicity** and **osmotic pressure** control the process of osmosis.
- Active mechanisms require an input of energy. Examples are **active transport** (sodium–potassium pump), endocytosis (phagocytosis and pinocytosis), receptor-mediated endocytosis, and exocytosis.



3.4 The Nucleus and the Endomembrane System

- The nucleus houses DNA, which contains **genes** that specify the order of amino acids in proteins. **Chromatin** is a combination of DNA molecules and proteins that make up **chromosomes.**
- The nucleus is surrounded by a **nuclear envelope** that contains **nuclear pores** for communication and the movement of materials.
- The **nucleolus** produces ribosomal RNA (rRNA).
- Protein synthesis occurs in **ribosomes,** small organelles composed of proteins and rRNA.

The Endomembrane System

The **endomembrane system** consists of the nuclear envelope, **endoplasmic reticulum** (**ER**), Golgi apparatus, lysosomes, and **vesicles.**

- The rough ER has ribosomes, where protein synthesis occurs.
- Smooth ER has no ribosomes and has various functions, including lipid synthesis.

- The **Golgi apparatus** processes and packages proteins and lipids into vesicles for secretion or movement into other parts of the cell.
- **Lysosomes** are specialized vesicles produced by the Golgi apparatus. They fuse with incoming vesicles to digest enclosed material, and they autodigest old cell parts.

3.5 The Cytoskeleton, Cell Movement, and Cell Junctions

- The **cytoskeleton** consists of **microtubules, actin filaments,** and **intermediate filaments** that give cells their shape; and it allows organelles to move about the cell. Microtubules are organized by **centrosomes. Cilia** and **flagella,** which contain microtubules, allow a cell to move.
- Cell junctions connect cells to form tissues and to facilitate communication between cells.
- The **extracellular matrix** (**ECM**) is located outside the plasma membrane. It may provide structure and regulate the movement of materials into the cell.

3.6 Metabolism and the Energy Reactions

Metabolic Pathways

- **Metabolism** represents all the chemical reactions that occur in a cell. A metabolic pathway is a series of reactions, each of which has its own enzyme. The materials entering these reactions are called **reactants,** and the materials leaving the pathway are called **products.**

Enzymes

- **Enzymes** bind their **substrates** in the **active site.**
- Enzymes accelerate chemical reactions by lowering the **energy of activation** ($\mathbf{E_a}$) needed to start the reaction.
- **Coenzymes,** such as **NAD^+** (**nicotinamide adenine dinucleotide**), are nonprotein molecules that assist enzymes.

Mitochondria and Cellular Respiration

- **Mitochondria** are involved in **cellular respiration,** which uses oxygen and releases carbon dioxide.
- During cellular respiration, mitochondria convert the energy of glucose into the energy of ATP molecules.

Cellular Respiration and Metabolism

- Cellular respiration includes three pathways: glycolysis, the citric acid cycle, and the electron transport chain.
- **Glycolysis** occurs in the cytoplasm and is **anaerobic.** It produces two pyruvate molecules and small amounts of ATP and NADH.
- The pyruvate molecules are modified by the preparatory reactions in the mitochondria before entering the citric acid cycle.
- The **citric acid cycle** occurs in the matrix of the mitochondria. Its role is to break C—C bonds and generate ATP, NADH, and $FADH_2$.
- The **electron transport chain** is located along the cristae of the mitochondria. It is an **aerobic** pathway that uses the electrons in the NADH and $FADH_2$ molecules to generate the majority of the ATP in the cell.
- If oxygen is not available in cells, the electron transport chain is inoperative, and **fermentation** (which does not require oxygen) occurs. Fermentation recycles NAD^+ molecules so the cell can produce a small amount of ATP by glycolysis.

ASSESS

TESTING YOURSELF

Choose the best answer for each question.

3.1 What Is a Cell?

1. As the size of a cell decreases, the ratio of its surface area to volume
   - **a.** increases.
   - **b.** decreases.
   - **c.** stays the same.
2. The cell theory states that
   - **a.** all life comes from preexisting cells.
   - **b.** all life is composed of cells.
   - **c.** the cell is the basic unit of life.
   - **d.** All of these are correct.

