GLOBAL EDITION

# Fundamentals of Anatomy & Physiology

ELEVENTH EDITION

Martini • Nath • Bartholomew

Pearson

# Chapters + Clinical Cases

# Spotlight Figures

**1–2** Levels of Organization

**2–4** Chemical Notation

**3–1** Anatomy of a Model Cell **3–7** Protein Synthesis, Processing, and Packaging **3–22** Overview of Membrane Transport **3–23** Stages of a Cell's Life Cycle **3–24** DNA Replication

**4–21** Inflammation and Regeneration

**5–3** The Epidermis

**6–11** Endochondral Ossification **6–17** Types of Fractures and Steps in Repair

**7–4** Sectional Anatomy of the Skull

**8–14** Sex Differences in the Human Skeleton

**9–2** Joint Movement

**10–10** Events at the Neuromuscular Junction **10–11** Excitation-Contraction Coupling **10–12** The Contraction Cycle and Cross-Bridge Formation

**11–3** Muscle Action

**12–8** Processes that Produce the Resting Membrane Potential **12–13** Generation of an Action Potential **12–14** Propagation of an Action Potential

**13–8** Structure, Function, and the Peripheral Distribution of Spinal Nerves ($T_1 - L_2$) **13–14** Spinal Reflexes

**14–4** Formation and Circulation of Cerebrospinal Fluid

**15–8** Somatic Sensory Pathways

**16–2** The Autonomic Nervous System

**17–2** Olfaction and Gustation **17–13** Refractive Problems **17–16** Photoreception

**18–2** Structural Classification of Hormones **18–3** G Proteins and Second Messengers **18–18** Diabetes Mellitus **18–20** The General Adaptation Syndrome

**19–1** The Composition of Whole Blood **19–8** Hemolytic Disease of the Newborn

**20–9** Heart Disease and Heart Attacks **20–13** Cardiac Arrhythmias

**21–33** Congenital Heart Problems

**22–21** Cytokines of the Immune System

**23–13** Pulmonary Ventilation **23–25** Control of Respiration

**24–15** The Regulation of Gastric Activity **24–27** The Chemical Events of Digestion

**25–4** The Electron Transport Chain and ATP Formation **25–10** Absorptive and Postabsorptive States

**26–16** Summary of Renal Function

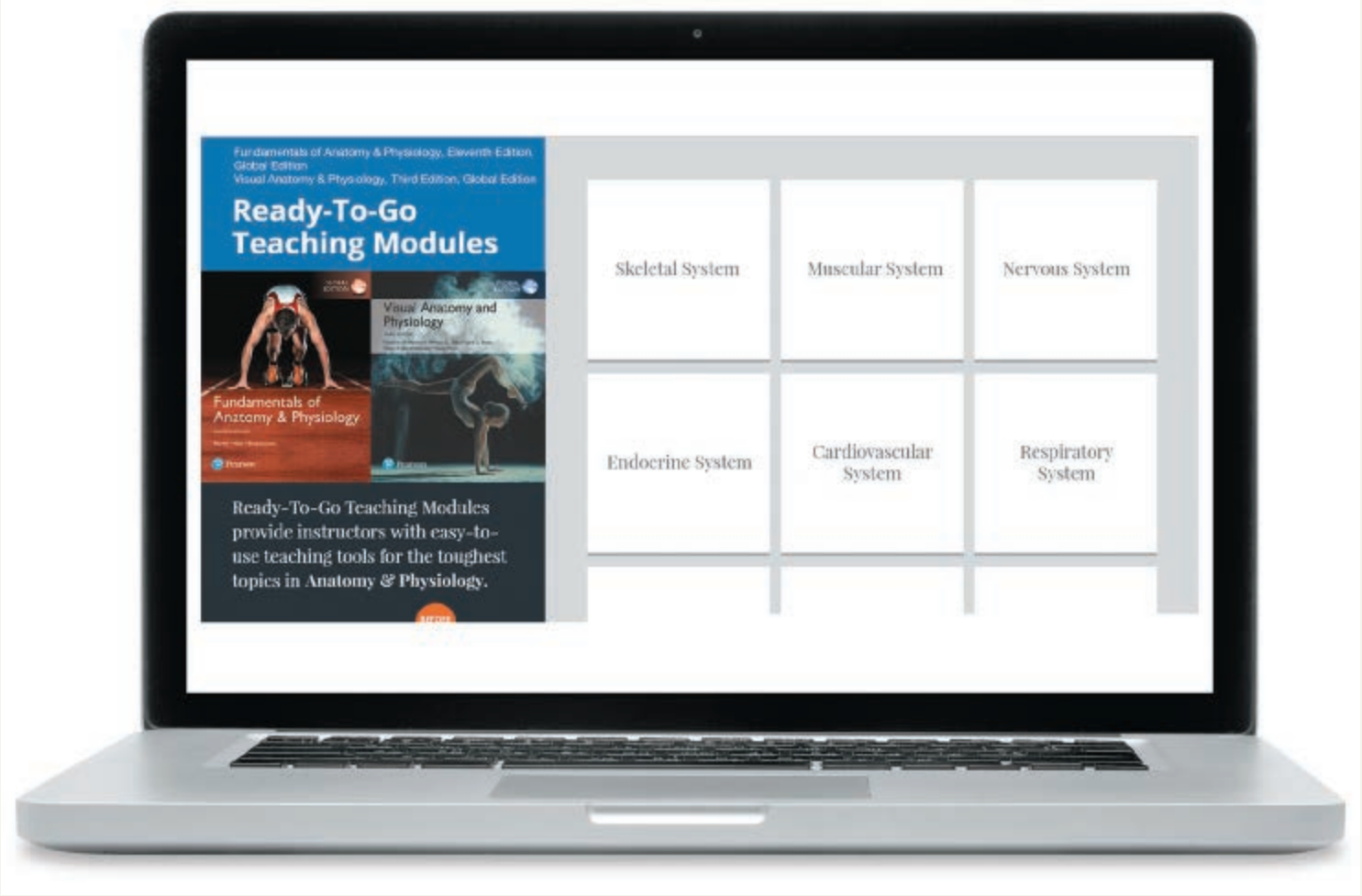
**27–18** The Diagnosis of Acid–Base Disorders

**28–12** Hormonal Regulation of Male Reproduction **28–24** Hormonal Regulation of Female Reproduction

**29–5** Extra-embryonic Membranes and Placenta Formation

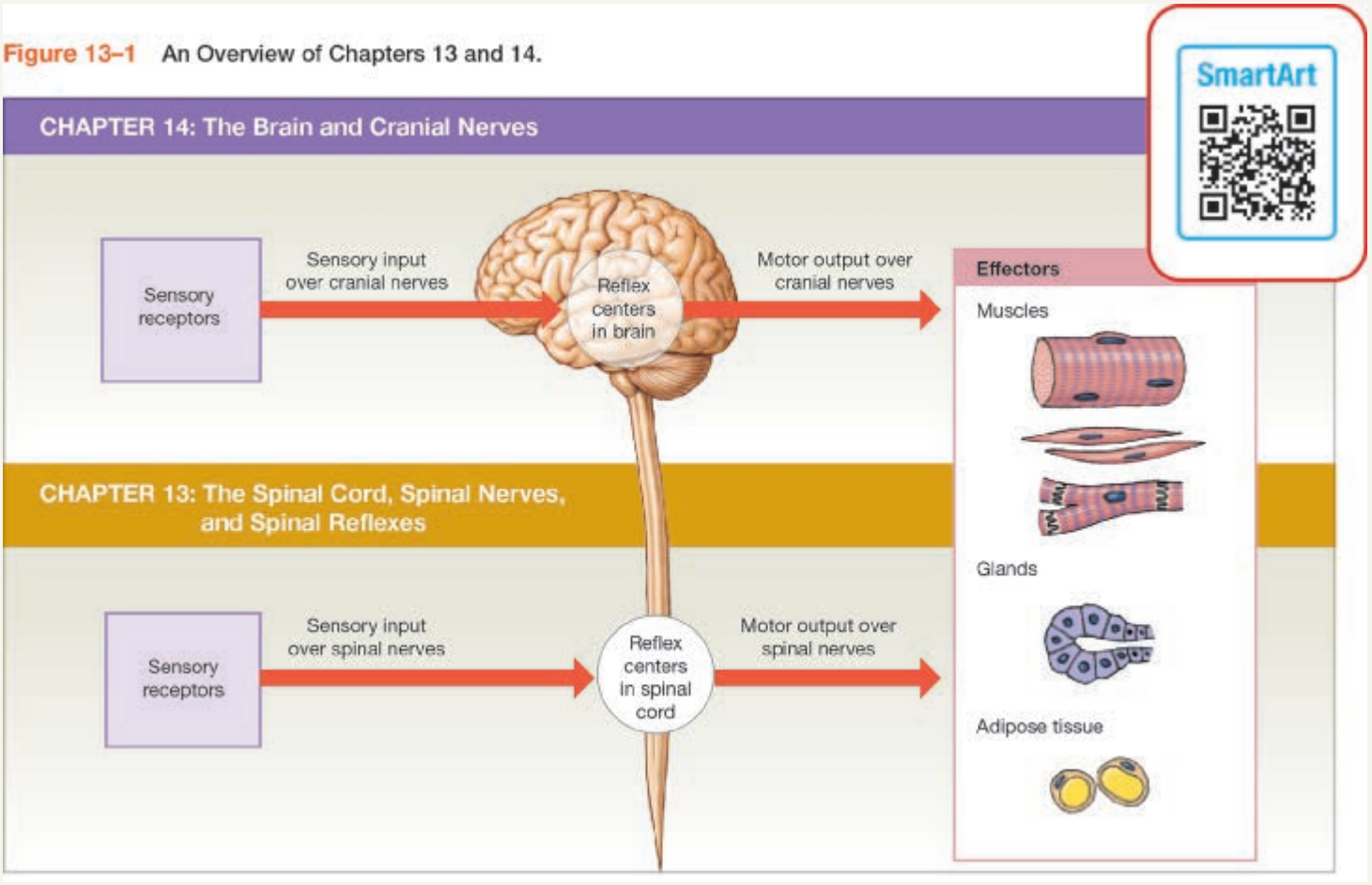
# Get Ready for a Whole New Mastering Experience

**NEW! Ready-to-Go Teaching Modules** help instructors find the best assets to use before, during, and after class to teach the toughest topics in A&P. Created by teachers for teachers, these curated sets of teaching tools save you time by highlighting the most effective and engaging animations, videos, quizzing, coaching and active learning activities from Pearson Mastering A&P.

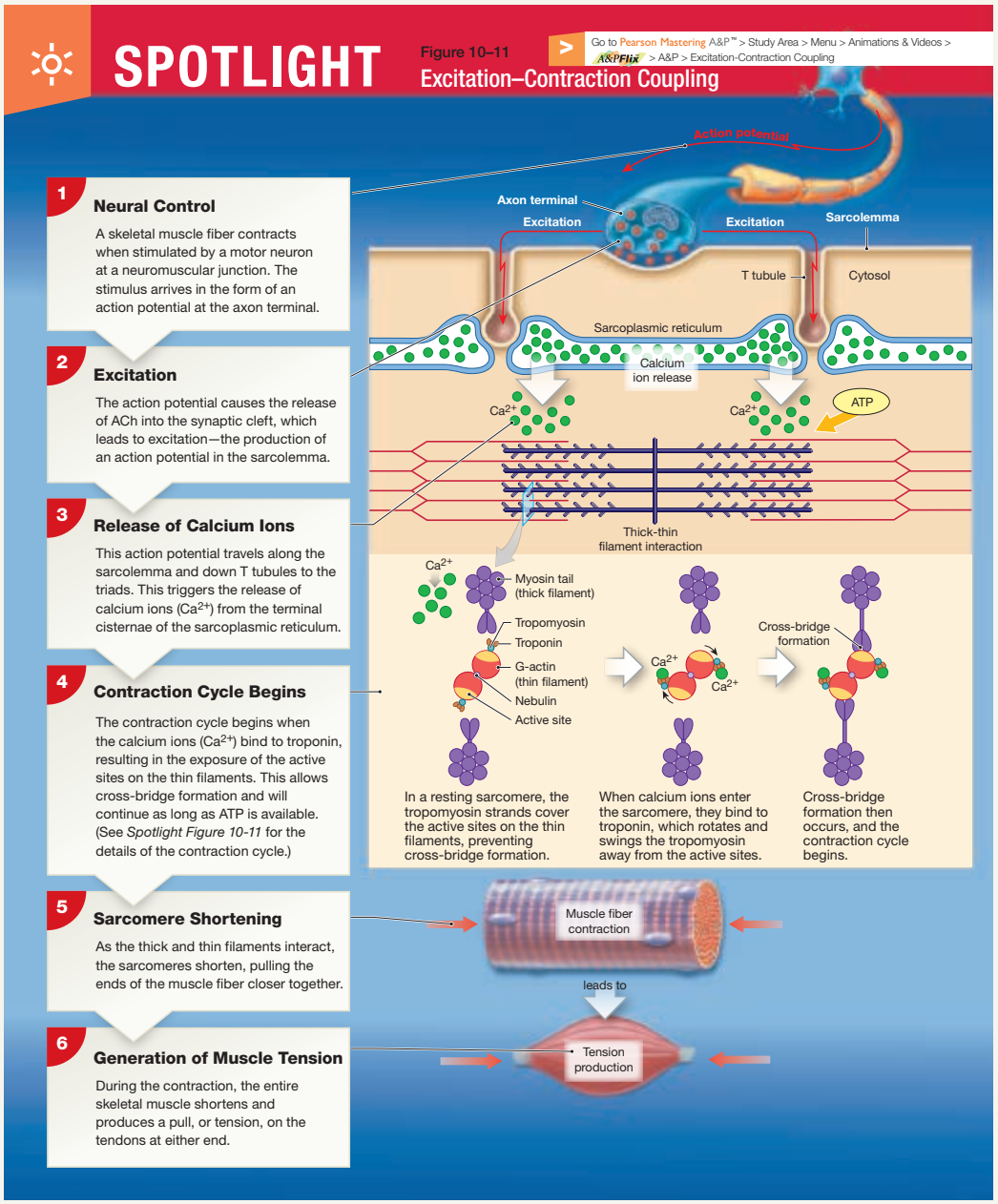


# Help Students
## Use Art More Effectively

**NEW! SmartArt Videos** help students navigate select, complex pieces of art for some of the toughest topics in A&P. Author Kevin Petti walks students through several figures and provides additional background and detail. The videos can be accessed via QR codes in the book and offer accompanying assignments through Pearson Mastering A&P.



**Spotlight Figures** provide highly visual one- and two-page presentations of tough topics in the book, with a particular focus on physiology.




**NEW! Pearson Mastering A&P references** within the chapter direct students to specific digital resources, such as tutorials, animations, and videos, that will help further their understanding of key concepts in the course.

# Systems Integration in the Classroom

**NEW! Build Your Knowledge** features show how each body system influences the others. As students progress through the book, they will build their knowledge about how the body systems work together to maintain homeostasis.



## Build Your Knowledge

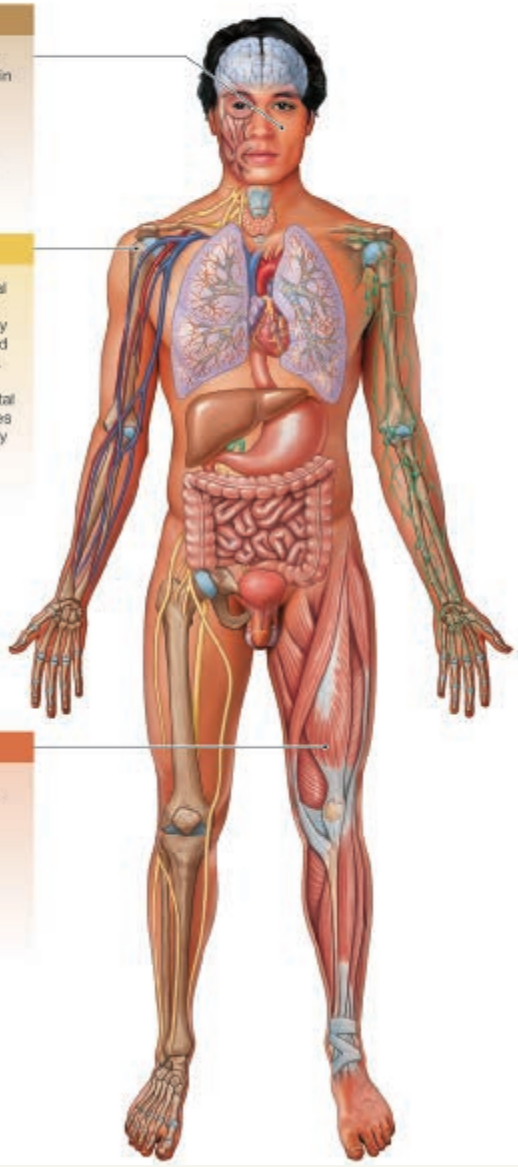
**Figure 11–24** Integration of the MUSCULAR system with the other body systems presented so far.

**Integumentary System**

- The Integumentary System removes excess body heat, synthesizes vitamin $D_3$ for calcium and phosphate absorption, and protects underlying muscles.
- The muscular system includes facial muscles that pull on the skin of the face to produce facial expressions

**Skeletal System**

- The Skeletal System provides mineral reserves for maintaining normal calcium and phosphate levels in body fluids, supports skeletal muscles, and provides sites of muscle attachment.
- The muscular system provides skeletal movement and support, and stabilizes bones and joints. Stresses exerted by tendons maintain normal bone structure and bone mass.



**Muscular System**

The muscular system performs these primary functions for the human body:

- It produces skeletal movement
- It helps maintain posture and body position
- It supports soft tissues
- It guards entrances and exits to the body
- It helps maintain body temperature

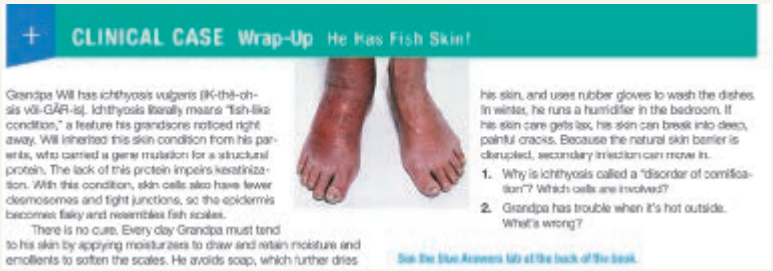
# and Beyond

**Clinical Cases** get students motivated for their future careers. Each chapter opens with a story-based Clinical Case related to the chapter content and ends with a Clinical Case Wrap-Up.

**CLINICAL CASE** He Has Fish Skin!

I shook his hand and immediately I knew something was different about him. When Will clasped my hand between both of his, I felt like my hand was sandwiched between two sheets of thick, shaggy sandpaper. There was none of the moistness or warmth of a usual handshake. These hands belonged to Grandpa Will.

Grandpa Will's grandsons adored him, and the feeling was mutual! They lured him into chasing them around the backyard. Because it was a hot summer day, play lasted all of 15 minutes and then Grandpa brought the gang back to the air-conditioned comfort of the house. He sank back into the recliner. He was flushed and breathing hard, but his shirt stayed dry and crisp—there wasn't a bead of sweat visible on him. The boys climbed onto his lap, laughing, as he encircled them with those coarse hands. "Oh, Grandpa, you feel like a fish!" **What is happening with Grandpa Will's integumentary system? To find out, turn to the Clinical Case Wrap-Up on p. 225.**



**CLINICAL CASE Wrap-Up** He Has Fish Skin!

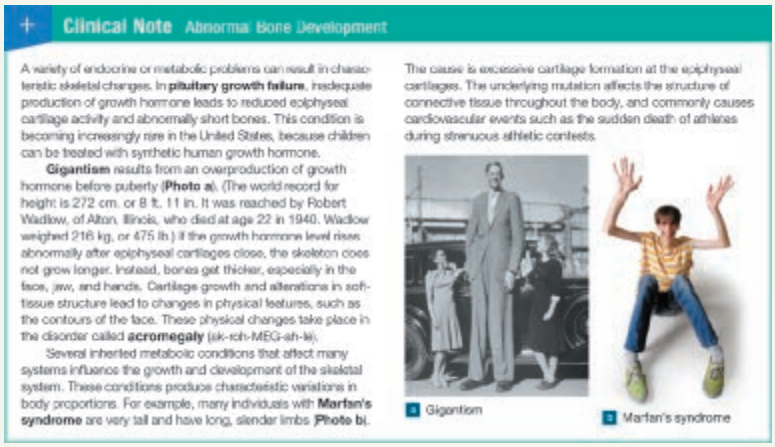
Grandpa Will has ichthyosis vulgaris (IK-thē-oh-sis vŭl-GĀR-is). Ichthyosis literally means "fish-like condition," a feature his grandsons noticed right away. Will inherited this skin condition from his parents, who carried a gene mutation for a structural protein. The lack of this protein impairs keratinization. With this condition, skin cells also have fewer desmosomes and tight junctions, so the epidermis becomes flaky and resembles fish scales.

There is no cure. Every day Grandpa must tend to his skin by applying moisturizers to draw and retain moisture and emollients to soften the scales. He avoids soap, which further dries his skin, and uses rubber gloves to wash the dishes. In winter, he runs a humidifier in the bedroom. If his skin care gets lax, his skin can break into deep, painful cracks. Because the natural skin barrier is disrupted, secondary infection can move in.

1. Why is ichthyosis called a "disorder of cornification"? Which cells are involved?
2. Grandpa has trouble when it's hot outside. What's wrong?

See the Blue Answers tab at the back of the book.

**Clinical Notes** appear within every chapter and expand upon topics just discussed. They present diseases and pathologies along with their relationship to normal function.



**Clinical Note** Abnormal Bone Development

A variety of endocrine or metabolic problems can result in characteristic skeletal changes. In **pituitary growth failure**, inadequate production of growth hormone leads to reduced epiphyseal cartilage activity and abnormally short bones. This condition is becoming increasingly rare in the United States, because children can be treated with synthetic human growth hormone.

**Gigantism** results from an overproduction of growth hormone before puberty (**Photo a**). (The world record for height is 272 cm, or 8 ft, 11 in. It was reached by Robert Wadlow, of Alton, Illinois, who died at age 22 in 1940. Wadlow weighed 216 kg, or 475 lb.) If the growth hormone level rises abnormally after epiphyseal cartilages close, the skeleton does not grow longer. Instead, bones get thicker, especially in the face, jaw, and hands. Cartilage growth and alterations in soft-tissue structure lead to changes in physical features, such as the contours of the face. These physical changes take place in the disorder called **acromegaly** (ak-roh-MEG-ah-lē).

Several inherited metabolic conditions that affect many systems influence the growth and development of the skeletal system. These conditions produce characteristic variations in body proportions. For example, many individuals with **Marfan's syndrome** are very tall and have long, slender limbs (**Photo b**). The cause is excessive cartilage formation at the epiphyseal cartilages. The underlying mutation affects the structure of connective tissue throughout the body, and commonly causes cardiovascular events such as the sudden death of athletes during strenuous athletic contests.

A Gigantism

B Marfan's syndrome

**Clinical Terms** end every chapter with a list of relevant clinical terms and definitions.

## Related Clinical Terms

**carbuncle:** A skin infection that often involves a group of hair follicles. The infected material forms a lump, which occurs deep in the skin; the medical term for multiple boils.

**cold sore:** A lesion that typically occurs in or around the mouth and is caused by a dormant herpes simplex virus that may be reactivated by factors such as stress, fever, or sunburn. Also called *fever blister.*

**comedo:** The primary sign of acne consisting of an enlarged pore filled with skin debris, bacteria, and sebum (oil); the medical term for a blackhead.

**dermatology:** The branch of medicine concerned with the diagnosis, treatment, and prevention of diseases of the skin, hair, and nails.

**eczema:** Rash characterized by inflamed, itchy, dry, scaly, or irritated skin.

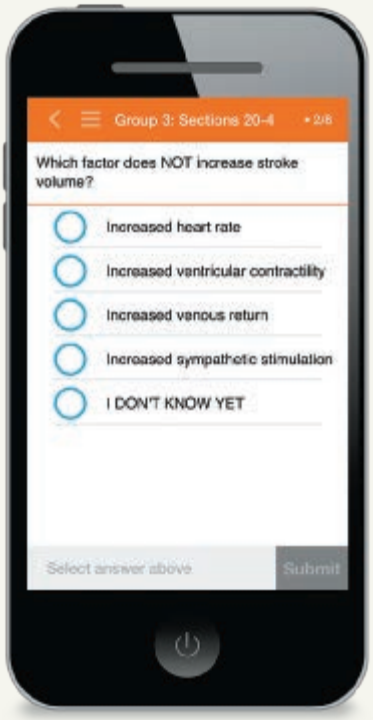
**frostbite:** Injury to body tissues caused by exposure to below-freezing temperatures, typically affecting the nose, fingers, or toes and sometimes resulting in gangrene.

**furuncle:** A skin infection involving an entire hair follicle and nearby skin tissue; the medical term for a boil.

**gangrene:** A term that describes dead or dying body tissue that occurs because the local blood supply to the tissue is either lost or is inadequate to keep the tissue alive.

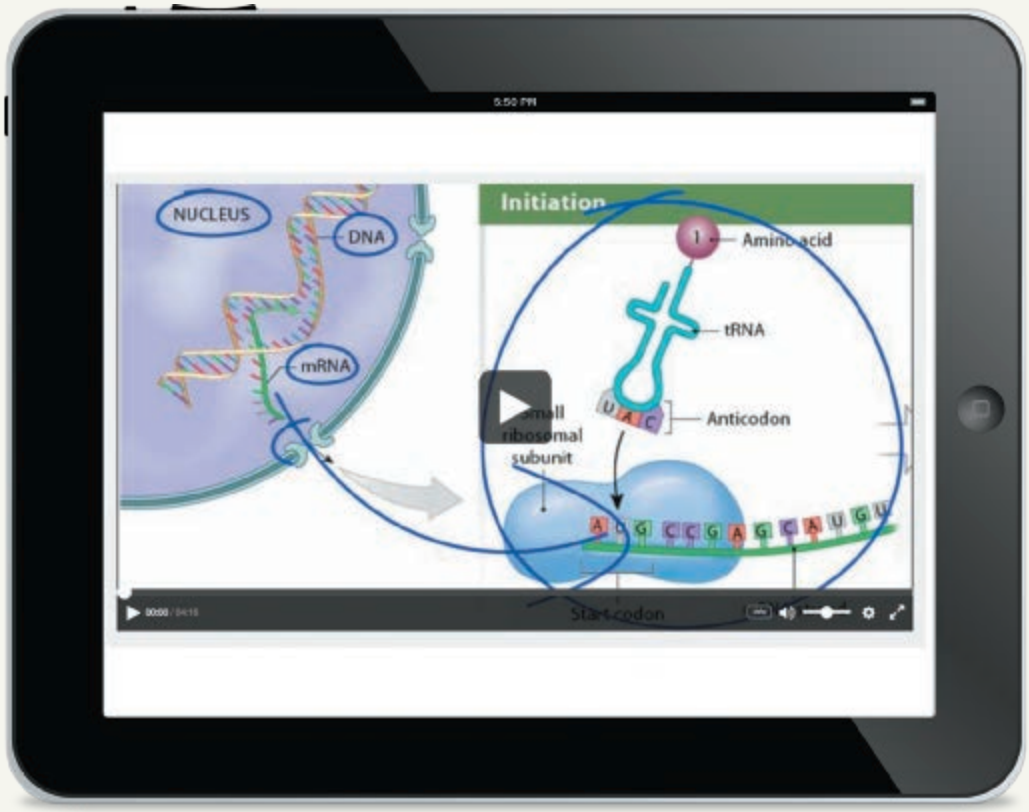
# Continuous Learning
## Before, During, and After Class

**Dynamic Study Modules** enable students to study more effectively on their own. With the Dynamic Study Modules mobile app, students can quickly access and learn the concepts they need to be more successful on quizzes and exams.




**NEW!** Instructors can now select which questions to assign to students.

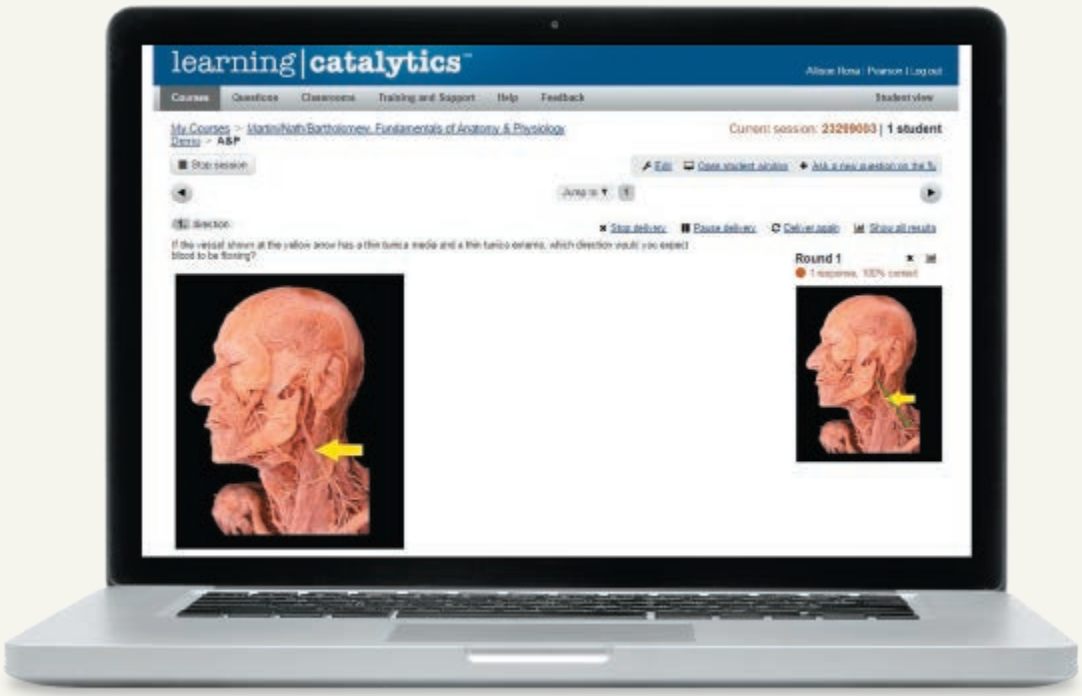
**NEW! SmartArt Videos** help students navigate some of the complex figures in the text. They are accessible via QR code in the book and are assignable in Pearson Mastering A&P.



# with Pearson Mastering A&P™

**Learning Catalytics** is a "bring your own device" (laptop, smartphone, or tablet) engagement, assessment, and classroom intelligence system. Students use their device to respond to open-ended questions and then discuss answers in class based on their responses.

> ***"My students are so busy and engaged answering Learning Catalytics questions during lecture that they don't have time for Facebook."***
>
> *—Declan De Paor, Old Dominion University*




# Pearson Mastering A&P™

**NEW! Interactive Physiology 2.0** helps students advance beyond memorization to a genuine understanding of complex physiological processes. Fun, interactive tutorials, games, and quizzes give students additional explanations to help them grasp difficult concepts. IP 2.0 features brand-new graphics, quicker navigation, and more robust interactivity.


## NEW IP 2.0 modules include:

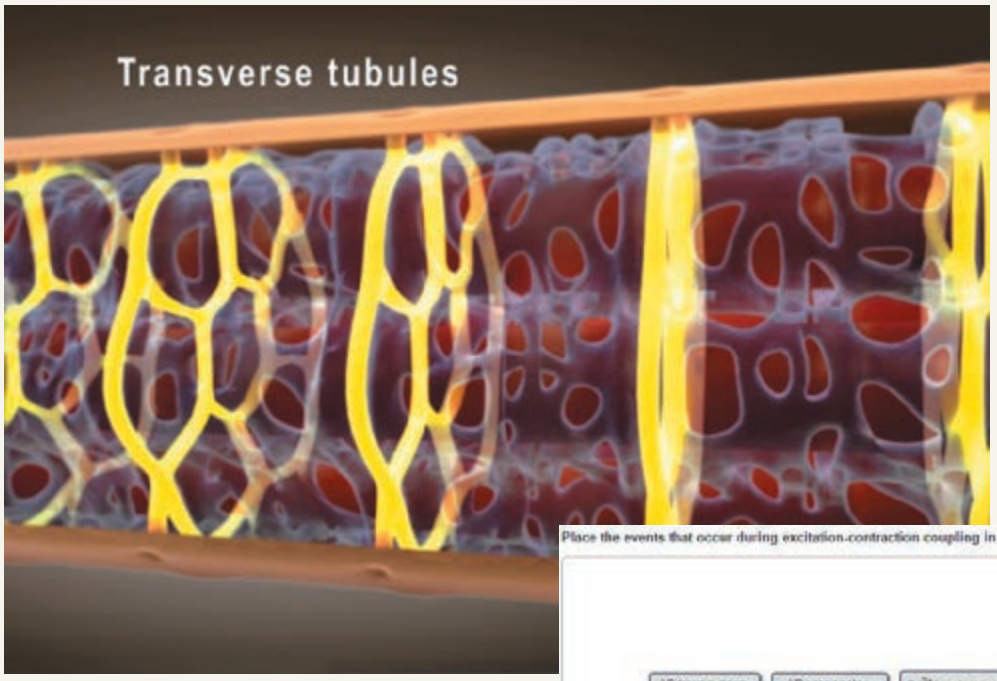
- Resting Membrane Potential
- Electrical Activity of the Heart
- Cardiac Output
- Factors Affecting Blood Pressure
- Generation of an Action Potential

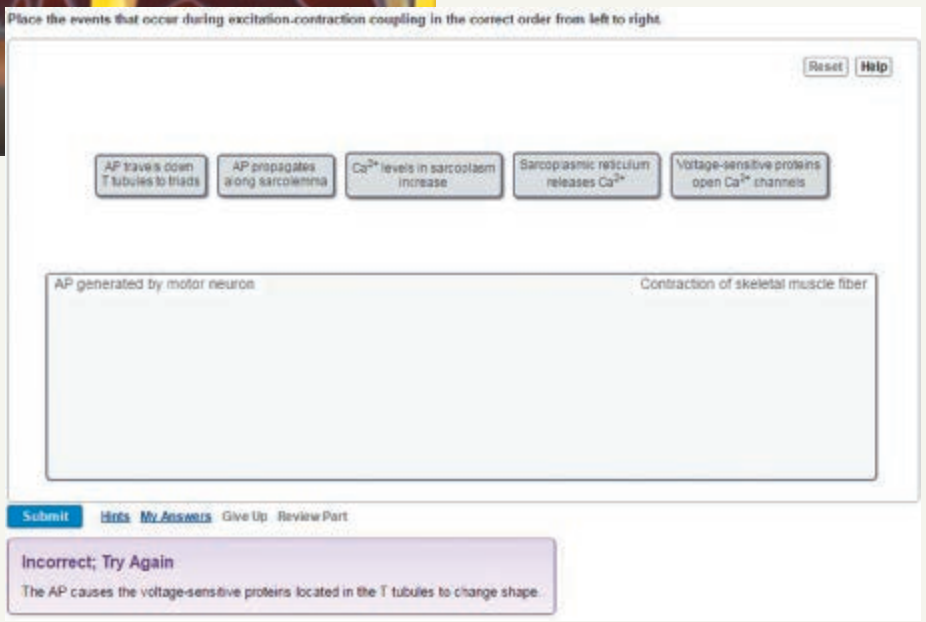
## Coming Soon:

- Cardiac Cycle
- Glomerular Filtration
- Neuromuscular Junction
- Tubular Reabsorption and Secretion
- Excitation Contraction Coupling

# More Practice, More Learning

**A&P Flix Coaching Activities** bring interactivity to these popular 3D movie-quality animations by asking students to answer questions related to the video.



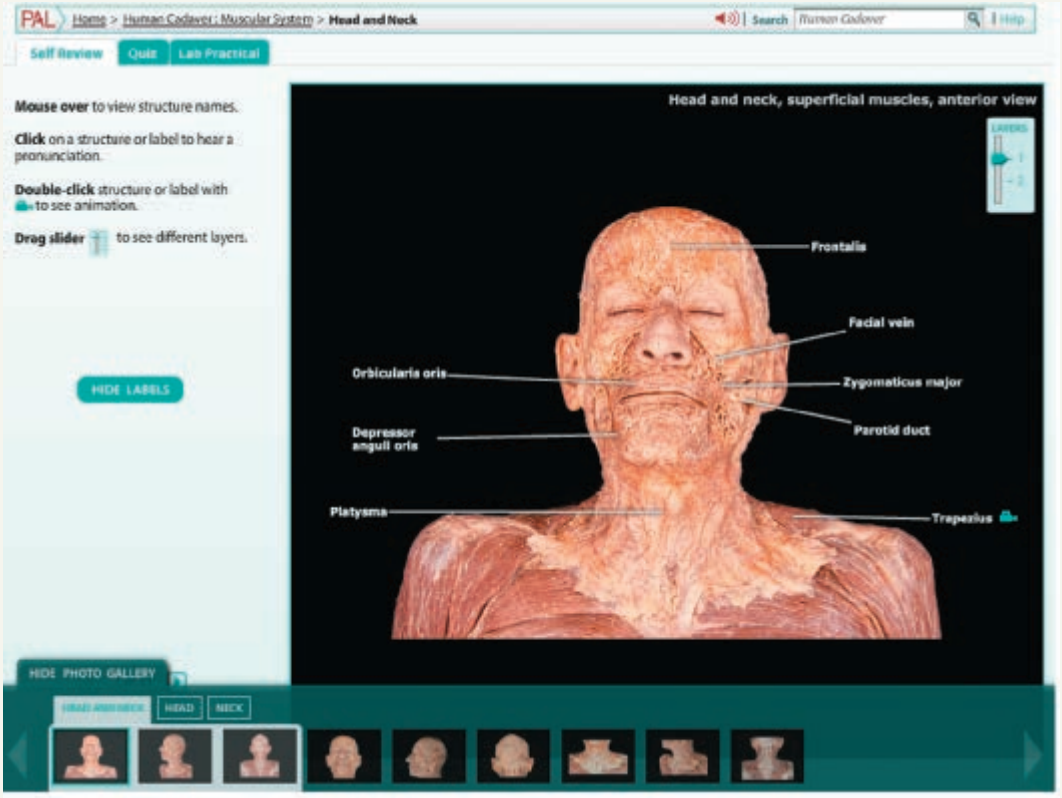




## Additional assignable Pearson Mastering A&P activities include:

- Spotlight Figure Coaching Activities
- Clinical Case Activities
- Clinical Note Activities
- Bone & Dissection Video Coaching Activities
- And More!

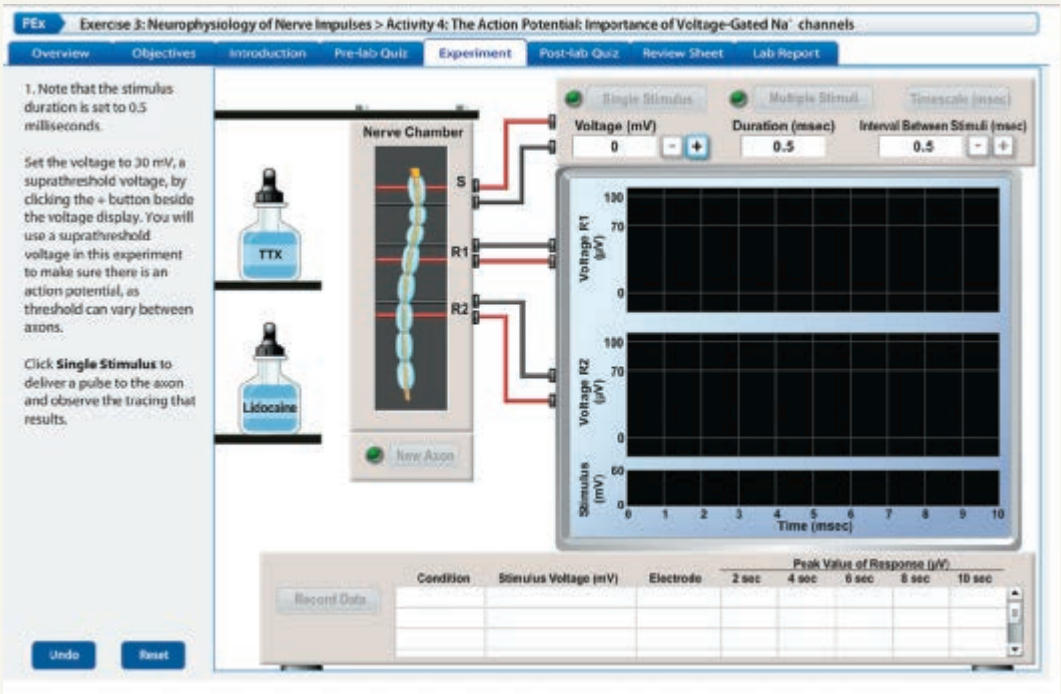
**NEW!** Beginning Fall 2017, all of the assignments from Wood's *Laboratory Manual for A&P featuring Martini Art*, 6e can be accessed in your *Fundamentals of A&P* Mastering course! Only one Pearson Mastering A&P code is needed to access these assignments.

# Pearson Mastering A&P™ Lab Practice




**Practice Anatomy Lab (PAL™ 3.0)** is a virtual anatomy study and practice tool that gives students 24/7 access to the most widely used lab specimens, including the human cadaver, anatomical models, histology, cat, and fetal pig. PAL 3.0 is easy to use and includes built-in audio pronunciations, rotatable bones, and simulated fill-in-the-blank lab practical exams.

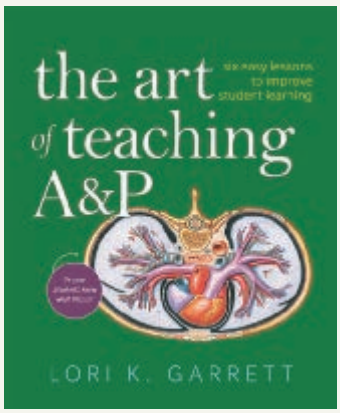
**PhysioEx 9.1** is an easy-to-use lab simulation program that allows students to conduct experiments that are difficult in a wet lab environment because of time, cost, or safety concerns. Students are able to repeat labs as often as they like, perform experiments without animals, and are asked to frequently stop and predict within the labs.



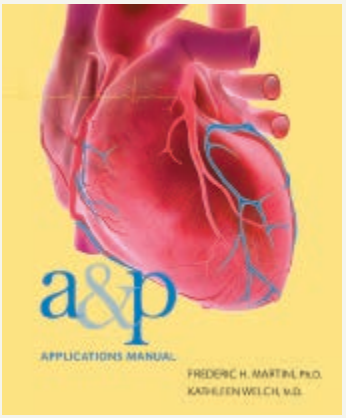
# Access the Complete Textbook Online with Pearson eText

**Powerful interactive and customization functions** include instructor and student note-taking, highlighting, bookmarking, search, and links to glossary terms.

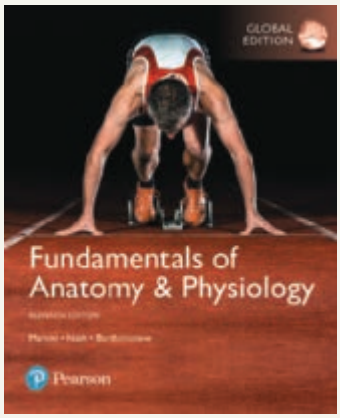
# Instructor and Student Support




**NEW! The Art of Teaching A&P: Six Easy Lessons to Improve Student Learning by Lori K. Garrett**
978-0-13-446951-5
0-13-446951-8
Author Lori Garrett *(Get Ready for A&P)* explores some of the most common challenges she's encountered in her classroom when using art to teach anatomy and physiology. From describing the challenge to researching why it occurs and proposing solutions to address it, Lori provides insight into how students look at images. She presents ideas for how educators can best use figures and illustrations to teach complex concepts without overwhelming or discouraging their students.

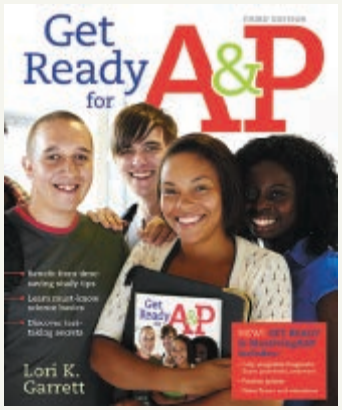



**A&P Applications Manual by Frederic H. Martini and Kathleen Welch**
978-0-32-194973-8
0-32-194973-0
This manual contains extensive discussions on clinical topics and disorders to help students apply the concepts of anatomy and physiology to daily life and their future health professions.

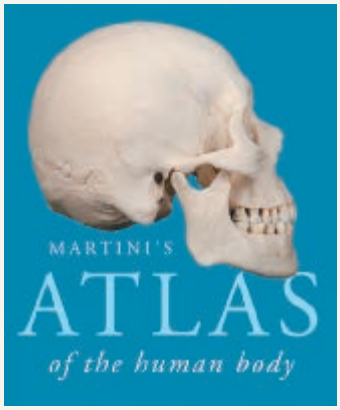



**A complete package of instructor resources includes:**

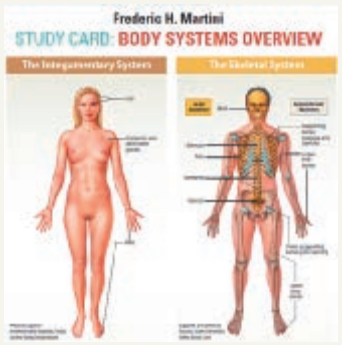
- Customizable PowerPoint slides (with **NEW! Annotations on how to present complex art during lecture)**
- All figures from the book in JPEG format
- A&P Flix 3D movie-quality animations on tough topics (available on Mastering)
- Test Bank
- And more!




**Get Ready for A&P by Lori K. Garrett**
978-0-32-181336-7
0-32-181336-7
This book and online component were created to help students be better prepared for their A&P course. Features include pre-tests, guided explanations followed by interactive quizzes and exercises, and end-of-chapter cumulative tests. Also available in the Study Area of Pearson Mastering A&P.




**Martini's Atlas of the Human Body by Frederic H. Martini**
978-0-32-194072-8
0-32-194072-5
The Atlas offers an abundant collection of anatomy photographs, radiology scans, and embryology summaries, helping students visualize structures and become familiar with the types of images seen in a clinical setting.




**Study Card for Martini: Body Systems Overview**
978-0-13-460995-9
0-13-460995-6
A six-panel laminated card showing all body systems and their organs and functions.

FUNDAMENTALS OF

# Anatomy & Physiology

Eleventh Edition
Global Edition


**Frederic H. Martini, Ph.D.**
University of Hawaii at Manoa

**Judi L. Nath, Ph.D.**
Lourdes University, Sylvania, Ohio

**Edwin F. Bartholomew, M.S.**

William C. Ober, M.D.
*Art Coordinator and Illustrator*

Claire E. Ober, R.N.
*Illustrator*

Kathleen Welch, M.D.
*Clinical Consultant*

Ralph T. Hutchings
*Biomedical Photographer*

Kevin Petti
San Diego Miramar College
SmartArt Videos

Christine Boudrie, M.D.
Lourdes University, Sylvania, Ohio
Clinical Cases

Ruth Anne O'Keefe, M.D.


Editor-in-Chief: *Serina Beauparlant*
Courseware Portfolio Manager: *Cheryl Cechvala*
Content Producer: *Jessica Picone*
Managing Producer: *Nancy Tabor*
Courseware Director, Content Development: *Barbara Yien*
Courseware Sr. Analyst: *Suzanne Olivier*
Acquisitions Editor, Global Edition: *Sourabh Maheshwari*
Senior Project Editor, Global Edition: *Amrita Naskar*
Courseware Editorial Assistant: *Kimberly Twardochleb*
Rich Media Content Producer: *Lauren Chen*
Associate Mastering Producer: *Kristen Sanchez*
Senior Media Editor, Global Edition: *Gargi Banerjee*
Senior Manufacturing Controller, Global Edition: *Trudy Kimber*
Manufacturing Manager, Global Edition: *Caterina Pellegrino*
Copyeditor: *Lorretta Palagi*
Art Coordinator: *Lisa Torri*
Design Manager: *Mark Ong*
Interior Designer: *tani hasegawa*
Cover Designer: *Lumina Datamatics Ltd.*
Rights & Permissions Project Manager: *Kathleen Zander, Jason Perkins*
Rights & Permissions Management: *Cenveo® Publisher Services*
Photo Researcher: *Kristin Piljay*
Manufacturing Buyer: *Stacey Weinberger*
Executive Marketing Manager: *Allison Rona*
Cover Photo Credit: *Stefan Schurr/Shutterstock*



Pearson Education Limited
KAO Two
KAO Park
Harlow
Essex CM17 9NA
England

and Associated Companies throughout the world

Visit us on the World Wide Web at:
www.pearsonglobaleditions.com



*Authorized adaptation from the United States edition, entitled* Fundamentals of Anatomy & Physiology, 11th edition, *ISBN 9780134396026, by Frederic H. Martini, Judi L. Nath, and Edwin F. Bartholomew, published by Pearson Education © 2018.*



Acknowledgements of third party content appear on page 1261, which constitutes an extension of this copyright page.



ISBN 10: 1-292-22986-1; ISBN 13: 978-1-292-22986-7 (Paperback)
ISBN 10: 1-292-22987-X; ISBN 13: 978-1-292-22987-4 (Hardback)

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

10 9 8 7 6 5 4 3 2 1

Typeset by Cenveo Publisher Services

Printed and bound by Vivar in Malaysia (Paperback) and by CTPS in China (Hardback)

# Text and Illustration Team

## Frederic (Ric) H. Martini, Ph.D.

*Author*

Dr. Martini received his Ph.D. from Cornell University in comparative and functional anatomy for work on the pathophysiology of stress. In addition to professional publications that include journal articles and contributed chapters, technical reports, and magazine articles, he is the lead author of 10 undergraduate texts on anatomy and physiology. Dr. Martini is currently affiliated with the University of Hawaii at Manoa and has a long-standing bond with the Shoals Marine Laboratory, a joint venture between Cornell University and the University of New Hampshire. He has been active in the Human Anatomy and Physiology Society (HAPS) for over 24 years and was a member of the committee that established the course curriculum guidelines for A&P. He is now a President Emeritus of HAPS after serving as President-Elect, President, and Past-President over 2005–2007. Dr. Martini is also a member of the American Physiological Society, the American Association of Anatomists, the Society for Integrative and Comparative Biology, the Australia/New Zealand Association of Clinical Anatomists, the Hawaii Academy of Science, the American Association for the Advancement of Science, and the International Society of Vertebrate Morphologists.

## Edwin F. Bartholomew, M.S.

*Author*

Edwin F. Bartholomew received his undergraduate degree from Bowling Green State University and his M.S. from the University of Hawaii. Mr. Bartholomew has taught human anatomy and physiology at both the secondary and undergraduate levels. In addition, he has taught courses ranging from botany to zoology at Maui Community College (now the University of Hawaii Maui College). For many years, he taught at historic Lahainaluna High School, the oldest high school west of the Rockies, where he assisted in establishing a Health Occupations Students of America (HOSA) chapter. He is a coauthor of *Fundamentals of Anatomy & Physiology, Visual Anatomy & Physiology, Essentials of Anatomy & Physiology, Visual Essentials of Anatomy & Physiology, Structure and Function of the Human Body,* and *The Human Body in Health and Disease* (all published by Pearson). Mr. Bartholomew is a member of the Human Anatomy and Physiology Society (HAPS), the National Association of Biology Teachers, the National Science Teachers Association, and the American Association for the Advancement of Science.

## Judi L. Nath, Ph.D.

*Author*

Dr. Judi Nath is a biology professor and the writer-in-residence at Lourdes University, where she teaches at both the undergraduate and graduate levels. Primary courses include anatomy, physiology, pathophysiology, medical terminology, and science writing. She received her bachelor's and master's degrees from Bowling Green State University, which included study abroad at the University of Salzburg in Austria. Her doctoral work focused on autoimmunity, and she completed her Ph.D. from the University of Toledo. Dr. Nath is devoted to her students and strives to convey the intricacies of science in captivating ways that are meaningful, interactive, and exciting. She has won the Faculty Excellence Award—an accolade recognizing effective teaching, scholarship, and community service—multiple times and in 2013 was named as an Ohio Memorable Educator. She is active in many professional organizations, notably the Human Anatomy and Physiology Society (HAPS), where she has served several terms on the board of directors. Dr. Nath is a coauthor of *Visual Anatomy & Physiology, Visual Essentials of Anatomy & Physiology, Anatomy & Physiology*, and *Human Anatomy* (published by Pearson), and she is the sole author of *Using Medical Terminology* and *Stedman's Medical Terminology* (published by Wolters Kluwer). Her favorite charities are those that have significantly affected her life, including the local Humane Society, the Cystic Fibrosis Foundation, and the ALS Association. In 2015, she and her husband established the Nath Science Scholarship at Lourdes University to assist students pursuing science-based careers. When not working, days are filled with family life, bicycling, and hanging with the dogs.

## William C. Ober, M.D.

*Art Coordinator and Illustrator*

Dr. Ober received his undergraduate degree from Washington and Lee University and his M.D. from the University of Virginia. He also studied in the Department of Art as Applied to Medicine at Johns Hopkins University. After graduation, Dr. Ober completed a residency in Family Practice and later was on the faculty at the University of Virginia in the Department of Family Medicine and in the Department of Sports Medicine. He also served as Chief of Medicine of Martha Jefferson Hospital in Charlottesville, Virginia. He is currently a Visiting Professor of Biology at Washington and Lee University, where he has taught several courses and

led student trips to the Galapagos Islands. He was on the Core Faculty at Shoals Marine Laboratory for 24 years, where he taught Biological Illustration every summer. Dr. Ober has collaborated with Dr. Martini on all of his textbooks in every edition.

### Claire E. Ober, R.N.

*Illustrator*

Claire E. Ober, R.N., B.A., practiced family, pediatric, and obstetric nursing before turning to medical illustration as a full-time career. She returned to school at Mary Baldwin College, where she received her degree with distinction in studio art. Following a 5-year apprenticeship, she has worked as Dr. Ober's partner in Medical & Scientific Illustration since 1986. She was on the Core Faculty at Shoals Marine Laboratory and co-taught the Biological Illustration course with Dr. Ober for 24 years. The textbooks illustrated by Medical & Scientific Illustration have won numerous design and illustration awards.

### Kathleen Welch, M.D.

*Clinical Consultant*

Dr. Welch received her B.A. from the University of Wisconsin–Madison, her M.D. from the University of Washington in Seattle, and did her residency in Family Practice at the University of North Carolina in Chapel Hill. Participating in the Seattle WWAMI rural medical education program, she studied in Fairbanks, Anchorage, and Juneau, Alaska, with time in Boise, Idaho, and Anacortes, Washington, as well. For 2 years, she served as Director of Maternal and Child Health at the LBJ Tropical Medical Center in American Samoa and subsequently was a member of the Department of Family Practice at the Kaiser Permanente Clinic in Lahaina, Hawaii, and on the staff at Maui Memorial Hospital. She was in private practice from 1987 until her retirement in 2012. Dr. Welch is a Fellow of the American Academy of Family Practice and a member of the Hawaii Medical Association, the Maui County Medical Association, and the Human Anatomy and Physiology Society (HAPS). With Dr. Martini, she has coauthored both a textbook on anatomy and physiology and the *A&P Applications Manual*. She and Dr. Martini were married in 1979, and they have one son.

### Ralph T. Hutchings

*Biomedical Photographer*

Mr. Hutchings was associated with the Royal College of Surgeons for 20 years. An engineer by training, he has focused for years on photographing the structure of the human body. The result has been a series of color atlases, including the *Color Atlas of Human Anatomy*, the *Color Atlas of Surface Anatomy*, and *The Human Skeleton* (all published by Mosby-Yearbook Publishing). For his anatomical portrayal of the human body, the International Photographers Association has chosen Mr. Hutchings as the best photographer of humans in the 20th century. He lives in North London, where he tries to balance the demands of his photographic assignments with his hobbies of early motor cars and airplanes.

### Christine Boudrie, M.D.

*Clinical Contributor*

Dr. Boudrie studied at Brown University in Providence, Rhode Island, for her B.S. in biology, and also obtained her M.D. there. After graduation she served in the National Health Service Corps, a program of the U.S. Public Health Service, which sponsored her last 2 years of medical school. She was assigned to provide health education to the rural communities of southeast Michigan with a special focus on seniors. She has had the great pleasure of working with a variety of undergraduate and graduate students in the Northeast and Midwest, earning teaching excellence awards and a nomination for Carnegie Foundation's U.S. Professor of the Year in 2014. Currently, she chairs the Department of Biology and Health Sciences at Lourdes University, a small Franciscan liberal arts school in northwest Ohio.

### Ruth Anne O'Keefe, M.D.

*Clinical Contributor*

Dr. O'Keefe did her undergraduate studies at Marquette University, attended graduate school at the University of Wisconsin, and received her M.D. from George Washington University. She was the first woman to study orthopedics at The Ohio State University during her residency. She did fellowship training in trauma surgery at Loma Linda University in California. She serves on the board of Global Health Partnerships, a group that partners with a clinic serving 35,000 people in remote Kenya. She lives in Albuquerque with her Sweet Ed. She is mother of four, grandmother of nine, and foster mother to many.

### Kevin Petti, PhD

*Smart Art Video Contributor*

Dr. Petti is a professor at San Diego Miramar College, and teaches courses in human anatomy and physiology, human dissection, and health education. He is President Emeritus of the Human Anatomy and Physiology Society (HAPS) and holds a doctorate from the University of San Diego. As a dual U.S./Italian citizen, he also teaches courses in Italy that focus on the genesis of anatomy as a science and its influence on the Renaissance masters.

# Preface

The Eleventh Edition of *Fundamentals of Anatomy & Physiology* is a comprehensive textbook that fulfills the needs of today's students while addressing the concerns of their teachers. We focused our attention on the question "How can we make this information meaningful, manageable, and comprehensible?" During the revision process, we drew upon our content knowledge, research skills, artistic talents, and years of classroom experience to make this edition the best yet.

The broad changes to this edition are presented in the **New to the Eleventh Edition** section below, and the specific changes are presented in the **Chapter-by-Chapter Changes in the Eleventh Edition** section that follows.

## New to the Eleventh Edition

In addition to the many technical changes in this edition, such as updated statistics and anatomy and physiology descriptions, we have made the following key changes:

- **NEW SmartArt Videos** help students better navigate key, complex pieces of art. Author Kevin Petti walks students through select pieces of art from the book, providing additional background and detail.
- **NEW design for homeostasis figures** replaces former Tenth Edition figures in various chapters.
- **NEW Questions have been added to selected figures in all chapters to reinforce text–art integration.**
- **Easier narrative leads to improved clarity of text.** Clearly organized text uses simpler, shorter, more active sentences, with a reading level that makes reading and studying easier for students.
- **Anatomical terms** have been updated based on *Terminologia Anatomica*, *Terminologia Histologica*, and *Terminologia Embryologica*. Eponyms continue to be included within the narrative.

## Hallmark Features of This Text

- **50 Spotlight Figures** provide highly visual one- and two-page presentations of tough topics in the book, with a particular focus on physiology.
- **29 Clinical Cases** get students motivated for their future careers. Each chapter opens with a story-based Clinical Case related to the chapter content and ends with a Clinical Case Wrap-Up.
- **The repetition of the chapter-opening Learning Outcomes below the coordinated section headings within the chapters** underscores the connection between the HAPS-based Learning Outcomes and the associated teaching points. Author Judi Nath sat on the Human Anatomy and Physiology Society (HAPS) committee that developed the HAPS Learning Outcomes recommended to A&P teachers, and the Learning Outcomes in this book are based on them.

## Chapter-by-Chapter Changes in the Eleventh Edition

This annotated Table of Contents provides examples of revision highlights in each chapter of the Eleventh Edition. For a more complete list of changes, please contact the publisher.

### Chapter 1: An Introduction to Anatomy and Physiology

- Added a new Section 1–1 on using the text and art in tandem.
- New separate section (1-4) on medical terminology.
- Reorganized the chapter to start with simpler anatomical topics and build to more complex physiological ones. Homeostasis and the roles of negative feedback now conclude the chapter as Sections 1–7 and 1–8, respectively.
- NEW Figure 1–1 A Conceptual Framework for Learning
- NEW Clinical Note: *Habeas Corpus* ("You Shall Have the Body")
- NEW Clinical Note: The Sounds of the Body
- Figure 1–8 The Control of Room Temperature (new homeostasis design)
- Figure 1–9 Negative Feedback: Control of Body Temperature (new homeostasis design)
- Former Spotlight Figure 1–10 Diagnostic Imaging Techniques is now a Clinical Note.
- Questions added to Figures 1–3, 1–4, 1–5, 1–6, and 1–9.

### Chapter 2: The Chemical Level of Organization

- Clinical Case: What Is Wrong with My Baby? revised
- Clinical Note: Radiation Sickness revised
- NEW Figure 2–1 Hydrogen Atom with Electron Cloud
- NEW Section 2–9 gathers together coverage of monomers, polymers, and functional groups to provide an overview to the organic compounds.
- Table 2–8.Turnover Times moved to the Appendix as Turnover Times of Organic Components of Four Cell Types.
- NEW Clinical Note: Too Sweet on Sugar?
- Questions added to Figures 2–3, 2–8, 2–9, 2–12, 2–15, 2–17, 2–24, and 2–26.

### Chapter 3: The Cellular Level of Organization

- Clinical Case: The Beat Must Go On! revised (new title)
- Figure 3–2 The Plasma Membrane revised (new added part b)
- Figure 3–8 Lysosome Functions revised
- NEW Clinical Note: Lysosomal Storage Disease
- NEW Clinical Note: Free Radicals
- Figure 3–13 The Process of Translation revised

- NEW Clinical Note: Drugs and the Plasma Membrane
- Figure 3–21 Receptor–Mediated Endocytosis revised
- Spotlight Figure 3–23 Stages of a Cell's Life Cycle revised
- Questions added to Figures 3–3, 3–9, 3–11, 3–15, 3–17, 3–18, and 3–19.

### Chapter 4: The Tissue Level of Organization

- NEW Figure 4–1 An Orientation to the Body's Tissues
- Figure 4–2 Cell Junctions revised (*basal lamina* replaces *clear layer* and *reticular lamina* replaces *dense layer*)
- Table 4–1.Classifying Epithelia revised
- Connective tissue proper has been separated out into its own section, Section 4–5. This section now also includes the discussion of fasciae.
- Figure 4–9 The Cells and Fibers of Connective Tissue Proper revised (added fibrocyte)
- Figure 4–10 Embryonic Connective Tissues revised (now share labels)
- The fluid connective tissues blood and lymph now have their own section, Section 4–6.
- Questions added to Figures 4–3, 4–14, 4–16, 4–18, and 4–19.

### Chapter 5: The Integumentary System

- NEW Clinical Case: He Has Fish Skin!
- Figure 5–1 The Components of the Integumentary System revised
- The dermis and hypodermis sections have been moved up to become Sections 5–2 and 5–3, respectively, to give students more anatomical background to understand the later physiological sections.
- Spotlight Figure 5–3 The Epidermis revised (matched SEM and art)
- NEW Clinical Note: Nips, Tucks, and Shots
- Figure 5–12 Hair Follicles and Hairs revised (new part b)
- Figure 5–14 Sweat Glands revised (uses *eccrine sweat glands* as primary term)
- NEW Clinical Note: Your Skin, A Mirror of Your Health
- NEW Clinical Note: Burns and Grafts
- NEW Build Your Knowledge Figure 5–15 Integration of the INTEGUMENTARY system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 5–1, 5–6, 5–8, 5–10, and 5–13.

### Chapter 6: Bones and Bone Structure (formerly called Osseous Tissue and Bone Structure)

- NEW Figure 6–4 Bone Lacking a Calcified Matrix
- Figure 6–5 Types of Bone Cells revised (art and layout to parallel text)
- NEW Figure 6–6 Osteons of Compact Bone (former part a removed)
- We now clarify in the section titles that Section 6–5 covers both interstitial and appositional growth, while remodeling is covered in Section 6–6.
- Spotlight Figure 6–17 Types of Fractures and Steps in Repair revised (tibia replaces humerus to better match photograph)
- Questions added to Figures 6–3, 6–5, 6–7, and 6–10.

### Chapter 7: The Axial Skeleton

- Figure 7–2 Cranial and Facial Subdivisions of the Skull revised
- Figure 7–3 The Adult Skull revised (hyphenates the terms *supra-orbital* and *infra-orbital*)
- Figure 7–9 The Ethmoid revised (*ethmoidal labyrinth* replaces *lateral mass*)
- Spotlight Figure 7–4 Sectional Anatomy of the Skull revised (updated trigeminal nerve [V] terminology)
- Figure 7–14 The Orbital Complex revised (art and photograph now share labels)
- Figure 7–15 The Nasal Complex revised (part b new art)
- Figure 7–17 The Vertebral Column revised (new color-coded vertebral regions)
- Figure 7–22 Sacrum and Coccyx revised (new coccyx label configuration)
- Questions added to Figures 7–16, 7–17, and 7–23.

### Chapter 8: The Appendicular Skeleton

- NEW Clinical Case: Timber!!
- Figure 8–6 Bones of the Right Wrist and Hand revised (carpal bones separated out into proximal and distal carpals)
- NEW Clinical Note: Shin Splints
- Clinical Note: Carpal Tunnel Syndrome includes new illustration
- Questions added to Figures 8–1, 8–6, 8–8, and 8–12.

### Chapter 9: Joints

- NEW Clinical Note: Bursitis and Bunions
- NEW Clinical Note: Dislocation
- Spotlight Figure 9–2 Joint Movement revised (headings labeled as parts a, b, and c; *plane joint* replaces *gliding joint*)
- Figure 9–5 Special Movements (part labels added; arrows moved onto photographs in new parts d and e)
- Section 9–5 now covers the hinge joints of the elbow and knee, while Section 9–6 covers the ball-and-socket shoulder and hip joints.
- NEW Build Your Knowledge Figure 9–11 Integration of the SKELETAL system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 9–1, 9–3, 9–6, and 9–9.

### Chapter 10: Muscle Tissue

- NEW Clinical Case: Keep on Keepin' On
- Figure 10–1 The Organization of Skeletal Muscles revised (added tendon attachment to bone)
- Figure 10–5 Sarcomere Structure, Superficial and Cross-Sectional Views revised (new figure icon)
- Figure 10–6 Levels of Functional Organization in a Skeletal Muscle revised (new grouping of art)
- Figure 10–7 Thin and Thick Filaments revised (new art for parts b, c, and d)
- Spotlight Figure 10–9 Events at the Neuromuscular Junction revised (art now shows $Na^+$ flow through membrane channels)
- Spotlight Figure 10–11 The Contraction Cycle and Cross-Bridge Formation revised (improved step boxes visibility)
- Figure 10–16 Effects of Repeated Stimulations revised (new art organization and explanatory text)
- Information about tension production at the level of skeletal muscles has been separated out into a new section, Section 10–6.
- Figure 10–20 Muscle Metabolism revised (text and art in bottom box)

- Figure 10–21 Fast versus Slow Fibers revised (micrograph is a TEM not LM)
- Coverage of muscle fatigue has been moved from the muscle metabolism section to the muscle performance section, Section 10–8.
- NEW Clinical Note: Electromyography
- Discussion on the effects of skeletal muscle aging has been moved from Chapter 11 and included with muscle hypertrophy and atrophy in Section 10–8.
- Questions added to Figures 10–3, 10–6, 10–14, and 10–21.

### Chapter 11: The Muscular System

- NEW Clinical Case: Downward-Facing Dog
- Figure 11–1 Muscle Types Based on Pattern of Fascicle Organization revised
- Figure 11–2 The Three Classes of Levers revised (new icons for each lever)
- Spotlight Figure 11–3 Muscle Action revised (new art in part c)
- The introduction to axial and appendicular muscles has been made into a separate section, Section 11–5, to provide an overview before we cover the muscles in detail.
- NEW Clinical Note: Signs of Stroke
- Figure 11–12 Oblique and Rectus Muscles and the Diaphragm revised (added *transversus thoracis* label to part c)
- Figure 11–17 Muscles That Move the Forearm and Hand revised (corrected leader for *triceps brachii, medial head*)
- Figure 11–18 Muscles That Move the Hand and Fingers revised
- Figure 11–21 Muscles That Move the Leg revised (*quadriceps femoris* replaces *quadriceps muscles*)
- NEW Build Your Knowledge Figure 11–24 Integration of the MUSCULAR system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 11–5, 11–6, 11–10, 11–17, 11–19, and 11–21.

### Chapter 12: Nervous Tissue

- Chapter title changed from Neural Tissue to Nervous Tissue
- Section 12–1 includes discussion of the Enteric Nervous System (ENS) as a third division of the nervous system
- Figure 12–1 A Functional Overview of the Nervous System revised (added a body figure to support text-art integration)
- Moved coverage of synapse structures from Section 12–2 into Section 12–7 so it is now right before students need it to understand synaptic function.
- Figure 12–3 Structural Classification of Neurons revised (moved part labels and text above art)
- Figure 12–5 Neuroglia in the CNS revised (deleted micrograph; label grouping for neuroglia)
- Schwann cell text updated (*neurolemmocytes* replaces *neurilemma cells* and *neurolemma* replaces *neurilemma*).
- Figure 12–7 Peripheral Nerve Regeneration after Injury revised
- Spotlight Figure 12–8 Resting Membrane Potential revised (text revised in first two columns)
- Figure 12–9 Electrochemical Gradients for Potassium and Sodium Ions revised (text revised in part c)
- Figure 12–11 Graded Potentials revised (text in step 2)
- NEW Spotlight Figure 12–13 Generation of an Action Potential revised (text in step boxes)
- Figure 12–14 Propagation of an Action Potential revised (added part labels)
- NEW Figure 12–16 Events in the Functioning of a Cholinergic Synapse revised (now runs across two pages; text in steps revised)
- Table 12–4 Representative Neurotransmitters and Neuromodulators revised (endorphins separated from opioids)
- Figure 12–17 Mechanisms of Neurotransmitter and Receptor Function revised (chemically gated ion channel art now matches that in previous figures)
- Questions added to Figures 12–2, 12–4, and 12–16.

### Chapter 13: The Spinal Cord, Spinal Nerves, and Spinal Reflexes

- Figure 13–1 An Overview of Chapters 13 and 14 revised
- Figure 13–2 Gross Anatomy of the Adult Spinal Cord revised (added new part b)
- Uses the term *posterior* and *anterior* in reference to spinal roots, ganglion, and rami instead of *dorsal* and *ventral* (e.g., Figure 13–3, 13–4, 13–5, and Spotlight Figure 13–8)
- Figure 13–6 A Peripheral Nerve revised (corrected magnified section in part a)
- NEW Figure 13–9 Nerve Plexuses and Peripheral Nerves revised (labels grouped and boxed)
- Figure 13–10 The Cervical Plexus revised (corrected cranial nerve designation, e.g., *accessory nerve [XI]* replaces *accessory nerve [N XI]*)
- Figure 13–12 The Lumbar and Sacral Plexuses revised (removed Clinical Note)
- Spotlight Figure 13–14 Spinal Reflexes revised (added part labels to better coordinate with text)
- Figure 13–15 The Classification of Reflexes revised (reorganized categories within inclusive boxes)
- Figure 13–17 The Plantar Reflex and Babinski Reflex revised (*Babinski reflex* replaces *Babinski sign/positive Babinski reflex* and *plantar reflex* replaces *negative Babinski reflex*)
- Questions added to Figures 13–3, 13–5, 13–9, and 13–15.

### Chapter 14: The Brain and Cranial Nerves

- Figure 14–1 An Introduction to Brain Structures and Functions revised (added part labels a–f to better coordinate with text)
- Figure 14–2 Ventricular System revised (*ventricular system of the brain* replaces *ventricles of the brain*)
- Figure 14–3 The Relationships among the Brain, Cranium, and Cranial Meninges revised *periosteal cranial dura* replaces *dura mater [periosteal layer]* and *meningeal cranial dura* replaces *dura mater [meningeal layer]*)
- Figure 14–5 The Diencephalon and Brainstem revised (corrected cranial nerve designation, e.g., in Cranial Nerves box, CN replaces N for nerve designations.)
- The sections on the midbrain (now Section 14–5) and cerebellum (now Section 14–6) have been switched, so that we now cover all of the brainstem together.
- Figure 14–10 The Thalamus revised (thalamic nuclei labels now color coded to clarify brain regions that receive thalamic input; *medial geniculate body* and *lateral geniculate body* replace *medial geniculate nucleus* and *lateral geniculate nucleus*)
- Figure 14–18 Origins of the Cranial Nerves revised (new brain cadaver photograph; cranial nerve labels boxed together)
- Questions added to Figures 14–1, 14–3, 14–9, 14–13, 14–15, 14–22, and 14–26.

### Chapter 15: Sensory Pathways and the Somatic Nervous System

- Figure 15–1 An Overview of Events Occurring Along the Sensory and Motor Pathways revised
- Figure 15–2 Receptors and Receptive Fields revised (different colors for each receptive field and added Epidermis and Free nerve endings labels)
- Figure 15–3 Tonic and Phasic Sensory Receptors revised (new background colors for graphs)
- Figure 15–4 Tactile Receptors in the Skin revised (added *myelin sheath* to afferent nerve fiber in part c; part d, *bulbous corpuscle* replaces *Ruffini corpuscle*; part e, *lamellar [pacinian] corpuscle* replaces *lamellated [pacinian] corpuscle*)
- NEW Figure 15–6 Locations and Functions of Chemoreceptors
- Figure 15–7 Sensory Pathways and Ascending Tracts in the Spinal Cord revised (*gracile fasciculus* replaces *fasciculus gracilis*, *cuneate fasciculus* replaces *fasciculus* cuneate)
- Spotlight Figure 15–8 Somatic Sensory Pathways revised (introduced "somatotopy" in Sensory Homunculus boxed text)
- Questions added to Figures 15–1, 15–2, 15–4, 15–7, and 15–10.

### Chapter 16: The Autonomic Nervous System and Higher-Order Functions

- NEW Clinical Case: Remember Me?
- NEW Spotlight Figure 16–2 The Autonomic Nervous System (incorporates old Figures 16–4 and 16–6. added Pons and Medulla oblongata labels on the art)
- A new summary Section 16–6 called "The differences in the organization of sympathetic and parasympathetic structures lead to widespread sympathetic effects and specific parasympathetic effects" has been created.
- The sections on memory, states of consciousness, and behavior have been combined into Section 16–9.
- Figure 16–11 The Reticular Activating System (RAS) revised (*CN II* and *CN VIII* replace *N II* and *N VIII*, respectively)
- NEW Build Your Knowledge Figure 16–12 Integration of the NERVOUS system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 16–1, 16–3, 16–4, 16–7, and 16–11.

### Chapter 17: The Special Senses

- Figure 17–1 The Olfactory Organs revised (I replaces N I)
- Spotlight Figure 17–2 Olfaction and Gustation revised (added part a and b labels)
- Figure 17–3 Papillae, Taste Buds, and Gustatory Receptor Cells revised (new figure title; added *Midline groove* label to part a)
- Figure 17–4 External Features and Accessory Structures of the Eye revised (*lateral angle* replaces *lateral canthus*, *medial angle* replaces *medial canthus*, *bulbar conjunctiva* replaces *ocular conjunctiva*, *eyelid* replaces *palpebrae*)
- Figure 17–5 The Sectional Anatomy of the Eye revised (*corneoscleral junction* replaces *corneal limbus*)
- Figure 17–6 The Pupillary Muscles revised (*dilator pupillae* replaces *pupillary dilator muscles*; *sphincter pupillae* replaces *pupillary constrictor*)
- Figure 17–7 The Organization of the Retina revised (*pigmented layer of retina* replaces *pigmented part of retina*; switched parts b and c to parallel new sequence in the text)
- A new overview section, Section 17–4, called "The focusing of light on the retina leads to the formation of a visual image" has been created in the text.
- Figure 17–10 Factors Affecting Focal Distance revised (clarified text within figure; added Focal point label to all the art)
- Figure 17–11 Accommodation revised (*fovea centralis* replaces *fovea*)
- Figure 17–14 Structure of Rods, Cones, and the Rhodopsin Molecule revised (*pigmented epithelium* replaces *pigment epithelium*)
- Figure 17–23 The Internal Ear revised (*ampullary crest* replaces *crista ampullaris*; clarified position of membranous labyrinth in part a art)
- Figure 17–24 The Semicircular Ducts revised (*ampullary cupula* replaces *cupula*; *vestibular nerve* replaces *vestibular branch* in part a)
- Figure 17–26 Pathways for Equilibrium Sensations revised (*cochlear nerve* replaces *cochlear branch*)
- Figure 17–30 Sound and Hearing revised (added new art to illustrate step 4)
- Figure 17–32 Pathways for Auditory Sensations revised (auditory replaces sound and acoustic in steps 2 and 5)
- Questions added to Figures 17–4, 17–7, 17–21, and 17–28.

### Chapter 18: The Endocrine System

- Figure 18–1 Organs and Tissues of the Endocrine System revised (clarified hormones in Gonads box)
- Table 18–1 Mechanisms of Intercellular Communication revised (added autocrine communication)
- Spotlight Figure 18–3 G Proteins and Second Messengers revised (added positive feedback involving protein kinase C; clarified calcium ion sources for binding with calmodulin)
- Figure 18–6 Three Mechanisms of Hypothalamic Control over Endocrine Function revised (removed numbers and added color coding to enhance links between hypothalamic structures and functions)
- Figure 18–7 The Hypophyseal Portal System and the Blood Supply to the Pituitary Gland revised (*regulatory hormones* replaces *regulatory factors*)
- Figure 18–8 Feedback Control of Endocrine Secretion revised (added two banners to separate part a from parts b and c; incorporated old part d with a new color-coded table within part a)
- Figure 18–9 Pituitary Hormones and Their Targets revised (added color codes to correlate with Figure 18–6)
- Figure 18–11 Synthesis and Regulation of Thyroid Hormones (added step art to part a that describes synthesis, storage, and secretion of thyroid hormones; added new homeostasis design to part b that illustrates the regulation of thyroid secretion)
- Figure 18–12 Anatomy of the Parathyroid Glands revised (*principal cells* replaces *chief cells*)
- Figure 18–13 Homeostatic Regulation of the Blood Calcium Ion Concentration revised (new homeostasis design)
- Figure 18–14 The Adrenal Gland and Adrenal Hormones revised (added new micrograph and new design for part c)
- Figure 18–17 Homeostatic Regulation of the Blood Glucose Concentration revised (new homeostasis design)
- Figure 18–19 Endocrine Functions of the Kidneys revised (new homeostasis design in part b)
- NEW Build Your Knowledge Figure 18–21 Integration of the ENDOCRINE system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 18–6, 18–8, 18–9, 18–14, and 18–17.

### Chapter 19: Blood

- NEW Clinical Case: Crisis in the Blood
- Section 19–1 now covers the main functions and characteristics of blood, as well as an introduction to both plasma and formed elements (combined with the old Section 19–2).
- Figure 19–4 Stages of RBC Maturation: Erythropoiesis and Figure 19–5 Recycling of Red Blood Cell Components sequence changed because of chapter reorganization.
- Figure 19–6 Blood Types and Cross-Reactions revised (corrected shapes of anti-A and anti-B antibodies)
- Figure 19–7 Blood Type Testing revised (anti-Rh replaces anti-D; added "clumping" or "no clumping" under test results for clarification)
- Figure 19–11 The Phases of Hemostasis (Vascular, Platelet, and Coagulation) and Clot Retraction revised (*clotting factors* replaces *platelet factors* in step 2; new blood clot SEM)
- Table 19–2.Differences in Blood Group Distribution revised
- Questions added to Figures 19–3, 19–5, 19–6, and 19–10.

### Chapter 20: The Heart

- Figure 20–1 An Overview of the Cardiovascular System revised (new art and boxed labels)
- Figure 20–2 The Location of the Heart in the Thoracic Cavity revised (*parietal layer of serous pericardium* replaces *parietal pericardium*)
- Figure 20–4 The Heart Wall revised (*visceral layer of serous pericardium* replaces *epicardium [visceral pericardium]*)
- Figure 20–5 The Sectional Anatomy of the Heart revised (*tricuspid valve* replaces *right AV [tricuspid] valve*; *mitral valve* replaces *left AV [mitral] valve*)
- Figure 20–7 Valves of the Heart and Blood Flow revised (red arrows replace black arrows in part a; black arrows deleted in part b)
- Figure 20–10 The Conducting System of the Heart and the Pacemaker Potential revised (*pacemaker potential* replaces *prepotential*)
- Figure 20–11 Impulse Conduction through the Heart and Accompanying ECG Tracings revised (added ECG tracings next to the step art)
- Figure 20–12 An Electrocardiogram (ECG) revised (*QRS complex* replaces *QRS interval* in part b)
- Figure 20–14 Cardiac Contractile Cells revised (cardiac contractile cells replaces *cardiac muscle cells*; former Figure 20–5 moved because of chapter reorganization to provide structural information right before functional information)
- Figure 20–15 Action Potentials in Cardiac Contractile Cells and Skeletal Muscle Fibers revised (*ventricular contractile cell* replaces *ventricular muscle cell*)
- Figure 20–16 Phases of the Cardiac Cycle revised (moved labels for Atrial systole, Atrial diastole, Ventricular systole, and Ventricular diastole to perimeter of art for increased correlation)
- Figure 20–17 Pressure and Volume Relationships in the Cardiac Cycle revised (modified colors of banners to match the perimeter art of Figure 20–16 Phases of the Cardiac Cycle for increased correlation)
- Figure 20–19 Factors Affecting Cardiac Output revised (added EDV and ESV)
- Figure 20–23 Factors Affecting Stroke Volume revised (added key)
- Figure 20–24 A Summary of the Factors Affecting Cardiac Output revised (deleted arrow from Preload to End-systolic volume box)
- Table 20–1 Structural and Functional Differences between Cardiac Contractile Cells and Skeletal Muscle Fibers revised (*cardiac contractile cells* replaces *cardiac muscle cells*)
- Questions added to Figures 20–1, 20–5, 20–11, 20–15, 20–21, and 20–24.

### Chapter 21: Blood Vessels and Circulation

- Figure 21–2 Histological Structures of Blood Vessels revised (added luminal diameters for all vessels)
- Figure 21–4 The Organization of a Capillary Bed revised (deleted metarterioles)
- Figure 21–8 Relationships among Vessel Luminal Diameter, Cross-Sectional Area, Blood Pressure, and Blood Velocity within the Systemic Circuit revised (*vessel luminal diameter* replaces *vessel diameter* in part a; *vessel lumens* replaces *vessels* in part b)
- Figure 21–11 Forces Acting across Capillary Walls revised (added tissue cells background)
- The discussion of vasomotion has been moved from Section 21–1 to Section 21–3, to cover this process with other vessel physiology.
- Figure 21–12 Short-Term and Long-Term Cardiovascular Responses revised (new homeostasis design)
- Figure 21–13 Baroreceptor Reflexes of the Carotid and Aortic Sinuses revised (new homeostasis design)
- Figure 21–14 The Chemoreceptor Reflexes revised (new homeostasis design)
- Figure 21–15 The Hormonal Regulation of Blood Pressure and Blood Volume revised (new homeostasis design)
- Figure 21–16 Cardiovascular Responses to Blood Loss revised (new homeostasis design)
- Figure 21–24 Arteries Supplying the Abdominopelvic Organs revised
- Figure 21–27 Major Veins of the Head, Neck, and Brain revised (added confluence of sinuses to parts a, b and c)
- Figure 21–28 The Venous Drainage of the Abdomen and Chest revised (*median sacral* replaces *medial sacral*; *hemi-azygos* replaces *hemiazygos*)
- Figure 21–29 Flowchart of Circulation to the Superior and Inferior Venae Cavae revised
- Figure 21–31 The Hepatic Portal System revised
- **NEW** Build Your Knowledge Figure 21–34 Integration of the CARDIOVASCULAR system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 21–2, 21–7, 21–12, 21–15, 21–21, and 21–29.

### Chapter 22: The Lymphatic System and Immunity

- The coverage of the lymphatic system is now Section 22–1.
- Figure 22–1 The Components of the Lymphatic System revised (Other Lymphoid Tissues and Organs heading replaces Lymphoid Tissues and Organs heading because lymph nodes are organs)
- Figure 22–5 Lymphoid Nodules moved (formerly Figure 22–7, moved due to chapter reorganization)
- Figure 22–6 The Structure of a Lymph Node revised and moved (*cortex* replaces *outer cortex*; *paracortex* replaces *deep cortex*; formerly Figure 22–8, moved due to chapter reorganization)
- Figure 22–7 The Thymus moved (formerly Figure 22–9, moved due to chapter reorganization)
- Figure 22–8 The Spleen moved (formerly Figure 22–10, moved due to chapter reorganization)
- The original Section 22–1 has been moved to become Section 22–2 and adapted so that it is now titled "Lymphocytes are important to the innate (nonspecific) and adaptive (specific) defenses that protect the body."
- We have broadened the definition of the term "immune response" from a "defense against specific antigens" to "the body's reaction to infectious agents and abnormal substances."

- Figure 22–9 The Origin and Distribution of Lymphocytes revised and moved (hemocytoblasts replaces multipotent hemopoietic stem cell; formerly Figure 22–10, moved due to chapter reorganization)
- Figure 22–10 Innate Defenses revised
- Figure 22–11 How Natural Killer Cells Kill Cellular Targets moved (formerly Figure 22–12, moved due to chapter reorganization)
- Figure 22–12 Interferons revised
- NEW Figure 22–13 Pathways of Complement Activation revised (added the Lectin Pathway)
- Figure 22–14 Inflammation and the Steps in Tissue Repair moved (formerly Figure 22–15, moved due to chapter reorganization)
- Figure 22–15 Classes of Lymphocytes revised and moved (*regulatory T cells* replaces *suppressor T cells*; formerly Figure 22–5, moved due to chapter reorganization)
- Figure 22–16 An Overview of Adaptive Immunity revised and moved (former title: An Overview of the Immune Response; formerly Figure 22–17, moved due to chapter reorganization)
- Figure 22–17 Forms of Immunity revised and moved (*acquired* replaces *induced*; formerly Figure 22–16, moved due to chapter reorganization)
- Figure 22–18 Antigens and MHC Proteins revised
- Spotlight Figure 22–21 Cytokines of the Immune System revised and moved (formerly Figure 22–28, moved due to chapter reorganization)
- Figure 22–22 A Summary of the Pathways of T Cell Activation revised and moved (*regulatory T cells* replaces *suppressor T cells*; formerly Figure 22–21, moved due to text reorganization)
- Figure 22–23 The Sensitization and Activation of B Cells moved (formerly Figure 22–22, moved due to chapter reorganization)
- Figure 22–24 Antibody Structure and Function moved (formerly Figure 22–23, moved due to chapter reorganization)
- Figure 22–27 An Integrated Summary of the Immune Response revised and moved (*regulatory T cells* replaces *suppressor T cells*; formerly Figure 22–26, moved due to chapter reorganization
- NEW Build Your Knowledge Figure 22–30 Integration of the LYMPHATIC system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 22–3, 22–8, 22–12, 22–17, 22–25, and 22–26.

### Chapter 23: The Respiratory System

- NEW Clinical Case: No Rest for the Weary
- Figure 23–3 The Structures of the Upper Respiratory System revised (*epithelial surface* replaces *superficial view* in micrograph of part a)
- Figure 23–3 The Structures of the Upper Respiratory System revised (*pharyngeal opening of auditory tube* replaces *nasopharyngeal meatus*)
- Original Sections 23–3 and 23–4 have been combined into a new Section 23–3 on the conducting portion of the lower respiratory system. This section now includes coverage of the bronchial tree.
- Figure 23–6 The Anatomy of the Trachea revised (cross-sectional diagram of trachea and esophagus replaces micrograph to better highlight trachealis)
- NEW Section 23–4 has been added titled "The respiratory portion of the lower respiratory system is where gas exchange occurs." This covers the respiratory bronchioles, alveolar ducts and alveoli, and the blood air barrier.
- Figure 23–7 The Bronchi, Lobules, and Alveoli of the Lung revised and moved (new art in part c; formerly Figure 23–9, moved due to chapter reorganization)
- Figure 23–8 Alveolar Organization revised and moved (*pneumocyte type I* and *type II* replaces *type I* and *type II pneumocyte*; *blood air barrier* replaces *respiratory membrane*; formerly Figure 23–10, moved due to chapter reorganization
- Figure 23–9 The Gross Anatomy of the Lungs revised and moved (formerly Figure 23–7, moved due to chapter reorganization)
- Figure 23–10 The Relationship between the Lungs and Heart revised (labeled Anterior border in part b; formerly Figure 23–8, moved due to chapter reorganization)
- Figure 23–11 An Overview of the Key Steps in Respiration revised
- NEW Figure 23–13 Primary and Accessory Respiratory Muscles
- NEW Spotlight Figure 23–14 Pulmonary Ventilation
- Figure 23–15 Pressure and Volume Changes during Inhalation and Exhalation revised and moved (outlined boxes with same color as respective line graphs for better correlation; formerly Figure 23–14, moved due to chapter reorganization)
- Figure 23–16 Pulmonary Volumes and Capacities revised
- Figure 23–18 An Overview of Respiratory Processes and Partial Pressures in Respiration revised (added new icon art)
- Figure 23–23 A Summary of the Primary Gas Transport Mechanisms revised (added oxygen and carbon dioxide partial pressure values)
- Spotlight Figure 23–25 Control of Respiration revised
- Figure 23–26 The Chemoreceptor Response to Changes in $P_{CO_2}$ revised (new homeostasis design)
- NEW Build Your Knowledge Figure 23–28 Integration of the RESPIRATORY system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 23–2, 23–7, 23–8, 23–13, 23–16, 23–20, and 23–26.

### Chapter 24: The Digestive System

- Figure 24–1 Components of the Digestive System revised (*mechanical digestion* replaces *mechanical processing*)
- Figure 24–2 The Mesenteries revised (added Visceral peritoneum label to part d)
- Figure 24–3 Histological Organization of the Digestive Tract revised (*muscular layer* replaces *muscularis externa*; *intestinal glands* replaces *mucosal glands*; *submucosal neural plexus* replaces *submucosal plexus*)
- Figure 24–4 Peristalsis revised (Initial State now step 1)
- Figure 24–6 Anatomy of the Oral Cavity revised (*oral vestibule* replaces *vestibule*; *frenulum of tongue* replaces *lingual frenulum*)
- Figure 24–7 The Teeth moved (formerly Figure 24–8, moved due to chapter reorganization)
- Figure 24–8 Deciduous and Permanent Dentitions revised (new title; *deciduous* replaces *primary*; *permanent* replaces *secondary*; *canine* replaces *cuspid*; formerly Figure 24–9, moved due to chapter reorganization)
- Figure 24–9 Anatomy of the Salivary Glands moved (formerly Figure 24–7, moved due to chapter reorganization)
- Section 24–3, titled "The pharynx and esophagus are passageways that transport the food bolus from the oral cavity to the stomach," now combines coverage of the pharynx, esophagus, and deglutition.
- Figure 24–12 Gross Anatomy of the Stomach revised (new title; *pyloric part* replaces *pylorus*)
- Figure 24–14 The Secretion of Hydrochloric Acid Ions revised (new title; *anion countertransport mechanism* replaces *countertransport mechanism*; added Dissociation label for clarification)

- Spotlight Figure 24–15 The Regulation of Gastric Activity revised (clarified Key in steps 1 and 2)
- The new Section 24–5 called "Accessory digestive organs, such as the pancreas and liver, produce secretions that aid in chemical digestion" now covers these accessory organs all in one place.
- Figure 24–16 Anatomy of the Pancreas moved (formerly Figure 24–18, moved due to chapter reorganization)
- Figure 24–17 Gross Anatomy of the Liver revised and moved (new title; added Peritoneal cavity label to part a; formerly Figure 24–19, moved due to chapter reorganization)
- Figure 24–18 Histology of the Liver revised and moved (*portal triad* replaces *portal area*; reoriented micrograph to better correlate with art in part b; renamed portal triad structures to *interlobular bile duct*, *interlobular vein*, and *interlobular artery*; *stellate macrophage* replaces *Kupffer cells*; formerly Figure 24–20, moved due to chapter reorganization)
- Figure 24–19 The Anatomy and Physiology of the Gallbladder and Bile Ducts revised (*bile duct* replaces *common bile duct*; formerly Figure 24–21, moved due to chapter reorganization)
- Figure 24–20 Gross Anatomy and Segments of the Intestine moved (new title; formerly Figure 24–16, moved due to chapter reorganization)
- Figure 24–21 Histology of the Intestinal Wall revised (new title; added new part c showing Paneth cells; *intestinal gland* replaces *intestinal crypt*; formerly Figure 24–17, moved due to chapter reorganization)
- Figure 24–22 The Secretion and Effects of Major Duodenal Hormones revised (new title; clarified secretin's primary effect)
- Figure 24–23 The Secretion and Effects of Major Digestive Tract Hormones revised (new title; added new pancreas art)
- Figure 24–25 Histology of the Colon revised (new title; added two more teniae coli to the icon art to show general positions of all three teniae coli)
- Added coverage of the microbiome under Section 24–7 on the large intestine.
- NEW Figure 24–26 The Defecation Reflex
- Spotlight Figure 24–27 The Chemical Events of Digestion revised
- Figure 24–27 Digestive Secretion and Water Reabsorption in the Digestive Tract revised (added new art next to Dietary Input box)
- **NEW** Build Your Knowledge Figure 23–28 Integration of the DIGESTIVE system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 24–4, 24–9, 24–12, 24–23, and 24–26.

### Chapter 25: Metabolism, Nutrition, and Energetics (title changed to include nutrition)

- NEW Figure 25–1 Metabolism of Organic Nutrients and Nutrient Pools
- We now cover oxidation–reduction reactions in Section 25–1.
- Figure 25–2 Glycolysis moved (formerly Figure 25–3)
- Figure 25–3 The Citric Acid Cycle revised and moved (*electron transport chain* replaces *electron transport system*; formerly Figure 25–4)
- NEW Spotlight Figure 25–4 The Electron Transport Chain and ATP Formation
- Figure 25–5 A Summary of the Energy Yield of Glycolysis and Aerobic Metabolism revised (total ATP yield from a glucose molecule based on new values of ATP yield per NADH [2.5 ATP vs. previous 3 ATP] and $FADH_2$ [1.5 ATP vs. previous 2 ATP]).
- Figure 25–6 Glycolysis and Gluconeogenesis revised (added NADH → NAD to show pyruvate is reduced to form lactate when oxygen is lacking)
- Figure 25–7 Lipolysis and Beta-Oxidation revised (new title; lowered total ATP yield)
- Figure 25–8 Lipid Transport and Use revised (formerly Figure 25–9)
- Spotlight Figure 25–10 Absorptive and Postabsorptive States revised (*membrane receptor* replaces *carrier protein*; formerly Spotlight Figure 25–11)
- Figure 25–11 MyPlate, MyWins revised (new title)
- Questions added to Figures 25–2, 25–5, 25–7, 25–8, and 25–14.

### Chapter 26: The Urinary System

- Figure 26–6 The Anatomy of a Representative Nephron and the Collecting System revised (new figure title; removed functional anatomy descriptions; *descending thin limb* replaces *thin descending limb* in all relevant figures)
- Figure 26–7 The Functional Anatomy of a Representative Nephron and the Collecting System revised (added *Extraglomerular mesangial cells* label in part a to clarify their distinction from juxtaglomerular cells; *intraglomerular mesangial cell* replaces *mesangial cell*)
- Figure 26–8 The Locations and Structures of Cortical and Juxtamedullary Nephrons moved (formerly Figure 26–7, renumbered because of chapter reorganization)
- Figure 26–9 An Overview of Urine Formation revised (added functional anatomy descriptions from former Figure 26–6)
- Figure 26–11 The Response to a Reduction in the GFR revised (new homeostasis design)
- There is a new section called Principles of Reabsorption and Secretion at the beginning of Section 26–5 to provide an overview of this process before we get into its details.
- Figure 26–12 Transport Activities at the PCT revised (corrected color of cotransport mechanism symbol in the art)
- A new Section 26–6 called "Countercurrent multiplication allows the kidneys to regulate the volume and concentration of urine" has been added to emphasize this content, especially the role of the medullary osmotic gradient. This also includes a more complete kidney function testing section.
- Spotlight Figure 26–16 Summary of Renal Function revised (added new step 8 discussing papillary duct permeability to urea and art showing urea transporter)
- Figure 26–18 Organs for Conducting and Storing Urine revised (deleted "[in urogenital diaphragm]" in part b)
- NEW Figure 26–20 The Control of Urination
- NEW Build Your Knowledge Figure 26–21 Integration of the URINARY system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 26–5, 26–6, 26–11, 26–14, and 26–18.

### Chapter 27: Fluid, Electrolyte, and Acid–Base Balance

- Figure 27–5 Homeostatic Regulation of Sodium Ion Concentration in Body Fluids revised (new homeostasis design)
- Figure 27–6 Integration of Fluid Volume Regulation and Sodium Ion Concentration in Body Fluids revised (new homeostasis design)
- Figure 27–7 Major Factors Involved in Disturbances of Potassium Ion Balance revised (new homeostasis design)
- Figure 27–8 Three Classes of Acids Found in the Body revised (*metabolic acids* replaces *organic acids*)

- Figure 27–13 pH Regulation of Tubular Fluid by Kidney Tubule Cells revised (incorporated buffer system type next to relevant chemical reactions for better art–text integration)
- Figure 27–15 Homeostatic Regulation of Acid–Base Balance revised (new homeostasis design)
- Figure 27–16 Responses to Metabolic Acidosis revised (new homeostasis design)
- Figure 27–17 Responses to Metabolic Alkalosis revised (new homeostasis design)
- Questions added to Figures 27–2, 27–7, 27–10, 27–14, and 27–16.