3.2 How Cells Are Organized

3. Prokaryotic cells contain all of the following except
   - **a.** cytoplasm.
   - **b.** a plasma membrane.
   - **c.** DNA.
   - **d.** a nucleus.
4. The endosymbiotic theory explains which of the following?
   - **a.** the origins of the first prokaryotic cell
   - **b.** the formation of the plasma membrane
   - **c.** why DNA is the genetic material in all cells
   - **d.** how eukaryotic cells evolved from prokaryotic cells

3.3 The Plasma Membrane and How Substances Cross It

5. Which of the following is not part of the fluid-mosaic model?
   - **a.** phospholipids
   - **b.** proteins
   - **c.** cholesterol
   - **d.** chromatin
6. Facilitated transport differs from diffusion in that facilitated diffusion
   - **a.** involves the passive use of a carrier protein.
   - **b.** involves the active use of a carrier protein.
   - **c.** moves a molecule from a low to a high concentration.
   - **d.** involves the use of ATP molecules.
7. When a cell is placed in a hypotonic solution,
   - **a.** solute exits the cell to equalize the concentration on both sides of the membrane.
   - **b.** water exits the cell toward the area of lower solute concentration.
   - **c.** water enters the cell toward the area of higher solute concentration.
   - **d.** solute exits and water enters the cell.

3.4 The Nucleus and Endomembrane System

For questions 8–11, match the description to the correct answer in the following key. Answers may be used more than once.

Key:

a. Golgi apparatus
b. nucleus
c. ribosome
d. lysosome

8. location of the chromatin and nucleolus

9. organelle where proteins and lipids from the ER are modified

10. contains digestive enzymes

11. the site of protein synthesis

12. The ribosomes on the rough endoplasmic reticulum assemble _____, while _____ are assembled in the smooth endoplasmic reticulum.
a. proteins; phospholipids
b. cholesterol; proteins
c. DNA; proteins
d. cholesterol; phospholipids

3.5 The Cytoskeleton, Cell Movement, and Cell Junctions

13. The cytoskeleton of a cell consists of all of the following except
a. microtubules.
b. actin filaments.
c. an extracellular matrix.
d. intermediate filaments.

14. Cilia and flagella are involved in
a. forming junctions between cells.
b. establishing the extracellular matrix.
c. cell-to-cell communication.
d. cell movement.

3.6 Metabolism and the Energy Reactions

15. The active site of an enzyme
a. is identical to that of any other enzyme.
b. is the part of the enzyme where the substrate can fit.
c. is destroyed during a chemical reaction.
d. is where the coenzyme binds.

16. Enzymes accelerate a chemical reaction by
a. reducing the amount of substrate produced.
b. lowering the energy of activation of the reaction.
c. increasing the energy of activation of the reaction.
d. reducing the amount of reactant needed.

17. Which of the following pathways produces the greatest amount of ATP?
a. the citric acid cycle
b. glycolosis
c. the electron transport chain
d. fermentation

18. Which of the following reactions is aerobic and recycles NAD^+ molecules?
a. glycolosis
b. the citric acid cycle
c. the electron transport chain
d. fermentation

ENGAGE

BioNOW

Want to know how this science is relevant to your life? Check out the BioNOW videos below:

- Cell Size
- Saltwater Filter
- Energy Part I: Energy Transfers
- Energy Part III: Cellular Respiration

1. Cell Size: Why would a larger surface-area-to-volume ratio increase metabolic efficiency?

2. Saltwater Filter: Explain how the potato uses the principles of diffusion to measure the salt concentration in the branch samples.

3. Energy Transfers: Explain how both laws of thermodynamics apply to the experiments in this video.

4. Cellular Respiration: What cellular processes are producing the CO_2 being measured in this experiment?

THINKING CRITICALLY

In the chapter opener, the child had malfunctioning lysosomes that caused an accumulation of fatty acid in his system. Each part of a cell plays an important role in the homeostasis of the entire body.

1. What might occur if the cells of the body contain malfunctioning mitochondria?

2. What would happen to homeostasis if enzymes were no longer produced in the body?

3. Knowing what you know about the function of a lysosome, what might occur if the cells' lysosomes are overproductive instead of malfunctioning?