### Chapter 28: The Reproductive System

- NEW Clinical Case: And Baby Makes Three?
- Section 28–2, retitled "The structures of the male reproductive system consist of the testes and scrotum, duct system, accessory glands, and penis," is now focused on male reproductive anatomy.
- FAP10 Figure 28–2 The Descent of the Testes deleted
- Figure 28–4 Anatomy of the Seminiferous Tubules revised (includes only parts a and b of former Figure 28–5)
- Figure 28–5 Anatomy of the Epididymis revised (former Figure 28–9 moved due to chapter reorganization)
- Figure 28–6 Anatomy of the Ductus Deferens and Accessory Glands revised and reorganized (former Figure 28–10 moved due to chapter reorganization)
- Figure 28–7 Anatomy of the Penis revised and reorganized (former Figure 28–11 moved due to chapter reorganization; new erectile tissue box)
- There is now a Section 28–3 called "Spermatogenesis occurs in the testes, and hormones from the hypothalamus, pituitary gland, and testes control male reproductive functions" that covers male reproductive physiology.
- Section 28–3 now starts with an Overview of Mitosis and Meiosis.
- NEW Figure 28–8 A Comparison of Chromosomes in Mitosis and Meiosis
- Figure 28–9 The Process of Spermatogenesis revised (former Figure 28–7 moved due to chapter reorganization; *sperm* replaces *spermatozoa*)
- Figure 28–10 Spermatogenesis in a Seminiferous Tubule revised (includes only parts c and d of former Figure 28–5; moved due to chapter reorganization)
- Figure 28–11 The Process of Spermiogenesis and Anatomy of a Sperm revised (former Figure 28–8 moved due to chapter reorganization; *sperm* replaces *spermatozoa*)
- The reworked Section 28–4 is now titled "The structures of the female reproductive system consist of the ovaries, uterine tubes, uterus, vagina, and external genitalia" and focuses on presenting the female reproductive anatomy.
- Figure 28–15 Anatomy of the Uterine Tubes revised (former Figure 28–17 moved due to chapter reorganization; new epithelial surface SEM)
- Figure 28–19 Anatomy of the Female External Genitalia revised (former Figure 28–22 moved due to chapter reorganization)
- The reworked Section 28–5 titled "Oogenesis occurs in the ovaries, and hormones from the hypothalamus, pituitary gland, and ovaries control female reproductive functions" presents female reproductive physiology. This section now gathers information on oogenesis, the ovarian cycle, and the uterine cycle, as well as their coordination.
- Figure 28–21 The Process of Oogenesis revised (new title; former Figure 28–15 moved due to chapter reorganization)
- Figure 28–22 Follicle Development and the Ovarian Cycle revised (former Figure 28–16 moved due to chapter reorganization; new ovary art)
- Figure 28–23 A Comparison of the Structure of the Endometrium during the Phases of the Uterine Cycle revised (new title; former Figure 28–20 moved due to chapter reorganization)
- Spotlight Figure 28–24 Hormonal Regulation of Female Reproduction revised (text in Follicle Phase of the Ovarian Cycle box changed to reflect that one tertiary follicle from a group becomes dominant; *Tertiary ovarian follicle development* label replaces *Follicle development* label; temperature ranges changed for both Celsius and Fahrenheit scales; and Menses label changed to Menstrual Phase)
- Under Section 28–6, there are new discussions of contraception and infertility, and sexually transmitted diseases.
- Under Section 28–7, there is a new discussion of development of internal reproductive organs, with a new Figure 28–26 The Development of Male and Female Internal Reproductive Organs.
- NEW Build Your Knowledge Figure 28–27 Integration of the REPRODUCTIVE system with the other body systems presented so far (replaces System Integrator)
- Questions added to Figures 28–7, 28–9, 28–11, 28–22, 28–23, and 28–25.

### Chapter 29: Development and Inheritance

- Figure 29–1 Fertilization revised (changed some titles and text in step art; clarified when DNA synthesis occurs)
- Figure 29–3 Stages in Implantation revised (*cytotrophoblast* replaces *cellular trophoblast*; *syncytiotrophoblast* replaces *syncytial trophoblast*)
- Figure 29–4 The Inner Cell Mass and Gastrulation revised (changed Gastrulation from Day 12 to Day 15)
- Spotlight Figure 29–5 Extra-Embryonic Membranes and Placenta Formation revised (added cervical plug to Week 10/step 5 art)
- Figure 29–6 Anatomy of the Placenta after the First Trimester revised (replaced first sentence of part a text)
- Figure 29–7 The First 12 Weeks of Development revised (new art at 3 weeks of development replaces Week 2 SEM)
- Section 29–5, now called "During the second and third trimesters, fetal development primarily involves growth and organ function," focuses on the fetal development during this period.
- Section 29–6, called "During gestation, maternal organ systems support the developing fetus; the reproductive system in particular undergoes structural and functional changes" now presents the maternal changes, including hormonal effects.
- Figure 29–12 The Milk Ejection Reflex revised (new title)
- Figure 29–17 Inheritance of an X-Linked Trait revised (former Figure 29–18 moved due to chapter reorganization)
- Figure 29–18 Crossing Over and Recombination revised (clarified text in part b; former Figure 29–17 moved due to chapter reorganization)
- Questions added to Figures 29–2, 29–4, 29–10, 29–14, and 29–15.

### Appendix

- NEW Table 3 Four Common Methods of Reporting Gas Pressure
- NEW Table 4 Turnover Times of Organic Components of Four Cell Types

# Acknowledgments

This textbook represents a group effort, and we would like to acknowledge the people who worked together with us to create this Eleventh Edition.

Foremost on our thank-you list are the instructors who offered invaluable suggestions throughout the revision process. We thank them for their participation and list their names and affiliations below.

**Lois Borek**, *Georgia State University*
**Angela Bruni**, *Mississippi Gulf Coast Community College*
**Marien Cendon**, *Miami Dade College, Kendall Campus*
**Jose Chestnut**, *Essex County College*
**James E. Clark**, *Manchester Community College*
**Ferdinand Esser**, *Mercy College*
**Robert S. Kellar**, *Northern Arizona University*
**Beth A. Kersten**, *State College of Florida*
**Mary Katherine Lockwood**, *University of New Hampshire*
**Naomi Machell**, *Delaware County Community College*
**Russell Nolan**
**Amanda R. Pendleton**, *Amarillo College*
**Louise Petroka**, *Gateway Community College*
**Courtney B. Ross**, *Gwinnett Technical College*
**Natalia Schmidt**, *Leeward Community College*
**Scott L. Simerlein**, *Purdue University North Central*
**Patricia Steinke**, *San Jacinto College Central*
**Diane G. Tice**, *Morrisville State College*
**Pauline Ward**, *Houston Community College*
**Sarah Ward**, *Colorado Northwestern Community College*
**Mary Weis**, *Collin College*
**Colleen Winters**, *Towson University*

The accuracy and currency of the clinical material in this edition reflects the work of our Clinical Case contributors, Christine Boudrie, M.D. and Ruth Anne O'Keefe, M.D., who provided constant, useful feedback on each chapter.

Virtually without exception, reviewers stressed the importance of accurate, integrated, and visually attractive illustrations in helping readers understand essential material. The revision of the art program was directed by Bill Ober, M.D., and Claire E. Ober, R.N. Their suggestions about presentation sequence, topics of clinical importance, and revisions to the proposed art were of incalculable value to us and to the project. The illustration program for this edition was further enhanced by the efforts of several other talented individuals. Jim Gibson designed many of the Spotlight Figures in the art program and consulted on the design and layout of the individual figures. His talents have helped produce an illustration program that is dynamic, cohesive, and easy to understand. Anita Impagliazzo helped create the photo/art combinations that have resulted in clearer presentations and a greater sense of realism in important anatomical figures. We are also grateful to the talented team at Imagineering (imagineeringart.com) for their dedicated and detailed illustrative work on key figures. The color micrographs in this edition were provided by Dr. Robert Tallitsch, and his assistance is much appreciated. Many of the striking anatomy photos in the text and in *Martini's Atlas of the Human Body* are the work of biomedical photographer Ralph Hutchings; his images played a key role in the illustration program.

We also express our appreciation to the editors and support staff at Pearson Science.

We owe special thanks to Senior Acquisitions Editor Cheryl Cechvala for shepherding this project from start to finish. Her ability to manage every detail with such fervor and interest is commendable. She also has an incredible command of the English language coupled with exceptional oratory ability—it's always fun having candid conversations. Although this was her first year as our editor, she possesses the skills of a seasoned veteran. She is our biggest advocate and is always willing to champion our cause—despite the challenges of working with authors. We are appreciative of all her efforts on our behalf.

Content Producer Jessica Picone was extremely skilled at keeping this project moving forward. Throughout every iteration, she kept track of the files, ensured we were on task, and maintained her high standards. Working with authors can be challenging, and Jessica was up for the task! Editorial Coordinator Kimberly Twardochleb was always available and answered every question we had with speed and accuracy. Having two highly skilled professionals working with us eased our burden. Thanks for not only preparing our material for publication, but making sure it was the best it could possibly be. This past year could not have happened without them.

Suzanne Olivier, our Development Editor, is the absolute best in the business. Suzanne's ability to look at science material in new ways was astonishing. Moreover, she skillfully encouraged us to think about presenting science information a bit differently, too. She played an essential part in revising this Eleventh Edition. Her unfailing attention to readability, consistency, and quality was indispensable to the authors in meeting our goal of delivering complex A&P content in a more student-friendly, learner-centered way.

We are grateful to Lorretta Palagi for her very careful attention to detail and consistency in her copyedit of the text and art.

This book would not exist without the extraordinary dedication of the Production team who solved many problems under pressure with unfailing good cheer. Norine Strang skillfully

led her excellent team at Cenveo to move the book smoothly through composition.

The striking cover and clear, navigable interior design were created by tani hasegawa. Thanks also to Mark Ong, Design Manager, who devised innovative solutions for several complex design challenges.

Thanks to our Photo Researcher, Kristin Piljay, and the permissions team at Cenveo for finding, obtaining, and coordinating all the photos in the photo program.

Thanks are also due to Kate Abderholden, Editorial Assistant, who served as project editor for the print supplements for instructors. Thanks also to Stacey Weinberger for handling the physical manufacturing of the book.

We are also grateful to Lauren Chen, Rich Media Content Producer, and Kristin Sanchez, Associate Mastering Producer, for their creative efforts on the media package, most especially Pearson Mastering A&P.

We would also like to express our gratitude to the following people at Pearson Science: Paul Corey, President, who continues to support all our texts; Barbara Yien, Director of Development, who kindly kept all phases moving forward under all circumstances; Allison Rona, Executive Marketing Manager; and the dedicated Pearson Science sales representatives for their continuing support of this project. Special thanks to Editor-in-Chief Serina Beauparlant, who took over the reins and worked closely with our new editor, Cheryl Cechvala, to ensure we had the resources necessary to publish what students need to succeed and what professors want in a textbook. And, a round of applause and a backflip go out to Derek Perrigo, Senior A&P Specialist, our biggest cheerleader.

To help improve future editions, we encourage you to send any pertinent information, suggestions, or comments about the organization or content of this textbook to us directly, using the e-mail addresses below. We warmly welcome comments and suggestions and will carefully consider them in the preparation of the Twelfth Edition.

***Frederic (Ric) H. Martini***
*Haiku, Hawaii*
martini@pearson.com

***Judi L. Nath***
*Sandusky, Ohio*
nath@pearson.com

***Edwin F. Bartholomew***
*Lahaina, Hawaii*
bartholomew@pearson.com

The publishers would like to thank the following for their contribution to the Global Edition:

### Contributor

**Christiane Van den Branden**, *Vrije Universiteit Brussel*

### Reviewers

**Snezana Kusljic**, *The University of Melbourne*
**Carine Smith**, *Stellenbosch University*
**Marjorie L. Wilson**, *Teesside University*

# Contents

## 6 Bones and Bone Structure 226



## 7 The Axial Skeleton 254

# UNIT 3 CONTROL AND REGULATION

## 12 Nervous Tissue 435



## 13 The Spinal Cord, Spinal Nerves, and Spinal Reflexes 479



## 18 The Endocrine System 656

## UNIT 4 FLUIDS AND TRANSPORT

## 21 Blood Vessels and Circulation 773



## 22 The Lymphatic System and Immunity 831

## 24 The Digestive System 930

## 25 Metabolism, Nutrition, and Energetics 985



## 26 The Urinary System 1022

# UNIT 6 CONTINUITY OF LIFE

## 28 The Reproductive System 1101



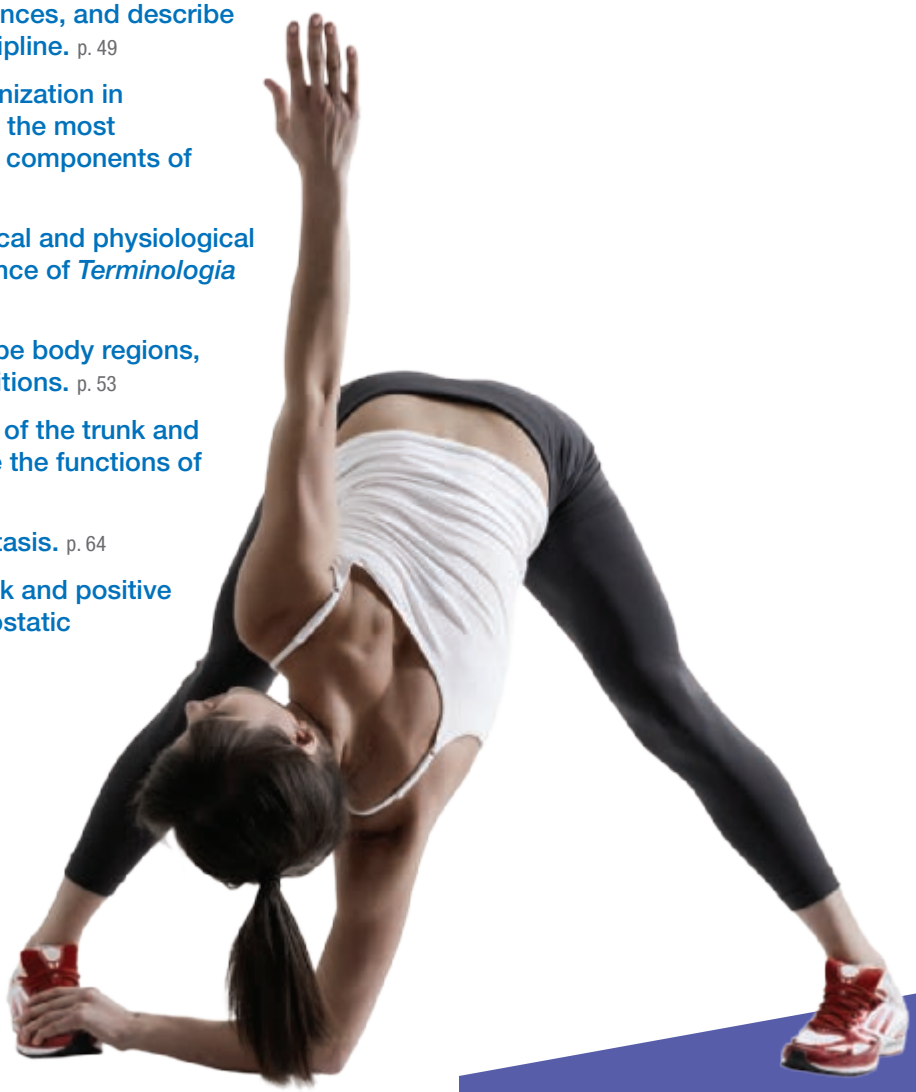
## 29 Development and Inheritance 1149

# 1 An Introduction to Anatomy and Physiology

## Learning Outcomes

These Learning Outcomes correspond by number to this chapter's sections and indicate what you should be able to do after completing the chapter.

- 1-1 ■ **Describe how to use the text and art to master learning.** p. 48
- 1-2 ■ **Define anatomy and physiology, explain the relationship between these sciences, and describe various specialties of each discipline.** p. 49
- 1-3 ■ **Identify the major levels of organization in organisms, from the simplest to the most complex, and identify the major components of each organ system.** p. 52
- 1-4 ■ **Describe the origins of anatomical and physiological terms, and explain the significance of *Terminologia Anatomica*.** p. 53
- 1-5 ■ **Use anatomical terms to describe body regions, body sections, and relative positions.** p. 53
- 1-6 ■ **Identify the major body cavities of the trunk and their subdivisions, and describe the functions of each.** p. 60
- 1-7 ■ **Explain the concept of homeostasis.** p. 64
- 1-8 ■ **Describe how negative feedback and positive feedback are involved in homeostatic regulation.** p. 65



## CLINICAL CASE Using A&P to Save a Life

An emergency medical technician (EMT) is on the way to the emergency department with a young victim of street violence. A knife with a 6-inch blade had been found next to the bleeding, unconscious man.

"We have a young male with multiple stab wounds. He has lost a lot of blood and we can barely get a blood pressure," the EMT radios to the triage nurse in the emergency department as the ambulance squeals through traffic. "We started an IV and we are pouring in fluid as fast as we can."

"Where are the wounds?" asks the receiving nurse.

"He has a deep wound in his right upper quadrant, just inferior to the diaphragm. I can see bruising from the hub of the knife around the wound, and there is another wound in his anterior right thigh. His pulse is 120 and thready (weak). His blood pressure is 60 over 30."

"How long has he been down?" questions the nurse.

"Less than a half hour. We intubated him (inserted a breathing tube) and started a large-bore IV as soon as we got there. We are 10 minutes out now."

"Keep the fluids going wide open, keep pressure on the thigh, and take him directly to Trauma Room 1," come the instructions. Meanwhile, the nurse orders the trauma team to Trauma Room 1, orders X-Ray to be on standby in the room, and requests 4 units of type O negative whole blood—the universal donor blood—from the blood bank. **Will the team be ready to save this young man?** **To find out, turn to the Clinical Case Wrap-Up on p. 72.**

## An Introduction to Studying the Human Body

Welcome to the field of human anatomy and physiology—known simply as A&P! In this textbook we will introduce you to the inner workings of the human body, giving information about both its structure (anatomy) and its function (physiology). Many students who use this book are preparing for jobs in health-related fields; but regardless of your career choice, you will find the information within these pages relevant to your future.

We will focus on the human body, but the principles you will learn apply to other living things as well. Our world contains an enormous diversity of living organisms, which vary widely in appearance and lifestyle. One aim of *biology*—the study of life—is to discover the unity and the patterns that underlie this diversity. As we study human anatomy and physiology, three main concepts will emerge: (1) the principle of complementarity of structure and function, (2) the hierarchy of structural relationships, and (3) homeostasis, the tendency toward internal balance. These principles are the foundation for learning about the human organism.

Before we begin with the science of human anatomy and physiology, let's turn our attention to the science of learning and learning strategies. To make the most of your learning experience, apply these strategies, which were collected from academic research.

### 1-1 To make the most of your learning, read the text and view the art together

Learning Outcome Describe how to use the text and art to master learning.

### Getting to Know Your Textbook

This first section of the book sets the stage for your success in this course and introduces you to the basic principles of learning. Just as there are three underlying concepts in A&P, there are two basic principles to using your textbook effectively to learn A&P. Practicing these principles will help you throughout your college career.

Let's start. Think back to your first childhood book. You most likely began with a "picture book." Then, as you learned the alphabet and developed speech, you progressed to "word books." The next step was "chapter books." Somewhere along the way, you quit looking at pictures and focused solely on the words (text). Maybe the shift in focus to text-based reading without looking at the pictures happened in high school. You began reading words—paragraph upon paragraph, page upon page of words. Now, you are in college, and we need to realign your focus.

In college, you are faced with lots of new terms, abstract concepts, and unfamiliar images. That's great, because college is intended to increase your knowledge and expand your horizons. However, research has shown that undergraduate students have a tendency to simply read the text (also called the *narrative*), without paying attention to the pictures (referred to as visuals, art, diagrams, illustrations, figures, or images). While you can certainly learn from this approach, further research demonstrates that when students *read the text and then look at the corresponding picture, they actually learn the material better*!

Although this may sound quite intuitive, most students do not do that. So, we wrote a book that truly integrates text with art to help you learn A&P. Please continue reading as we walk you through the process of using a textbook to enhance your learning. Much of what we're about to tell you applies to most

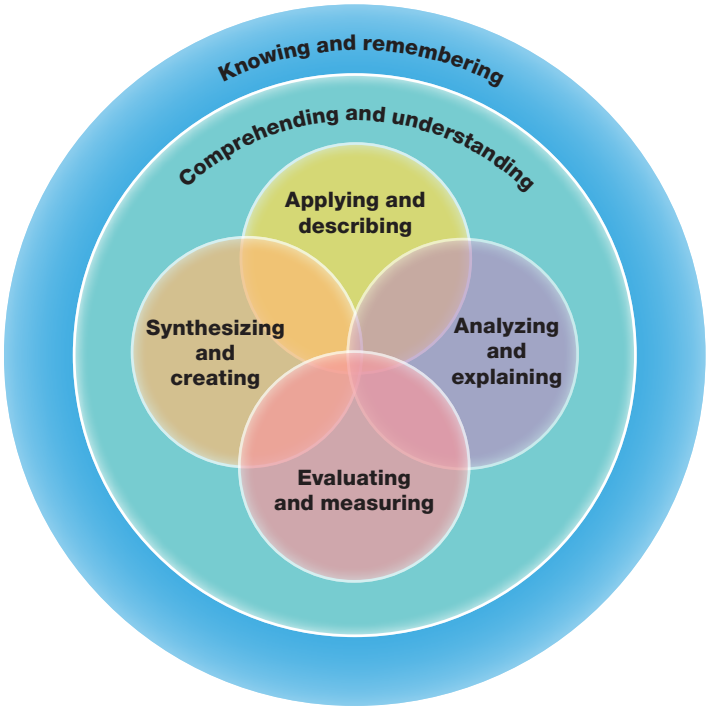
of your college textbooks, but we'll focus on this book, since it was designed for students such as you.

## Anatomy of a Chapter

Your book is broken down into *sections* with *text–art integration*, and specific *learning outcomes* for each section based on a *learning classification scheme*. A **section** is a unit about a topic that continues to build on previously learned topics. The sectional layout promotes logical, efficient navigation through the material, while callouts to figures integrate the text with the art. **Text–art integration** implies that the figures are close to the lines of text and that the figure legends are adjacent to the art. Look at that figure when you see a callout for it. The figure callouts look like this: (Figure 1–1). They are color-coded on purpose so you can stop reading, look at the figure, and then find your place again when you go back to reading the text. So, *strategy #1 is to read the text and then study the image that goes along with the narrative.*

**Learning outcomes** are educational objectives that use key verbs and target specific skills, goals, aims, and achievements. The learning outcomes appear at the beginning of each chapter and within the chapter under the sentence-based headings. *Strategy #2 is to pay attention to these learning outcomes because they are tied directly to testing and tell you what you should be able to do after reading that specific section and studying the images*. These learning outcomes are based on a **learning classification scheme**, which identifies the fundamental levels of learning from lower order skills to those of higher-order skills.

Figure 1–1 A Conceptual Framework for Learning.




You'll see key verbs in your learning outcomes and you'll notice some overlap among them within the levels of learning. From lower to higher, these levels are (1) knowing and remembering, (2) comprehending and understanding, (3) applying and describing, (4) analyzing and explaining, (5) evaluating and measuring, and (6) synthesizing and creating (Figure 1–1). (Here is where you can practice using what you just learned: Look at that figure, think about it, and then return to this text.) If you practice these basic strategies—(1) read the narrative and study the image and (2) pay attention to the learning outcomes—you are well on your way to success!

### Checkpoint

1. **Describe a learning outcome.**
2. **Explain how to use your textbook most effectively to enhance your learning.**

See the blue Answers tab at the back of the book.

## 1-2 Anatomy (structure) and physiology (function) are closely integrated

Learning Outcome Define anatomy and physiology, explain the relationship between these sciences, and describe various specialties of each discipline.

**Anatomy** is the study of internal and external body structures and their physical relationships among other body parts. In contrast, **physiology** is the study of how living organisms perform their vital functions. Someone studying anatomy might, for example, examine where a particular muscle attaches to the skeleton. Someone studying physiology might consider how a muscle contracts or what forces a contracting muscle exerts on the skeleton. You will be studying both anatomy and physiology in this text, so let's look at the relationships between these sciences.

Anatomy and physiology are closely integrated, both in theory and practice. Anatomical information provides clues about functions, and physiological processes can be explained only in terms of the underlying anatomy. This is a very important concept in living systems:

> All specific functions are performed by specific structures, and the form of a structure relates to its function. This is known as the *principle of complementarity of structure and function*.

The link between structure and function is always present, but not always understood. For example, the anatomy of the heart was clearly described in the 15th century, but almost 200 years passed before the heart's pumping action was demonstrated.

Anatomists and physiologists approach the relationship between structure and function from different perspectives. To understand the difference, suppose you asked an anatomist and

a physiologist to examine a car and report their findings. The anatomist might begin by measuring and photographing the various parts of the car and, if possible, taking it apart and putting it back together. The anatomist could then explain its key *structural relationships*—for example, how the pistons are seated in the engine cylinders, how the crankshaft is connected to the pistons, and how the transmission links the drive shaft to the axles and, thus, to the wheels. The physiologist also would note the relationships among the car's parts, but he or she would focus mainly on its *functional* characteristics, such as how the combustion of gasoline in the cylinders moves the pistons up and down and makes the drive shaft rotate, and how the transmission conveys this motion to the axles and wheels so that the car moves. Additionally, he or she might also study the amount of power that the engine could generate, the amount of force transmitted to the wheels in different gears, and so forth.

Our basic approach in this textbook will be to start with the descriptive anatomy of body structures (appearance, size, shape, location, weight, and color) before considering the related functions. Sometimes the groups of organs that make up an *organ system* perform very diverse functions, and in those cases we consider the functions of each individual organ separately. A good example is our discussion of the digestive system and its organs. You will learn about the functions of the salivary glands in one section, and the functions of the tongue in another. In other systems, the organs work together so extensively that we present an overall discussion of their physiology, after we describe the system's anatomy. The lymphatic system (which contains a network of vessels) and the cardiovascular system, for example, are treated using this approach.

## Anatomy

When you look at something, how far away you are from it often determines what you see. You get a very different view of your neighborhood from a satellite photo than from your front yard. Similarly, your method of observation has a dramatic effect on your understanding of the structure of the human body. Based on the degree of structural detail being considered, we divide **human anatomy**, the study of the structure of the human body, into *gross (macroscopic) anatomy* and *microscopic anatomy.*

### Gross Anatomy

**Gross anatomy**, or *macroscopic anatomy*, involves examining fairly large structures. Gross anatomy (from the Latin term *grossus*, meaning "thick" or "massive") can be conducted without using a microscope and can involve the study of anatomy by dissecting a cadaver. There are many different forms of gross anatomy:

- *Surface anatomy*, or superficial anatomy, is the study of the general form of the body's surface, especially in relation to its deeper parts.
- *Regional anatomy* focuses on the anatomical organization of specific areas of the body, such as the head, neck, or trunk. Many advanced courses in anatomy stress a regional approach, because it emphasizes the spatial relationships among structures already familiar to students.
- *Sectional anatomy* is the study of the relationship of the body's structures by examining cross sections of the tissue or organ.
- *Systemic anatomy* is the study of the structure of *organ systems*, which are groups of organs that function together in a coordinated manner. Examples include the *skeletal system*, composed primarily of bones; the *muscular system*, made up of skeletal muscles; and the *cardiovascular system*, consisting of the heart, blood, and vessels. We take a systemic anatomy approach in this book because this format works better to clarify the functional relationships among the component organs. We introduce the 11 organ systems in the human body later in the chapter.
- *Clinical anatomy* includes a number of subspecialties important in clinical practice. Examples include *pathological anatomy* (anatomical features that change during illness), *radiographic anatomy* (anatomical structures seen using specialized imaging techniques), and *surgical anatomy* (anatomical landmarks important in surgery).
- *Developmental anatomy* describes the changes in form that take place between conception and adulthood. The techniques of developmental anatomists are similar to those used in gross anatomy and in microscopic anatomy (discussed next) because developmental anatomy considers anatomical structures over a broad range of sizes—from a single cell to an adult human. The most extensive structural changes take place during the first two months of development. The study of these early developmental processes is called **embryology** (em-brē-OL-ō-jē).

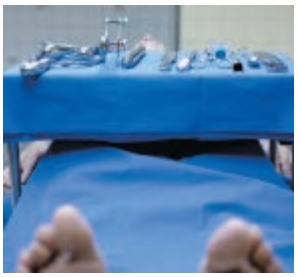
### Microscopic Anatomy

**Microscopic anatomy** deals with structures that we cannot see without magnification. The boundaries of microscopic anatomy are set by the limits of the equipment we use. With a dissecting microscope you can see tissue structure. With a light microscope, you can see basic details of cell structure. And with an electron microscope, you can see individual molecules that are only a few nanometers (billionths of a meter) across.

Microscopic anatomy includes two major subdivisions: cytology and histology. **Cytology** (sī-TOL-ō-jē) is the study of the internal structure of individual *cells*, the simplest units of life. Cells are made up of chemical substances in various combinations, and our lives depend on the chemical processes that take place in the trillions of cells in the body. For this reason, we consider basic chemistry (Chapter 2) before we examine cell structure (Chapter 3). **Histology** (his-TOL-ō-jē)

## + Clinical Note *Habeas Corpus* ("You Shall Have the Body")

It is the first day of Anatomy. Students await the arrival of their white-coated and gloved professor. Anxiety mounts as a stretcher covered in surgical drapes is wheeled in. This is the cadaver. Who will faint? *Will it be me?* For many students in the health professions, cadaver dissection is a cornerstone of their training. These students are following in a revered tradition that began 2300 years ago with the first examinations of the body after death by Greek royal physicians. The expression "a skeleton in your closet" dates from a later era when medical students had to procure bodies on their own for study (and keep them hidden in the closet). There is much to be learned from death. Cadaver dissections also reveal much about life. After working closely on a cadaver for months, students develop an attachment to "their" body, often naming it. The intimate revelations of the scalpel, the highly personal variations of human anatomy, the Rubik's cube of disease, and the stark reality of death combine to leave a deep intellectual and emotional mark on the student. Students and faculty may end the course with a ceremony to pay their respects to this human body and to this privileged experience.



is the examination of *tissues*—groups of specialized cells that work together to perform specific functions (Chapter 4). Tissues combine to form *organs*, such as the heart, kidney, liver, or brain, each with specific functions. Many organs are easy to examine without a microscope, so at the organ level we cross the boundary from microscopic anatomy to gross anatomy. As we proceed through the text, we will consider details at all levels, from microscopic to macroscopic.

## Physiology

**Human physiology** is the study of the functions, or workings, of the human body. These functions are complex processes and much more difficult to examine than most anatomical structures. As a result, there are even more specialties in physiology than in anatomy. Examples include the following:

- *Cell physiology*, the study of the functions of cells, is the cornerstone of human physiology. Cell physiology looks at the chemistry of the cell. It includes both chemical processes within cells and chemical interactions among cells.
- *Organ physiology* is the study of the function of specific organs. An example is *cardiac physiology*, the study of heart function—how the heart works.
- *Systemic physiology* includes all aspects of the functioning of specific organ systems. Cardiovascular physiology, respiratory physiology, and reproductive physiology are examples.
- *Pathological physiology* is the study of the effects of diseases on organ functions or system functions. Modern medicine depends on an understanding of both normal physiology and pathological physiology.

Physicians normally use a combination of anatomical, physiological, chemical, and psychological information when they evaluate patients. When a patient presents with **signs** (an objective disease indication like a fever) and **symptoms** (a subjective disease indication, such as tiredness), the physician will look at the structures affected (gross anatomy), perhaps collect a fluid or tissue sample (microscopic anatomy) for analysis, and ask questions to find out what changes from normal functioning the patient is experiencing. Think back to your last trip to a doctor's office. Not only did the physician examine your body, noting any anatomical abnormalities, but he or she also evaluated your physiological processes by asking questions, observing your movements, listening to your body sounds, taking your temperature, and perhaps requesting chemical analyses of fluids such as blood or urine.

In evaluating all these observations to reach a diagnosis, physicians rely on a logical framework based on the scientific method. The **scientific method** is a system of advancing knowledge that begins by proposing a hypothesis to answer a question, and then testing that hypothesis with data collected through observation and experimentation. This method is at the core of all scientific thought, including medical diagnosis.

## √ Checkpoint

3. **Define *anatomy*.**
4. **Define *physiology*.**
5. **Describe how anatomy and physiology are closely related.**
6. **What is the difference between gross anatomy and microscopic anatomy?**
7. **Identify several specialties of physiology.**
8. **Why is it difficult to separate anatomy from physiology?**

See the blue Answers tab at the back of the book.

## 1-3 Levels of organization progress from chemicals to a complete organism

**Learning Outcome** Identify the major levels of organization in organisms, from the simplest to the most complex, and identify major components of each organ system.

Our understanding of how the human body works is based on investigations of its different levels of organization. Higher levels of organization are more complex and more variable than lower levels. Chapters 2, 3, and 4 consider the chemical, cellular, and tissue levels of organization of the human body. These levels are the foundations of more complex structures and vital processes, as we describe in Chapters 5–29. The six levels of organization of the human body are shown in **Spotlight Figure 1–2** and include:

- *The Chemical Level.* **Atoms** are the smallest stable units of matter. They can combine to form **molecules** with complex shapes. The atomic components and unique three-dimensional shape of a particular molecule determine its function. For example, complex protein molecules form filaments that produce the contractions of muscle cells in the heart. We explore this level of organization in Chapter 2.
- *The Cellular Level.* **Cells** are the smallest living units in the body. Complex molecules can form various types of larger structures called *organelles*. Each organelle has a specific function in a cell. Energy-producing organelles provide the energy needed for heart muscle cell contractions. We examine the cellular level of organization in Chapter 3.
- *The Tissue Level.* A **tissue** is a group of cells working together to perform one or more specific functions. Heart muscle cells, also called cardiac muscle cells (*cardium*, heart), interact with other types of cells and with materials outside the cell to form cardiac muscle tissue. We consider the tissue level of organization in Chapter 4.
- *The Organ Level.* **Organs** are made of two or more tissues working together to perform specific functions. Layers of cardiac muscle tissue, in combination with another type of tissue called connective tissue, form the bulk of the wall of the heart, which is a hollow, three-dimensional organ.
- *The Organ System Level.* A group of organs interacting to perform a particular function forms an **organ system**. Each time the heart contracts, for example, it pushes blood into a network of blood vessels. Together, the heart, blood, and blood vessels make up the cardiovascular system, one of 11 organ systems in the body. This system functions to distribute oxygen and nutrients throughout the body.
- *The Organism Level.* An individual life form is an **organism**. In our case, an individual human is the highest level of organization that we consider. All of the body's organ systems must work together to maintain the life and health of the organism.

The organization at each level determines not only the structural characteristics but also the functions of higher levels. For example, the arrangement of atoms and molecules at the chemical level creates the protein filaments and organelles at the cellular level that give individual cardiac muscle cells the ability to contract. At the tissue level, these cells are linked, forming cardiac muscle tissue. The structure of the tissue ensures that the contractions are coordinated, producing a powerful heartbeat. When that beat occurs, the internal anatomy of the heart, an organ, enables it to function as a pump. The heart is filled with blood and connected to the blood vessels, and its pumping action circulates blood through the vessels of the cardiovascular system. Through interactions with the respiratory, digestive, urinary, and other systems, the cardiovascular system performs a variety of functions essential to the survival of the organism.

Something that affects a system will ultimately affect each of the system's parts. For example, after massive blood loss, the heart cannot pump blood effectively. When the heart cannot pump and blood cannot flow, oxygen and nutrients cannot be distributed to the heart or around the body. Very soon, the cardiac muscle tissue begins to break down as individual muscle cells die from oxygen and nutrient starvation. These changes will not be restricted to the cardiovascular system. All cells, tissues, and organs in the body will be damaged. **Spotlight Figure 1–2** illustrates the levels of organization and introduces the 11 interdependent, interconnected organ systems in the human body.

The cells, tissues, organs, and organ systems of the body coexist in a relatively small, shared environment, much like the residents of a large city. Just as city dwellers breathe the same air and drink the water supplied by the local water company, cells in the human body absorb oxygen and nutrients from the fluids that surround them. If a city is blanketed in smog or its water supply is contaminated, its inhabitants will become ill. Similarly, if the body fluid composition becomes abnormal, cells will be injured or destroyed. For example, suppose the temperature or salt content of the blood changes. The effect on the heart could range from the need for a minor adjustment (heart muscle tissue contracts more often, raising the heart rate) to a total disaster (the heart stops beating, so the individual dies).

### Checkpoint

9. **Identify the major levels of organization of the human body from the simplest to the most complex.**
10. **Identify the organ systems of the body and cite some major structures of each.**
11. **At which level of organization does a histologist investigate structures?**

See the blue Answers tab at the back of the book.

## 1-4 Medical terminology is important to understanding anatomy and physiology

**Learning Outcome** Describe the origins of anatomical and physiological terms, and explain the significance of *Terminologia Anatomica.*

Early anatomists faced serious problems when trying to communicate. Saying that a bump is "on the back," for example, does not give very precise information about its location. So anatomists created illustrated maps of the human body and gave each structure a specific name. They used prominent anatomical structures as landmarks, measured distances in centimeters or inches, and discussed these subjects in specialized directional terms. Modern anatomists continue and build on these practices. In effect, anatomy uses a special language that you must learn almost at the start of your study.

That special language, called **medical terminology**, involves using word roots, prefixes, suffixes, and combining forms to build terms related to the body in health and disease. Many of the anatomical and physiological terms you will encounter in this textbook are derived from Greek or Latin roots that originated more than 1500 years ago. In fact, the term *anatomy* is derived from Greek roots that mean "a cutting open"; the term *physiology* also comes from Greek. Learning the word parts used in medical terminology will greatly assist in your study of anatomy and physiology and in your preparation for any health-related career.

There are four basic building blocks—or word parts—of medical terms. *Word roots* are the basic, meaningful parts of a term that cannot be broken down into another term with another definition. *Prefixes* are word elements that are attached to the beginning of words to modify their meaning but cannot stand alone. *Suffixes* are similar to prefixes, except they are word elements or letters added to the end of a word or word part to form another term. *Combining forms* are independent words or word roots that are used in combination with words, prefixes, suffixes, or other combining forms to build a new term. As we introduce new terms, we will provide notes on pronunciation and relevant word parts. In addition, the table inside the back cover of your textbook lists many commonly used word roots, prefixes, suffixes, and combining forms.

To illustrate the building of medical terms, consider the word *pathology* (puh-THOL-ō-jē). Breaking this word into its basic parts reveals its meaning. The prefix *path-* refers to disease (the Greek term for "disease" is *pathos*). The suffix *-ology* means "study of." So pathology is the study of disease.

Latin and Greek terms are not the only ones that have been imported into the anatomical vocabulary over the centuries, and this vocabulary continues to expand. Many anatomical structures and clinical conditions were first named after either the discoverer or, in the case of diseases, the most famous victim. During the past 100 years, most of these commemorative names, or **eponyms** (EH-pō-nimz), have been replaced by more precise terms. Where appropriate, we will give both the eponym and the more precise term, because in clinical medicine, both terms may be used.

To avoid the miscommunication that plagued the early anatomists, it is important for scientists throughout the world to use the same name for each body structure. In 1998, two scientific organizations—the Federative Committee on Anatomical Terminology (FCAT) and the International Federation of Associations of Anatomists (IFAA)—published *Terminologia Anatomica* (*TA*). *Terminologia Anatomica* established the worldwide standard for human anatomical terminology. The successor of FCAT is the Federative International Programme on Anatomical Terminologies (FIPAT). In April 2011, FIPAT published *TA* online. Latin continues to be the language of anatomy, but this reference provides an English equivalent term for each anatomical structure. For example, the *tendo calcaneus* (Latin) is also called the calcaneal tendon (English). You may know the structure better by its eponym, the Achilles tendon. Eponyms are not found in *TA*. We have used *TA* as our standard in preparing this textbook.

### Checkpoint

12. **Describe medical terminology.**
13. **Define *eponym*.**
14. **Name the book that serves as the international standard for anatomical terms.**

See the blue Answers tab at the back of the book.

## 1-5 Anatomical terms describe body regions, anatomical positions and directions, and body sections

**Learning Outcome** Use anatomical terms to describe body regions, body sections, and relative positions.

Anatomists use anatomical terms to describe body regions, relative positions and directions, and body sections, as well as major body cavities and their subdivisions. In the following sections we introduce the terms used in superficial anatomy and sectional anatomy.

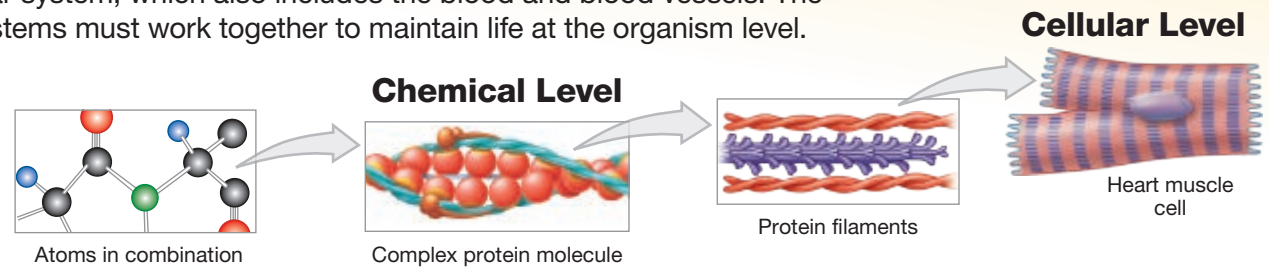
### Surface Anatomy

**Surface anatomy** involves locating structures on or near the body surface. A familiarity with anatomical landmarks (structures that can be felt or palpated), anatomical regions (specific areas used for reference purposes), and terms for anatomical directions will make the material in subsequent chapters easier to understand.

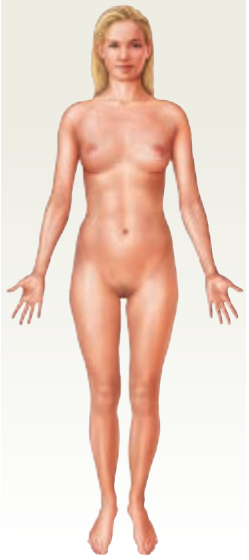
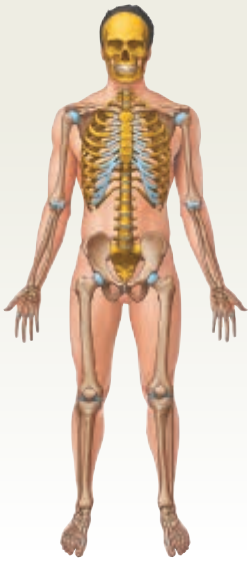
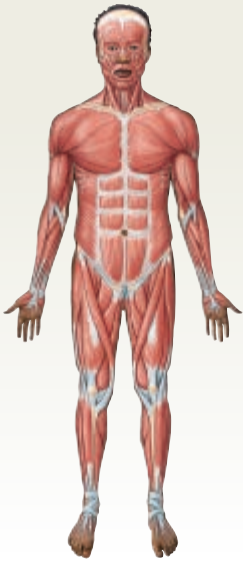
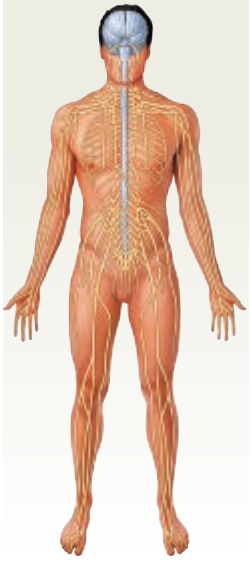
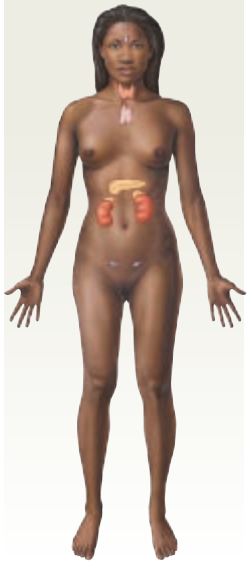
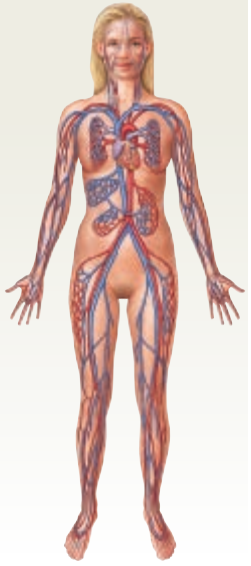
# SPOTLIGHT

Figure 1–2
## Levels of Organization

Interacting atoms form molecules that combine to form the protein filaments of a heart muscle cell. Such cells interlock, forming heart muscle tissue, which makes up most of the walls of the heart, a three-dimensional organ. The heart is only one component of the cardiovascular system, which also includes the blood and blood vessels. The various organ systems must work together to maintain life at the organism level.



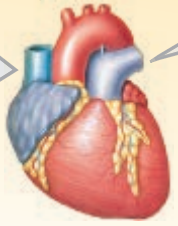

# THE ORGAN SYSTEMS

| Integumentary | Skeletal | Muscular | Nervous | Endocrine | Cardiovascular |
|---|---|---|---|---|---|
|  |  |  |  |  |  |
| **Major Organs**<br>• Skin<br>• Hair<br>• Sweat glands<br>• Nails<br><br>**Functions**<br>• Protects against environmental hazards<br>• Helps regulate body temperature<br>• Provides sensory information | **Major Organs**<br>• Bones<br>• Cartilages<br>• Associated ligaments<br>• Bone marrow<br><br>**Functions**<br>• Provides support and protection for other tissues<br>• Stores calcium and other minerals<br>• Forms blood cells | **Major Organs**<br>• Skeletal muscles and associated tendons<br><br>**Functions**<br>• Provides movement<br>• Provides protection and support for other tissues<br>• Generates heat that maintains body temperature | **Major Organs**<br>• Brain<br>• Spinal cord<br>• Peripheral nerves<br>• Sense organs<br><br>**Functions**<br>• Directs immediate responses to stimuli<br>• Coordinates or moderates activities of other organ systems<br>• Provides and interprets sensory information about external conditions | **Major Organs**<br>• Pituitary gland<br>• Thyroid gland<br>• Pancreas<br>• Adrenal glands<br>• Gonads<br>• Endocrine tissues in other systems<br><br>**Functions**<br>• Directs long-term changes in the activities of other organ systems<br>• Adjusts metabolic activity and energy use by the body<br>• Controls many structural and functional changes during development | **Major Organs**<br>• Heart<br>• Blood<br>• Blood vessels<br><br>**Functions**<br>• Distributes blood cells, water, and dissolved materials including nutrients, waste products, oxygen, and carbon dioxide<br>• Distributes heat and assists in control of body temperature |

## Tissue Level

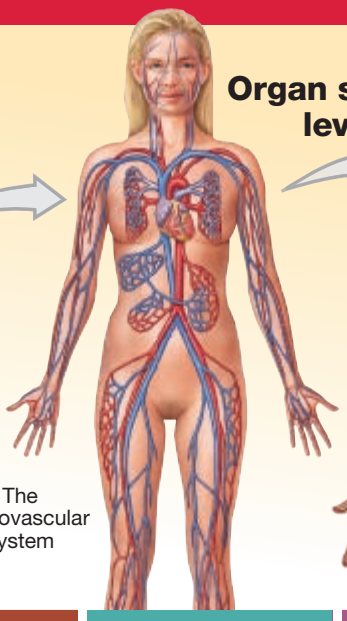
Cardiac muscle tissue

## Organ Level



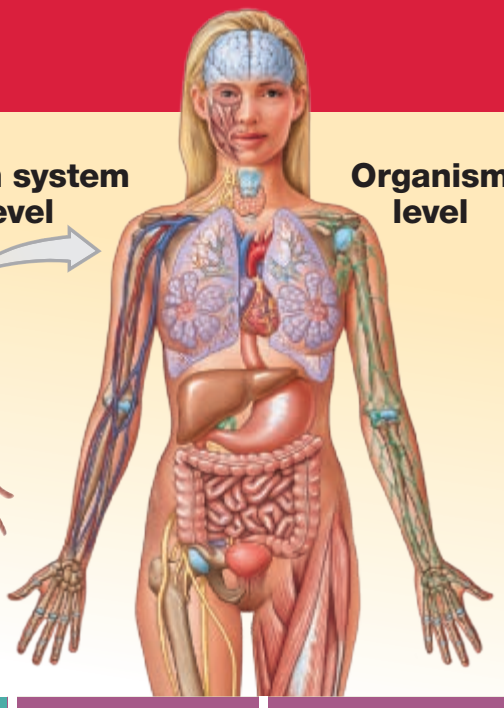
The heart

## Organ system level



The cardiovascular system

## Organism level

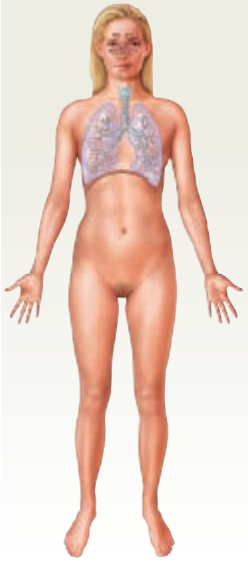


### Lymphatic

**Major Organs**
- Spleen
- Thymus
- Lymphatic vessels
- Lymph nodes
- Tonsils

**Functions**
- Defends against infection and disease
- Returns tissue fluids to the bloodstream

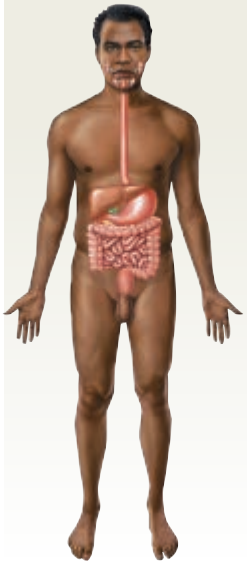
### Respiratory



**Major Organs**
- Nasal cavities
- Sinuses
- Larynx
- Trachea
- Bronchi
- Lungs
- Alveoli

**Functions**
- Delivers air to alveoli (sites in lungs where gas exchange occurs)
- Provides oxygen to bloodstream
- Removes carbon dioxide from bloodstream
- Produces sounds for communication

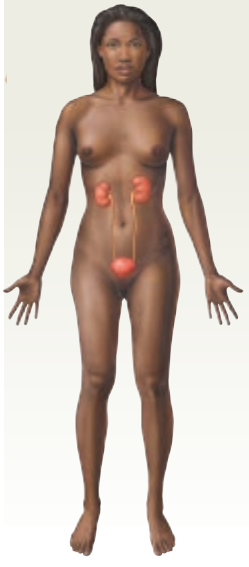
### Digestive



**Major Organs**
- Teeth
- Tongue
- Pharynx
- Esophagus
- Stomach
- Small intestine
- Large intestine
- Liver
- Gallbladder
- Pancreas

**Functions**
- Processes and digests food
- Absorbs and conserves water
- Absorbs nutrients
- Stores energy reserves

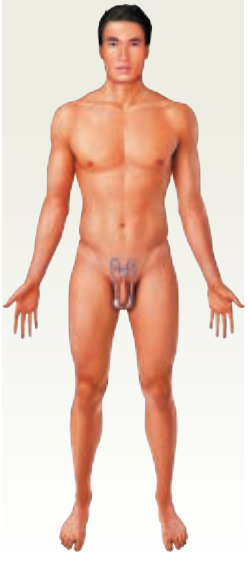
### Urinary



**Major Organs**
- Kidneys
- Ureters
- Urinary bladder
- Urethra

**Functions**
- Excretes waste products from the blood
- Controls water balance by regulating volume of urine produced
- Stores urine prior to voluntary elimination
- Regulates blood ion concentrations and pH

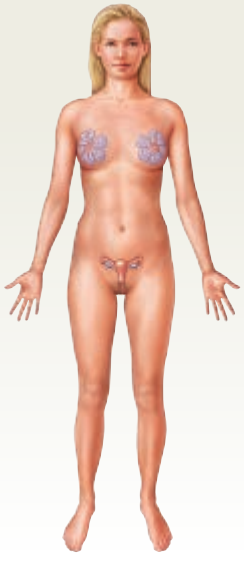
### Male Reproductive



**Major Organs**
- Testes
- Epididymides
- Ductus deferentia
- Seminal vesicles
- Prostate gland
- Penis
- Scrotum

**Functions**
- Produces male sex cells (sperm), seminal fluids, and hormones
- Sexual intercourse

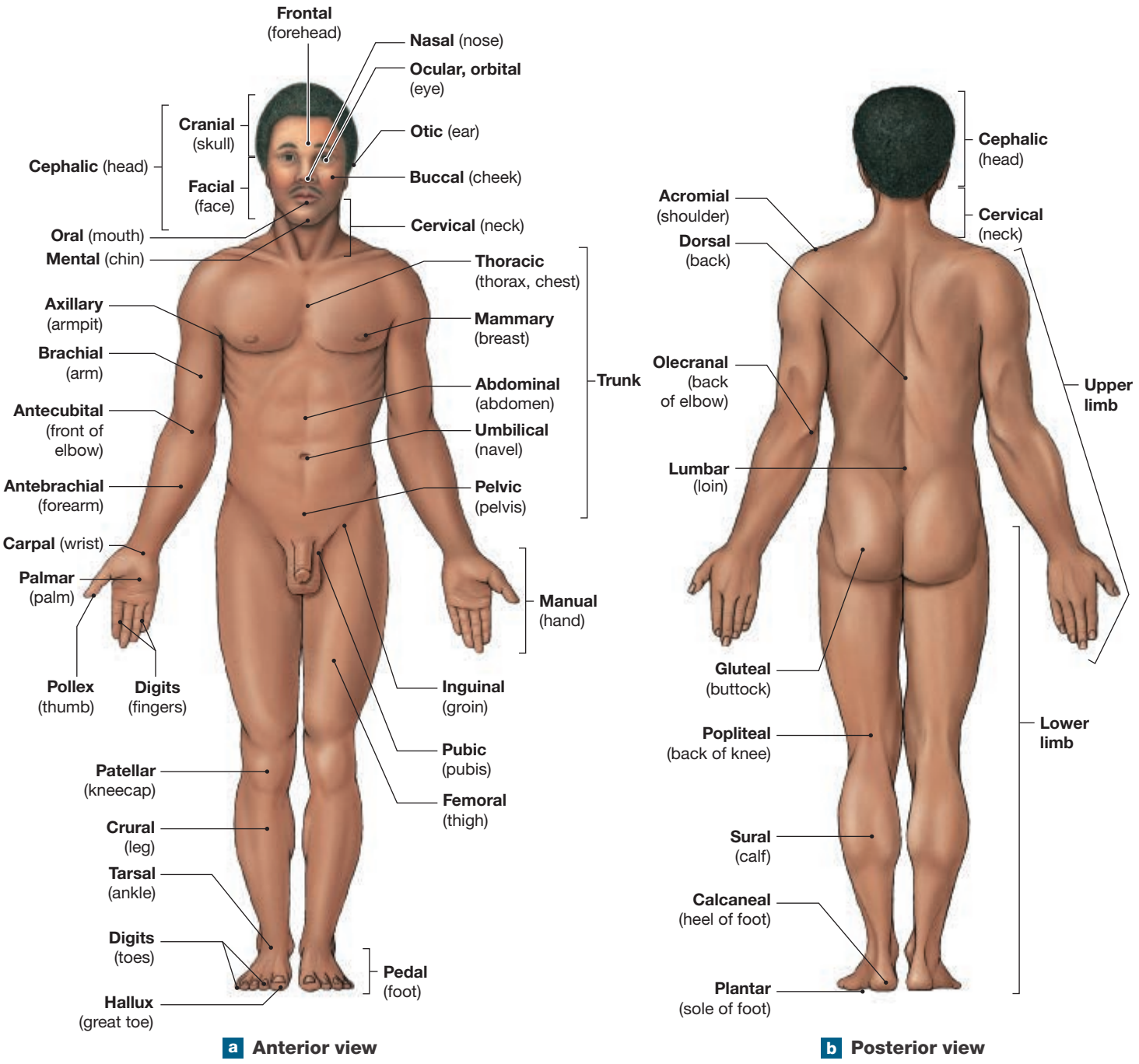
### Female Reproductive



**Major Organs**
- Ovaries
- Uterine tubes
- Uterus
- Vagina
- Labia
- Clitoris
- Mammary glands

**Functions**
- Produces female sex cells (oocytes) and hormones
- Supports developing embryo from conception to delivery
- Provides milk to nourish newborn infant
- Sexual intercourse

**Figure 1–3 Anatomical Landmarks.** Anatomical terms are shown in boldface type and common names are in plain type.




**?** Are the following anatomical landmarks visible from the anterior or posterior view: dorsal, gluteal, calcaneal?

## Anatomical Landmarks

Figure 1–3 presents important anatomical landmarks. Understanding the terms and their origins will help you remember both the location of a particular structure and its name. For example, *brachial* refers to the arm, and later we will consider the *brachialis muscle* and the *brachial artery*, which are in the arm, as their names suggest.

The standard anatomical reference for the human form is the **anatomical position**. This is also called the *anatomic position*. When the body is in this position, the hands are at the sides with the palms facing forward, and the feet are together. Figure 1–3a shows an individual in the anatomical position as seen from the front, called an *anterior view*. Figure 1–3b shows

the body as seen from the back, called a *posterior view*. Unless otherwise noted, all descriptions in this text refer to the body in the anatomical position. A person lying down is said to be **supine** (sū-PĪN) when face up, and **prone** when face down.

### Tips & Tools

Supine means "up." In order to carry a bowl of *soup*, your hand must be in the *supine* position.

## Anatomical Regions

To describe a general area of interest or injury, clinicians and anatomists often need broader terms in addition to specific landmarks. They use two methods—dividing into quadrants and dividing into regions—to map the surface of the abdomen and pelvis.

Clinicians refer to four **abdominopelvic quadrants** (Figure 1–4a) formed by a pair of imaginary perpendicular lines that intersect at the umbilicus (navel). This simple method of dividing into quadrants provides useful references for describing the location of aches, pains, and injuries. Knowing the location can help the clinician determine the possible cause. For example, tenderness in the right lower quadrant (RLQ) is a symptom of appendicitis. Tenderness in the right upper quadrant (RUQ), however, may indicate gallbladder or liver problems.

Anatomists prefer more precise terms to describe the location and orientation of internal organs. They recognize nine **abdominopelvic regions** (Figure 1–4b). Figure 1–4c shows the relationships among quadrants, regions, and internal organs.

### Tips & Tools

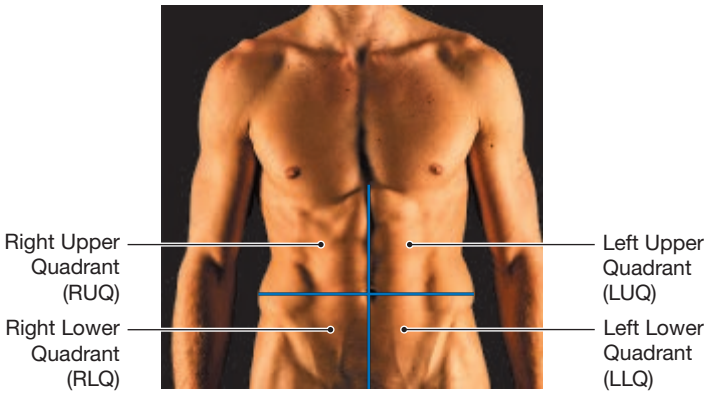
The imaginary lines dividing the abdominopelvic regions resemble a tic-tac-toe game.

## Anatomical Directions

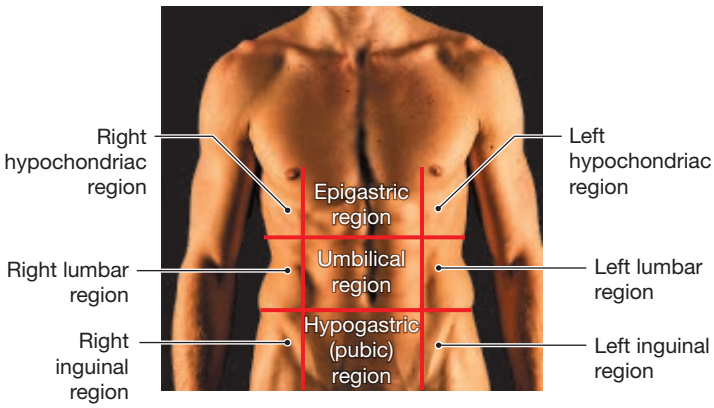
Figure 1–5 introduces the main directional terms and some examples of their use. There are many different terms, and some can be used interchangeably. For example, *anterior* refers to the front of the body when viewed in the anatomical position. In humans, this term is equivalent to *ventral*, which refers to the belly. *Posterior* refers to the back of the body; this term is equivalent to *dorsal*. When reading anatomical descriptions, remember that the terms *left* and *right* always refer to the left and right sides of the *subject*, not of the observer.

Before you read further, analyze the image in detail, and practice using the terms. We start using these terms in the rest of this chapter. If you are familiar with the basic vocabulary, the anatomical descriptions throughout this textbook will be easier to follow.

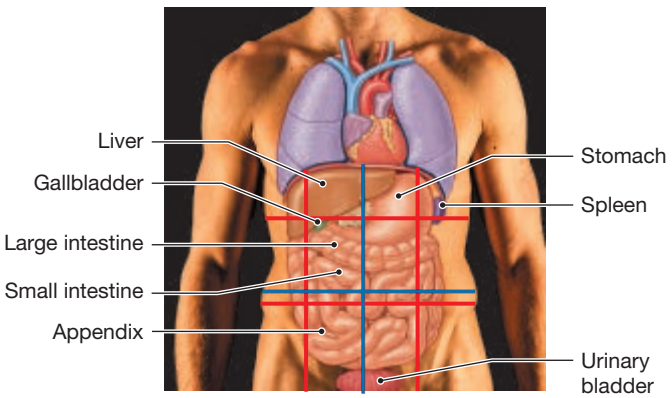
**Figure 1–4** Abdominopelvic Quadrants and Regions.




**a** **Abdominopelvic quadrants**. The four abdominopelvic quadrants are formed by two perpendicular lines that intersect at the navel. The terms for these quadrants, or their abbreviations, are most often used in clinical discussions.




**b** **Abdominopelvic regions**. The nine abdominopelvic regions provide more precise regional descriptions.




**c** **Anatomical relationships**. The relationship between the abdominopelvic quadrants and regions and the locations of the internal organs are shown here.

**?** In which abdominopelvic quadrant and region is the stomach predominantly found?

**Figure 1–5** Directional References.

**Superior:** Above; at a higher level (in the human body, toward the head)

The head is superior to the chest. **Superior**

Right Left

**Proximal**
Toward the point of attachment of a limb to the trunk
The shoulder is *proximal* to the wrist.

**Lateral**
Away from the midline

**Medial**
Toward the midline

**Proximal**

**Distal**
Away from the point of attachment of a limb to the trunk
The fingers are *distal* to the wrist.

**Distal**

**a Anterior view**

**Cranial or Cephalic**
Toward the head
The *cranial* nerves are in the head.

**Posterior or Dorsal**
***Posterior:*** The back surface
***Dorsal:*** The back. (equivalent to posterior when referring to the human body)
The scapula (shoulder blade) is located *posterior* to the rib cage.

**Anterior or Ventral**
***Anterior:*** The front surface
***Ventral:*** The belly side. (equivalent to anterior when referring to the human body)
The umbilicus (navel) is on the *anterior* (or *ventral)* surface of the trunk.

**Caudal**
Toward the tail; (coccyx in humans)
Fused *caudal* vertebrae form the skeleton of the tail (coccyx).

**b Lateral view**

OTHER DIRECTIONAL TERMS

**Superficial**
At, near, or relatively close to the body surface
The skin is *superficial* to underlying structures.

**Deep**
Toward the interior of the body; farther from the surface
The bone of the thigh is *deep* to the surrounding skeletal muscles.

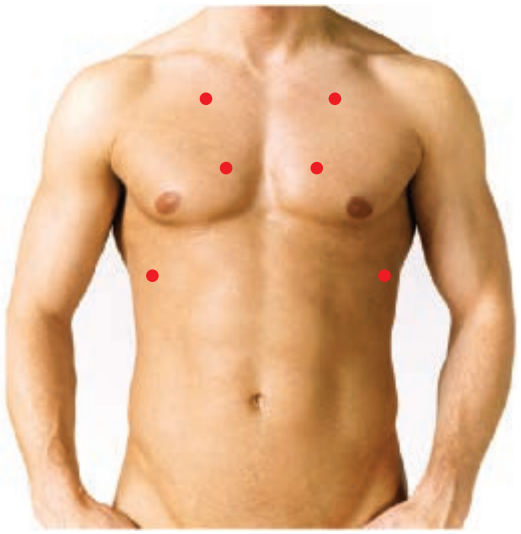
**Inferior:** Below; at a lower level; toward the feet

The knee is inferior to the hip. **Inferior**

**?** Using directional references for a person in the anatomical position, how would you describe the relationship of the hand compared to the elbow? To the groin?

## + Clinical Note The Sounds of the Body

We pay attention to the sounds of the body because they provide evidence of normal function. Midwives and doctors used to place their ears directly on the patient's body to listen. Then a piece of new-fangled technology, called the *stethoscope*, was invented in 1816 that gave the patient more privacy and the practitioner a better listen. *Auscultation* (aws-kul-TĀ-shun) is the practice of listening to the various sounds made by body organs with a stethoscope. After a surgical operation, the recovery room nurse auscultates the patient's abdomen to listen for bowel sounds (called by the imitative term *borborygmi* [bor-bō-RIG-mī]). These sounds confirm that the intestine is resuming its characteristic motility after anesthesia. When students get their college physicals, the practitioner auscultates the lungs over the dorsal surface of the body and superior to the clavicles (where the tips of the lungs lie). It is a thrilling moment when a pregnant woman hears her baby's heartbeat for the first time with the help of an ultrasound technician. A Doppler ultrasound device bounces sound waves off of a fetus's heart that are detected at the mother's skin surface in her pubic region (see Clinical Note: Diagnostic Imaging Techniques, pp. 62–63). The heartbeat is usually first heard when the fetus is about 12 weeks old. The sounds of an adult heart are heard at the general locations labeled on the anterior thoracic region of the body shown here. The heart sounds of "lubb-dupp" (which you will study in Chapter 20) tell us that heart valves are closing correctly during the heart's cycle. However, an unexpected "whoosh" can alert us to the possibility of a medical problem called a *heart murmur*.



## Sectional Anatomy

Sometimes the only way to understand the relationships among the parts of a three-dimensional object is to slice through it and look at the internal organization. A slice through a three-dimensional object is called a *section*.

An understanding of sectional views is particularly important now that imaging techniques enable us to see inside the living body. These views are sometimes difficult to interpret, but it is worth spending the time required to understand what they show. Once you are able to interpret sectional views, you will have a good mental model for studying the anatomy and physiology of a particular region or system. Radiologists and other medical professionals responsible for interpreting medical scans spend much of their time analyzing sectional views of the body.

Any section through a three-dimensional object can be described in reference to a **sectional plane**, as indicated in **Figure 1–6**. A *plane* is a two-dimensional flat surface, and a section is a single view or slice along a plane. Common planes are frontal (coronal), sagittal, and transverse (horizontal).

- The **frontal (coronal) plane** is a vertical plane that divides the body or organ into anterior and posterior portions. A cut in this plane is called a **frontal section**, or *coronal section*.
- The **sagittal plane** is a vertical plane that divides the body into left and right portions. A cut in this plane is called a **sagittal section**. If the plane lies in the middle, it is called a **midsagittal plane**, and if it is offset from the middle, it is called a **parasagittal plane**.
- The **transverse plane** divides the body into *superior* and *inferior* portions. A cut in this plane is called a **transverse section**, or *cross section*. Unless otherwise noted, in this textbook all anatomical diagrams that present cross-sectional views of the body are oriented as though the subject were supine with you, the observer, standing at the subject's feet and looking toward the head.

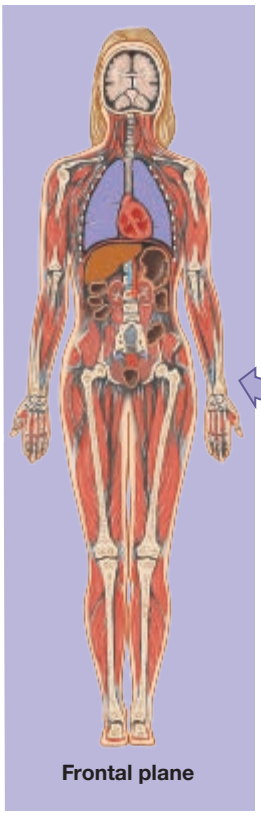
The atlas that accompanies this text contains images of sections taken through the body in various planes.

### √ Checkpoint

15. **What is the purpose of anatomical terms?**
16. **For a body in the anatomical position, describe an anterior view and a posterior view.**

See the blue Answers tab at the back of the book.

**Figure 1–6** Sectional Planes.

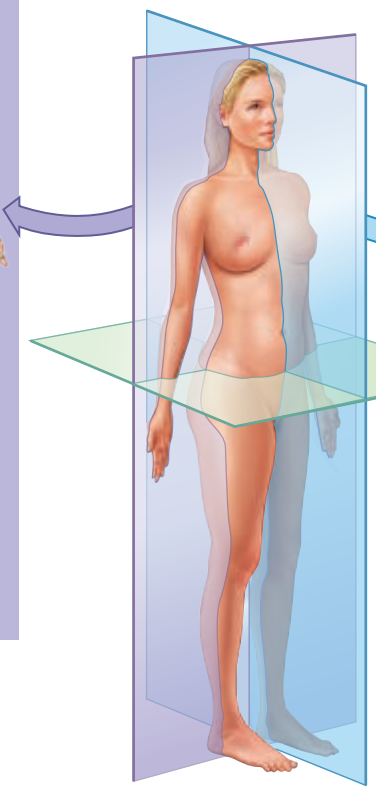


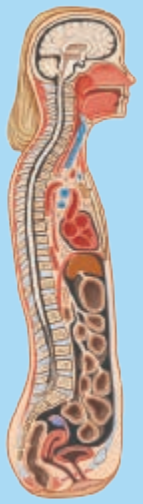

**Frontal or coronal plane**

Plane is oriented parallel to long axis

A *frontal*, or *coronal*, *section* separates anterior and posterior portions of the body. Coronal usually refers to sections passing through the skull.

Directional term: frontally or coronally






**Sagittal plane**

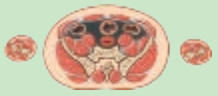
Plane is oriented parallel to long axis

A *sagittal section* separates right and left portions. You examine a sagittal section, but you section sagittally.

In a *midsagittal section*, the plane passes through the midline. It separates the body into equal right and left sides.

A *parasagittal section* misses the midline. It separates the body into unequal right and left sides.

Directional term: sagittally




**Transverse, or horizontal, plane**

Plane is oriented perpendicular to long axis

A *transverse*, or *cross*, *section* separates superior and inferior portions of the body.

Directional term: transversely or horizontally

**?** Which plane separates the body into superior and inferior portions? Which plane separates the body into anterior and posterior portions?

## 1-6 Body cavities of the trunk protect internal organs and allow them to change shape

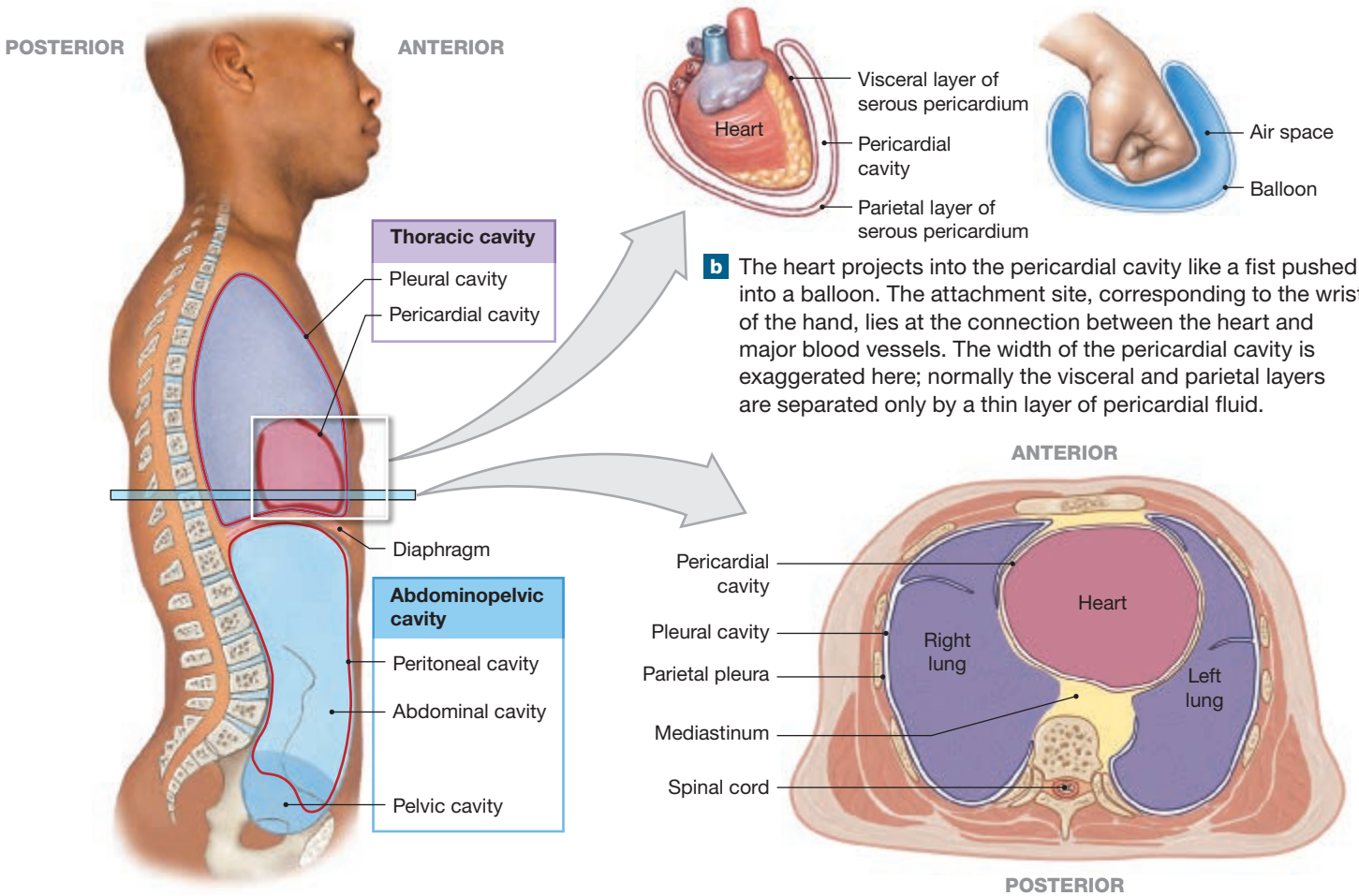
**Learning Outcome** Identify the major body cavities of the trunk and their subdivisions, and describe the functions of each.

The body's trunk is subdivided into three major regions established by the body wall: the thoracic, abdominal, and pelvic regions. Most of our vital organs are located within these regions of the trunk. The true **body cavities** are closed, fluid filled, and lined by a thin tissue layer called a *serous membrane,* or *serosa*. The vital organs of the trunk are suspended within these body cavities; they do not simply lie there. Early anatomists used the term *cavity* when referring to internal regions. For example, everything deep to the chest wall of the thoracic region is considered to be within the **thoracic cavity**, and all of the structures deep to the abdominal and pelvic walls are said to lie within the **abdominopelvic cavity**. Internally, the **diaphragm** (DĪ-uh-fram), a flat muscular sheet, separates these anatomical regions.

The boundaries of the true body cavities and the regional "cavities" are not identical. For example, the thoracic cavity contains two *pleural cavities* (each surrounding a lung), the *pericardial cavity* (surrounding the heart), and the *mediastinum* (a large tissue mass). The *peritoneal cavity* (surrounding abdominal organs) extends only partway into the pelvic cavity (surrounding pelvic organs). Figure 1–7 shows the boundaries between the subdivisions of the thoracic cavity and the abdominopelvic cavity.

The body cavities of the trunk have two essential functions: (1) They protect delicate organs from shocks and impacts, and (2) they permit significant changes in the size and shape of

**Figure 1–7** Relationships among the Subdivisions of the Body Cavities of the Trunk.




**a** A lateral view showing the body cavities of the trunk. The muscular diaphragm subdivides them into a superior thoracic cavity and an inferior abdominopelvic cavity. Three of the four adult true body cavities are shown and outlined in red; only one of the two pleural cavities can be shown in a sagittal section.

**b** The heart projects into the pericardial cavity like a fist pushed into a balloon. The attachment site, corresponding to the wrist of the hand, lies at the connection between the heart and major blood vessels. The width of the pericardial cavity is exaggerated here; normally the visceral and parietal layers are separated only by a thin layer of pericardial fluid.

**c** A transverse section through the thoracic cavity, showing the central location of the pericardial cavity. The mediastinum and pericardial cavity lie between the two pleural cavities. Note that this transverse or cross-sectional view is oriented as though you were standing at the feet of a supine person and looking toward that person's head. This inferior view of a transverse section is the standard presentation for clinical images. Unless otherwise noted, transverse or cross-sectional views in this text use this same orientation (*see Clinical Note: Diagnostic Imaging Techniques*).

internal organs. For example, the lungs, heart, stomach, intestines, urinary bladder, and many other organs can expand and contract without distorting surrounding tissues or disrupting the activities of nearby organs because they project into body cavities.

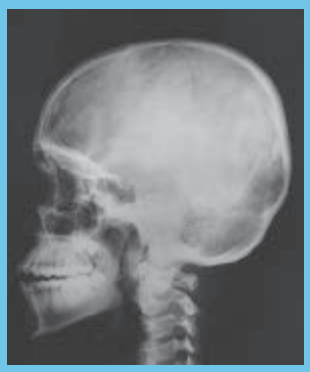
The internal organs that are enclosed by these cavities are known as **viscera** (VIS-e-ruh). A delicate serous membrane lines the walls of these internal cavities and covers the surfaces of the enclosed viscera. A watery fluid, called *serous fluid*, moistens serous membranes, coats opposing surfaces, and reduces friction. The portion of a serous membrane that directly covers a visceral organ is called the *visceral serosa*. The opposing layer that lines the inner surface of the body wall or chamber is called the *parietal serosa*. The parietal and visceral membranes are one membrane: The parietal serosa folds back onto itself, forming the visceral serosa. Because the moist parietal and visceral serosae are usually in close contact, the body cavities are called *potential spaces*. In some clinical conditions, however, excess fluid can accumulate within these potential spaces, increasing their volume and exerting pressure on the enclosed viscera.

## The Thoracic Cavity

The thoracic cavity contains the lungs and heart; associated organs of the respiratory, cardiovascular, and lymphatic systems; the inferior portions of the esophagus; and the thymus (Figure 1–7a, c). The thoracic cavity is subdivided into the left and right **pleural cavities** (holding the lungs), separated by

During the past several decades, rapid progress has been made in discovering more accurate and more detailed ways to image the human body, both in health and disease.

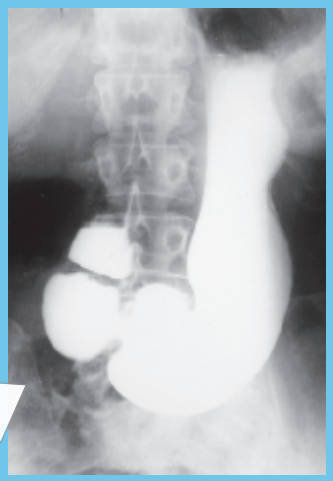
## X-rays



An x-ray of the skull, taken from the left side

**X-rays** are the oldest and still the most common method of imaging. X-rays are a form of high-energy radiation that can penetrate living tissues. An x-ray beam travels through the body before striking a photographic plate. Not all of the projected x-rays arrive at the film. The body absorbs or deflects some of those x-rays. The ability to stop the passage of x-rays is referred to as **radiopacity**. When taking an x-ray, these areas that are impenetrable by x-rays appear light or white on the exposed film and are said to be **radiopaque**. In the body, air has the lowest radiopacity. Fat, liver, blood, muscle, and bone are increasingly radiopaque. As a result, radiopaque tissues look white, and less radiopaque tissues are in shades of gray to black.

To use x-rays to visualize soft tissues, a very radiopaque substance must be introduced. To study the upper digestive tract, a radiopaque barium solution is ingested by the patient. The resulting x-ray shows the contours of the stomach and intestines.



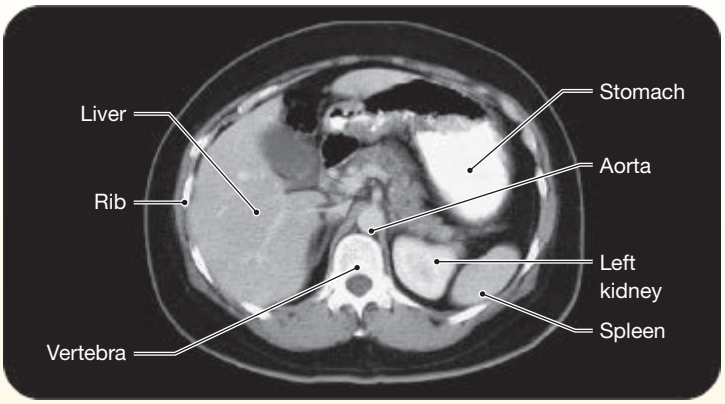
A **barium-contrast x-ray** of the upper digestive tract

## Standard Scanning Techniques

More recently, a variety of **scanning techniques** dependent on computers have been developed to show the less radiopaque, soft tissues of the body in much greater detail.



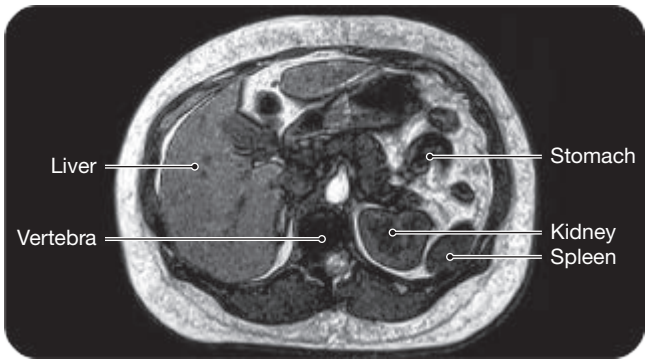

Diagrammatic views showing the relative position and orientation of the CT scan below and the MRI to the right.




### CT scan of the abdomen

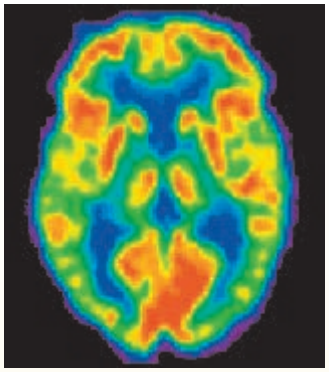
**CT** (computed tomography) **scans** use computers to reconstruct sectional views. A single x-ray source rotates around the body, and the x-ray beam strikes a sensor monitored by the computer. The x-ray source completes one revolution around the body every few seconds. It then moves a short distance and repeats the process. The result is usually displayed as a sectional view in black and white, but it can be colorized for visual effect. CT scans show three-dimensional relationships and soft tissue structures more clearly than do standard x-rays.

- Note that when anatomical diagrams or scans present cross-sectional views, the sections are presented from an inferior perspective, as though the observer were standing at the feet of a person in the supine position and looking toward the head of the subject.




## MRI scan of the abdomen

An **MRI** of the same region (in this case, the abdomen) can show soft tissue structure in even greater detail than a CT scan. Magnetic resonance imaging surrounds part or all of the body with a magnetic field 3000 times as strong as that of Earth. This field causes particles within atoms throughout the body to line up in a uniform direction. Energy from pulses of radio waves are absorbed and released by the different atoms. The released energy is used to create a detailed image of the soft tissue structure.

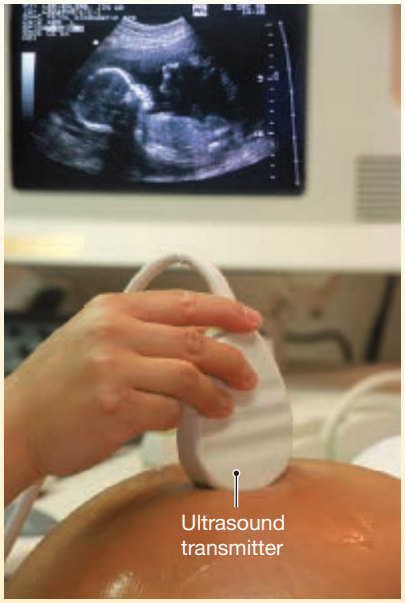


## PET scan of the brain

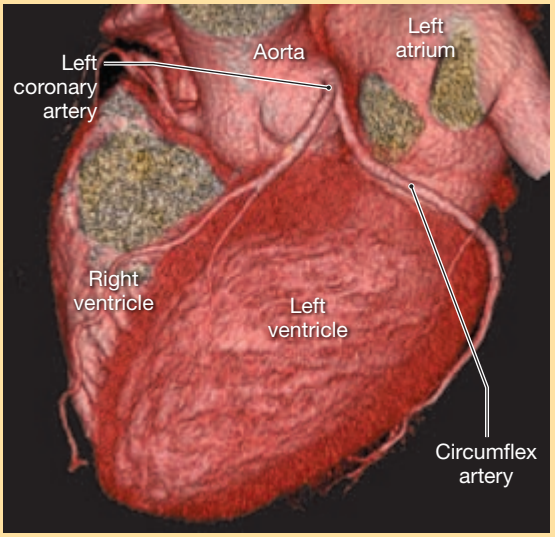
Positron emission tomography (**PET**) is an imaging technique that assesses metabolic and physiological activity of a structure. A PET scan is an important tool in evaluating healthy and diseased brain function.

## Ultrasound of the uterus

In **ultrasound** procedures, a small transmitter contacting the skin broadcasts a brief, narrow burst of high-frequency sound and then detects the echoes. The sound waves are reflected by internal structures, and a picture, or **echogram**, is assembled from the pattern of echoes. These images lack the clarity of other procedures, but no adverse effects have been reported, and fetal development can be monitored without a significant risk of birth defects. Special methods of transmission and processing permit analysis of the beating heart without the complications that can accompany dye injections.

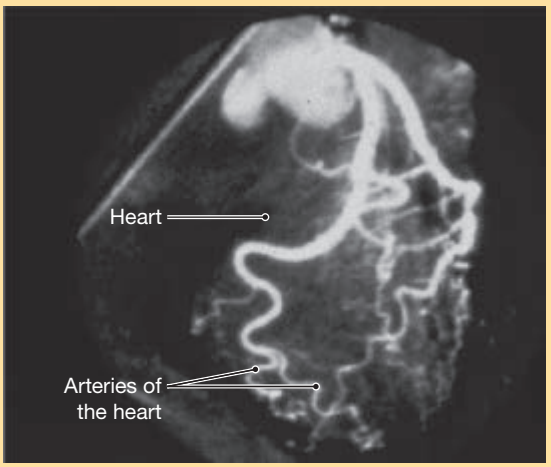



# Special Scanning Methods




## Spiral scan of the heart

A **spiral CT scan** is a form of three-dimensional imaging technology that is becoming increasingly important in clinical settings. During a spiral CT scan, the patient is on a platform that advances at a steady pace through the scanner while the imaging source, usually x-rays, rotates continuously around the patient. Because the x-ray detector gathers data quickly and continuously, a higher quality image is generated, and the patient is exposed to less radiation as compared to a standard CT scanner, which collects data more slowly and only one slice of the body at a time.




## Digital subtraction angiography of coronary arteries

**Digital subtraction angiography** (**DSA**) is used to monitor blood flow through specific organs, such as the brain, heart, lungs, and kidneys. X-rays are taken before and after radiopaque dye is administered, and a computer "subtracts" details common to both images. The result is a high-contrast image showing the distribution of the dye.

a mass of tissue called the **mediastinum** (mē-dē-a-STĪ-num). Each pleural cavity surrounds a lung and is lined by a slippery serous membrane that reduces friction as the lung expands and recoils during breathing. The serous membrane lining a pleural cavity is called a *pleura* (PLOOR-ah). The *visceral pleura* covers the outer surfaces of a lung, and the *parietal pleura* covers the mediastinal surface and the inner body wall.

The mediastinum consists of a mass of connective tissue that surrounds, stabilizes, and supports the esophagus, trachea, and thymus, as well as the major blood vessels that originate or end at the heart. The mediastinum also contains the **pericardial cavity**, a small chamber that surrounds the heart. The relationship between the heart and the pericardial cavity resembles that of a fist pushing into a balloon (Figure 1–7b). The wrist corresponds to the *base* (attached portion) of the heart, and the balloon corresponds to the serous membrane that lines the pericardial cavity. The serous membrane associated with the heart is called the *pericardium* (*peri-*, around + *cardium*, heart). The layer covering the heart is the *visceral layer of serous pericardium*, and the opposing surface is the *parietal layer of serous pericardium*. During each beat, the heart changes in size and shape. The pericardial cavity permits these changes, and the slippery pericardial serous membrane lining prevents friction between the heart and nearby structures in the thoracic cavity.

## The Abdominopelvic Cavity

The abdominopelvic cavity extends from the diaphragm to the pelvis. It is subdivided into a superior *abdominal cavity* and an inferior *pelvic cavity* (Figure 1–7a). The abdominopelvic cavity contains the **peritoneal** (per-i-tō-NĒ-al) **cavity**, a potential space lined by a serous membrane known as the *peritoneum* (per-i-tō-NĒ-um). The *parietal peritoneum* lines the inner surface of the body wall. A narrow space containing a small amount of fluid separates the parietal peritoneum from the *visceral peritoneum*, which covers the enclosed organs. You are probably already aware of the movements of the organs in this cavity. Most of us have had at least one embarrassing moment when a digestive organ contracted, producing a movement of liquid or gas and a gurgling or rumbling sound. The peritoneum allows the organs of the digestive system to slide across one another without damage to themselves or the walls of the cavity.

The **abdominal cavity** extends from the inferior (toward the feet) surface of the diaphragm to the level of the superior (toward the head) margins of the pelvis. This cavity contains the liver, stomach, spleen, small intestine, and most of the large intestine. (Look back at Figure 1–4c that shows the positions of most of these organs.) The organs are partially or completely enclosed by the peritoneal cavity, much as the heart and lungs are enclosed by the pericardial and pleural cavities, respectively. A few organs, such as the kidneys and pancreas, lie between the peritoneal lining and the muscular wall of the abdominal cavity. Those organs are said to be *retroperitoneal* (*retro*, behind).

The **pelvic cavity** is inferior to the abdominal cavity. The bones of the pelvis form the walls of the pelvic cavity, and a layer of muscle forms its floor. The pelvic cavity contains the urinary bladder, various reproductive organs, and the distal (farthest) portion of the large intestine. In females, the pelvic cavity contains the ovaries, uterine tubes, and uterus. In males, it contains the prostate gland and seminal glands (seminal vesicles). The pelvic cavity also contains the inferior portion of the peritoneal cavity. The peritoneum covers the ovaries and the uterus in females, as well as the superior portion of the urinary bladder in both sexes. Organs such as the urinary bladder and the distal portions of the ureters and large intestine, which extend inferior to the peritoneal cavity, are said to be *infraperitoneal*.

The true body cavities of the trunk in the adult share a common embryological origin. The term "dorsal body cavity" is sometimes used to refer to the internal chamber of the skull (cranial cavity) and the space enclosed by the vertebrae (vertebral cavity). These chambers, which are defined by bony structures, are anatomically and embryonically distinct from true body cavities, and the term "dorsal body cavity" is not encountered in either clinical anatomy or comparative anatomy. For these reasons, we have avoided using that term in our discussion of body cavities.

A partial list of chambers, or spaces, within the body that are not true body cavities would include the cranial cavity, vertebral cavity, oral cavity, digestive cavity, orbits (eye sockets), tympanic cavity of each middle ear, nasal cavities, and paranasal sinuses (air-filled chambers within some cranial bones that are connected to the nasal cavities). These structures will be discussed in later chapters.

The Clinical Note: Diagnostic Imaging Techniques on pp. 62–63 highlights some clinical tests commonly used for viewing the interior of the body.

### Checkpoint

17. **Name two essential functions of the body cavities of the trunk.**
18. **Describe the various body cavities of the trunk.**

See the blue Answers tab at the back of the book.

## 1-7 Homeostasis, the state of internal balance, is continuously regulated

Learning Outcome Explain the concept of homeostasis.

**Homeostasis** (hō-mē-o-STĀ-sis; from the Greek *homeo*, similar + *stasis*, state of standing) refers to the existence of a stable internal environment. Various physiological processes act to prevent harmful changes in the composition of body fluids and the environment inside our cells. Maintaining homeostasis is absolutely vital to an organism's survival. Failure to maintain homeostasis soon leads to illness or even death. The principle of homeostasis is the central theme of this text and the foundation of all modern physiology.

## Mechanisms of Homeostatic Regulation

**Homeostatic regulation** is the adjustment of physiological systems to preserve homeostasis. Physiological systems have evolved to maintain homeostasis in an environment that is often inconsistent, unpredictable, and potentially dangerous. An understanding of homeostatic regulation is crucial to making accurate predictions about the body's responses to both normal and abnormal conditions.

Homeostatic regulation involves two general mechanisms: autoregulation and extrinsic regulation.

1. **Autoregulation** is a process that occurs when a cell, tissue, organ, or organ system adjusts in response to some environmental change. For example, when the oxygen level decreases in a tissue, the cells release chemicals that widen, or dilate, blood vessels. This dilation increases the blood flow and provides more oxygen to the region.
2. **Extrinsic regulation** is a process that results from the activities of the nervous system or endocrine system. These organ systems detect an environmental change and send an electrical signal (nervous system) or chemical messenger (endocrine system) to control or adjust the activities of another or many other systems simultaneously. For example, when you exercise, your nervous system issues commands that increase your heart rate so that blood will circulate faster. Your nervous system also causes blood flow to be reduced to less active organs, such as the digestive tract. The oxygen in circulating blood is then available to the active muscles, which need it most.

In general, the nervous system directs rapid, short-term, and very specific responses. For example, if you accidentally set your hand on a hot stove, the heat would produce a painful, localized disturbance of homeostasis. Your nervous system would respond by ordering specific muscles to contract and pull your hand away from the stove. These contractions last only as long as the neural activity continues, usually a matter of seconds.

In contrast, the endocrine system releases chemical messengers called *hormones* into the bloodstream. These molecular messengers can affect tissues and organs throughout the body. The responses may not be immediately apparent, but they may persist for days or weeks. Examples of homeostatic regulation dependent on endocrine function include the long-term regulation of blood volume and composition, and the adjustment of organ system function during starvation.

## An Overview of the Process of Homeostatic Regulation

Regardless of the system involved, homeostatic regulation always works to keep the internal environment within certain limits, or a range. A homeostatic regulatory mechanism consists of three parts: (1) a **receptor**, a sensor that is sensitive to a particular stimulus or environmental change; (2) a **control center**, which receives and processes the information supplied by the receptor and sends out commands; and (3) an **effector**, a cell or organ that responds to the commands of the control center and whose activity either opposes or enhances the stimulus. You are probably already familiar with similar mechanical regulatory mechanisms, such as the one involving the thermostat in your house or apartment (Figure 1–8a).

The thermostat is the control center. It receives information about room temperature from an internal or remote thermometer (a receptor). The setting on the thermostat establishes the **set point**, or desired value, which in this case is the temperature you select. (In our example, the set point is 22°C, or about 72°F.) The function of the thermostat is to keep room temperature within acceptable limits, usually within a degree or so of the set point. In summer, the thermostat performs this function by controlling an air conditioner (an effector). When the temperature at the thermometer rises above the set point, the thermostat turns on the air conditioner, which then cools the room. Then, when the temperature at the thermometer returns to the set point, the thermostat turns off the air conditioner. The control is not precise, especially if the room is large, and the thermostat is located on just one wall. Over time, the temperature in the center of the room fluctuates in a range above and below the set point (Figure 1–8b).

We can summarize the essential feature of temperature control by a thermostat very simply: A variation outside the set point triggers an automatic response that corrects the situation. In this way, variation in temperature is kept within an acceptable range. Now let's explore how the body uses a similar method of regulation called negative feedback.

### Checkpoint

19. Define *homeostasis*.
20. Which general mechanism of homeostatic regulation always involves the nervous or endocrine system?
21. Why is homeostatic regulation important to an organism?

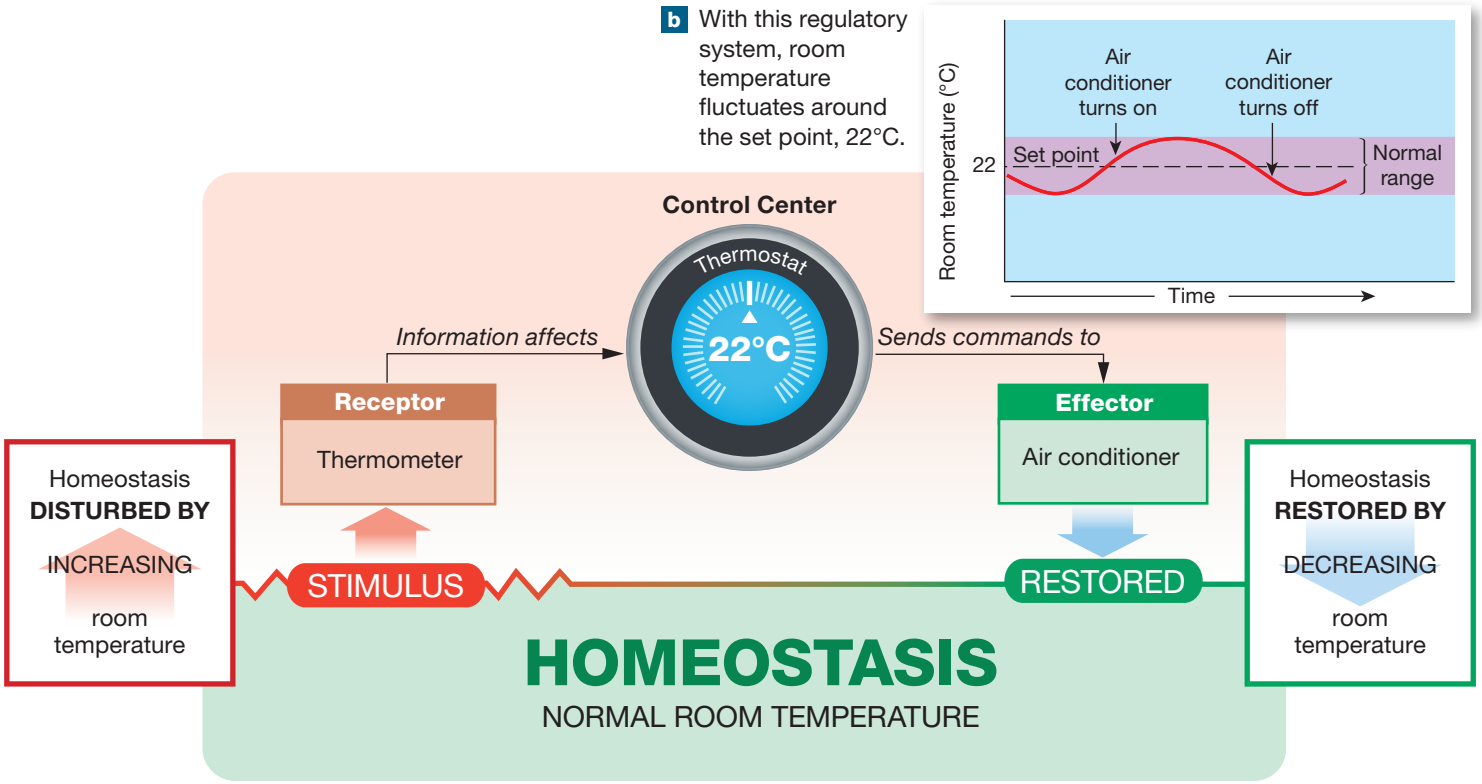
See the blue Answers tab at the back of the book.

## 1-8 Negative feedback opposes variations from normal, whereas positive feedback enhances them

Learning Outcome Describe how negative feedback and positive feedback are involved in homeostatic regulation.

To keep variation in key body systems within ranges that are compatible with our long-term survival, the body uses a method of homeostatic regulation called *negative feedback*. In this process, an effector activated by the control center opposes,

**Figure 1–8** The Control of Room Temperature.




**a** In response to input from a receptor (a thermometer), a control center (a thermostat) triggers an effector response (either an air conditioner or a heater) that restores normal temperature. In this case, when room temperature rises above the set point, the thermostat turns on the air conditioner, and the temperature returns to normal.

or *negates*, the original stimulus. In this way, negative feedback tends to minimize change. The body also has another method of homeostatic regulation called *positive feedback*, which instead tends to enhance or *increase* the change that triggered it. However, most homeostatic regulatory mechanisms involve negative feedback. Let's examine the roles of negative and positive feedback in homeostasis before considering the roles of organ systems in regulating homeostasis.

## The Role of Negative Feedback in Homeostasis

An important example of **negative feedback**, a way of counteracting a change, is the control of body temperature, a process called *thermoregulation*. In thermoregulation, the relationship between heat loss, which takes place mainly at the body surface, and heat production, which takes place in all active tissues, is altered.

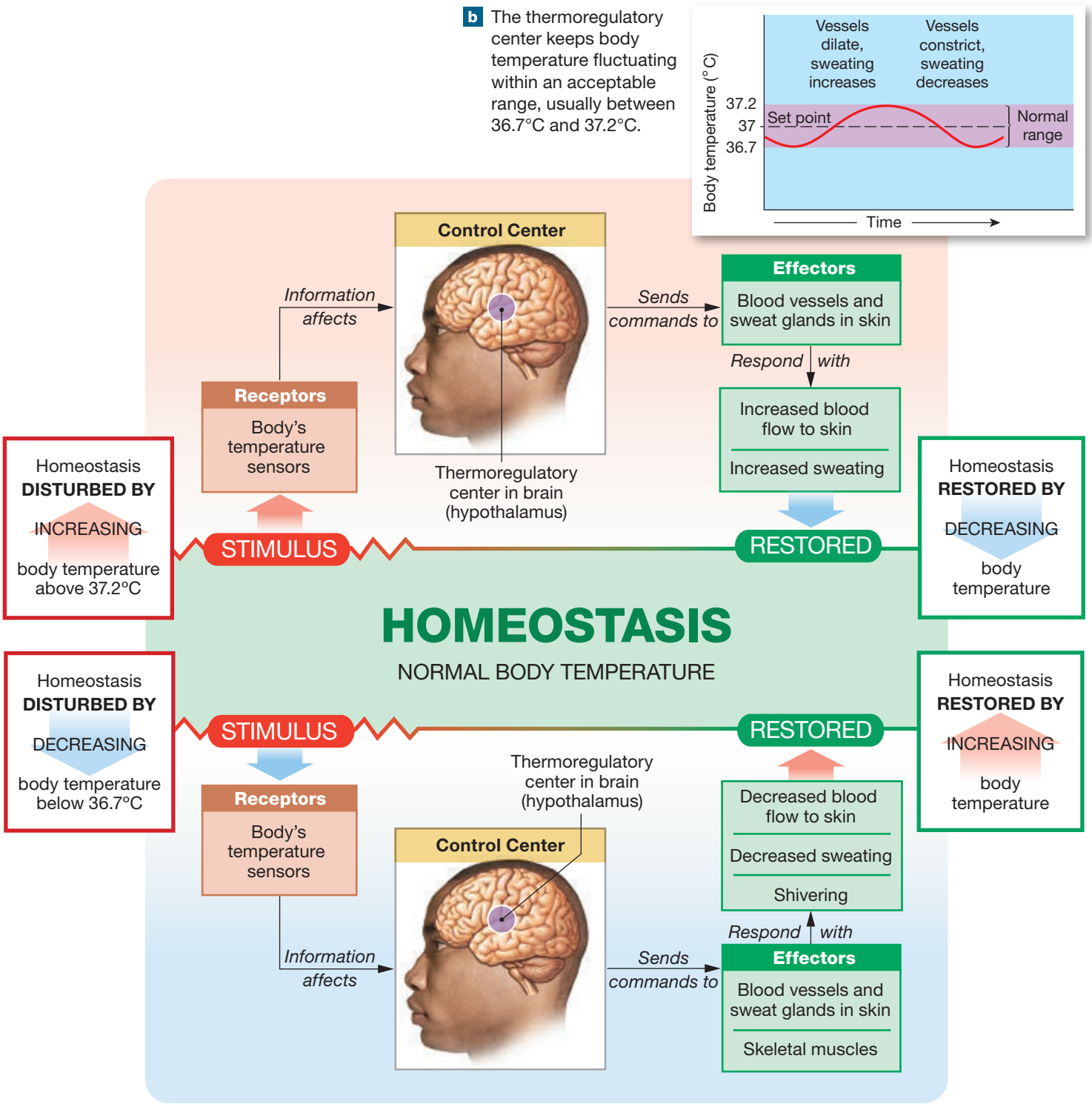
In the homeostatic control of body temperature (Figure 1–9a), the thermoregulatory control center is in the *hypothalamus*, a region of the brain. This control center receives information from two sets of temperature receptors, one in the skin and the other within the hypothalamus. At the normal set point, body temperature (as measured with an oral thermometer) is approximately 37°C (98.6°F).

If body temperature rises above 37.2°C, activity in the control center targets two effectors: (1) muscle tissue lining the walls of blood vessels supplying blood to the skin and (2) sweat glands. The muscle tissue relaxes so the blood vessels dilate (widen), increasing blood flow through vessels near the body surface, and the sweat glands speed up their secretion of sweat. The skin then acts like a radiator by losing heat to the environment, and the evaporation of sweat speeds the process.

As body temperature returns to normal, temperature in the hypothalamus decreases, and the thermoregulatory center becomes less active. Blood flow to the skin and sweat gland activity then decrease to previous levels. Body temperature drops below the set point as the secreted sweat evaporates.

Negative feedback is the primary mechanism of homeostatic regulation, and it provides long-term control over the body's internal conditions and systems. Homeostatic mechanisms using negative feedback normally ignore minor variations. They maintain a normal *range* rather than a fixed value. In our example, body temperature fluctuated around the set-point temperature (Figure 1–9b). The regulatory process itself

**Figure 1–9 Negative Feedback: Control of Body Temperature.** In negative feedback, a stimulus produces a response that opposes or negates the original stimulus.




**a** Events in the regulation of body temperature, which are comparable to those shown in *Figure 1–8*. A control center in the brain (the hypothalamus) functions as a thermostat with a set point of 37°C. If body temperature exceeds 37.2°C, heat loss is increased through increased blood flow to the skin and increased sweating.

**?** If a person's body temperature gets too high, the body will respond by decreasing its temperature to restore homeostasis. What are some of the body's homeostatic responses to decrease body temperature?

is dynamic. That is, it is constantly changing because the set point may vary with changing environments or differing activity levels. For example, when you are asleep, your thermoregulatory set point is lower. When you work outside on a hot day (or when you have a fever), it is set higher. Body temperature can vary from moment to moment or from day to day for any individual, due to either (1) small fluctuations around the set point or (2) changes in the set point. Comparable variations take place in all other aspects of physiology.

The variability among individuals is even greater than that within an individual. Each of us has homeostatic set points determined by genetic factors, age, gender, general health, and environmental conditions. For this reason, it is impractical to define "normal" homeostatic conditions very precisely. By convention, physiological values are reported either as average values obtained by sampling a large number of individuals, or as a range that includes 95 percent or more of the sample population.

For example, for 95 percent of healthy adults, body temperature ranges between 36.7°C and 37.2°C (98.1°F and 98.9°F). The other 5 percent of healthy adults have resting body temperatures that are below 36.7°C or above 37.2°C. These temperatures are perfectly normal for them, and the variations have no clinical significance. Physicians must keep this variability in mind when they review lab reports, because unusual values—even those outside the "normal" range—may represent individual variation rather than disease.

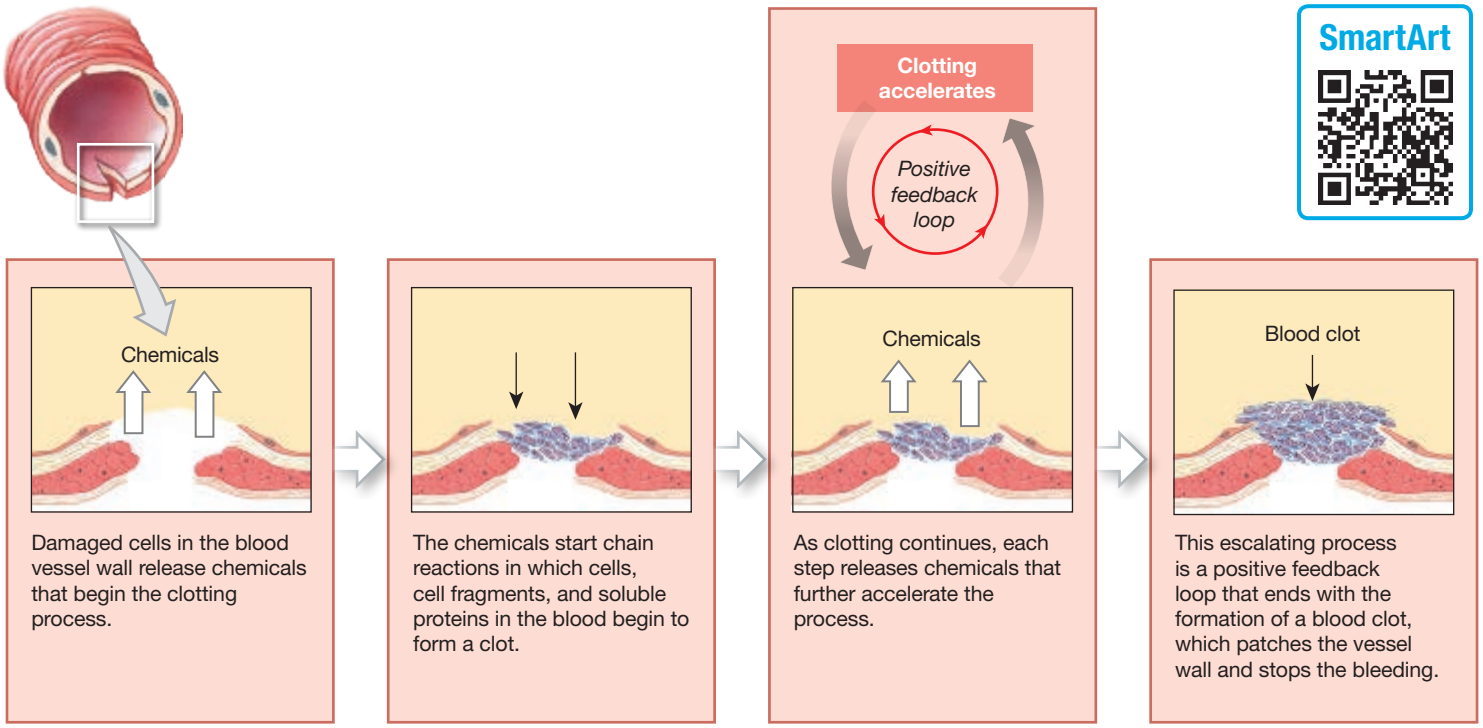
## The Role of Positive Feedback in Homeostasis

In **positive feedback**, an initial stimulus produces a response that amplifies or enhances the original change in conditions, rather than opposing it. You seldom encounter positive feedback in your daily life, simply because it tends to produce extreme responses. For example, suppose that the thermostat in Figure 1–8a was accidentally connected to a heater rather than to an air conditioner. Now when room temperature rises above the set point, the thermostat turns on the heater, causing a further rise in room temperature. Room temperature will continue to increase until someone switches off the thermostat, turns off the heater, or intervenes in some other way. This kind of escalating cycle is often called a **positive feedback loop**.

In the body, positive feedback loops are typically found when a potentially dangerous or stressful process must be completed quickly to restore homeostasis. For example, the immediate danger from a severe cut is the loss of blood, which can lower blood pressure and reduce the efficiency of the heart. The body's response to this blood loss is blood clotting, diagrammed in Figure 1–10. We will examine blood clotting more closely in Chapter 19. Labor and delivery are another example of positive feedback in action, as we will discuss in Chapter 29.

The human body is amazingly effective at maintaining homeostasis. Nevertheless, an infection, injury, or genetic abnormality can sometimes have effects so severe that homeostatic

**Figure 1–10 Positive Feedback: Blood Clotting.** In positive feedback, a stimulus produces a response that accelerates or enhances the original change in conditions, rather than opposing it.



mechanisms cannot fully compensate for them. One or more variables within the internal environment may then be pushed outside their normal range of values. When this happens, organ systems begin to malfunction, producing a state known as illness, or **disease**. In Chapters 5–29, we devote much attention to the mechanisms that bring about a variety of human diseases.

## Systems Integration, Equilibrium, and Homeostasis

Homeostatic regulation controls aspects of the internal environment that affect every cell in the body. No single organ system has total control over any of these aspects. Instead, such control requires the coordinated efforts of multiple organ systems. In later chapters we will explore the functions of each organ system and see how the systems interact to preserve homeostasis. Table 1–1 lists the roles of various organ systems in regulating several important functions that are subject to homeostatic control. Note that in each case such regulation involves several organ systems.

A **state of equilibrium** exists when opposing processes or forces are in balance. In the case of body temperature, a state of equilibrium exists when the rate of heat loss equals the rate of heat production. Each physiological system functions to maintain a state of equilibrium that keeps vital conditions within a normal range of values. This is often called a state of **dynamic equilibrium** because physiological systems are continually adapting and adjusting to changing conditions. For example, when muscles become more active, more heat is produced. More heat must then be lost at the skin surface to reestablish a state of equilibrium before body temperature rises outside normal ranges. Yet the adjustments made to control body temperature have other consequences. The sweating that increases heat loss at the skin surface increases losses of both water and salts. Other systems must then compensate for these losses and reestablish an equilibrium state for water and salts.

Note this general pattern: Any adjustments made by one physiological system have direct and indirect effects on a variety of other systems. Maintaining homeostasis is like a juggling act that keeps lots of different objects in the air.

Each organ system interacts with and depends on other organ systems, but introductory students may often find it easier to learn the basics of anatomy and physiology one system at a time. Chapters 5–29 are organized around individual systems, but remember that these systems all work together. The 11 *Build Your Knowledge Figures* in later chapters will help reinforce this message. Each provides an overview of one system's functions and summarizes its functional relationships with systems covered in previous chapters.

**Table 1–1 The Roles of Organ Systems in Homeostatic Regulation**

| Internal Stimulus | Primary Organ Systems Involved | Functions of the Organ Systems |
|---|---|---|
| **Body temperature** | Integumentary system | Heat loss |
| | Muscular system | Heat production |
| | Cardiovascular system | Heat distribution |
| | Nervous system | Coordination of blood flow, heat production, and heat loss |
| **Body fluid composition** | | |
| Nutrient concentration | Digestive system | Nutrient absorption, storage, and release |
| | Cardiovascular system | Nutrient distribution |
| | Urinary system | Control of nutrient loss in the urine |
| | Skeletal system | Mineral storage and release |
| Oxygen, carbon dioxide levels | Respiratory system | Absorption of oxygen, elimination of carbon dioxide |
| | Cardiovascular system | Internal transport of oxygen and carbon dioxide |
| Levels of toxins and pathogens | Lymphatic system | Removal, destruction, or inactivation of toxins and pathogens |
| **Body fluid volume** | Urinary system | Elimination or conservation of water from the blood |
| | Digestive system | Absorption of water; loss of water in feces |
| | Integumentary system | Loss of water through perspiration |
| | Cardiovascular system and lymphatic system | Distribution of water throughout body tissues |
| **Waste concentration** | Urinary system | Excretion of wastes from the blood |
| | Digestive system | Elimination of wastes from the liver in feces |
| | Cardiovascular system | Transport of wastes products to sites of excretion |
| **Blood pressure** | Cardiovascular system | Pressure generated by the heart moves blood through blood vessels |
| | Nervous system and endocrine system | Adjustments in heart rate and blood vessel diameter can raise or lower blood pressure |

## Checkpoint

22. Explain the function of negative feedback systems.
23. What happens to the body when homeostasis breaks down?
24. Explain how a positive feedback system works.
25. Why is positive feedback helpful in blood clotting but unsuitable for the regulation of body temperature?
26. Define *equilibrium*.
27. When the body continuously adapts by using homeostatic mechanisms, it is said to be in a state of _____ equilibrium.

See the blue Answers tab at the back of the book.

# 1 Chapter Review

## Study Outline

### An Introduction to Studying the Human Body p. 48

1. Biology is the study of life. One of its goals is to discover the unity and the patterns that underlie the diversity of organisms.

### 1-1 To make the most of your learning, read the text and view the art together p. 48

2. This text is divided into **sections**, which are units about a topic that continues to build on previously learned topics.
3. To enhance learning, the text and art should be read and studied together. For this reason, there is **text–art integration** whereby the figures are placed in proximity to the narrative.
4. **Learning outcomes** are tied to testing and tell the reader what educational goals should be achieved after reading each section. Learning outcomes are based on a **learning classification scheme**, which identifies the fundamental levels of learning from lower order skills to those of higher order skills. *(Figure 1–1)*

### 1-2 Anatomy (structure) and physiology (function) are closely integrated p. 49

5. **Anatomy** is the study of internal and external structures of the body and the physical relationships among body parts. **Physiology** is the study of how living organisms perform their vital functions. All physiological functions are performed by specific structures.
6. All specific functions are performed by specific structures.
7. In **gross** *(macroscopic)* **anatomy**, we consider features that are visible without a microscope. This field includes *surface anatomy* (general form and superficial markings), *regional anatomy* (anatomical organization of specific areas of the body), *sectional anatomy* (relationship of the body's structures by examining cross sections of tissues or organs), and *systemic anatomy* (structure of organ systems). *Clinical anatomy* includes anatomical subspecialties important to the practice of medicine. In *developmental anatomy*, we examine the changes in form that occur between conception and physical maturity. In *embryology*, we study developmental processes that occur during the first two months of development.
8. The equipment used determines the limits of *microscopic anatomy*. In **cytology**, we analyze the internal structure of individual cells. In **histology**, we examine **tissues**, groups of cells that perform specific functions. Tissues combine to form **organs**, anatomical structures with multiple functions. *(Spotlight Figure 1–2)*
9. Human physiology is the study of the functions of the human body. It is based on *cell physiology*, the study of the functions of cells. In *organ physiology*, we study the physiology of specific organs. In *systemic physiology*, we consider all aspects of the functioning of specific organ systems. In *pathological physiology*, we study the effects of diseases on organ or system functions.



### 1-3 Levels of organization progress from chemicals to a complete organism p. 52

10. Anatomical structures and physiological mechanisms occur in a series of interacting levels of organization. *(Spotlight Figure 1–2)*
11. The 11 **organ systems** of the body are the integumentary, skeletal, muscular, nervous, endocrine, cardiovascular, lymphatic, respiratory, digestive, urinary, and reproductive systems. *(Spotlight Figure 1–2)*

### 1-4 Medical terminology is important to understanding anatomy and physiology p. 53

12. **Medical terminology** is the use of word roots, prefixes, suffixes, and combining forms to construct anatomical, physiological, or medical terms.
13. *Terminologia Anatomica* was used as the standard in preparing your text.

### 1-5 Anatomical terms describe body regions, anatomical positions and directions, and body sections p. 53

14. The standard arrangement for anatomical reference is called the **anatomical position**. A person who is lying down is either **supine** (face up) or **prone** (face down). *(Figure 1–3)*
15. **Abdominopelvic quadrants** and **abdominopelvic regions** represent two approaches to describing anatomical regions of that portion of the body. *(Figure 1–4)*
16. The use of special directional terms provides clarity for the description of anatomical structures. *(Figure 1–5)*
17. The three **sectional planes** (**transverse**, or *horizontal*, **plane**; **frontal**, or *coronal*, **plane**; and **sagittal plane**) describe relationships among the parts of the three-dimensional human body. *(Figure 1–6)*

### 1-6 Body cavities of the trunk protect internal organs and allow them to change shape p. 60

18. **Body cavities** protect delicate organs and permit significant changes in the size and shape of internal organs. The body cavities of the trunk surround organs of the respiratory, cardiovascular, digestive, urinary, and reproductive systems. *(Figure 1–7)*
19. The **diaphragm** divides the (superior) **thoracic** and (inferior) **abdominopelvic cavities**. The thoracic cavity consists of two **pleural cavities** (each surrounding a lung) with a central tissue mass known as the **mediastinum**. Within the mediastinum is the **pericardial cavity**, which surrounds the heart. The abdominopelvic cavity consists of the **abdominal cavity** and the **pelvic cavity** and contains the *peritoneal cavity*, a chamber lined by the *peritoneum*, a *serous membrane*. *(Figure 1–7)*
20. Diagnostic imaging techniques are used in clinical medicine to view the body's interior.

### 1-7 Homeostasis, the state of internal balance, is continuously regulated p. 64

21. **Homeostasis** is the existence of a stable environment within the body.
22. Physiological systems preserve homeostasis through **homeostatic regulation**.
23. **Autoregulation** occurs when a cell, tissue, organ, or organ system adjusts its activities automatically in response to some environmental change. **Extrinsic regulation** results from the activities of the nervous system or endocrine system.
24. Homeostatic regulation mechanisms usually involve a **receptor** that is sensitive to a particular stimulus; a **control center**, which receives and processes the information supplied by the receptor and then sends out commands; and an **effector** that responds to the commands of the control center and whose activity either opposes or enhances the stimulus. *(Figure 1–8)*

### 1-8 Negative feedback opposes variations from normal, whereas positive feedback enhances them p. 65

25. **Negative feedback** is a corrective mechanism involving an action that directly opposes a variation from normal limits. *(Figure 1–9)*
26. In **positive feedback**, an initial stimulus produces a response that exaggerates or enhances the change in the original conditions, creating a **positive feedback** loop. *(Figure 1–10)*
27. No single organ system has total control over the body's internal environment; all organ systems work together. *(Table 1–1)*

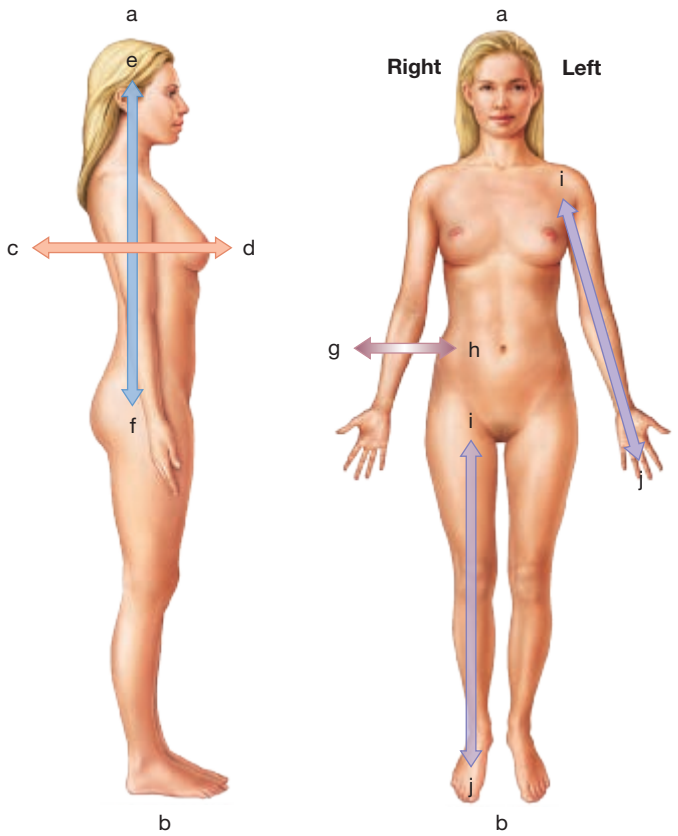


## Review Questions

See the blue Answers tab at the back of the book.

### LEVEL 1 Reviewing Facts and Terms

1. Label the directional terms in the figures below.




**(a)** _____ **(b)** _____
**(c)** _____ **(d)** _____
**(e)** _____ **(f)** _____
**(g)** _____ **(h)** _____
**(i)** _____ **(j)** _____

Match each numbered item with the most closely related lettered item. Use letters for answers in the spaces provided.

| | | | |
|---|---|---|---|
| ____ | **2.** anatomy | **(a)** | study of tissues |
| ____ | **3.** physiology | **(b)** | constant internal environment |
| ____ | **4.** histology | **(c)** | face-up position |
| ____ | **5.** mediastinum | **(d)** | study of functions |
| ____ | **6.** homeostasis | **(e)** | positive feedback |
| ____ | **7.** muscle | **(f)** | organ system |
| ____ | **8.** liver | **(g)** | thoracic tissue mass |
| ____ | **9.** skeletal | **(h)** | negative feedback |
| ____ | **10.** temperature regulation | **(i)** | serous membrane |
| ____ | **11.** labor and delivery | **(j)** | study of internal and external body structures |
| ____ | **12.** supine | **(k)** | diaphragm |
| ____ | **13.** prone | **(l)** | tissue |
| ____ | **14.** divides thoracic and abdominopelvic body cavities | **(m)** | peritoneal cavity |
| ____ | **15.** abdominopelvic cavity | **(n)** | organ |
| ____ | **16.** pericardium | **(o)** | face-down position |

17. The following is a list of six levels of organization that make up the human body:
    **(1)** tissue **(2)** cell
    **(3)** organ **(4)** chemical
    **(5)** organism **(6)** organ system
    The correct order, from the simplest to the most complex level, is **(a)** 2, 4, 1, 3, 6, 5, **(b)** 4, 2, 1, 3, 6, 5, **(c)** 4, 2, 1, 6, 3, 5, **(d)** 4, 2, 3, 1, 6, 5, **(e)** 2, 1, 4, 3, 5, 6.
18. The study of the internal structure of individual cells is called **(a)** cell physiology, **(b)** cytology, **(c)** histology, **(d)** systemic anatomy.

19. The increasingly forceful labor contractions during childbirth are an example of **(a)** receptor activation, **(b)** effector shutdown, **(c)** negative feedback, **(d)** positive feedback.
20. Failure of homeostatic regulation in the body results in **(a)** autoregulation, **(b)** extrinsic regulation, **(c)** disease, **(d)** positive feedback.
21. A plane that runs parallel to the long axis of the body, dividing the body into equal right and left sides, is a **(a)** midsagittal section, **(b)** transverse section, **(c)** coronal section, **(d)** parasagittal section.
22. Which body cavity would enclose each of the following organs? **(a)** uterus, **(b)** prostate gland, **(c)** spleen, **(d)** lung.
23. The parietal pleura covers the **(a)** outer surfaces of a lung, **(b)** heart, **(c)** inner thoracic body wall, **(d)** enclosed abdominal organs.
24. A learning outcome is best described as **(a)** a goal of learning after reading a section based on a learning classification scheme, **(b)** an abstract concept linking anatomy to physiology, **(c)** a type of homeostatic mechanism, **(d)** the same thing as text–art integration.

### LEVEL 2 Reviewing Concepts

25. **(a)** Define *anatomy*. **(b)** Define *physiology*.
26. The two major body cavities of the trunk are the **(a)** pleural cavity and pericardial cavity, **(b)** pericardial cavity and peritoneal cavity, **(c)** pleural cavity and peritoneal cavity, **(d)** thoracic cavity and abdominopelvic cavity.
27. What distinguishes autoregulation from extrinsic regulation?
28. Describe the anatomical position.
29. Which sectional plane could divide the body so that the face remains intact? **(a)** sagittal plane, **(b)** frontal (coronal) plane, **(c)** equatorial plane, **(d)** midsagittal plane, **(e)** parasagittal plane.
30. Which the following is *not* an example of negative feedback? **(a)** Increased pressure in the aorta triggers mechanisms to lower blood pressure. **(b)** A rise in blood calcium levels triggers the release of a hormone that lowers blood calcium levels. **(c)** A rise in estrogen during the menstrual cycle increases the number of progesterone receptors in the uterus. **(d)** Increased blood sugar stimulates the release of a hormone from the pancreas that stimulates the liver to store blood sugar.

### LEVEL 3 Critical Thinking and Clinical Applications

31. The hormone *insulin* is released from the pancreas in response to an increased level of glucose (sugar) in the blood. If this hormone is controlled by negative feedback, what effect would insulin have on the blood glucose level?
32. A stroke occurs when blood flow to the brain is disrupted, causing brain cells to die. Why might a stroke result in a rise or fall of normal body temperature?

## CLINICAL CASE Wrap-Up Using A&P to Save a Life

The patient is wheeled through the door and into Trauma Room 1. He is barely alive. Because of the location of the abdominal wound, in the right upper quadrant, and the likely depth of the wound, more than 6 inches, it is probable that the liver has been lacerated. Depending on the angle of the knife, sections of large intestine, containing bacteria that are deadly when released into the abdominal cavity, have probably also been lacerated. Any blood spilled onto the street or into the patient's abdominal cavity is lost from the cardiovascular system and cannot carry oxygen to body tissues. For this reason, the trauma nurse is ready with blood for transfusion.

An x-ray shows free air in the abdominal cavity, a sure sign the large intestine is cut. It also shows a fluid level indicating free blood in the abdominal cavity. Both conditions need immediate surgical attention. The patient is taken directly to the operating room where a surgeon performs open abdominal surgery. The lacerations of the liver and large intestine are repaired and the bleeding is stopped. A diverting colostomy is performed, creating an opening from the large intestine through the abdominal wall in the right lower quadrant, proximal to the level of injury. This will allow the injured large intestine to rest while healing. A life is saved because an EMT, trauma nurse, and surgeon know their anatomy and physiology.

1. Besides the liver and most of the large intestine, what other major organs are in the abdominal cavity?
2. If the deep knife wound had been superior to the diaphragm, what body cavity would the knife have entered, and what organs does it contain?

See the blue Answers tab at the back of the book.

## Related Clinical Terms

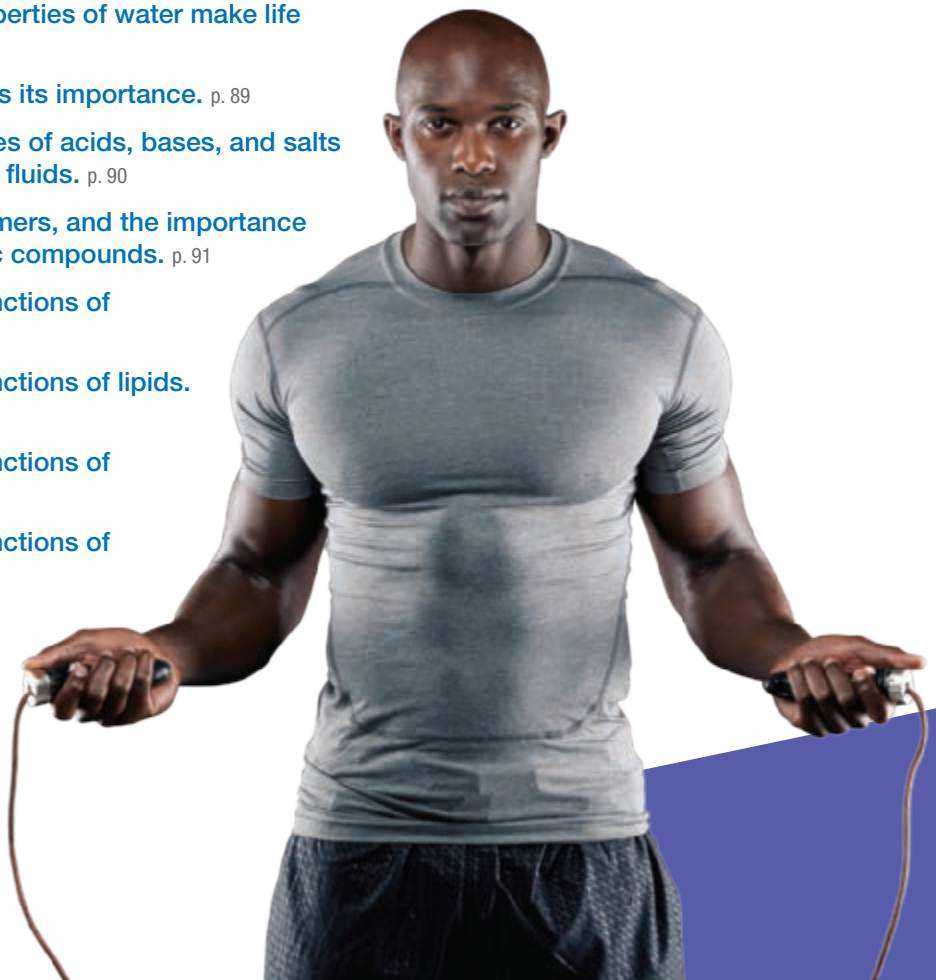
**acute:** A disease of short duration but typically severe.
**chemotherapy:** The treatment of disease or mental disorder by the use of chemical substances, especially the treatment of cancer by cytotoxic and other drugs.
**chronic:** Illness persisting for a long time or constantly recurring. Often contrasted with *acute*.
**epidemiology:** The branch of science that deals with the incidence, distribution, and possible control of diseases and other factors relating to health.
**etiology:** The science and study of the cause of diseases.
**idiopathic:** Denoting any disease or condition of unknown cause.
**morbidity:** The state of being diseased or unhealthy, or the incidence of disease in a population.
**pathophysiology:** The functional changes that accompany a particular syndrome or disease.
**syndrome:** A condition characterized by a group of associated symptoms.

# 2 The Chemical Level of Organization

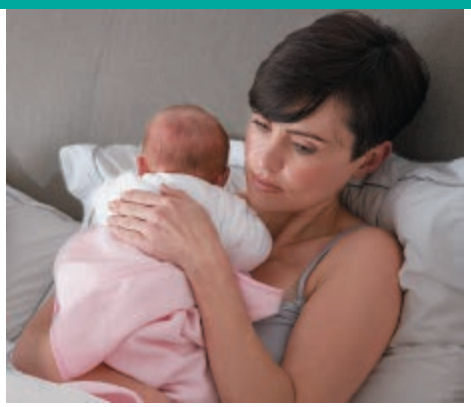
## Learning Outcomes

These Learning Outcomes correspond by number to this chapter's sections and indicate what you should be able to do after completing the chapter.





## CLINICAL CASE What Is Wrong with My Baby?



Sean is Maureen's first baby. Maureen and her husband, Conner, had enjoyed an uncomplicated pregnancy and delivery. Maureen had felt healthy throughout the pregnancy, but something was wrong with her baby.

Sean is 1 month old, and not thriving. He seems to have a good appetite and breast-feeds as if he were starving; yet he has dropped 20 percent of his normal birth weight of 7 pounds, 8 ounces. He is down to only 6 pounds at his 1-month checkup, and his skin looks "wrinkly." His stools appear greasy and foamy. Maureen also notices that Sean's skin tastes salty.

Most alarmingly, he seems to be having some difficulty breathing. His breathing is wheezy. Maureen and Conner are both from big families, and none of the babies has ever been sickly like this. **What is wrong with baby Sean? To find out, turn to the Clinical Case Wrap-Up on p. 110.**

## An Introduction to the Chemical Level of Organization

In this chapter we consider the structure of *atoms*, the basic chemical building blocks. You will also learn how atoms can combine to form increasingly complex structures, and how those types of complex structures function in the human body.

## 2-1 Atoms are the basic particles of matter

Learning Outcome Describe an atom and how atomic structure affects interactions between atoms.

Our study of the human body begins at the chemical level of organization. **Chemistry** is the science that deals with the structure of **matter**, defined as anything that takes up space and has mass. **Mass**, the amount of material in matter, is a physical property that determines the weight of an object in Earth's gravitational field. For our purposes, the mass of an object is the same as its weight. However, the two are not always equivalent: In orbit you would be weightless, but your mass would remain unchanged.

The smallest stable units of matter are called **atoms**. Air, elephants, oranges, oceans, rocks, and people are all composed of atoms in varying combinations. The unique characteristics of each object, living or nonliving, result from the types of atoms involved and the ways those atoms combine and interact.

Atoms are composed of **subatomic particles**. Many different subatomic particles exist, but only three—*protons, neutrons*, and *electrons*—are important for understanding the chemical properties of matter. Protons and neutrons are similar in size and mass, but **protons** ($p^+$) have a positive electrical charge. **Neutrons** (n or $n^0$) are electrically *neutral*, or uncharged. **Electrons** ($e^-$) are much lighter than protons—only 1/1836 as massive—and have a negative electrical charge. For this reason, the mass of an atom is determined primarily by the number of protons and neutrons in the **nucleus**, the central region of an atom. The mass of a large object, such as your body, is the sum of the masses of all its component atoms.

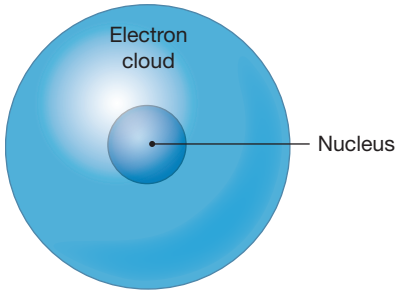
### Atomic Structure

Atoms normally contain equal numbers of protons and electrons. The number of protons in an atom is known as its **atomic number**. *Hydrogen* (represented as H) is the simplest atom, with an atomic number of 1. An atom of hydrogen contains one proton and one electron. Hydrogen's proton is located in the center of the atom and forms the nucleus. Hydrogen atoms seldom contain neutrons, but when neutrons are present, they are also located in the nucleus. All atoms other than hydrogen have both neutrons and protons in their nuclei.

Electrons travel around the nucleus at high speed, within a spherical area called the **electron cloud** (Figure 2–1). We often illustrate atomic structure in the simplified form shown for hydrogen in Figure 2–2a (see p. 76). In this two-dimensional representation, the electrons occupy a circular **electron shell**. One reason an electron tends to remain in its electron shell is that the negatively charged electron is attracted to the positively charged proton. The attraction between opposite electrical charges is an example of an *electrical force*. As you will see in later chapters, electrical forces are involved in many physiological processes.

The dimensions of the electron cloud determine the overall size of the atom. To get an idea of the scale involved, consider that

**Figure 2–1 Hydrogen Atom with Electron Cloud.** This space-filling model of a hydrogen atom depicts the three-dimensional electron cloud formed by the single electron orbiting the nucleus.




if the nucleus were the size of a tennis ball, the electron cloud of a hydrogen atom would have a radius of 10 km (about 6 miles!). In reality, atoms are so small that atomic measurements are reported in nanometers (NAN-ō-mē-terz) (nm). One nanometer is $10^{-9}$ meter (0.000000001 m), or one billionth of a meter. The very largest atoms approach 0.5 nm in diameter.

## Elements and Isotopes

An **element** is a pure substance composed of atoms of only one kind. Atoms are the smallest particles of an element that still retain the characteristics of that element. As a result, each element has uniform composition and properties. Each element includes all the atoms with the same number of protons, and thus the same atomic number. Only 92 elements exist in nature. Researchers have created about two dozen additional elements through nuclear reactions in laboratories.

Every element has a chemical symbol, an abbreviation recognized by scientists everywhere. Most of the symbols are easy to connect with the English names of the elements (O for oxygen, N for nitrogen, C for carbon, and so on), but a few are abbreviations of their Latin names. For example, the symbol for sodium, Na, comes from the Latin word *natrium*.

Elements cannot be changed or broken down into simpler substances, whether by chemical processes, heating, or other ordinary physical means. For example, an atom of carbon always remains an atom of carbon, regardless of the chemical events in which it may take part.

Our bodies consist of many elements, and the 13 most abundant elements are listed in Table 2–1. Our bodies also contain atoms of another 14 elements—called *trace elements*—that are present in very small amounts.

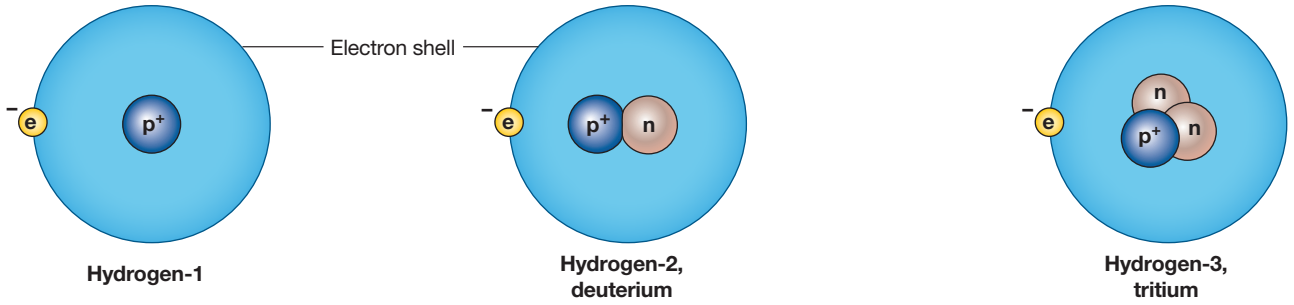
The atoms of a single element all have the same number of protons, but they can differ in the number of neutrons in the nucleus. For example, most hydrogen nuclei consist of just a single proton, but 0.015 percent also contain 1 neutron, and a very small percentage contain 2 neutrons (Figure 2–2). Atoms of the same element whose nuclei contain different numbers of neutrons are called **isotopes**.

Different isotopes of an element have essentially identical chemical properties, and are alike except in mass. The **mass number**—the total number of protons plus neutrons in the nucleus of an atom—is used to designate isotopes. For example, hydrogen has 3 isotopes, distinguished by their mass numbers (1, 2, or 3). Hydrogen-1, or $^{1}H$, has 1 proton and 1 electron (Figure 2–2a). Hydrogen-2, or $^{2}H$, also known as *deuterium*, has 1 proton, 1 electron, and 1 neutron (Figure 2–2b). Hydrogen-3,

**Table 2–1 Principal Elements in the Human Body**

| Element (% of total body weight) | Significance |
|---|---|
| **Oxygen, O** (65) | A component of water and other compounds; gaseous form is essential for respiration |
| **Carbon, C** (18.6) | Found in all organic molecules |
| **Hydrogen, H** (9.7) | A component of water and most other compounds in the body |
| **Nitrogen, N** (3.2) | Found in proteins, nucleic acids, and other organic compounds |
| **Calcium, Ca** (1.8) | Found in bones and teeth; important for membrane function, nerve impulses, muscle contraction, and blood clotting |
| **Phosphorus, P** (1.0) | Found in bones and teeth, nucleic acids, and high-energy compounds |
| **Potassium, K** (0.4) | Important for proper membrane function, nerve impulses, and muscle contraction |
| **Sodium, Na** (0.2) | Important for blood volume, membrane function, nerve impulses, and muscle contraction |
| **Chlorine, Cl** (0.2) | Important for blood volume, membrane function, and water absorption |
| **Magnesium, Mg** (0.06) | A cofactor for many enzymes |
| **Sulfur, S** (0.04) | Found in many proteins |
| **Iron, Fe** (0.007) | Essential for oxygen transport and energy capture |
| **Iodine, I** (0.0002) | A component of hormones of the thyroid gland |
| **Trace elements:** silicon (Si), fluorine (F), copper (Cu), manganese (Mn), zinc (Zn), selenium (Se), cobalt (Co), molybdenum (Mo), cadmium (Cd), chromium (Cr), tin (Sn), aluminum (Al), boron (B), and vanadium (V) | Some function as cofactors; the functions of many trace elements are poorly understood |

**Figure 2–2 The Structure of Hydrogen Atoms.** Three forms of hydrogen atoms are shown using the two-dimensional electron-shell model, which indicates the spherical electron cloud surrounding the nucleus.




**a** A typical hydrogen nucleus contains 1 proton and no neutrons.

**b** A deuterium ($^2$H) nucleus contains 1 proton and 1 neutron.

**c** A tritium ($^3$H) nucleus contains 1 proton and 2 neutrons.

or $^3$H, also known as *tritium*, has 1 proton, 1 electron, and 2 neutrons (Figure 2–2c).

The nuclei of some isotopes are unstable, or radioactive. That is, they spontaneously break down and give off *radiation* (energy in the form of moving subatomic particles or waves) in measurable amounts. Such isotopes are called **radioisotopes**. The breakdown process is called *radioactive decay*. The decay rate of a radioisotope is commonly expressed as its **half-life**: the time required for half of a given amount of the isotope to decay. Radioisotopes differ radically in how rapidly they decay; their half-lives range from fractions of a second to billions of years.

Weakly radioactive isotopes are sometimes used in diagnostic procedures to monitor the structural or functional characteristics of internal organs. However, strongly radioactive isotopes are dangerous, because the radiation they give off can alter the number of electrons in an atom, break apart molecules, and destroy cells and tissues.

## Atomic Weights

A typical *oxygen* atom has an atomic number of 8 and contains 8 protons and 8 neutrons. The mass number of this isotope is therefore 16. The mass numbers of other isotopes of oxygen depend on the number of neutrons present. Mass numbers are useful because they tell us the number of subatomic particles in the nuclei of different atoms. However, they do not tell us the *actual* mass of the atoms. For example, they do not take into account the masses of the electrons or the slight difference between the mass of a proton and that of a neutron. The actual mass of an atom of a specific isotope is known as its *atomic mass*.

The unit used to express atomic mass is the *atomic mass unit* (amu), or *dalton*. By international agreement, 1 amu is equal to one-twelfth the mass of a carbon-12 atom. One atomic mass unit is very close to the mass of a single proton or neutron. Thus, the atomic mass of an atom of the most common isotope of hydrogen is very close to 1, and that of the most common isotope of oxygen is very close to 16.

The **atomic weight** of an element is an average of the different atomic masses and proportions of its different isotopes. This results in the atomic weight of an element being very close to the mass number of the most common isotope of that element. For example, the mass number of the most common isotope of hydrogen is 1, but the atomic weight of hydrogen is closer to 1.01, primarily because some hydrogen atoms (0.02 percent) have a mass number of 2, and even fewer have a mass number of 3. (The periodic table of the elements in the Appendix at the back of this book shows the atomic weight of each element.)

Atoms take part in chemical reactions in fixed numerical ratios. To form water, for example, exactly 2 atoms of hydrogen combine with 1 atom of oxygen. But individual atoms are far too small and too numerous to be counted, so to determine the number of atoms chemists use a unit called the *mole*. For any element, a **mole** (abbreviated *mol*) is a specific quantity with a weight in grams equal to that element's atomic weight.

The mole is useful because 1 mol of a given element always contains the same number of atoms as 1 mol of any other element (just as we use *dozen* to stand for 12 items). That number (called *Avogadro's number*) is $6.023 \times 10^{23}$, or about 600 billion trillion. Expressing relationships in moles rather than in grams makes it much easier to keep track of the relative numbers of atoms in chemical samples and processes. For example, if a report stated that a sample contains 0.5 mol of hydrogen atoms and 0.5 mol of oxygen atoms, you would know immediately that the 2 elements were present in equal numbers. That would not be so evident if the report stated that there were 0.505 g of hydrogen atoms and 8.00 g of oxygen atoms. Most chemical analyses and clinical laboratory tests report data in moles (mol), millimoles (mmol—1/1000 mol, or $10^{-3}$ mol), or micromoles (μmol—1/1,000,000 mol, or $10^{-6}$ mol).

## Electrons and Energy Levels

Atoms are electrically neutral. In other words, every positively charged proton is balanced by a negatively charged electron. Thus, each increase in the atomic number has a comparable increase in the number of electrons traveling around the nucleus.

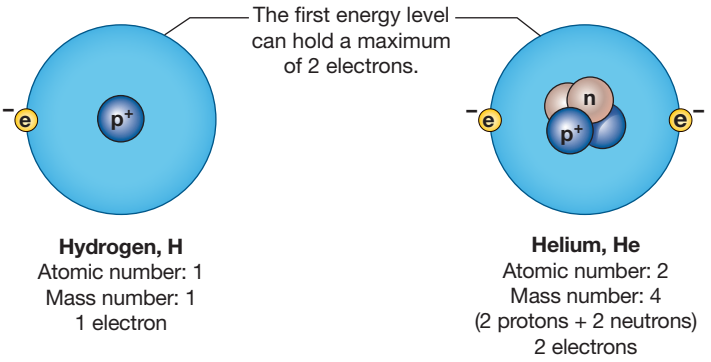
Within the electron cloud, electrons occupy an orderly series of *energy levels*. The electrons in an energy level may travel in complex patterns around the nucleus, but for our purposes the patterns can be diagrammed as a series of concentric electron shells. The first electron shell is the one closest to the nucleus, and it corresponds to the lowest energy level of electrons. Note that the terms *electron shell* and *energy level* can generally be used interchangeably.

There are up to eight energy levels in atoms, depending on their atomic number, but let's just look at the first three here. Each energy level is limited in the number of electrons it can hold. The first energy level can hold at most 2 electrons. The next two levels can each hold up to 8 electrons, an observation called the *octet rule*. Note that the maximum number of electrons that may occupy shells 1 through 3 corresponds to the number of elements in rows 1 through 3 of the periodic table of the elements (see Appendix). The electrons in an atom occupy successive shells in an orderly manner: The first energy level fills before any electrons enter the second, and the second energy level fills before any electrons enter the third.

The outermost energy level, or electron shell, forms the "surface" of the atom and is called the **valence shell**. (The *valence* of an element refers to its combining power with other atoms.) The number of electrons in this level determines the chemical properties of the element. Atoms with unfilled valence shells are unstable—that is, they will react with other atoms, usually in ways that result in full valence shells. In contrast, atoms with a filled valence shell are stable and therefore do not readily react with other atoms.

As indicated in Figure 2–3a, a hydrogen atom has 1 electron in the first energy level, the valence shell, so that level is unfilled. Therefore, a hydrogen atom readily reacts with other atoms. A helium atom has 2 electrons in its first energy level, which means its valence shell is filled (Figure 2–3b). This makes the helium atom very stable; it will not ordinarily react with other atoms. A lithium atom has 3 electrons (Figure 2–3c). Its first energy level can hold only 2 of them, so lithium has a single electron in a second, unfilled energy level. Thus, like hydrogen, lithium is unstable and reactive. The valence shell is filled in a neon atom, which has an atomic number of 10 (Figure 2–3d). Neon atoms, like helium atoms and other elements in the far right column of the periodic table, are very stable. The atoms of elements that are most important to biological systems are unstable (see Table 2–1, p. 75). Their instability promotes atomic interactions to form larger structures.

**Figure 2–3 The Arrangement of Electrons into Energy Levels.** The electron-shell model is also used to indicate the relative energy of electrons in an atom.

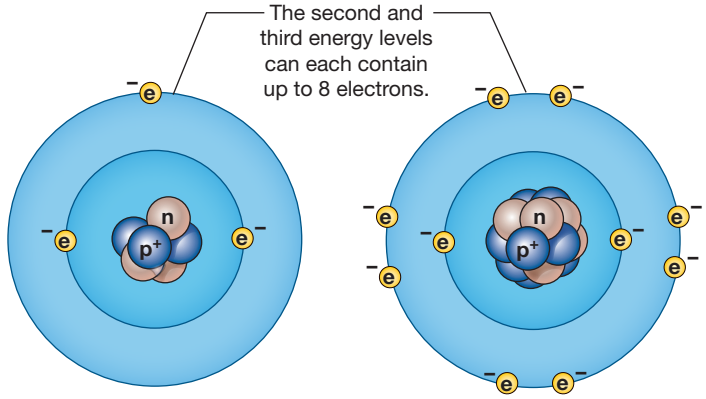



**Hydrogen, H**
Atomic number: 1
Mass number: 1
1 electron

**Helium, He**
Atomic number: 2
Mass number: 4
(2 protons + 2 neutrons)
2 electrons

**a Hydrogen (H).** A typical hydrogen atom has 1 proton and 1 electron. The electron orbiting the nucleus occupies the first, or lowest, energy level, diagrammed as an electron shell.

**b Helium (He).** An atom of helium has 2 protons, 2 neutrons, and 2 electrons. The 2 electrons orbit in the same energy level.




**Lithium, Li**
Atomic number: 3
Mass number: 6
(3 protons + 3 neutrons)
3 electrons

**Neon, Ne**
Atomic number: 10
Mass number: 20
(10 protons + 10 neutrons)
10 electrons

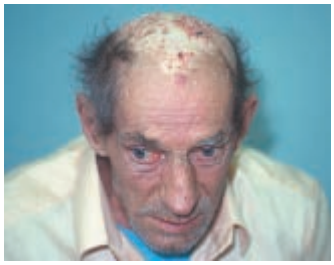
**c Lithium (Li).** A lithium atom has 3 protons, 3 neutrons, and 3 electrons. The first energy level can hold only 2 electrons, so the third electron occupies the second energy level.

**d Neon (Ne).** A neon atom has 10 protons, 10 neutrons, and 10 electrons. The second level can hold up to 8 electrons; thus, both the first and second energy levels are filled.

**?** How many electrons can the second energy level hold when it is completely filled?

## + Clinical Note Radiation Sickness

*Radiation sickness* results from excessive exposure to ionizing radiation. It is characterized by fatigue, nausea, vomiting, and loss of teeth and hair. More severe cases cause anemia (low red blood cell count), central nervous damage, and death. In a clinical setting, it can occur when large doses of cancer-treating radiation are given to a person over a short time period. (X-rays and CT scans use low-dose radiation and do not cause radiation sickness.) The amount of radiation received determines how sick a person can become. In 2011, a tsunami damaged a nuclear reactor in Fukushima, Japan, releasing a lethal radioactive form of iodine, I-131. Since then, public health officials have made potassium iodide (KI) available to people who live near such reactors. This benign salt saturates the thyroid gland with stable (nonradioactive) iodine so that it cannot absorb I-131.



## √ Checkpoint

1. Define *atom*.
2. Atoms of the same element that have different numbers of neutrons are called _____.
3. How is it possible for two samples of hydrogen to contain the same number of atoms, yet have different weights?

See the blue Answers tab at the back of the book.

## 2-2 Chemical bonds are forces formed by interactions between atoms

**Learning Outcome** Compare the ways in which atoms combine to form molecules and compounds.

Elements without active chemical properties are said to be *inert*. The noble gases helium, neon, and argon have filled valence shells and are called *inert gases*, because their atoms do not undergo chemical reactions.

Elements with unfilled valence shells, such as hydrogen and lithium, are called *reactive*, because they readily interact or combine with other atoms. Reactive atoms become stable by gaining, losing, or sharing electrons to fill their valence shells. The interactions often involve the formation of **chemical bonds**, which hold the participating atoms together once the chemical reaction has ended.

When chemical bonding takes place, new chemical entities called *molecules* and *compounds* are created. Chemical bonding may or may not involve the sharing of electrons. The term **molecule** refers to any chemical structure consisting of atoms held together by shared electrons. A **compound** is a pure chemical substance made up of atoms of two or more different elements in a fixed proportion, regardless of whether electrons are shared or not. The two categories overlap, but they are not the same. Not all molecules are compounds, because some molecules consist of atoms of only one element. (For example, two oxygen atoms can be joined by sharing electrons to form a molecule of oxygen.) And not all compounds consist of molecules, because some compounds, such as ordinary table salt (sodium chloride) are held together by bonds that do not involve shared electrons.

Many substances, however, fit both categories. Take water, for example. Water is a compound because it contains two different elements—hydrogen and oxygen—in a fixed proportion of two hydrogen atoms to one oxygen atom. It also consists of molecules, because the two hydrogen atoms and one oxygen atom are held together by shared electrons. As we will see in later sections, most biologically important compounds, from carbohydrates to DNA, are molecules.

Regardless of the type of bonding involved, a chemical compound has properties that can be quite different from those of its components. For example, a mixture of hydrogen gas and oxygen gas can explode, but the explosion is a chemical reaction that produces liquid water, a compound used to put out fires.

The **molecular weight** of a molecule or compound is the sum of the atomic weights of its component atoms. It follows from the definition of the mole given previously (p. 76) that the molecular weight of a molecule or compound in grams is equal to the mass of 1 mol of molecules or a compound. Molecular weights are important because we cannot handle individual molecules or parts of a compound nor can we easily count the billions involved in chemical reactions in the body.

As an example of how to calculate a molecular weight, let's use water, or $H_2O$. The atomic weight of hydrogen is 1.0079. To simplify our calculations, we round that value to 1. Then, 1 hydrogen molecule ($H_2$) with its 2 atoms has a molecular weight of $2(1 \times 2 = 2)$. One oxygen atom has an atomic weight of 16. Summing up, the molecular weight of 1 molecule of $H_2O$ is 18. One mole of water molecules would then have a mass of 18 grams.

The human body consists of countless molecules and compounds, so it is a challenge to describe these substances and their varied interactions. Chemists simplify such descriptions through a standardized system of *chemical notation*. The basic rules of this system for atoms and molecules are described in **Spotlight Figure 2–4a,b**.

# SPOTLIGHT

Figure 2–4
## Chemical Notation

In order to discuss the specific compounds that occur in the human body, we must be able to describe chemical compounds and reactions clearly. To do this, we use a simple form of "chemical shorthand" known as **chemical notation**. Chemical notation enables us to describe complex events briefly and precisely; its rules are summarized below.

### a Atoms

The symbol of an element indicates 1 atom of that element. A number preceding the symbol of an element indicates more than 1 atom of that element.

### b Molecules

A numerical subscript following the symbol of an element indicates the number of atoms of that element in a molecule.

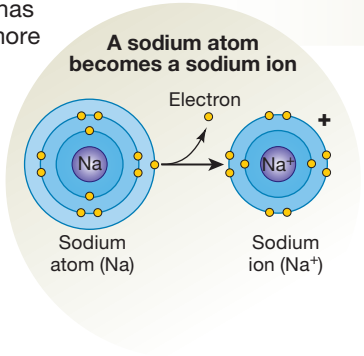
### c Reactions

In a description of a chemical reaction, the participants at the start of the reaction are called reactants, and the reaction generates one or more products. Chemical reactions are represented by chemical equations. An arrow indicates the direction of the reaction, from reactants (usually on the left) to products (usually on the right). In the following reaction, 2 atoms of hydrogen combine with 1 atom of oxygen to produce a single molecule of water.

### d Ions

A superscript plus or minus sign following the symbol of an element indicates an ion. A single plus sign indicates a cation with a charge of +1. (The original atom has given up 1 electron.) A single minus sign indicates an anion with a charge of –1. (The original atom has gained 1 electron.) If more than 1 electron is involved, the charge on the ion is indicated by a number preceding the plus or minus sign.

| VISUAL REPRESENTATION | | CHEMICAL NOTATION | |
|---|---|---|---|
| H<br>1 atom of hydrogen | O<br>1 atom of oxygen | H<br>1 atom of hydrogen | O<br>1 atom of oxygen |
| H H<br>2 atoms of hydrogen | O O<br>2 atoms of oxygen | 2H<br>2 atoms of hydrogen | 2O<br>2 atoms of oxygen |
| H H<br>hydrogen molecule<br>composed of 2 hydrogen atoms | O O<br>oxygen molecule<br>composed of 2 oxygen atoms | $H_2$<br>hydrogen molecule | $O_2$<br>oxygen molecule |
| H H O<br>water molecule<br>composed of 2 hydrogen atoms and 1 oxygen atom | | $H_2O$<br>water molecule | |
| H H + O → H H O<br>**Reactants** **Product**<br>Chemical reactions neither create nor destroy atoms; they merely rearrange atoms into new combinations. Therefore, the numbers of atoms of each element must always be the same on both sides of the equation for a chemical reaction. When this is the case, the equation is balanced. | | $2H + O \longrightarrow H_2O$<br>Balanced equation | |
| | | $2H + 2O \longrightarrow H_2O$<br>Unbalanced equation | |
| $Na^+$<br>sodium ion<br>the sodium atom has given up 1 electron | $Cl^-$<br>chloride ion<br>the chlorine atom has gained 1 electron | $Ca^{2+}$<br>calcium ion<br>the calcium atom has given up 2 electrons | |
| | | $Na^+$<br>sodium ion | $Cl^-$<br>chloride ion |
| | | $Ca^{2+}$<br>calcium ion | |



In the sections that follow, we consider three basic types of chemical bonds: *ionic bonds*, *covalent bonds*, and *hydrogen bonds*.

## Ionic Bonds

An **ion** is an atom or group of atoms that has an electric charge, either positive or negative. Ions with a positive charge (+) are called **cations** (KAT-ī-onz). Ions with a negative charge (−) are called **anions** (AN-ī-onz).

### Tips & Tools

Think of the ***t*** in ca***t***ion as a plus sign (+) to remember that a ca***t***ion has a positive charge, and think of the ***n*** in a***n***ion as standing for ***n***egative (−) to remember that a***n***ions have a ***n***egative charge.

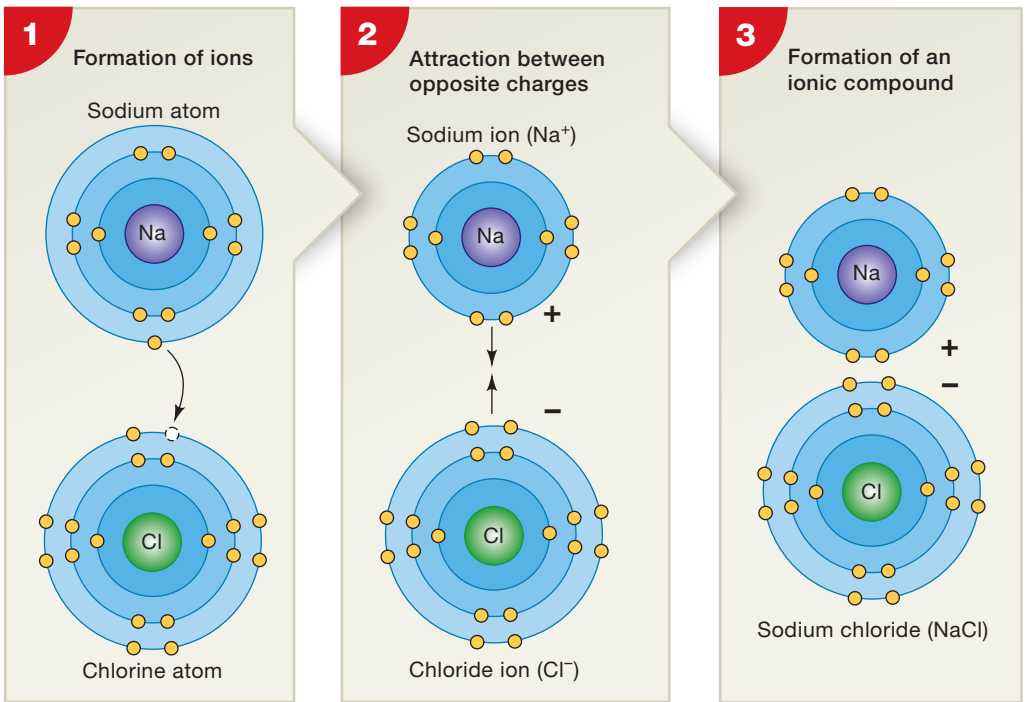
Atoms become ions by losing or gaining electrons, so ions have an unequal number of protons and electrons. We assign a value of +1 to the charge on a proton, while the charge on an electron is −1. An atom that loses an electron becomes a cation with a charge of +1, because it then has 1 proton that lacks a corresponding electron. Losing a second electron would give the cation a charge of +2. Adding an extra electron to a neutral atom produces an anion with a charge of −1. Adding a second electron gives the anion a charge of −2 (**Spotlight Figure 2–4d**).

**Ionic bonds** are chemical bonds created by the electrical attraction between anions and cations. In the formation of an ionic bond, the following steps occur:

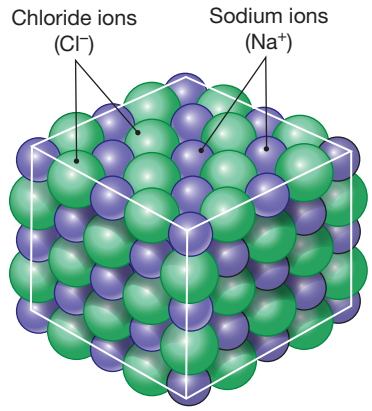
1. One atom—the *electron donor*—loses one or more electrons and becomes a cation, with a positive (+) charge. Another atom—the *electron acceptor*—gains those same electrons and becomes an anion, with a negative (−) charge.
2. Attraction between the opposite charges then draws the two ions together.
3. An ionic compound is formed.

**Figure 2–5a** illustrates the formation of an ionic bond. The sodium atom diagrammed in 1 has an atomic number of 11, so this atom normally contains 11 protons and 11 electrons. (Because neutrons are electrically neutral, they do not affect the formation of ions or ionic bonds.) Electrons fill the first and second energy levels, and a single electron occupies the valence shell. Losing that 1 electron would give the sodium atom a full valence shell—the second energy level—and would produce a **sodium ion**, with a charge of +1. (The chemical shorthand for a sodium ion is $Na^+$.) But a sodium atom cannot simply throw

**Figure 2–5** The Formation of Ionic Bonds.




**a Formation of an ionic bond.** 1 A sodium (Na) atom gives up an electron, which is gained by a chlorine (Cl) atom. 2 Because the sodium ion ($Na^+$) and chloride ion ($Cl^-$) have opposite charges, they are attracted to one another. 3 The association of sodium and chloride ions forms the ionic compound sodium chloride.




**b Sodium chloride crystal.** Large numbers of sodium and chloride ions form a crystal of sodium chloride (table salt).

**c Photo of sodium chloride crystals**

Go to Pearson Mastering A&P™ > Study Area > Get Ready for A&P > 2. Get Ready for A&P Website> Chapter 5: Chemistry > Chemical Bonding: Video Tutor: Introduction to Chemical Bonding

away the electron: The electron must be donated to an electron acceptor. A chlorine atom has seven electrons in its valence shell, so it needs only one electron to achieve stability. A sodium atom can provide the extra electron. In the process (1), the chlorine atom becomes a **chloride ion** ($Cl^-$) with a charge of −1.

Both atoms have now become stable ions with filled outermost energy levels. But the two ions do not move apart after the electron transfer, because the positively charged sodium ion is attracted to the negatively charged chloride ion (2). The combination of oppositely charged ions forms an *ionic compound*—in this case, **sodium chloride**, or NaCl (3). Large numbers of sodium and chloride ions interact to form highly structured crystals, held together by the strong electrical attraction of oppositely charged ions (Figure 2–5b,c).

Note that ionic compounds are not molecules. That is because they consist of a group of ions rather than atoms bonded by shared electrons. Sodium chloride and other ionic compounds are common in body fluids, but they are not present as intact crystals. When placed in water, many ionic compounds dissolve, and some or all of the component anions and cations separate.

## Covalent Bonds

Some atoms can complete their valence shells not by gaining or losing electrons, but by sharing electrons with other atoms. Such sharing creates **covalent** (kō-VĀ-lent) **bonds** between the atoms involved.

Individual hydrogen atoms, as diagrammed in Figure 2–2a, do not exist in nature. Instead, we find hydrogen molecules. Molecular hydrogen consists of a pair of hydrogen atoms (Figure 2–6). In chemical shorthand, molecular hydrogen is $H_2$, where H is the chemical symbol for hydrogen, and the subscript 2 indicates the number of atoms. Molecular hydrogen is a gas that is present in the atmosphere in very small quantities. When the two hydrogen atoms share their electrons, each electron whirls around both nuclei. The sharing of one pair of electrons creates a **single covalent bond**, which can be represented by a single line ( — ) in the *structural formula* of a molecule.

Oxygen, with an atomic number of 8, has 2 electrons in its first energy level and 6 in its second. The oxygen atoms diagrammed in Figure 2–6 become stable by sharing two pairs of electrons, forming a **double covalent bond**, represented by two lines (═) in its structural formula. Molecular oxygen ($O_2$) is an atmospheric gas that most organisms need to survive. Our cells would die without a relatively constant supply of oxygen.

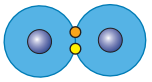
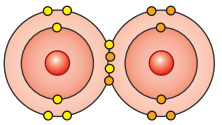
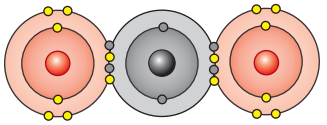
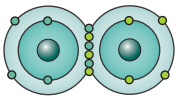
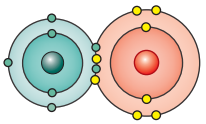
In our bodies, chemical processes that consume oxygen generally also produce **carbon dioxide** ($CO_2$) as a waste product. Each of the oxygen atoms in a carbon dioxide molecule forms double covalent bonds with the carbon atom, as Figure 2–6 shows.

A triple covalent bond is the sharing of three pairs of electrons, and is indicated by three lines (≡) in a structural formula. A triple covalent bond joins 2 nitrogen atoms to form molecular nitrogen ($N_2$) (see Figure 2–6). Molecular nitrogen accounts for about 79 percent of our planet's atmosphere, but our cells ignore it completely. In fact, deep-sea divers live for long periods while breathing artificial air that does not contain nitrogen. (We discuss the reasons for eliminating nitrogen under these conditions in the Decompression Sickness Clinical Note in Chapter 23.)

Covalent bonds usually form molecules in which the valence shells of the atoms involved are filled. An atom, ion, or molecule that contains unpaired electrons in its valence shell is called a *free radical*. Free radicals are highly reactive. Almost as fast as it forms, a free radical enters additional reactions that are typically destructive. For example, free radicals can damage or destroy vital compounds, such as proteins. Evidence suggests that the cumulative damage from free radicals inside and outside our cells is a major factor in the aging process. Free radicals sometimes form in the course of normal metabolism, but cells have several methods of removing or inactivating them.

*Nitric oxide* (NO), however, is a free radical with several important functions in the body (see Figure 2–6). It reacts readily with other atoms or molecules, but it is involved in chemical communication in the nervous system, in the control of blood vessel diameter, in blood clotting, and in the defense against bacteria and other pathogens (disease-causing organisms).

**Figure 2–6** Covalent Bonds in Five Common Molecules.

| Molecule | Electron-Shell Model and Structural Formula |
|---|---|
| Hydrogen ($H_2$) |  H–H |
| Oxygen ($O_2$) |  O=O |
| Carbon dioxide ($CO_2$) |  O=C=O |
| Nitrogen ($N_2$) |  N≡N |
| Nitric oxide (NO) |  N=O |

Go to Pearson Mastering A&P™ > Study Area > Get Ready for A&P > 2. Get Ready for A&P Website> Chapter 5: Chemistry > Chemical Bonding: Video Tutor: Ionic Bonding

## Tips & Tools

Remember this mnemonic for the covalent bonding of hydrogen, oxygen, nitrogen, and carbon atoms: HONC 1234. ***H***ydrogen shares *1* pair of electrons (H—), ***o***xygen shares *2* pairs (—O—), ***n***itrogen shares 3 pairs (—$\overset{|}{\underset{|}{N}}$—), and ***c***arbon shares *4* pairs (—$\overset{|}{\underset{|}{C}}$—).

### Nonpolar Covalent Bonds

Covalent bonds are very strong, because the shared electrons hold the atoms together. In typical covalent bonds the atoms remain electrically neutral, because each shared electron spends just as much time "at home" as away. (If you and a friend were tossing a pair of baseballs back and forth as fast as you could, on average, each of you would have just one baseball.)

Many covalent bonds involve an equal sharing of electrons. Such bonds are called **nonpolar covalent bonds**. They occur, for instance, between 2 atoms of the same type. Nonpolar covalent bonds are very common. In fact, those involving carbon atoms form most of the structural components of the human body.

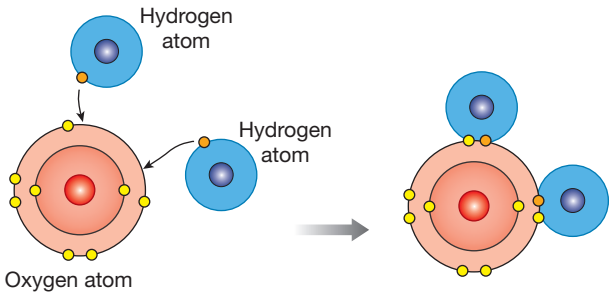
### Polar Covalent Bonds

Covalent bonds involving different types of atoms may involve an unequal sharing of electrons, because the elements differ in how strongly they attract electrons. An unequal sharing of electrons creates a **polar covalent bond**. In chemistry, *polarity* refers to a separation of positive and negative electric charge. It can apply to a bond or entire molecule. For example, in a molecule of water, an oxygen atom forms covalent bonds with 2 hydrogen atoms (Figure 2–7a). The oxygen nucleus (with its 8 protons) has a much stronger attraction for the shared electrons than the hydrogen atoms (each with a single proton). As a result, the electrons spend more time orbiting the oxygen nucleus than orbiting the hydrogen nuclei.

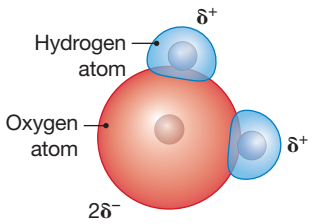
Because the oxygen atom has two extra electrons most of the time, it develops a slight (partial) negative charge, indicated by $\delta^-$, as shown in Figure 2–7b. At the same time, each hydrogen atom develops a slight (partial) positive charge, $\delta^+$, because its electron is away much of the time. (Suppose you and a friend were tossing a pair of baseballs back and forth, but one of you returned them as fast as possible while the other held onto them for a while before throwing them back. One of you would now, on average, have more than one baseball, and the other would have less than one.)

The unequal sharing of electrons makes polar covalent bonds somewhat weaker than nonpolar covalent bonds. Polar covalent bonds often create *polar molecules*—molecules that have positive and negative ends. Water is the most important polar molecule in the body.

**Figure 2–7 Water Molecules Contain Polar Covalent Bonds.**




**a Formation of a water molecule.** In forming a water molecule, an oxygen atom completes its valence shell by sharing electrons with a pair of hydrogen atoms. The sharing is unequal, because the oxygen atom holds the electrons more tightly than do the hydrogen atoms.




**b Electric charges on a water molecule.** Because the oxygen atom has 2 extra electrons much of the time, it develops a slight negative charge, and the hydrogen atoms become weakly positive. The bonds in a water molecule are polar covalent bonds.

### Hydrogen Bonds

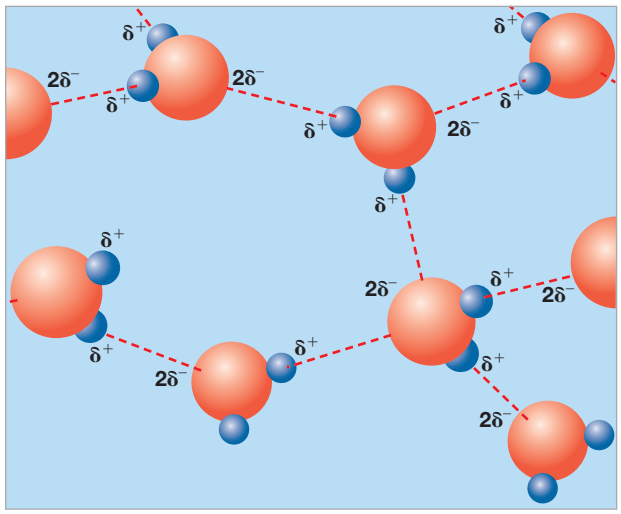
Covalent and ionic bonds tie atoms together to form molecules and/or compounds. Other, comparatively weak forces also act between adjacent molecules, and even between atoms within a large molecule. The most important of these weak attractive forces is the hydrogen bond. A **hydrogen bond** is the attraction between a slight positive charge ($\delta^+$) on the hydrogen atom of a polar covalent bond and a slight negative charge ($\delta^-$) on an oxygen, nitrogen, or fluorine atom of another polar covalent bond.

Hydrogen bonds are too weak to create molecules, but they can change the shapes of molecules or pull molecules closer together. For example, hydrogen bonding occurs between water molecules, forming clumps, or groups, of interconnected water molecules (Figure 2–8). At a water surface, this attraction between water molecules slows the rate of evaporation and creates what is known as *surface tension*. Surface tension acts as a barrier that keeps lightweight objects that cannot break through the top layer of water molecules from entering the water. For example, it allows insects to walk across the surface of a pond or puddle. Similarly, the surface tension in a layer of tears on the eye prevents dust particles from touching the surface of the



Go to Pearson Mastering A&P™ > Study Area > Get Ready for A&P > 2. Get Ready for A&P Website> Chapter 5: Chemistry > Chemical Bonding: Video Tutor: Covalent Bonding

**Figure 2–8 Hydrogen Bonds Form between Water Molecules.** The hydrogen atoms of a water molecule have a slight positive charge, and the oxygen atom has a slight negative charge (*see Figure 2–7b*). The distances between these molecules have been exaggerated for clarity.




? Hydrogen bonds do not form between two hydrogen atoms. Where do hydrogen bonds form?

eye. At the cellular level, hydrogen bonds affect the shapes and properties of large, complex molecules, such as proteins and nucleic acids (including DNA).

## States of Matter

Most matter in our environment exists in one of three states: solid, liquid, or gas. *Solids* keep their volume and their shape at ordinary temperatures and pressures. A lump of granite, a brick, and a textbook are solid objects. *Liquids* have a constant volume, but no fixed shape. The shape of a liquid is determined by the shape of its container. Water, coffee, and soda are liquids. A *gas* has no constant volume and no fixed shape. Gases can be compressed or expanded, and unlike liquids they will fill a container of any size. The most familiar example is the air of our atmosphere.

What determines whether a substance is a solid, liquid, or gas? A matter's state depends on the degree of interaction among its atoms or molecules. The particles of a solid are held tightly together, while those of a gas are very far apart. Water is the only substance that occurs as a solid (ice), a liquid (water), and a gas (water vapor) at temperatures compatible with life. Water exists as a liquid over a broad range of temperatures primarily because of hydrogen bonding among the water molecules. We talk more about water's unusual properties in Section 2-6.

### Checkpoint

4. Define *chemical bond* and identify several types of chemical bonds.
5. Which kind of bond holds atoms in a water molecule together? What attracts water molecules to one another?
6. Both oxygen and neon are gases at room temperature. Oxygen combines readily with other elements, but neon does not. Why?

See the blue Answers tab at the back of the book.

# 2-3 Decomposition, synthesis, and exchange reactions are important types of chemical reactions in physiology

**Learning Outcome** Distinguish among the major types of chemical reactions that are important for studying physiology.

Cells stay alive and functional by controlling chemical reactions. In a **chemical reaction**, new chemical bonds form between atoms, or existing bonds between atoms are broken. These changes take place as atoms in the reacting substances, called **reactants**, are rearranged to form different substances, or **products** (see Spotlight Figure 2–4c).

In effect, each cell is a chemical factory. Cells use chemical reactions to provide the energy they need to maintain homeostasis and to perform essential functions such as growth, maintenance and repair, secretion (discharging from a cell), and contraction. All of the reactions under way in the cells and tissues of the body at any given moment make up its **metabolism** (me-TAB-ō-lizm).

## Basic Energy Concepts

An understanding of some basic relationships between matter and energy is helpful for any discussion of chemical reactions. **Work** is the movement of an object or a change in the physical structure of matter. In your body, work includes movements such as walking or running, and also the synthesis of *organic* (carbon-containing) molecules and the conversion of liquid water to water vapor (evaporation). **Energy** is the capacity to do work, and movement or physical change cannot take place without energy. The two major types of energy are kinetic energy and potential energy:

- **Kinetic energy** is the energy of motion—energy that can be transferred to another object and do work. When you fall off a ladder, it is kinetic energy that does the damage.

- **Potential energy** is stored energy—energy that has the potential to do work. It may derive from an object's position (you standing on a ladder) or from its physical or chemical structure (a stretched spring or a charged battery).

Kinetic energy must be used in climbing the ladder, in stretching the spring, or in charging the battery. The resulting potential energy is converted back into kinetic energy when you descend, the spring recoils, or the battery discharges. The kinetic energy can then be used to perform work. For example, in an MP3 player, the chemical potential energy stored in small batteries is converted to kinetic energy that vibrates the sound-producing membranes in headphones or external speakers.

Energy cannot be destroyed: It can only be converted from one form to another. A conversion between potential energy and kinetic energy is never 100 percent efficient. Each time an energy exchange occurs, some of the energy is released in the form of heat. *Heat* is an increase in random molecular motion, and the temperature of an object is proportional to the average kinetic energy of its molecules. Heat can never be completely converted to work or any other form of energy, and cells cannot capture it or use it to do work.

Cells do work as they use energy to synthesize complex molecules and move materials into, out of, and within the cell. The cells of a skeletal muscle at rest, for example, contain potential energy in the form of the positions of protein filaments and the covalent bonds between molecules inside the cells. When a muscle contracts, it performs work. Potential energy is converted into kinetic energy, and heat is released. The amount of heat is proportional to the amount of work done. As a result, when you exercise, your body temperature rises.

## Types of Chemical Reactions

Three types of chemical reactions are important to the study of physiology: decomposition reactions, synthesis reactions, and exchange reactions. Many of these chemical reactions are also *reversible reactions*.

### Decomposition Reactions

A **decomposition reaction** breaks a molecule into smaller fragments. Here is a diagram of a simple *decomposition reaction*:

$$AB \longrightarrow A + B$$

Decomposition reactions take place outside cells as well as inside them. For example, a typical meal contains molecules of fats, sugars, and proteins that are too large and too complex to be absorbed and used by your body. Decomposition reactions in the digestive tract break these molecules down into smaller fragments that can be absorbed.

Decomposition reactions involving water are important in the breakdown of complex molecules in the body. In this process, which is called a **hydrolysis reaction** (hī-DROL-i-sis; *hydro-*, water + *lysis*, a loosening), one of the bonds in a complex molecule is broken, and the components of a water molecule (H and OH) are added to the resulting fragments:

$$AB + H_2O \longrightarrow AH + BOH$$

Collectively, the decomposition reactions of complex molecules within the body's cells and tissues are referred to as **catabolism** (ka-TAB-ō-lizm; *katabole*, a throwing down). When a covalent bond—a form of potential energy—is broken, it releases kinetic energy that can do work. By harnessing the energy released in this way, cells carry out vital functions such as growth, movement, and reproduction.

### Synthesis Reactions

*Synthesis* (SIN-the-sis) is the opposite of decomposition. A **synthesis reaction** assembles smaller molecules into larger molecules. A simple synthetic reaction is diagrammed here:

$$A + B \longrightarrow AB$$

Synthesis reactions may involve individual atoms or the combination of molecules to form even larger products. The formation of water from hydrogen and oxygen molecules is a synthesis reaction. Synthesis always involves the formation of new chemical bonds, whether the reactants are atoms or molecules.

A **dehydration synthesis**, or *condensation*, **reaction** is the formation of a complex molecule by the removal of a water molecule:

$$AH + BOH \longrightarrow AB + H_2O$$

Dehydration synthesis is the opposite of hydrolysis. We look at examples of both reactions in later sections (Sections 2-9, 2-10, and 2-11).

Collectively, the synthesis of new molecules within the body's cells and tissues is known as **anabolism** (a-NAB-ō-lizm; *anabole*, a throwing upward). Anabolism is usually considered an "uphill" process because it takes energy to create a chemical bond (just as it takes energy to push something uphill). Cells must balance their energy budgets, with catabolism providing the energy to support anabolism and other vital functions.

### Tips & Tools

To remember the difference between anabolism (synthesis) and catabolism (breakdown), relate the terms to words you already know: *Anabolic* steroids are used to build up muscle tissue, while both *catastrophe* and *catabolism* involve destruction (breakdown).

### Exchange Reactions

In an **exchange reaction**, parts of the reacting molecules are shuffled around to produce new products:

$$AB + CD \longrightarrow AD + CB$$

The reactants and products contain the same components (A, B, C, and D), but those components are present in different combinations. In an exchange reaction, the reactant molecules AB and CD must break apart (a decomposition) before they can interact with each other to form AD and CB (a synthesis).

### Reversible Reactions

At least in theory, chemical reactions are reversible, so if $A + B \longrightarrow AB$, then $AB \longrightarrow A + B$. Many important biological reactions are freely reversible. Such reactions can be represented as an equation:

$$A + B \rightleftharpoons AB$$

This equation indicates that, in a sense, two reactions are taking place at the same time. One is a synthesis reaction ($A + B \rightarrow AB$) and the other is a decomposition reaction ($AB \rightarrow A + B$).

Recall from Chapter 1 that a state of *equilibrium* exists when opposing processes or forces are in balance. At equilibrium, the rates of the two reactions are in balance. As fast as one molecule of AB forms, another degrades into A + B.

What happens when equilibrium is disturbed—say, if you add more AB? In our example, the rate of the synthesis reaction is directly proportional to the frequency of encounters between A and B. In turn, the frequency of encounters depends on the degree of crowding. (You are much more likely to bump into another person in a crowded room than in a room that is almost empty.) So adding more AB molecules will increase the rate of conversion of AB to A and B. The amounts of A and B will then increase, leading to an increase in the rate of the reverse reaction—the formation of AB from A and B. Eventually, a balance, or equilibrium, is again established.

### Tips & Tools

Jell-O provides an example of a physical reversible reaction. Once Jell-O has been refrigerated, the gelatin sets up and forms a solid, but if it sits without refrigeration for too long, it turns back into a liquid again.

### Checkpoint

7. **Using the rules for chemical notation, how is an ion's electrical charge represented?**
8. **Using the rules for chemical notation, write the molecular formula for glucose, a compound composed of 6 carbon atoms, 12 hydrogen atoms, and 6 oxygen atoms.**
9. **Identify and describe three types of chemical reactions important to human physiology.**
10. **In cells, glucose, a six-carbon molecule, is converted into two three-carbon molecules by a reaction that releases energy. What type of reaction is this?**

See the blue Answers tab at the back of the book.

## 2-4 Enzymes speed up reactions by lowering the energy needed to start them

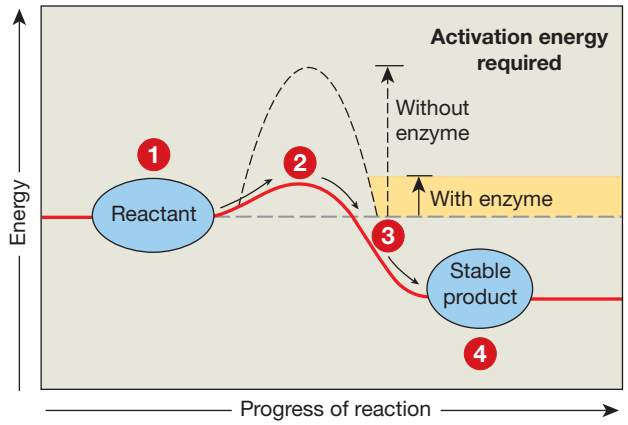
**Learning Outcome** Describe the crucial role of enzymes in metabolism.

Most **biochemical reactions** (those that happen in living organisms) do not take place spontaneously, or if they do, they occur so slowly that they would be of little value to living cells. Before a reaction can proceed, enough energy must be provided to activate the reactants. The amount of energy required to start a reaction is called the **activation energy**. Many reactions can be activated by changes in temperature or acidity, but such changes are deadly to cells. For example, every day your cells break down complex sugars as part of your normal metabolism. Yet to break down a complex sugar in a laboratory, you must boil it in an acidic solution. Your cells don't have that option! Temperatures that high and solutions that corrosive would immediately destroy living tissues. Instead, your cells use special proteins called *enzymes* to catalyze (speed up) most of the complex synthesis and decomposition reactions in your body.

**Enzymes** promote chemical reactions by lowering their required activation energy (Figure 2–9). In doing so, they make it possible for chemical reactions, such as the breakdown of sugars, to proceed under conditions compatible with life. Cells make enzyme molecules, each of which promotes a specific reaction.

Enzymes belong to a class of substances called **catalysts** (KAT-uh-lists; *katalysis*, dissolution), compounds that speed up

**Figure 2–9 Enzymes Lower Activation Energy.** Enzymes lower the activation energy required for a chemical reaction to proceed readily (in order, from 1–4) under conditions in the body.




? Which number represents the greatest amount of energy that must be overcome during the reaction? Which number represents the lowest amount of reaction energy?

chemical reactions without themselves being permanently changed or consumed. Enzymatic reactions, which are reversible, can be written as

$$A + B \overset{\text{enzyme}}{\rightleftharpoons} AB$$

An appropriate enzyme can accelerate, or speed up, a reaction, but an enzyme affects only the *rate* of the reaction, not its direction or the products that are formed. An enzyme cannot bring about a reaction that would otherwise be impossible. Enzymatic reactions are generally reversible, and they proceed until equilibrium is reached.

The complex reactions that support life take place in a series of interlocking steps, each controlled by a specific enzyme. Such a reaction sequence is called a *metabolic pathway*. A synthetic pathway can be diagrammed as

$$A \xrightarrow[\text{Step 1}]{\text{enzyme 1}} B \xrightarrow[\text{Step 2}]{\text{enzyme 2}} C \xrightarrow[\text{Step 3}]{\text{enzyme 3}} \text{and so on.}$$

In many cases, the steps in the synthetic pathway differ from those in the decomposition pathway, and separate enzymes are often involved.

It takes activation energy to start a chemical reaction, but once it has begun, the reaction as a whole may absorb or release energy as it proceeds to completion. If the amount of energy released is greater than the activation energy needed to start the reaction, there will be a net release of energy. Reactions that release energy are said to be **exergonic** (*exo-*, outside + *ergon*, work). Exergonic reactions are relatively common in the body. They generate the heat that maintains your body temperature.

If more energy is required to begin the reaction than is released as it proceeds, the reaction as a whole will absorb energy. Such reactions are called **endergonic** (*endo-*, inside). The synthesis of molecules such as fats and proteins results from endergonic reactions.

### Checkpoint

11. **What is an enzyme?**
12. **Why are enzymes needed in our cells?**

See the blue Answers tab at the back of the book.

## 2-5 Inorganic compounds lack carbon, and organic compounds contain carbon

**Learning Outcome** Distinguish between inorganic compounds and organic compounds.

The human body is very complex, but it contains relatively few elements (see **Table 2–1**, p. 75). Just knowing the identity and quantity of each element in the body will not help you understand the body any more than memorizing the alphabet will help you understand this text. Just as 26 letters can be combined to form thousands of different words in this text, only about 26 elements combine to form thousands of different chemical compounds in our bodies. As we saw in Chapter 1, these compounds make up the living cells that form the body's framework and carry on all its life processes. Learning about the major classes of chemical compounds will help you to understand the structure and function of the human body.

Two of the major classes of compounds are nutrients and metabolites. **Nutrients** are the substances from food that are necessary for normal physiological functions. Nutrients include carbohydrates, proteins, lipids (fats), vitamins, minerals, and water. **Metabolites** (me-TAB-ō-līts; *metabole,* change) are substances that are involved in, or are a by-product of, metabolism. We can broadly categorize nutrients and metabolites as either inorganic or organic. **Inorganic compounds** generally do not contain carbon and hydrogen atoms as their primary structural components. (If present, they do not form C—H bonds.) In contrast, carbon and hydrogen always form the basis for **organic compounds**. Their molecules can be much larger and more complex than inorganic compounds. *Carbohydrates*, *proteins*, and *lipids* are organic nutrients used by the body—we cover these in later sections.

The most important inorganic compounds in the body are as follows:

- *carbon dioxide*, a by-product of cell metabolism;
- *oxygen*, an atmospheric gas required in important metabolic reactions;
- *water*, which accounts for more than half of our body weight; and
- *acids, bases,* and *salts*—compounds held together partially or completely by ionic bonds.

In the next section, we focus on water, its properties, and how those properties establish the conditions necessary for life. Most of the other inorganic molecules and compounds in the body exist in association with water, the primary component of our body fluids. Both carbon dioxide and oxygen, for example, are gas molecules that are transported in body fluids. Also, all the inorganic acids, bases, and salts we will discuss are dissolved in body fluids.

### Checkpoint

13. **Compare inorganic compounds to organic compounds.**

See the blue Answers tab at the back of the book.

## 2-6 Physiological systems depend on water

**Learning Outcome** Explain how the chemical properties of water make life possible.

**Water ($H_2O$)** is the most important substance in the body. It makes up to two-thirds of total body weight. A change in the body's water content can be fatal, because virtually all physiological systems will be affected.

Although water is familiar to everyone, it has some highly unusual properties: universal solvent, reactivity, high heat capacity, and lubrication. All are important to the human body.

- *Universal Solvent*. A remarkable number of inorganic and organic molecules and compounds are water *soluble*, meaning they will dissolve or break up in water. The individual particles become distributed within the water, and the result is a **solution**—a uniform mixture of two or more substances. The liquid in which other atoms, ions, or molecules are distributed is called the **solvent**. The dissolved substances are the **solutes**. In *aqueous* (AK-wē-us) *solutions*, water is the solvent. Water is often called a "universal solvent" because more substances dissolve in it than any other liquid.
- *Reactivity*. In our bodies, chemical reactions take place in water, but water molecules are also reactants in some reactions. Hydrolysis and dehydration synthesis are two examples noted earlier in the chapter.
- *High Heat Capacity*. **Heat capacity** is the quantity of heat required to raise the temperature of a unit mass of a substance 1°C. Water has an unusually high heat capacity, because water molecules in the liquid state are attracted to one another through hydrogen bonding. Important consequences of this attraction include the following:
  - The temperature of water must be quite high (it requires a lot of energy) to break all of the hydrogen bonds between individual water molecules, and allow them to escape and become water vapor, a gas. Therefore, water remains a liquid over a broad range of environmental temperatures, and the freezing and boiling points of water are far apart.
  - Water carries a great deal of heat away with it when it changes from a liquid to a gas. This feature explains the cooling effect of perspiration on the skin.
  - An unusually large amount of heat energy is required to change the temperature of 1 g of water by 1°C. As a result, a large mass of water changes temperature slowly. This property is called *thermal inertia*. Thermal inertia helps stabilize body temperature because water accounts for up to two-thirds of the weight of the human body.
- *Lubrication*. Water is an effective lubricant because there is little friction between water molecules. So even a thin layer of water between two opposing surfaces will greatly reduce friction between them. (That is why driving on wet roads can be tricky. Your tires may start sliding on a layer of water rather than maintaining contact with the road.) Within joints such as the knee, an aqueous solution prevents friction between the opposing surfaces. Similarly, a small amount of fluid in the body cavities prevents friction between internal organs, such as the heart or lungs, and the body wall. ↩ p. 61

## The Properties of Aqueous Solutions

Water's chemical structure makes it an unusually effective solvent. The covalent bonds in a water molecule are oriented so that the hydrogen atoms are fairly close together. As a result, the water molecule has positive- and negative-charged ends, or poles (Figure 2–10a). For this reason, a water molecule is called a **polar molecule**.

Many inorganic compounds are held together partly or completely by ionic bonds. In water, these compounds undergo **dissociation** (di-sō-sē-Ā-shun)—the splitting of a compound into smaller molecules. **Ionization** (ī-on-i-ZĀ-shun) is the dissociation into ions. In this process, ionic bonds are broken as the individual ions interact with the positive or negative ends of polar water molecules (Figure 2–10b). The result is a mixture of cations and anions surrounded by water molecules. The water molecules around each ion form a *hydration sphere* that isolates the ions from each other, thus preventing the formation of ionic bonds.

An aqueous solution containing anions and cations will conduct an electrical current. When this happens, cations $(+)$ move toward the negative side, and anions $(-)$ move toward the positive side. Electrical forces across plasma membranes affect the functioning of all cells, and small electrical currents carried by ions are essential to muscle contraction and nerve function. (We will discuss these processes in more detail in Chapters 10 and 12.)

### Electrolytes and Body Fluids

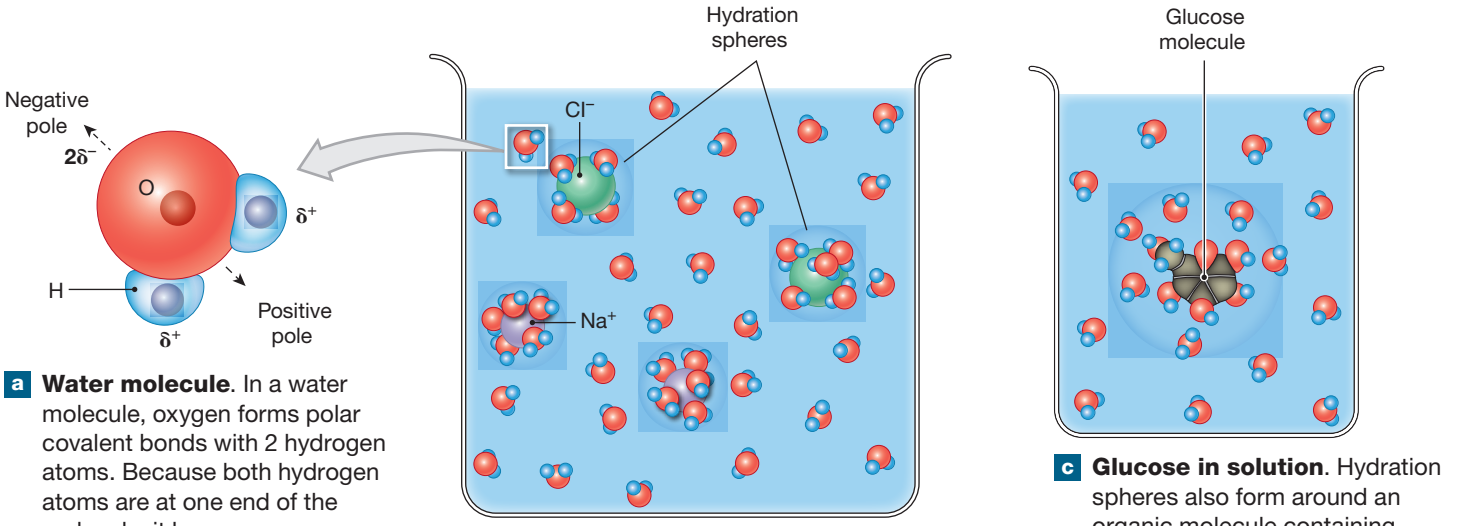
Soluble inorganic substances whose ions will conduct an electrical current in solution are called **electrolytes** (e-LEK-trō-lītz). Sodium chloride in solution is an electrolyte. The dissociation of electrolytes in blood and other body fluids releases a variety of ions. Table 2–2 lists important electrolytes and the ions released when they dissociate.

Changes in the concentrations of electrolytes in body fluids will disturb almost every vital function. For example, a declining potassium ion $(K^+)$ level will lead to a general muscular paralysis, and a rising concentration will cause weak and irregular heartbeats. The concentrations of ions in body fluids are

**Table 2–2 Important Electrolytes That Dissociate in Body Fluids**

| Electrolyte | Ions Released |
|---|---|
| **NaCl** (sodium chloride) | $\rightarrow Na^+ + Cl^-$ |
| **KCl** (potassium chloride) | $\rightarrow K^+ + Cl^-$ |
| **$CaPO_4$** (calcium phosphate) | $\rightarrow Ca^{2+} + PO_4^{2-}$ |
| **$NaHCO_3$** (sodium bicarbonate) | $\rightarrow Na^+ + HCO_3^-$ |
| **$MgCl_2$** (magnesium chloride) | $\rightarrow Mg^{2+} + 2Cl^-$ |
| **$Na_2HPO_4$** (sodium hydrogen phosphate) | $\rightarrow 2Na^+ + HPO_4^{2-}$ |
| **$Na_2SO_4$** (sodium sulfate) | $\rightarrow 2Na^+ + SO_4^{2-}$ |

**Figure 2–10** Water Molecules Surround Solutes in Aqueous Solutions.




**a** **Water molecule**. In a water molecule, oxygen forms polar covalent bonds with 2 hydrogen atoms. Because both hydrogen atoms are at one end of the molecule, it has an uneven distribution of electric charges, creating positive and negative poles.

**b** **Sodium chloride in solution**. Ionic compounds, such as sodium chloride, dissociate in water as the polar water molecules break the ionic bonds in the large crystal structure. Each ion in solution is surrounded by water molecules, creating hydration spheres.

**c** **Glucose in solution**. Hydration spheres also form around an organic molecule containing polar covalent bonds. If the molecule binds water strongly, as does glucose, it will be carried into solution—in other words, it will dissolve. Note that the molecule does not dissociate, as occurs for ionic compounds.

carefully regulated, mostly by the coordination of activities at the kidneys (ion excretion), the digestive tract (ion absorption), and the skeletal system (ion storage or release).

### Hydrophilic and Hydrophobic Compounds

Some organic molecules contain polar covalent bonds, which also attract water molecules. The hydration spheres that form may then carry these molecules into solution. Molecules that interact readily with water molecules in this way are called **hydrophilic** (hī-drō-FIL-ik; *hydro-*, water + *philos*, loving). Glucose, an important soluble sugar, is one example (Figure 2–10c).

When nonpolar molecules are exposed to water, hydration spheres do not form and the molecules do not dissolve. Molecules that do not readily interact with water are called **hydrophobic** (hī-drō-FŌB-ik; *hydro-*, water + *phobos*, fear). Fats and oils of all kinds are some of the most familiar hydrophobic molecules. For example, body fat deposits consist of large, hydrophobic droplets trapped in the watery interior of cells. Gasoline and heating oil are hydrophobic molecules not found in the body. When accidentally spilled into lakes or oceans, they form long-lasting oil slicks instead of dissolving.

**Tips & Tools**

To distinguish between hydrophobic and hydrophilic, remember that a phobia is a fear of something, and that *-philic* ends with "lic," which resembles "like."

### Colloids and Suspensions

Body fluids may contain large and complex organic molecules, such as proteins, that are held in solution by their association with water molecules (see Figure 2–10c). A solution containing dispersed proteins or other large molecules is called a **colloid** (KOL-oyd). Liquid Jell-O is a familiar colloid. The particles or molecules in a colloid will remain in solution indefinitely.

In contrast, a **suspension** contains large particles in solution, but if undisturbed, its particles will settle out of solution due to the force of gravity. For example, stirring beach sand into a bucket of water creates a temporary suspension that will last only until the sand settles to the bottom. Whole blood is another temporary suspension, because the blood cells are suspended in the blood plasma. If clotting is prevented, the cells in a blood sample will gradually settle to the bottom of the container. Measuring that settling rate, or "sedimentation rate," is a common laboratory test.

### Checkpoint

14. **Explain how the chemical properties of water make life possible.**

See the blue Answers tab at the back of the book.

## 2-7 Body fluid pH is vital for homeostasis

**Learning Outcome** Explain what pH is and discuss its importance.

A hydrogen atom involved in a chemical bond or participating in a chemical reaction can easily lose its electron to become a **hydrogen ion ($H^+$)**. Hydrogen ions are extremely reactive in solution. In excessive numbers, they will disrupt cell and tissue functions. As a result, the concentration of hydrogen ions in body fluids must be regulated precisely.

A few hydrogen ions are normally present even in a sample of pure water, because some of the water molecules dissociate spontaneously, releasing cations and anions. The dissociation of water is a reversible reaction. We can represent it as

$$H_2O \rightleftharpoons H^+ + OH^-$$

Notice that the dissociation of one water molecule yields a hydrogen ion ($H^+$) and a **hydroxide** (hī-DROK-sīd) **ion** ($OH^-$).

However, very few water molecules ionize in pure water, so the number of hydrogen and hydroxide ions is small. The quantities are usually reported in moles, making it easy to keep track of the numbers of hydrogen and hydroxide ions. One liter of pure water contains about 0.0000001 mol of hydrogen ions and an equal number of hydroxide ions. In other words, the concentration of hydrogen ions in a solution of pure water is 0.0000001 mol per liter. This can be written as

$$[H^+] = 1 \times 10^{-7} \text{mol/L}$$

The brackets around the $H^+$ signify "the concentration of," another example of chemical notation.

The hydrogen ion concentration in body fluids is so important to physiological processes that we use a special shorthand to express it. The **pH** of a solution is defined as the negative logarithm of the hydrogen ion concentration in moles per liter. So instead of using the equation $[H^+] = 1 \times 10^{-7}$ mol/L, we say that the pH of pure water is $-(-7)$, or 7.

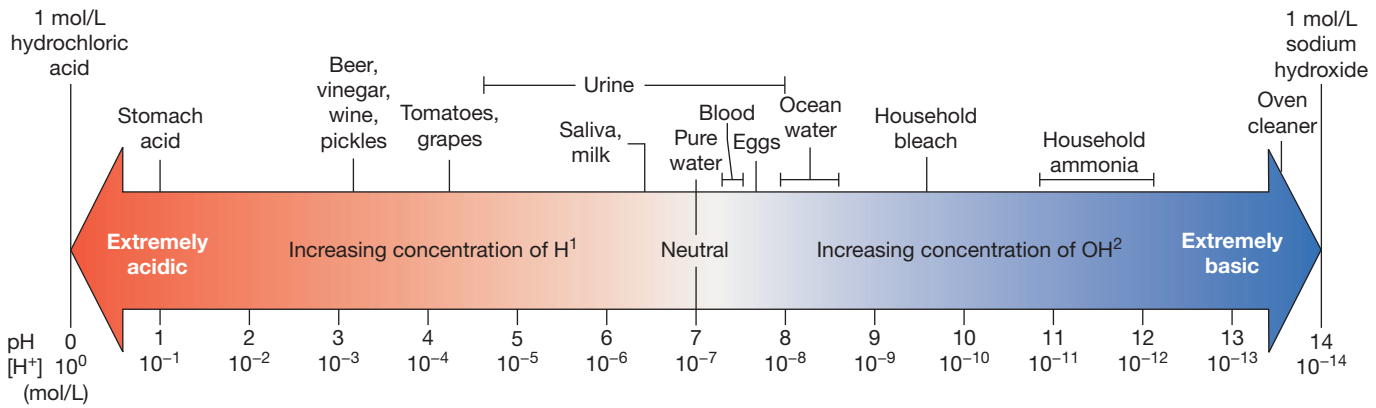
Using pH values saves space, but always remember that the pH number is an *exponent* and that the pH scale is logarithmic. For instance, a pH of 6 ($[H^+] = 1 \times 10^{-6}$, or 0.000001 mol/L) means that the concentration of hydrogen ions is *10 times greater than* it is at a pH of 7 ($[H^+] = 1 \times 10^{-7}$, or 0.0000001 mol/L). The pH scale ranges from 0 to 14 (Figure 2–11).

Pure water has a pH of 7, but as Figure 2–11 indicates, solutions display a wide range of pH values, depending on the nature of the solutes involved:

- A solution with a pH of 7 is said to be **neutral**, because it contains equal numbers of hydrogen and hydroxide ions.
- A solution with a pH below 7 is **acidic** (a-SI-dik), meaning that it contains more hydrogen ions than hydroxide ions.
- A solution with a pH above 7 is **basic**, or *alkaline* (AL-kuh-lin), meaning that it has more hydroxide ions than hydrogen ions.

The normal pH of blood ranges from 7.35 to 7.45. Abnormal fluctuations in pH can damage cells and tissues by breaking chemical bonds, changing the shapes of proteins, and altering cellular functions. *Acidosis* is an abnormal physiological state caused by low blood pH (below 7.35). A pH below 7 can produce coma. Likewise, *alkalosis* results from an abnormally high pH (above 7.45). A blood pH above 7.8 generally causes uncontrollable and sustained skeletal muscle contractions.

**Figure 2–11 The pH Scale Indicates Hydrogen Ion Concentration.** The pH scale is logarithmic; an increase or decrease of one unit corresponds to a tenfold change in $H^+$ concentration.



### Checkpoint

15. **Define pH, and explain how the pH scale relates to acidity and alkalinity.**
16. **What is the significance of pH in physiological systems?**

See the blue Answers tab at the back of the book.

## 2-8 Acids, bases, and salts have important physiological roles

**Learning Outcome** Describe the physiological roles of acids, bases, and salts and the role of buffers in body fluids.

### Acids and Bases

The body contains *acids* and *bases* that may cause acidosis or alkalosis, respectively. An **acid** (*acere*, sour) is any solute that dissociates in solution and releases hydrogen ions, lowering the pH. A hydrogen atom that loses its electron consists solely of a proton, so we often refer to hydrogen ions simply as protons, and to acids as *proton donors*. In contrast, a **base** is a solute that removes hydrogen ions from a solution, raising the pH. It acts as a *proton acceptor*. Acids and bases are often identified in terms of *strength*. Strength is a measure of the degree of dissociation of either an acid or a base when it is in solution. There are both strong and weak acids and bases.

A *strong acid* dissociates completely in solution, and the reaction occurs essentially in one direction only. *Hydrochloric acid* (HCl) is a representative strong acid. In water, it ionizes as follows:

$$HCl \longrightarrow H^+ + Cl^-$$

The stomach produces this powerful acid to help break down food. Hardware stores sell HCl under the name muriatic acid, for cleaning concrete and swimming pools.

In solution, many bases release a hydroxide ion ($OH^-$). Hydroxide ions have an attraction for hydrogen ions and react quickly with them to form water molecules. A *strong base* dissociates completely in solution. *Sodium hydroxide*, NaOH, is a strong base. In solution, it releases sodium ions and hydroxide ions:

$$NaOH \longrightarrow Na^+ + OH^-$$

Strong bases have a variety of industrial and household uses. Drain openers (such as Drāno) and lye are two familiar examples.

*Weak acids* and *weak bases* do not dissociate completely. At equilibrium, a significant number of molecules remain intact in the solution. For the same number of molecules in solution, weak acids and weak bases have less impact on pH than do strong acids and strong bases. *Carbonic acid* ($H_2CO_3$) is a weak acid found in body fluids. In solution, carbonic acid reversibly dissociates into a hydrogen ion and a *bicarbonate ion*, $HCO_3^-$:

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

### Salts

A **salt** is an ionic compound containing any cation except a hydrogen ion, and any anion except a hydroxide ion. Because they are held together by ionic bonds, many salts dissociate completely in water, releasing cations and anions. For example, sodium chloride (NaCl) dissociates immediately in water, releasing $Na^+$ and $Cl^-$. Sodium and chloride ions are the most abundant ions in body fluids. However, many other ions are present in lesser amounts as a result of the dissociation of other ionic compounds. Ionic concentrations in the body are regulated in ways we describe in Chapters 26 and 27.

The dissociation of sodium chloride does not affect the local concentrations of hydrogen ions or hydroxide ions. For this reason, NaCl, like many salts, is a "neutral" solute. It does not make a solution more acidic or more basic. In contrast, some salts may interact with water molecules and indirectly affect the concentrations of $H^+$ and $OH^-$ ions. Thus, in some cases, the dissociation of salts makes a solution slightly acidic or slightly basic.

### Buffers and pH Control

**Buffers** are compounds that stabilize the pH of a solution by removing or replacing hydrogen ions. *Buffer systems* usually involve a weak acid and its related salt, which functions as a weak base. For example, the carbonic acid–bicarbonate buffer system (detailed in Chapter 27) consists of carbonic acid and sodium bicarbonate, $NaHCO_3$, otherwise known as baking soda. Buffers and buffer systems in body fluids help maintain the pH within normal limits. The pH of several body fluids is included in Figure 2–11.

The use of antacids is one example of the type of reaction that takes place in buffer systems. Antacids use sodium bicarbonate to neutralize excess hydrochloric acid in the stomach.

Note that the effects of neutralization are most evident when you add a strong acid to a strong base. For example, by adding hydrochloric acid to sodium hydroxide, you neutralize both the strong acid and the strong base:

$$HCl + NaOH \longrightarrow H_2O + NaCl$$

This neutralization reaction produces water and a salt—in this case, the neutral salt sodium chloride.

### Checkpoint

17. **Define the following terms: *acid*, *base*, and salt.**
18. **How does an antacid help decrease stomach discomfort?**

See the blue Answers tab at the back of the book.

## 2-9 Living things contain organic compounds made up of monomers, polymers, and functional groups

**Learning Outcome:** Describe monomers and polymers, and the importance of functional groups in organic compounds.

The macromolecules of living things are all organic compounds. Many of these large organic molecules are made up of long chains of carbon atoms linked by covalent bonds. The carbon atoms typically form additional covalent bonds with hydrogen or oxygen atoms and, less commonly, with nitrogen, phosphorus, sulfur, iron, or other elements.

The *macromolecules* of life are complex structures with varied functions and properties. They include carbohydrates, lipids, proteins, and nucleic acids. Each macromolecule is made up of monomer subunits. A **monomer** (MON-ō-mer; *mono-* single + *-mer*, member of a group) is a molecule that can be bonded to other identical molecules to form a **polymer**. Repeating monomers join together through *dehydration synthesis* reactions to form polymers, sometimes called *mers*.

The monomers of carbohydrates, lipids, proteins, and nucleic acids are separated, or released, through *hydrolysis reactions*. As a result of such reactions, carbohydrates release monosaccharides, lipids (fats) release fatty acids and glycerol, proteins release amino acids, and nucleic acids release nucleotides. We discuss the structures and functions of these molecules in the next four sections.

Organic compounds are diverse, but certain groupings of atoms, known as *functional groups*, are responsible for the characteristic reactions of a particular compound. Furthermore, these functional groups greatly influence the properties of any molecule of which they are a part. Table 2–3 details the functional groups you will study in this chapter.

### Checkpoint

19. What macromolecules are important to living things?
20. Which functional group acts as an acid?

See the blue Answers tab at the back of the book.

## 2-10 Carbohydrates contain carbon, hydrogen, and oxygen in a 1:2:1 ratio

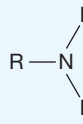
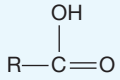
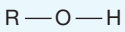
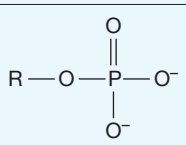
**Learning Outcome** Discuss the structures and functions of carbohydrates.

A **carbohydrate** is an organic molecule that contains carbon, hydrogen, and oxygen in a ratio near 1:2:1. Familiar carbohydrates include the sugars and starches that make up about half of the typical U.S. diet. Carbohydrates typically account for less than 1 percent of total body weight. Carbohydrates are most important as energy sources that are catabolized. In the following sections, we focus on *monosaccharides*, *disaccharides*, and *polysaccharides*.

### Monosaccharides

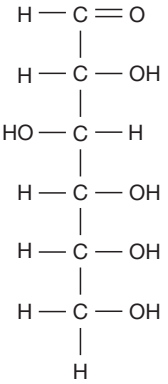
A **monosaccharide** (mon-ō-SAK-uh-rīd; *mono-*, single + *sakcharon*, sugar), or *simple sugar*, is a carbohydrate with three to seven carbon atoms. Depending on how many carbons it contains, a monosaccharide can be called a *triose* (three carbon atoms), *tetrose* (four carbon atoms), *pentose* (five carbon atoms), *hexose* (six carbon atoms), or *heptose* (seven carbon atoms). The *-ose* ending indicates a sugar. The hexose **glucose** (GLŪ-kōs), $C_6H_{12}O_6$, is the most important metabolic "fuel" in the body. Monosaccharides such as glucose dissolve readily in water and are rapidly distributed throughout the body by blood and other body fluids.

**Table 2–3 Important Functional Groups of Organic Compounds**

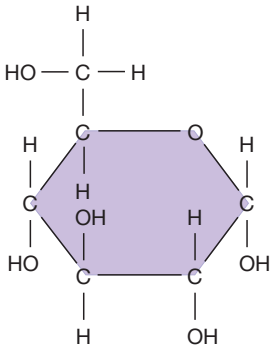
| Functional Group | Structural Formula* | Importance | Examples |
|---|---|---|---|
| **Amino group** —$NH_2$ |  | Acts as a base, accepting $H^+$, depending on pH; can form bonds with other molecules | Amino acids |
| **Carboxyl group** —COOH |  | Acts as an acid, releasing $H^+$ to become R—$COO^-$ | Fatty acids, amino acids |
| **Hydroxyl group** —OH |  | May link molecules through dehydration synthesis (condensation); hydrogen bonding between hydroxyl groups and water molecules; affects solubility | Carbohydrates, fatty acids, amino acids |
| **Phosphate group** —$PO_4$ |  | May link other molecules to form larger structures; may store energy in high-energy bonds | Phospholipids, nucleic acids, high-energy compounds |

*A structural formula shows the covalent bonds within a molecule or functional group (see Figure 2–6). The letter R represents the term *R group* and is used to denote the rest of the molecule to which a functional group is attached.

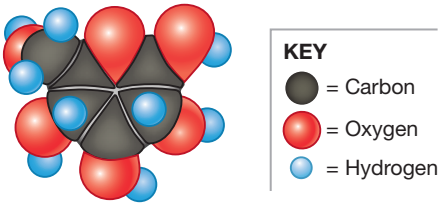
**Figure 2–12 The Structures of Glucose.** Note that the ring form, the most common form of glucose, is represented with a kind of shorthand in later figures: We leave out the carbon atom at five corners of the hexagon, although we do show the oxygen atom at the remaining corner.



**a** The structural formula of the straight-chain form



**b** The structural formula of the ring form, the most common form of glucose




**c** A three-dimensional model showing the organization of atoms in the ring form

**?** How many oxygen atoms are shown in each glucose structure?

As shown by two-dimensional diagrams known as *structural formulas*, the atoms in a glucose molecule may form either a straight chain (Figure 2–12a) or a ring (Figure 2–12b). In the body, the ring form is more common. A three-dimensional model shows the arrangement of atoms in the ring form most accurately (Figure 2–12c).

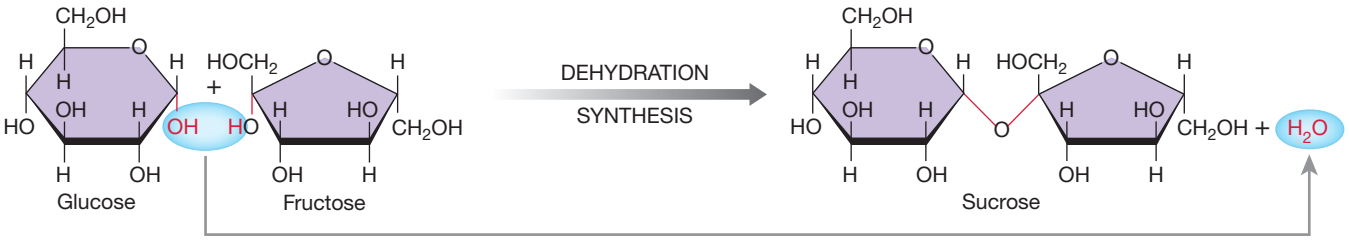
The three-dimensional structure of an organic molecule is an important characteristic, because it usually determines the molecule's fate or function. Some molecules have the same molecular formula—in other words, the same types and numbers of atoms—but different structures. Such molecules are called **isomers**. The body usually treats different isomers as distinct molecules. For example, the monosaccharides glucose and fructose are isomers. *Fructose* is a hexose found in many fruits and in secretions of the male reproductive tract. It has the same chemical formula as glucose, $C_6H_{12}O_6$, but the arrangement of its atoms differs from that of glucose. As a result, separate enzymes and reaction sequences control its breakdown and synthesis.

## Disaccharides and Polysaccharides

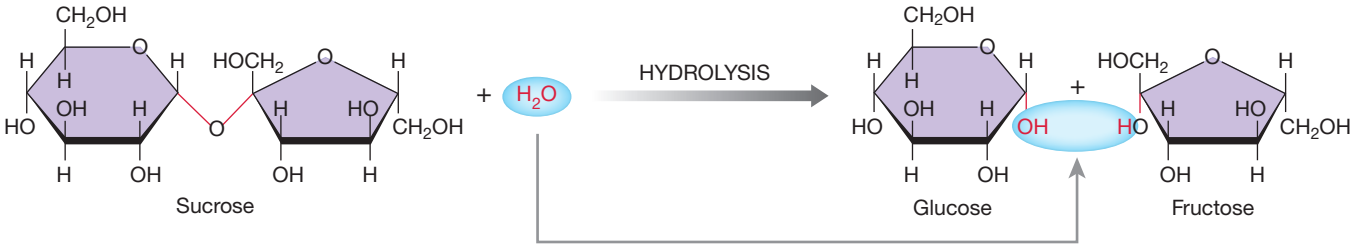
Carbohydrates other than simple sugars are complex molecules composed of monosaccharide building blocks, or monomers. Two monosaccharide monomers joined together form a **disaccharide** (dī-SAK-uh-rīd; *di-*, two). Disaccharides such as *sucrose* (table sugar) have a sweet taste and, like monosaccharides, are quite soluble in water.

The formation of sucrose involves a dehydration synthesis reaction (Figure 2–13a). Recall that dehydration synthesis reactions link molecules together by the removal of a water

**Figure 2–13 The Formation and Breakdown of Complex Sugars.**




**a** **Formation of the disaccharide sucrose through dehydration synthesis.** During dehydration synthesis, 2 molecules are joined by the removal of a water molecule.




**b** **Breakdown of sucrose into simple sugars by hydrolysis.** Hydrolysis reverses the steps of dehydration synthesis; a complex molecule is broken down by the addition of a water molecule.

molecule. The breakdown of sucrose into simple sugars is an example of hydrolysis, or breakdown by the addition of a water molecule (Figure 2–13b). Hydrolysis is the functional opposite of dehydration synthesis.

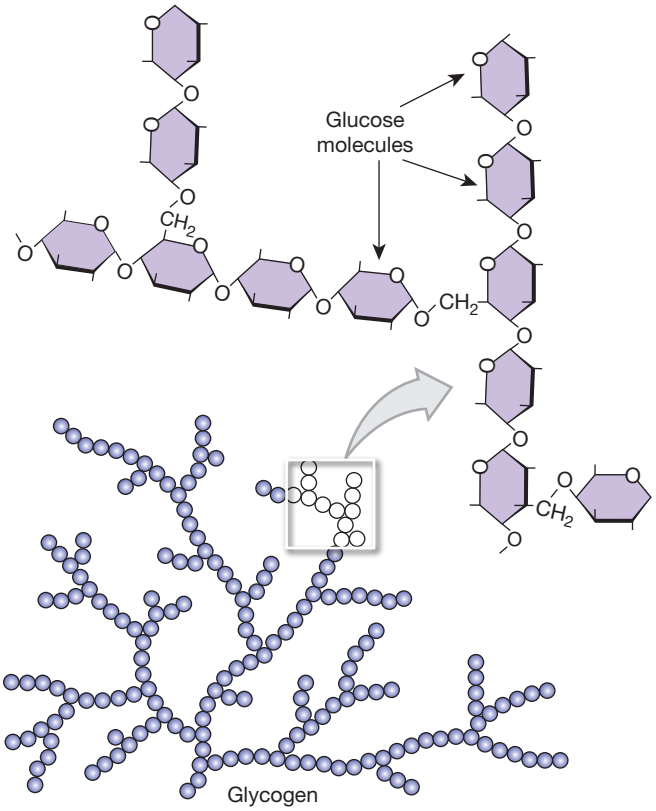
Many foods contain disaccharides, but all carbohydrates except monosaccharides must be broken apart through hydrolysis before they can provide useful energy. Most popular junk foods (high in calories but otherwise lacking in nutritional content), such as candies and sodas, are full of monosaccharides (commonly fructose) and disaccharides (generally sucrose). Some people cannot tolerate sugar for medical reasons. Others avoid it in an effort to control their weight (because excess sugars are converted to fat for long-term storage). Many of these people use *artificial sweeteners* in their foods and beverages. These compounds have a very sweet taste, but they either cannot be broken down in the body or are used in insignificant amounts.

More complex carbohydrates result when repeated dehydration synthesis reactions add additional monosaccharides or disaccharides. These large molecules (polymers) are called **polysaccharides** (pol-ē-SAK-uh-rīdz; *poly-*, many). Polysaccharide chains can be straight or highly branched. *Cellulose*, a structural component of many plants, is a polysaccharide that our bodies cannot digest because the particular linkages between the glucose molecules cannot be cleaved by enzymes in the body. Foods such as celery, which contains cellulose, water, and little else, contribute fiber to digestive wastes but do not provide a source of energy.

*Starches* are large polysaccharides formed from glucose molecules. Most starches are manufactured by plants. Your digestive tract can break these molecules into monosaccharides. Starches such as those in potatoes and grains are a major dietary energy source.

The polysaccharide **glycogen** (GLĪ-kō-jen), or *animal starch*, has many side branches consisting of chains of glucose molecules (Figure 2–14). Like most other starches, glycogen does not dissolve in water or other body fluids. Muscle cells make and store glycogen. When muscle cells have a high demand for glucose, glycogen molecules are broken down. When the need is low, these cells absorb glucose from the bloodstream and rebuild glycogen reserves. Table 2–4 summarizes information about carbohydrates.

**Figure 2–14 The Structure of the Polysaccharide Glycogen.** Liver and muscle cells store glucose as the polysaccharide glycogen, a long, branching chain of glucose molecules.




### Checkpoint

21. **Plant starch and glycogen are both polysaccharides. What monomer do they have in common?**

See the blue Answers tab at the back of the book.

## 2-11 Lipids often contain a carbon-to-hydrogen ratio of 1:2

**Learning Outcome** Discuss the structures and functions of lipids.

Like carbohydrates, **lipids** (*lipos*, fat) contain carbon, hydrogen, and oxygen, and the carbon-to-hydrogen ratio is near 1:2. However, lipids contain much less oxygen than do carbohydrates with the same number of carbon atoms.

**Table 2–4 Carbohydrates in the Body**

| Structural Class | Examples | Primary Function | Remarks |
|---|---|---|---|
| **Monosaccharides (simple sugars)** | Glucose, fructose | Energy source | Manufactured in the body and obtained from food; distributed in body fluids |
| **Disaccharides** | Sucrose, lactose, maltose | Energy source | Sucrose is table sugar, lactose is in milk, and maltose is malt sugar found in germinating grain; all must be broken down to monosaccharides before absorption |
| **Polysaccharides** | Glycogen | Storage of glucose | Glycogen is in animal cells; other starches and cellulose are within or around plant cells |

The hydrogen-to-oxygen ratio is therefore very large. For example, a representative lipid, such as lauric acid (found in coconut, laurel, and palm kernel oils), has a formula of $C_{12}H_{24}O_2$. Lipids may also contain small quantities of phosphorus, nitrogen, or sulfur. Familiar lipids include *fats*, *oils*, and *waxes*. Most lipids are hydrophobic, or insoluble in water, but special transport mechanisms carry them into the bloodstream.

Lipids form essential structural components of all cells. In addition, lipid deposits are important as energy reserves. On average, lipids provide twice as much energy as carbohydrates do, gram for gram, when broken down in the body. When the supply of lipids exceeds the demand for energy, the excess is stored in fat deposits. For this reason, there has been great interest in developing *fat substitutes* that provide less energy, but have the same desirable taste and texture as the fats found in many foods.

Lipids normally make up 12–18 percent of the total body weight of adult men, and 18–24 percent for adult women. Many kinds of lipids exist in the body. We will consider five classes of lipids: *fatty acids*, *eicosanoids*, *glycerides*, *steroids*, and *phospholipids and glycolipids*.

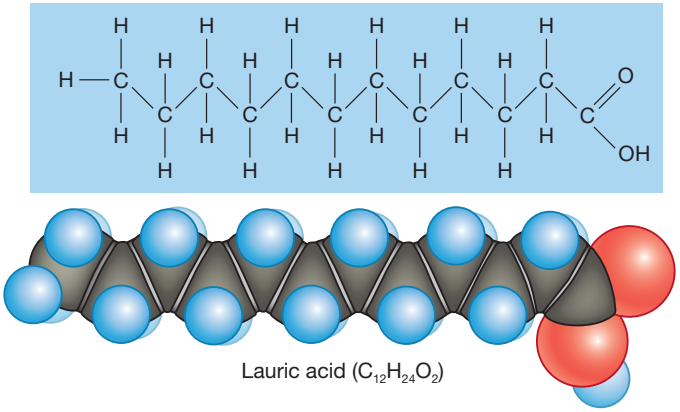
## Fatty Acids

**Fatty acids** are long carbon chains with hydrogen atoms attached. They are one of the monomers of lipids. One end of the carbon chain is always attached to a *carboxyl* (kar-BOK-sil) *group*, —COOH (see **Table 2–3**). The name *carboxyl* should help you remember that a carbon and a hydroxyl (—OH) group are the important structural features of fatty acids. The carbon chain attached to the carboxyl group is known as the *hydrocarbon tail* of the fatty acid. **Figure 2–15a** shows a representative fatty acid, *lauric acid*.

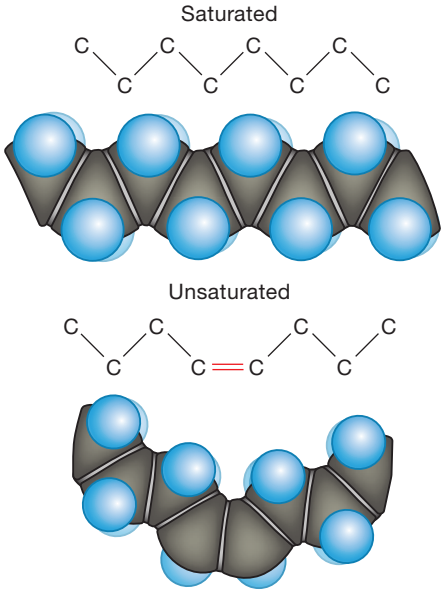
Fatty acids have a very limited solubility in water. When a fatty acid is in solution, only the carboxyl end associates with water molecules, because that is the only hydrophilic portion of the molecule. The hydrocarbon tail is hydrophobic. In general, the longer the hydrocarbon tail, the lower the solubility of the molecule.

Fatty acids may be either saturated or unsaturated (**Figure 2–15b**). These terms refer to the number of hydrogen atoms bound to the carbon atoms in the hydrocarbon tail. In a *saturated* fatty acid, each carbon atom in the tail has four single covalent bonds (see **Figure 2–15a**). Within the tail, two of those bonds bind adjacent carbon atoms, and the other two bind hydrogen atoms. The carbon atom at the end of the tail binds three hydrogen atoms. In an *unsaturated* fatty acid, one or more of the single covalent bonds between the carbon atoms have been replaced by a double covalent bond. As a result, the carbon atoms involved will each bind only one hydrogen atom rather than two. This changes the shape of the hydrocarbon tail, giving it a sharp bend, as you can see in **Figure 2–15b**. The change also affects the way the fatty acid is metabolized.

**Figure 2–15** Fatty Acids.




**a** Lauric acid shows two structural characteristics common to all fatty acids: a long chain of carbon atoms and a carboxyl group (—COOH) at one end.




**b** A fatty acid is either saturated (has single covalent bonds only) or unsaturated (has one or more double covalent bonds). The presence of a double bond causes a sharp bend in the molecule.

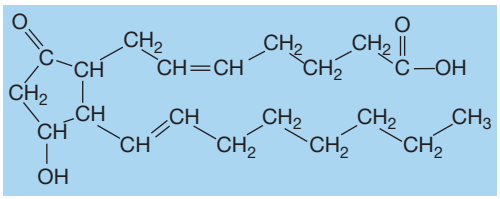
**?** What type of bond does an unsaturated fatty acid contain that a saturated fatty acid does not?

A *monounsaturated* fatty acid has a single double bond in the hydrocarbon tail. A *polyunsaturated* fatty acid contains two or more double bonds.

## Eicosanoids

**Eicosanoids** (ī-KŌ-sa-noydz) are lipids derived from *arachidonic* (ah-rak-i-DON-ik) *acid*, a fatty acid that must be absorbed in the diet because the body cannot synthesize it. The two

**Figure 2–16 Prostaglandins.** Prostaglandins contain 20 carbon atoms and a 5-carbon ring.



major classes of eicosanoids are *leukotrienes* and *prostaglandins*. **Leukotrienes** (lū-kō-TRĪ-ēnz) are produced mostly by cells involved with coordinating the responses to injury or disease. We consider leukotrienes in Chapters 18 and 22.

**Prostaglandins** (pros-tuh-GLAN-dinz) are short-chain fatty acids in which five of the carbon atoms are joined in a ring (Figure 2–16). These compounds are released by cells to coordinate or direct local cellular activities, and they are extremely powerful even in small quantities. Virtually all tissues synthesize and respond to them. The effects of prostaglandins vary with their structure and their release site. Prostaglandins released by damaged tissues, for example, stimulate nerve endings and produce the sensation of pain (Chapter 15). Those released in the uterus help trigger the start of labor contractions (Chapter 29).

The body uses several types of chemical messengers. Those that are produced in one part of the body and have effects on distant parts are called *hormones*. Hormones are distributed throughout the body in the bloodstream, but most prostaglandins affect only the area in which they are produced. As a result, prostaglandins are often called *local hormones*. The distinction is not a rigid one, however, as some prostaglandins also enter the bloodstream and affect other areas. We discuss hormones and prostaglandins in Chapter 18.

## Glycerides

Unlike monosaccharides, individual fatty acids cannot be strung together in a chain by dehydration synthesis to form a polymer. But they can be attached to a modified simple sugar, **glycerol** (GLIS-er-ol), through a similar reaction. The result is a lipid known as a **glyceride** (GLIS-er-īd). Dehydration synthesis reactions can produce a **monoglyceride** (mon-ō-GLIS-er-īd), consisting of glycerol plus one fatty acid. Subsequent reactions can yield a **diglyceride** (glycerol + two fatty acids) and then a **triglyceride** (glycerol + three fatty acids), as in Figure 2–17. Hydrolysis breaks the glycerides into fatty acids and glycerol (monomers). Comparing Figure 2–17 with Figure 2–13 shows that dehydration synthesis and hydrolysis operate the same way, whether the molecules involved are carbohydrates or lipids.

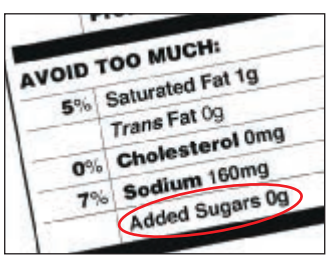
Triglycerides, also known as *triacylglycerols* or *neutral fats*, are important lipid polymers. They have the following important functions:

- *Energy Source*. Fat deposits in the body represent a significant energy reserve. In times of need, the triglycerides are taken apart by hydrolysis, yielding fatty acids that can be broken down to provide energy.

## + Clinical Note Too Sweet on Sugar?

A baby's first and favorite taste is sweet: mother's milk is rich in *lactose* (milk sugar), a disaccharide of glucose and galactose. This preference for sweet persists throughout life. It is easier to tempt the poor appetite of a frail, elderly person with a bowl of pudding than with a bowl of steamed kale. Manufacturers of processed foods know this.

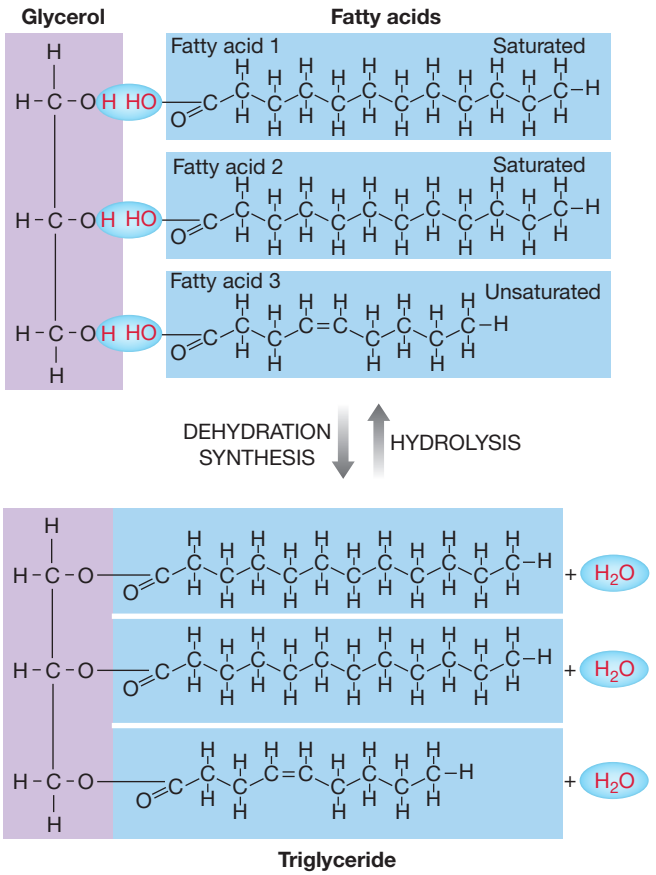
When heart disease became endemic in the United States, holding first place as the killer of Americans, the medical community advocated a low-fat diet for heart health. Artery-clogging fats were removed from manufactured foods—such as cookies, soups, and other boxed, bagged, and frozen products—and replaced with sugar for flavor and mouth appeal.




The sweetening of the American diet has wreaked a new kind of havoc on American health. Dental hygienists see more *dental caries* (cavities). Obesity is climbing at an alarming rate. Grade-school children are developing more *type 2 diabetes*, formerly called "adult-onset diabetes." These serious and potentially fatal diseases generally did not appear until a person had lived several decades with a poor lifestyle.

Glucose is a necessary nutrient. Our body's cells depend on it for fuel; our neurons (brain cells) require it. However, we should meet our glucose needs through complex carbohydrates, or polysaccharides (such as glycogen). In contrast to simple sugars, complex carbohydrates are digested slowly by decomposition reactions in the digestive tract. The component monosaccharides of glucose are released and absorbed gradually, maintaining a steady blood glucose level. In turn, the pancreas is signaled only as needed to make the protein hormone *insulin*, which stimulates the transport of glucose into the body's cells. Complex carbohydrates promote satiety (fullness) and support healthy sugar metabolism.

**Figure 2–17 Triglyceride Formation.** The formation of a triglyceride involves the attachment of fatty acids to a glycerol molecule through dehydration synthesis. In this example, a triglyceride is formed by the attachment of one unsaturated and two saturated fatty acids to a glycerol molecule.




? What makes fatty acid 3 an unsaturated fatty acid?

- *Insulation*. Fat deposits under the skin serve as insulation, slowing heat loss to the environment. Heat loss across a layer of lipids is only about one-third of the heat loss through other tissues.
- *Protection*. A fat deposit around a delicate organ such as a kidney provides a cushion that protects against bumps or jolts.

Triglycerides are stored in the body as lipid droplets within cells. The droplets absorb and accumulate lipid-soluble vitamins, drugs, or toxins that appear in body fluids. This accumulation has both positive and negative effects. For example, the body's lipid reserves retain both valuable lipid-soluble vitamins (A, D, E, K) and potentially dangerous lipid-soluble pesticides, such as the now-banned DDT.

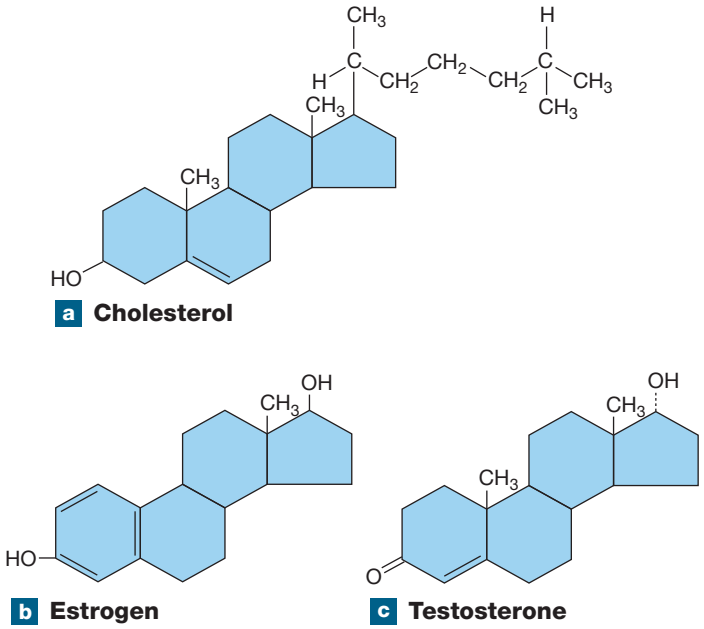
## Steroids

**Steroids** are large lipid molecules that share a distinctive four-ring carbon structure (Figure 2–18). They differ in the functional groups that are attached to this basic framework. The steroid **cholesterol** (kō-LES-ter-ol; *chole-*, bile + *stereos*, solid) and related steroids are important for several reasons:

- The outer boundary of all animal cells, called a plasma membrane, contains cholesterol (Figure 2–18a). Cells need cholesterol to maintain their plasma membranes, as well as for cell growth and division.
- Steroid hormones are involved in the regulation of sexual function. Examples include the sex hormones *estrogen* and *testosterone* (Figure 2–18b,c).
- Steroid hormones are important in the regulation of tissue metabolism and mineral balance. Examples include *corticosteroids* from the adrenal cortex, which play a role in carbohydrate and protein metabolism, and *calcitriol* from the kidneys, a hormone important in the regulation of the body's calcium ion concentrations.
- Steroid derivatives called *bile salts* are required for the normal processing of dietary fats. The liver produces bile salts and secretes them in bile. They interact with lipids in the intestinal tract and assist with the digestion and absorption of lipids.

The body obtains cholesterol in two ways: (1) by absorbing it from animal products in the diet and (2) by synthesizing it. Liver,

**Figure 2–18 Steroids Have a Complex Four-Ring Structure.** Individual steroids differ in the side chains attached to the carbon rings.



meat, shellfish, and egg yolks are especially rich dietary sources of cholesterol. People with *hypercholesterolemia*, a condition characterized by very high levels of blood cholesterol, have an increased risk of developing a form of heart disease called coronary artery disease (CAD). In CAD, excess cholesterol deposits on arterial walls, forming plaques that obstruct blood flow to the heart. Currently, it is suggested that a healthy person consume no more than 300 mg of cholesterol per day, and others with diabetes, high cholesterol, or heart disease should consume no more than 200 mg per day. Unfortunately, the blood cholesterol level can be difficult to control by dietary restriction alone because the body can synthesize cholesterol as well. In fact, the body makes more than enough, so strict vegetarians do not need to eat animal products to ensure adequate amounts of cholesterol.

### Phospholipids and Glycolipids

**Phospholipids** (FOS-fō-lip-idz) and **glycolipids** (GLĪ-kō-lip-idz) are structurally related, and our cells can synthesize both types of lipids, primarily from fatty acids. In a *phospho*lipid, a *phosphate group* ($PO_4^{3-}$) links a diglyceride to a nonlipid group (Figure 2–19a). There are different types of phospholipids; the one shown in this figure is lecithin. In a *glyco*lipid, a carbohydrate is attached to a diglyceride (Figure 2–19b). Note that placing *-lipid* last in these names indicates that the molecule consists primarily of lipid.

The long hydrocarbon tails of phospholipids and glycolipids are hydrophobic, but the opposite ends, the nonlipid *heads*, are hydrophilic. In water, large numbers of these molecules tend to form droplets, or *micelles* (mī-SELZ), with the hydrophilic portions on the outside (Figure 2–19c). Most meals contain a mixture of lipids and other organic molecules, and micelles form as the food breaks down in your digestive tract. In addition to phospholipids and glycolipids, micelles may contain other insoluble lipids, such as steroids, glycerides, and long-chain fatty acids.

Phospholipids and glycolipids (as well as cholesterol) are called *structural lipids*, because they help form and maintain intracellular structures called membranes. At the cellular level, *membranes* are sheets or layers composed mainly of lipids. For example, the plasma membrane surrounding each cell is composed primarily of phospholipids. It separates the aqueous solution inside the cell from the aqueous solution outside the cell. Also, various internal membranes subdivide the interior of the cell into specialized compartments, each with a distinctive chemical nature and, as a result, a different function.

The five types of lipids and their characteristics are summarized in Table 2–5.

### Checkpoint

22. **Describe lipids.**
23. **Which lipids would you find in human plasma membranes?**

See the blue Answers tab at the back of the book.

## 2-12 Proteins contain carbon, hydrogen, oxygen, and nitrogen and are formed from amino acids

**Learning Outcome** Discuss the structures and functions of proteins.

**Proteins** are the most abundant organic molecules in the human body and in many ways the most important. The human body contains many different proteins, and they account for about 20 percent of total body weight. All proteins contain carbon, hydrogen, oxygen, and nitrogen. Smaller quantities of sulfur and phosphorus may also be present. *Amino acids* are simple organic compounds (monomers) that combine to form proteins (polymers). p. 91

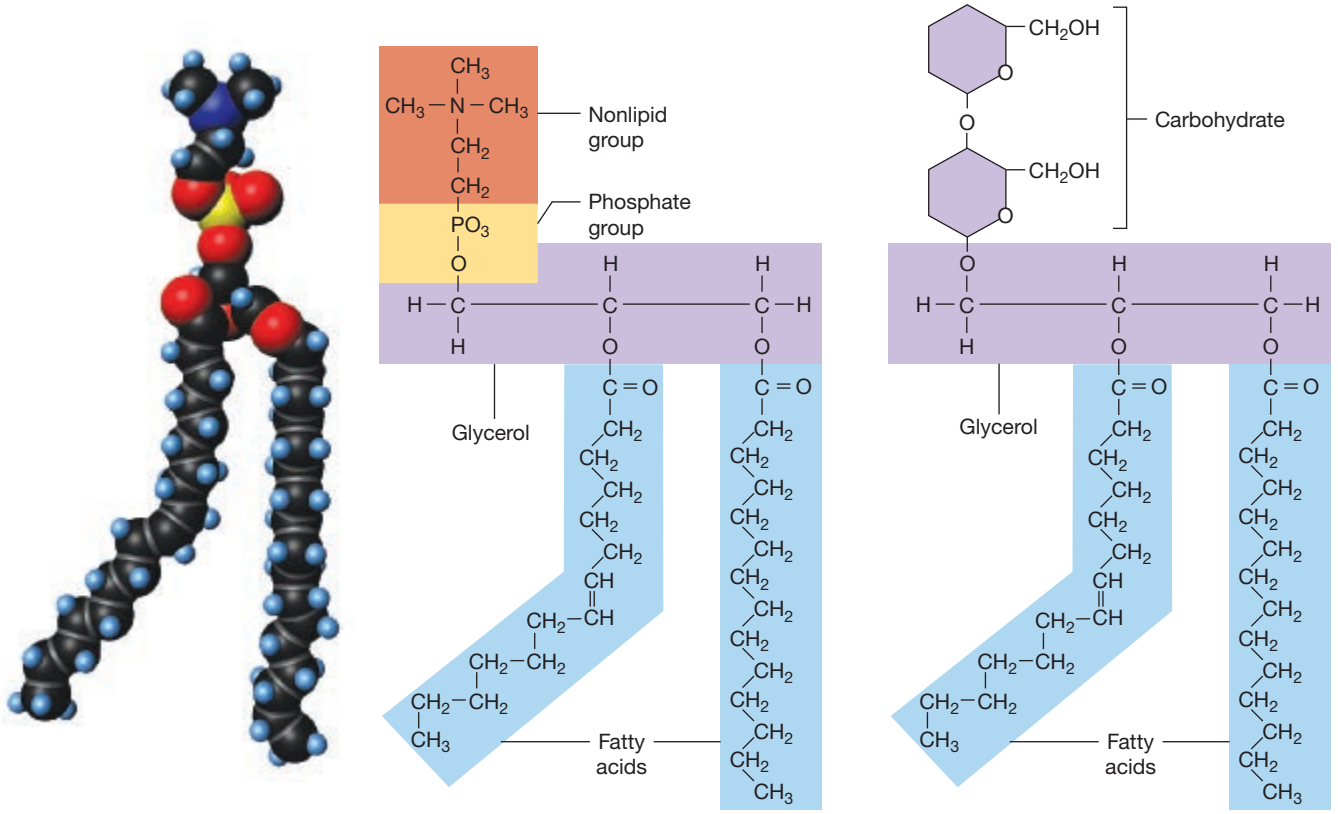
Proteins carry out a variety of essential functions, which we can group into the following major categories:

- *Support. Structural proteins* create a three-dimensional framework for the body. They provide strength, organization, and support for cells, tissues, and organs.

**Table 2–5 Representative Lipids and Their Functions in the Body**

| Lipid Type | Example(s) | Primary Functions | Remarks |
|---|---|---|---|
| **Fatty acids** | Lauric acid | Energy source | Absorbed from food or synthesized in cells; transported in the blood |
| **Eicosanoids** | Prostaglandins, leukotrienes | Chemical messengers coordinating local cellular activities | Prostaglandins are produced in most body tissues |
| **Glycerides** | Monoglycerides, diglycerides, triglycerides | Energy source, energy storage, insulation, and physical protection | Stored in fat deposits; must be broken down to fatty acids and glycerol before they can be used as an energy source |
| **Steroids** | Cholesterol | Structural component of plasma membranes, hormones, digestive secretions in bile | All have the same four-carbon ring framework |
| **Phospholipids, glycolipids** | Lecithin (a phospholipid) | Structural components of plasma membranes | Derived from fatty acids and nonlipid components |

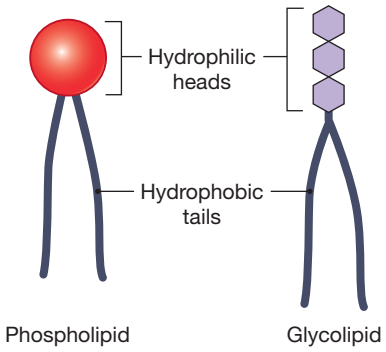
**Figure 2–19** Phospholipids and Glycolipids.

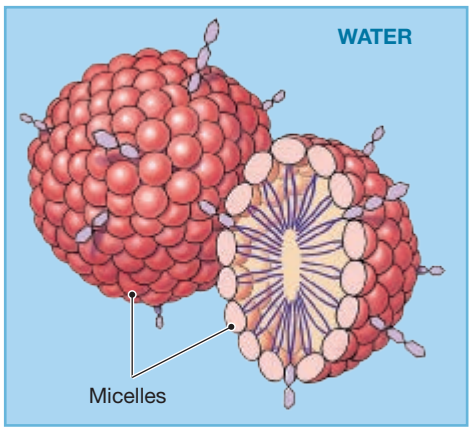



**a** The phospholipid *lecithin*. In a phospholipid, a phosphate group links a nonlipid molecule to a diglyceride.

**b** In a glycolipid, a carbohydrate is attached to a diglyceride.

**c** When large numbers of phospholipids and glycolipids are in water, they form micelles, with the hydrophilic heads facing the water molecules, and the hydrophobic tails on the inside of each droplet.




- *Movement*. *Contractile proteins* bring about muscular contraction. Related proteins are responsible for the movement of individual cells.
- *Transport*. Special *transport proteins* bind many substances for transport in the blood, including insoluble lipids, respiratory gases, special minerals such as iron, and several hormones. These substances would not otherwise be transported in the blood. Other specialized proteins move materials from one part of a cell to another.
- *Buffering*. Proteins provide a buffering action and in this way help prevent dangerous changes in the pH of body fluids.

- *Metabolic Regulation*. Many proteins are enzymes, which as you may recall speed up chemical reactions in cells. The sensitivity of enzymes to environmental factors such as temperature and pH is extremely important in controlling the pace and direction of metabolic reactions.
- *Coordination and Control*. Protein hormones can influence the metabolic activities of every cell in the body or affect the function of specific organs or organ systems.
- *Defense*. Proteins defend the body in many ways. The tough, waterproof proteins of the skin, hair, and nails protect the body from environmental hazards. Proteins called *antibodies* help protect us from disease by taking part in the *immune response*. Special *clotting proteins* restrict bleeding after an injury.

## Protein Structure

Proteins are organic polymers that consist of long chains of similar organic molecules called **amino acids**. Twenty different amino acid monomers occur in significant quantities in the body. All 20 amino acids are small, water-soluble molecules. A typical protein contains 1000 amino acids, while the largest protein complexes have 100,000 or more.

Each amino acid consists of five parts (Figure 2–20):

- a central carbon atom,
- a hydrogen atom,
- an *amino group* ($—NH_2$),
- a carboxyl group ($—COOH$),
- an *R group* (a variable *side chain* of one or more atoms that identifies a specific amino acid).

The name *amino acid* refers to the presence of the amino group and the carboxyl group, which all amino acids have in common. At physiological pH levels, the carboxyl group can act as an acid by releasing a hydrogen ion to become a *carboxyl ion* ($COO^-$). The amino group can act as a base by accepting a hydrogen ion, to become an amino ion ($—NH_3^+$). The result is a molecule that has both positive and negative charges, but a net charge of zero. Such molecules are called *zwitterions*, derived from the German word that means "hybrid."

**Figure 2–20 Amino Acids.** Each amino acid consists of a central carbon atom to which four different groups are attached: a hydrogen atom, an amino group ($—NH_2$), a carboxyl group ($—COOH$), and a variable side group designated as R.

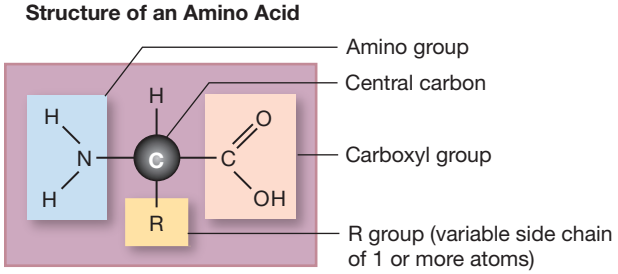
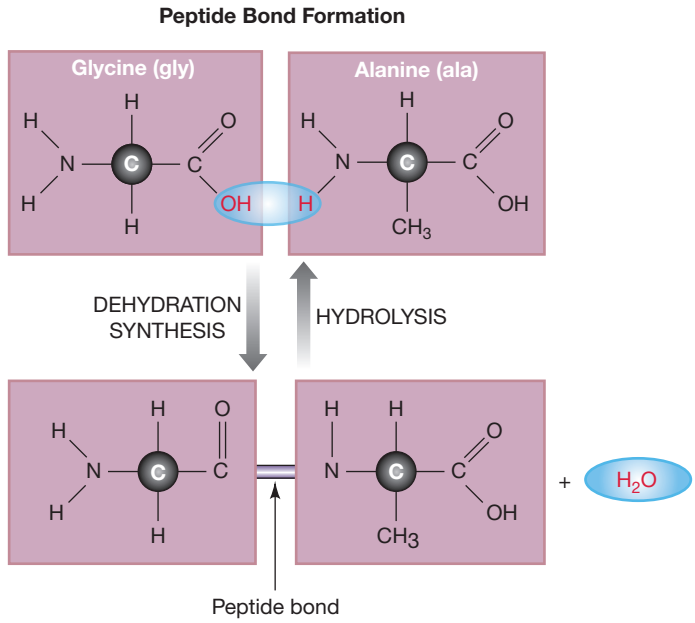



**Figure 2–21 The Formation of Peptide Bonds.** Peptides form as dehydration synthesis creates a peptide bond between the carboxyl group of one amino acid and the amino group of another. In this example, a peptide bond links the amino acids glycine (for which R = H) and alanine (R = $CH_3$) to form a dipeptide.




A protein begins to form as amino acids are strung together into long chains. Figure 2–21 shows how dehydration synthesis can link two representative amino acids: *glycine* and *alanine*. This reaction creates a covalent bond between the carboxyl group of one amino acid and the amino group of another. Such a bond is known as a **peptide bond**. Molecules consisting of amino acids held together by peptide bonds are called **peptides**. The molecule created in this example is called a *dipeptide*, because it contains two amino acids.

The chain can be lengthened by the addition of more amino acids. Attaching a third amino acid produces a *tripeptide*. Tripeptides and larger peptide chains are called **polypeptides**. Polypeptides with more than 100 amino acids are usually called proteins. Familiar proteins include *hemoglobin* in red blood cells, *collagen* in skin, bones, and muscles, and *keratin* in fingernails and hair.

The different atoms of the R groups distinguish one amino acid from another, giving each its own chemical properties. For example, different R groups are polar, nonpolar, or electrically charged. Amino acids with nonpolar R groups are hydrophobic, whereas amino acids with polar R groups that form hydrogen bonds with water are hydrophilic. Amino acids with electrically charged R groups are strongly hydrophilic.

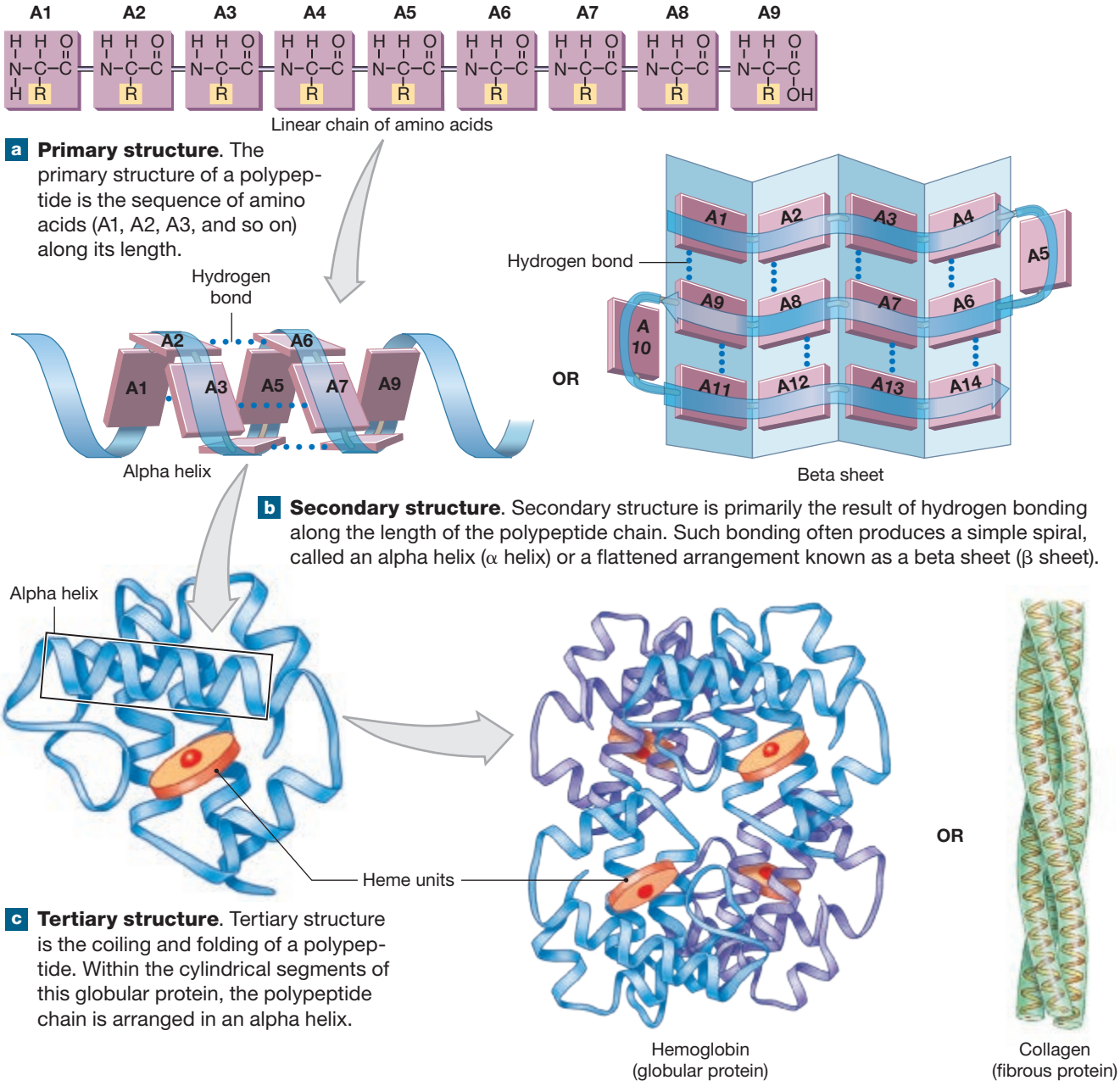
The properties of the R groups contribute to the overall shape and function of proteins.

## Protein Shape

The characteristics of a particular protein are determined in part by the R groups on its amino acids. But the properties of a protein are more than just the sum of the properties of its parts, for polypeptides can have highly complex shapes that are important to their function. Proteins can have four levels of structural complexity (Figure 2–22):

1. **Primary structure** is the sequence of amino acids along the length of a single polypeptide (Figure 2–22a).

**Figure 2–22** Protein Structure.



Peptide bonds are responsible for the primary structure of proteins.

2. **Secondary structure** is the shape that results from the presence of hydrogen bonds between atoms at different parts of the polypeptide chain. Hydrogen bonding may create either an *alpha helix* (simple spiral) or *beta sheet* (a flat pleated sheet) (Figure 2–22b). Which one forms depends on where hydrogen bonding takes place between the sequence of amino acids in the polypeptide chain. The alpha helix is the more common form, but a given polypeptide chain may have both helical and pleated sections. Ribbon diagrams are used to represent the three-dimensional structure of proteins. An alpha helix appears as a coiled ribbon, beta sheets as arrows, and less-structured polypeptide chains as narrow ribbons or tubes.
3. **Tertiary structure** is the complex coiling and folding that gives a protein its final three-dimensional shape (Figure 2–22c). Tertiary structure results primarily from hydrophobic and hydrophilic interactions between the R groups of the polypeptide chain and the surrounding water molecules, and to a lesser extent from interactions between the R groups of amino acids in different parts of the molecule. Most such interactions are relatively weak. One, however, is very strong: the *disulfide bond*, a covalent bond that may form between the sulfur atoms of two molecules of the amino acid *cysteine* located at different sites along the chain (not shown). Disulfide bonds create permanent loops or coils in a polypeptide chain.
4. **Quaternary structure** is the interaction between individual polypeptide chains to form a protein complex (Figure 2–22d). Each of the polypeptide subunits has its own secondary and tertiary structures. For example, the protein *hemoglobin* contains four subunits. In Figure 2–22d, the polypeptide subunits with the same color (blue or purple) have the same structure. The hemoglobin in red blood cells binds and transports oxygen. *Collagen*, composed of three windings of alpha helical polypeptides, is the most abundant structural protein and is found in skin, bones, muscles, cartilages, and tendons. Collagen fibers form the framework that supports cells in most tissues. In *keratin*, two alpha helical polypeptides are wound together like the strands of a rope. Keratin is the tough, water-resistant protein at the surface of the skin and in nails and hair.

### Fibrous and Globular Proteins

Proteins fall into two general structural classes on the basis of their overall shape and properties:

- **Globular proteins** are compact, generally rounded, and soluble in water. Many enzymes, hormones, and other molecules that circulate in the bloodstream are globular proteins. These proteins can function only if they remain in solution. The unique shape of each globular protein comes from its tertiary structure. Hemoglobin and *myoglobin*, a protein in muscle cells, are both globular proteins. The enzymes that control chemical reactions inside cells are also globular proteins.
- **Fibrous proteins** form extended sheets or strands. Fibrous proteins are tough, durable, and generally insoluble in water. They usually play structural roles in the body. Their shapes are usually due to secondary structure (for proteins with the pleated-sheet form) or quaternary structure (as we just described for collagen and keratin).

### Protein Shape and Function

The shape of a protein determines its functional characteristics, and the sequence of amino acids ultimately determines its shape. The 20 amino acids can be linked in an astonishing number of combinations, creating proteins of enormously varied shape and function. Changing only 1 of the 10,000 or more amino acids in a protein can significantly alter the way the protein functions. For example, several cancers and *sickle cell anemia*, a blood disorder, result from changing just a single amino acid in the amino acid sequences of complex proteins.

The tertiary and quaternary shapes of complex proteins depend not only on their amino acid sequence, but also on the local environmental conditions. Small changes in the ionic composition, temperature, or pH of their surroundings can affect the function of proteins. Protein shape can also be affected by hydrogen bonding to other molecules in solution. The significance of these factors is most striking when we consider enzymes, for these proteins are essential to the metabolic operations in every one of our cells.

## Enzyme Function

Enzymes are among the most important of all the body's proteins. As noted earlier in this chapter, enzymes catalyze the chemical reactions that sustain life. Almost everything that happens inside the human body does so because a specific enzyme makes it possible.

The reactants in enzymatic reactions are called **substrates**. As in other types of chemical reactions, the interactions among substrates yield specific products. Before an enzyme can function as a catalyst—accelerating a chemical reaction without itself being permanently changed or consumed—the substrates must bind to a special region of the enzyme. This region is called the **active site**. It is typically a groove or pocket into which one or more substrates nestle, like a key fitting into a lock. Weak electrical attractive forces, such as hydrogen bonding, reinforce the physical fit. The tertiary or quaternary structure of the enzyme molecule determines the shape of the active site. Although enzymes are proteins, any organic or inorganic compound that will bind to the active site can be a substrate.

**Figure 2–23 A Simplified View of Enzyme Structure and Function.** Each enzyme contains a specific active site somewhere on its exposed surface.

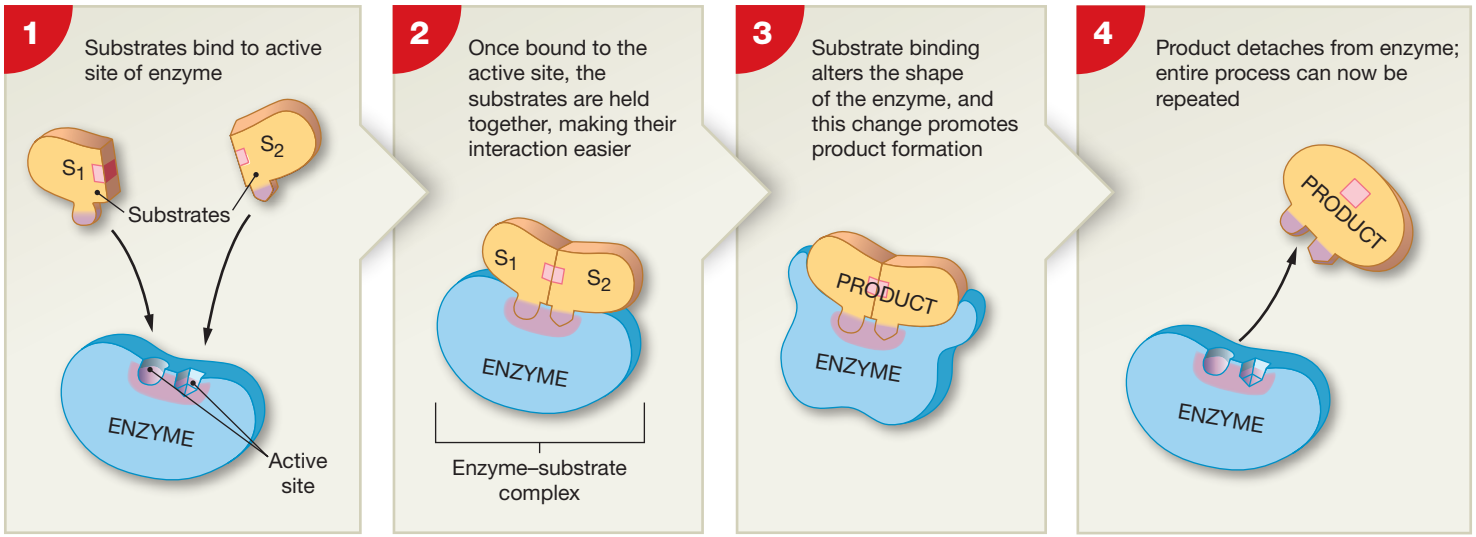



**Figure 2–23** presents one example of enzyme structure and function. Substrates bind to the enzyme at its active site (1). Substrate binding produces an *enzyme–substrate complex* (2). Substrate binding typically produces a temporary, reversible change in the shape of the enzyme that may place physical stresses on the substrate molecules, leading to product formation (3). The product is then released, freeing the enzyme to repeat the process (4).

Enzymes work quickly, cycling rapidly between substrates and products. For example, an enzyme providing energy during a muscular contraction performs its reaction sequence 100 times per second. Hydrolytic enzymes can work even faster, breaking down almost 20,000 molecules a second!

**Figure 2–23** shows an enzyme that catalyzes a synthesis reaction. Other enzymes may catalyze decomposition reactions, reversible reactions, or exchange reactions. Regardless of the reaction they catalyze, all enzymes share the basic characteristics of specificity, saturation limits, and regulation:

- *Specificity*. Each enzyme catalyzes only one type of reaction, a characteristic called **specificity**. An enzyme's specificity is due to the ability of its active sites to bind only to substrates with particular shapes and charges. For this reason, differences in enzyme structure that do not affect the active site and do not change the response of the enzyme to substrate binding do not affect enzyme function. Such enzyme variants are called *isozymes*.
- *Saturation Limits*. The rate of an enzymatic reaction is directly related to the concentrations of substrate molecules and enzymes. An enzyme molecule must encounter appropriate substrates before it can catalyze a reaction. The higher the substrate concentration, the more frequent these encounters. When substrate concentrations are high enough that every enzyme molecule is cycling through its reaction sequence at top speed, further increases in substrate concentration will not affect the rate of reaction unless additional enzyme molecules are provided. The substrate concentration required to reach the maximum rate of reaction is called the *saturation limit*. An enzyme that has reached its saturation limit is said to be **saturated**. To increase the reaction rate further, the cell must increase the number of enzyme molecules available. This is one important way that cells promote specific reactions.
- *Regulation*. Each cell contains an assortment of enzymes, and any particular enzyme may be active under one set of conditions and inactive under another. Virtually anything that changes the tertiary or quaternary shape of an enzyme can turn it "on" or "off" and in this way control reaction rates inside the cell. Because the shape change is immediate, enzyme activation or inactivation is an important method of short-term control over reaction rates and metabolic pathways. Here we will consider only one example of enzyme regulation: the presence or absence of *cofactors*.

## Cofactors and Enzyme Function

A **cofactor** is an ion or a molecule that must bind to an enzyme before substrates can also bind. Without a cofactor, the enzyme is intact but nonfunctional. With the cofactor, the enzyme can catalyze a specific reaction. Examples of ionic cofactors include calcium ion ($Ca^{2+}$) and magnesium ion ($Mg^{2+}$), which bind at the enzyme's active site. Cofactors may also bind at other sites, as long as they produce a change in the shape of the active site that makes substrate binding possible.

**Coenzymes** are nonprotein organic molecules that function as cofactors. Our bodies convert many vitamins into essential coenzymes. *Vitamins*, detailed in Chapter 25, are

organic nutrients structurally related to lipids or carbohydrates, but have unique functional roles. Because the human body cannot synthesize most of the vitamins it needs, you must obtain them from your diet.

### Temperature and pH Affect Enzyme Function

Each enzyme works best at specific temperatures and pH values. As temperatures rise, protein shape changes and enzyme function deteriorates. Eventually the protein undergoes **denaturation**, a change in tertiary or quaternary structure that makes it nonfunctional. You see permanent denaturation when you fry an egg. As the temperature rises, the proteins in the egg white denature. Eventually, the proteins become completely and irreversibly denatured, forming an insoluble white mass. In the body, death occurs at very high body temperatures (above 43°C, or 110°F) because structural proteins and enzymes soon denature, causing irreparable damage to organs and organ systems.

Enzymes are equally sensitive to changes in pH. *Pepsin*, an enzyme that breaks down food proteins in the stomach, works best at a pH of 2.0 (strongly acidic). Your small intestine contains *trypsin*, another protein-degrading enzyme. Trypsin works only in an alkaline environment, with an optimum pH of 7.7 (weakly basic).

### Glycoproteins and Proteoglycans

**Glycoproteins** (GLĪ-kō-prō-tēnz) and **proteoglycans** (prō-tē-ō-GLĪ-kanz) are combinations of protein and carbohydrate molecules. Glyco*proteins* are large proteins with small carbohydrate groups attached. These molecules may function as enzymes, antibodies, hormones, or protein components of plasma membranes. Glycoproteins in plasma membranes play a major role in identifying normal versus abnormal cells. They are also important in the immune response (Chapter 22). Glycoprotein secretions called *mucins* absorb water to form **mucus**. Mucus coats and lubricates the surfaces of the reproductive and digestive tracts.

Proteo*glycans* are large polysaccharide molecules linked by polypeptide chains. Proteoglycans bind adjacent cells together, and give tissue fluids a viscous (syrupy) consistency.

### Checkpoint

24. **Describe a protein.**
25. **How does boiling a protein affect its structural and functional properties?**

See the blue Answers tab at the back of the book.

## 2-13 DNA and RNA are nucleic acids

Learning Outcome Discuss the structures and functions of nucleic acids.

**Nucleic** (nū -KLĀ-ik) **acids** are large organic molecules composed of carbon, hydrogen, oxygen, nitrogen, and phosphorus. Nucleic acids store and process information at the molecular level inside cells. The two classes of nucleic acid molecules are **deoxyribonucleic** (dē-oks-ē-rī-bō-nū -KLĀ-ik) **acid (DNA)** and **ribonucleic** (rī-bō-nū-KLĀ-ik) **acid (RNA)**. As we will see, these two classes of nucleic acids differ in composition, structure, and function.

The primary role of nucleic acids is to store and transfer information—specifically, information essential to the synthesis of proteins within our cells. The DNA in our cells encodes the information needed to build proteins, while several forms of RNA cooperate to build specific proteins using the information provided by DNA.

DNA contains the instructions for making proteins with correct shapes and therefore correct functions. Those proteins then control our inherited characteristics. For example, by directing the synthesis of structural proteins, DNA determines all of our physical characteristics, including eye color, hair color, and blood type. By directing the synthesis of many functional proteins, including enzymes, DNA regulates all aspects of cellular metabolism, including the creation and destruction of lipids, carbohydrates, and other vital molecules.

In this section, we look at how nucleic acids are structured, and the similarities and differences between DNA and RNA. In Chapter 3 we detail the ways that DNA and RNA work together.

### Structure of Nucleic Acids

A nucleic acid consists of one or two long chains of repeating subunits. The individual subunits (monomers) of the chain are called **nucleotides**. Each nucleotide has three parts (Figure 2–24a): (1) a pentose (five-carbon sugar) attached to both, (2) a phosphate group and (3) a **nitrogenous** (nitrogen-containing) **base**. The pentose is either **ribose** (in RNA) or **deoxyribose** (in DNA).

Five nitrogenous bases occur in nucleic acids: **adenine (A)**, **guanine (G)**, **cytosine (C)**, **thymine (T)**, and **uracil (U)**. Adenine and guanine are double-ringed molecules called *purines* (Figure 2–24b). The other three bases are single-ringed molecules called *pyrimidines* (Figure 2–24c). Both RNA and DNA contain adenine, guanine, and cytosine. Uracil occurs only in RNA and thymine occurs only in DNA.

A nucleotide forms when a phosphate group binds to a pentose already attached to a nitrogenous base. A nucleic acid forms when nucleotides are joined by dehydration synthesis, which attaches the phosphate group of one nucleotide to the sugar of another. The "backbone" of a nucleic acid molecule is a linear sugar-to-phosphate-to-sugar sequence, with the nitrogenous bases projecting to one side.

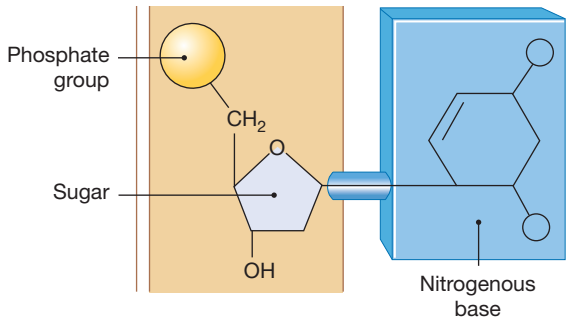
### Comparison of RNA and DNA

In both DNA and RNA, it is the sequence of nitrogenous bases that carries the information about how to make proteins.

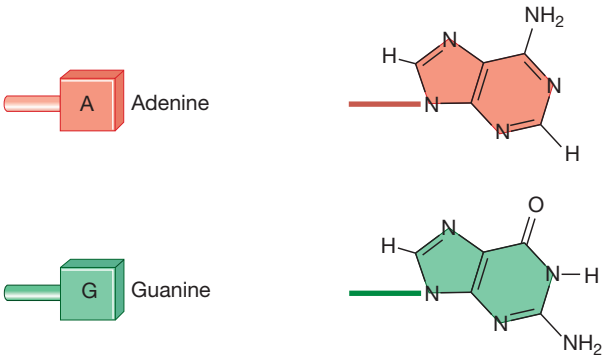
**Figure 2–24 Nucleotides and Nitrogenous Bases.**

**a Nucleotide structure**

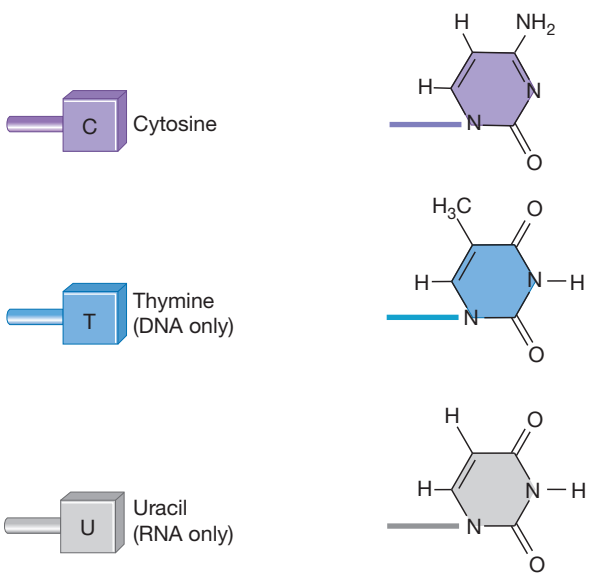
The nitrogenous base may be a purine or a pyrimidine.




**b Purines**

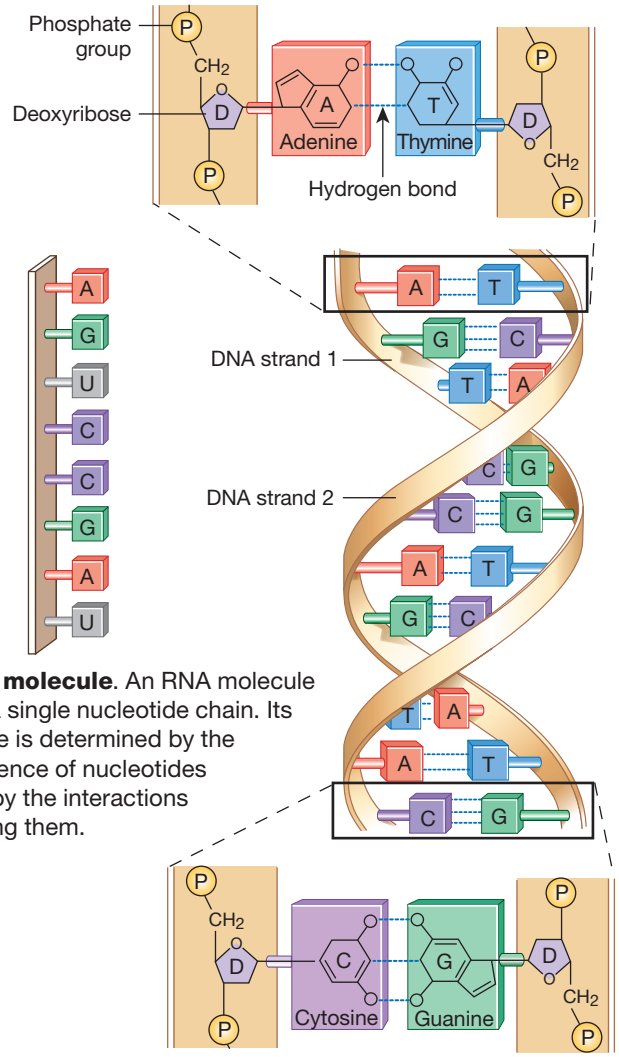



**c Pyrimidines**




? What structural differences make adenine and guanine different from cytosine, thymine, and uracil?

**Figure 2–25 The Structure of Nucleic Acids.** The nucleic acids RNA and DNA are long chains of nucleotides.




**a RNA molecule**. An RNA molecule has a single nucleotide chain. Its shape is determined by the sequence of nucleotides and by the interactions among them.

**b DNA molecule**. A DNA molecule has a pair of nucleotide chains linked by hydrogen bonding between complementary base pairs.

However, there are other important structural differences between the two types of nucleic acids. A molecule of RNA consists of a single chain of nucleotides (Figure 2–25a). Its shape depends on the order of the nucleotides and the interactions among them. Our cells have various forms of RNA with different shapes and functions. As we will see in Chapter 3, protein synthesis requires three types of RNA: (1) *messenger RNA (mRNA)*, (2) *transfer RNA (tRNA)*, and (3) *ribosomal RNA (rRNA)*. There are also other types of RNA whose roles are under active research.

A DNA molecule consists of a *pair* of nucleotide chains, with two sugar-phosphate backbones on the outside and the nitrogenous bases projecting inward (Figure 2–25b). Hydrogen bonding between opposing nitrogenous bases

**Table 2–6 Comparison of RNA and DNA**

| Characteristic | RNA | DNA |
|---|---|---|
| **Sugar** | Ribose | Deoxyribose |
| **Nitrogenous bases** | Adenine (A) | Adenine |
| | Guanine (G) | Guanine |
| | Cytosine (C) | Cytosine |
| | Uracil (U) | Thymine (T) |
| **Number of nucleotides in typical molecule** | Varies from fewer than 100 nucleotides to about 50,000 | Always more than 45 million |
| **Shape of molecule** | Varies with hydrogen bonding along the length of the strand; three main types (mRNA, rRNA, tRNA) | Paired strands coiled in a double helix |
| **Function** | Performs protein synthesis as directed by DNA | Stores genetic information that controls protein synthesis |

holds the two strands together. The shapes of the nitrogenous bases allow adenine to bond only to thymine, and cytosine to bond only to guanine. As a result, the combinations adenine–thymine (A–T) and cytosine–guanine (C–G) are known as **complementary base pairs**, and the two nucleotide chains of the DNA molecule are known as **complementary strands**. The two strands of DNA twist around one another in a double helix that resembles a spiral staircase. Each step of the staircase corresponds to one complementary base pair.

Through a sequence of events described in Chapter 3 , the cell uses one of the two complementary DNA strands to provide the information needed to synthesize a specific protein. Table 2–6 summarizes our comparison of RNA and DNA.

## Checkpoint

26. **Describe a nucleic acid.**
27. **A large organic molecule made of the sugar ribose, nitrogenous bases, and phosphate groups is which kind of nucleic acid?**

See the blue Answers tab at the back of the book.

## 2-14 ATP is a high-energy compound used by cells

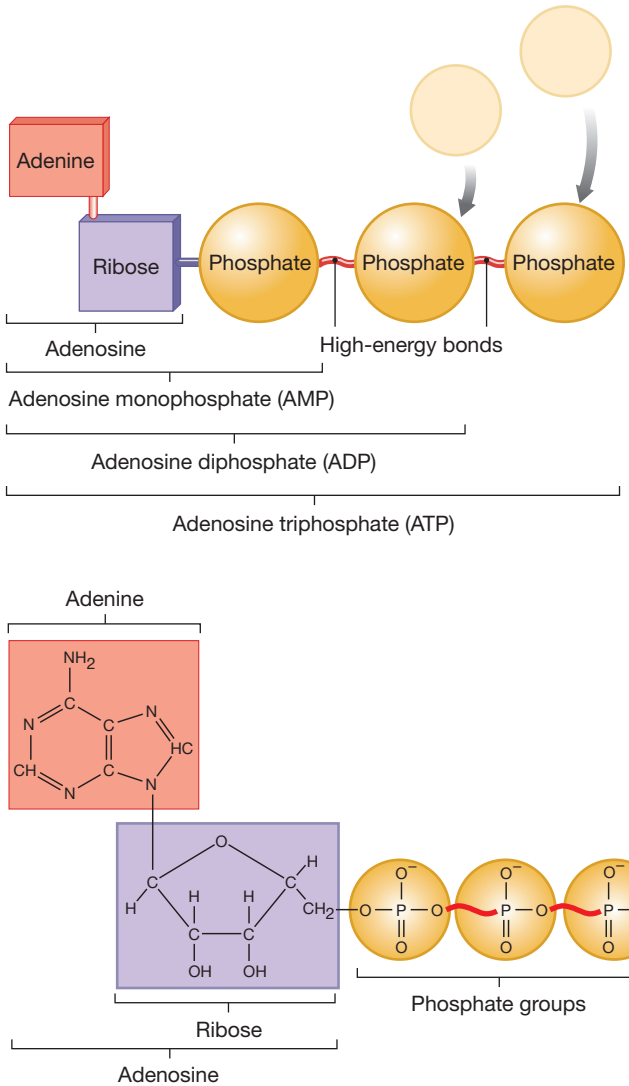
**Learning Outcome** Discuss the structures and functions of high-energy compounds.

To perform their vital functions, cells must use energy, which they obtain by breaking down organic substrates (catabolism). To be useful, that energy must be transferred from molecule to molecule or from one part of the cell to another.

The usual method of energy transfer involves the creation and breakdown of high-energy bonds by enzymes within cells. A *high-energy bond* is a covalent bond whose breakdown releases energy the cell can use directly. In our cells, a high-energy bond generally binds a phosphate group ($PO_4^{3-}$) to an organic molecule. The product with such a bond is called a **high-energy compound**. Most high-energy compounds are derived from nucleotides, the building blocks of nucleic acids (Figure 2–26).

The process of attaching a phosphate group to another molecule is called **phosphorylation** (fos-for-i-LĀ-shun). This

**Figure 2–26 The Structure of ATP.** A molecule of ATP is formed by attaching two phosphate groups to the nucleotide adenosine monophosphate. These two phosphate groups are connected by high-energy bonds incorporating energy released by catabolism. Cells most often obtain quick energy to power cellular operations by removing one phosphate group from ATP, forming ADP (adenosine diphosphate). ADP can later be reconverted to ATP, and the cycle repeated.




? How many phosphorylations does AMP undergo to become ATP?

process does not necessarily produce high-energy bonds. For example, in the synthesis of sucrose, a phosphate group is first attached to glucose. The creation of a high-energy compound requires (1) a phosphate group, (2) enzymes capable of catalyzing the reactions involved, and (3) suitable organic substrates to which the phosphate can be added.

The most important such substrate is the nucleotide **adenosine monophosphate (AMP)**, which already contains one phosphate group. Attaching a second phosphate group produces **adenosine diphosphate (ADP)**. A significant energy input is required to convert AMP to ADP, and the second phosphate is attached by a high-energy bond. Even more energy is required to add a third phosphate and create the high-energy compound **adenosine triphosphate (ATP)** (Figure 2–26).

The conversion of ADP to ATP is the most important method of storing energy in our cells. The breakdown of ATP to ADP is the most important method of releasing energy. The relationships involved in this energy transfer can be diagrammed as

$$\text{ADP} + \text{phosphate group} + \text{energy} \rightleftharpoons \text{ATP} + H_2O$$

The hydrolytic breakdown of ATP to ADP requires an enzyme known as **adenosine triphosphatase (ATPase)**, as well as a molecule of water**.** Throughout life, cells continuously generate ATP from ADP and then use the energy provided by the breakdown of ATP to perform vital functions, such as the synthesis of proteins or the contraction of muscles.

ATP is our most abundant high-energy compound, but there are others. They are typically other nucleotides that have undergone phosphorylation. For example, *guanosine triphosphate (GTP)* is a nucleotide-based high-energy compound that transfers energy in specific enzymatic reactions.

Table 2–7 summarizes the inorganic and organic compounds covered in this chapter.

### Checkpoint

28. **Describe ATP.**
29. **What molecule is produced by the phosphorylation of ADP?**

See the blue Answers tab at the back of the book.

**Table 2–7 Classes of Inorganic and Organic Compounds**

| Class | Building Blocks (Elements and/or Monomers) | Sources | Functions |
|---|---|---|---|
| INORGANIC | | | |
| **Water** | Hydrogen and oxygen atoms | Absorbed from the diet or generated by metabolism | Solvent; transport medium for dissolved materials and heat; cooling through evaporation; medium for chemical reactions; reactant in hydrolysis |
| **Acids, bases, salts** | $H^+$, $OH^-$, various anions and cations | Obtained from the diet or generated by metabolism | Structural components; buffers; sources of ions |
| **Dissolved gases** | O, C, N, and other atoms | Atmosphere, metabolism | $O_2$: required for cellular metabolism<br>$CO_2$: generated by cells as a waste product<br>NO: chemical messenger in cardiovascular, nervous, and lymphatic systems |
| ORGANIC | | | |
| **Carbohydrates** | C, H, O, in some cases N; CHO in a 1:2:1 ratio<br>Monosaccharide monomers | Obtained from the diet or manufactured in the body | Energy source; some structural role when attached to lipids or proteins; energy storage |
| **Lipids** | C, H, O, in some cases N or P; CHO not in 1:2:1 ratio<br>Fatty acids and glycerol monomers | Obtained from the diet or manufactured in the body | Energy source; energy storage; insulation; structural components; chemical messengers; protection |
| **Proteins** | C, H, O, N, commonly S<br>Amino acid monomers | 20 common amino acids; roughly half can be manufactured in the body, others must be obtained from the diet | Catalysts for metabolic reactions; structural components; movement; transport; buffers; defense; control and coordination of activities |
| **Nucleic acids** | C, H, O, N, and P; nucleotides composed of phosphates, sugars, and nitrogenous bases<br>Nucleotide monomers | Obtained from the diet or manufactured in the body | Storage and processing of genetic information |
| **High-energy compounds** | Nucleotides joined to phosphates by high-energy bonds | Synthesized by all cells | Storage or transfer of energy |

# 2 Chapter Review

## Study Outline

### An Introduction to the Chemical Level of Organization p. 74

1. Chemicals combine to form complex structures.

### 2-1 Atoms are the basic particles of matter p. 74

2. Atoms are the smallest units of matter. They consist of **protons**, **neutrons**, and **electrons**. Protons and neutrons reside in the **nucleus** of an atom.
3. The number of protons in an atom is its **atomic number**. Each **element** includes all the atoms that have the same number of protons and thus the same atomic number.
4. Within an atom, an **electron cloud** surrounds the nucleus. *(Figure 2–1)*
5. The **mass number** of an atom is the total number of protons and neutrons in its nucleus. **Isotopes** are atoms of the same element whose nuclei contain different numbers of neutrons.
6. Electrons occupy an orderly series of **energy levels**, commonly illustrated as **electron shells**. The electrons in the outermost energy level, or **valence shell**, determine an element's chemical properties. *(Figures 2–2, 2–3)*

### 2-2 Chemical bonds are forces formed by interactions between atoms p. 78

7. Atoms can combine through chemical reactions that create **chemical bonds**. A **molecule** is any chemical structure consisting of atoms held together by covalent bonds. A **compound** is a chemical substance made up of atoms of two or more elements in a fixed proportion.
8. The rules of **chemical notation** are used to describe chemical compounds and reactions. (*Spotlight Figure 2–4*)
9. An **ionic bond** results from the attraction between **ions**, atoms that have gained or lost electrons. **Cations** are positively charged; **anions** are negatively charged. *(Figure 2–5)*
10. Atoms that share electrons to form a molecule are held together by **covalent bonds**. A sharing of one pair of electrons is a **single covalent bond**; a sharing of two pairs is a **double covalent bond**; and a sharing of three pairs is a **triple covalent bond**. A bond with equal sharing of electrons is a **nonpolar covalent bond**; a bond with unequal sharing of electrons is a **polar covalent bond**. *(Figures 2–6, 2–7)*
11. A **hydrogen bond** is a weak, but important, electrical attraction that can affect the shapes and properties of molecules. *(Figure 2–8)*
12. Matter can exist as a *solid*, a *liquid*, or a *gas*, depending on the nature of the interactions among the component atoms or molecules.
13. The **molecular weight** of a molecule or a compound is the sum of the atomic weights of its component atoms.

### 2-3 Decomposition, synthesis, and exchange reactions are important types of chemical reactions in physiology p. 83

14. A chemical reaction occurs when **reactants** are rearranged to form one or more **products**. Collectively, all the **chemical reactions** in the body constitute its **metabolism**. Through metabolism, cells capture, store, and use energy to maintain homeostasis and to perform essential functions.
15. **Work** is the movement of an object or a change in the physical structure of matter. **Energy** is the capacity to perform work.
16. **Kinetic energy** is the energy of motion. **Potential energy** is stored energy that results from the position or structure of an object. Conversions from potential to kinetic energy (or vice versa) are not 100 percent efficient. Every such energy conversion releases *heat*.
17. A chemical reaction is classified as a **decomposition**, a **synthesis**, or an **exchange reaction**.
18. Cells gain energy to power their functions by **catabolism**, the breakdown of complex molecules. Much of this energy supports **anabolism**, the synthesis of new molecules.
19. All chemical reactions are theoretically reversible. At **equilibrium**, the rates of two opposite reactions are in balance.

### 2-4 Enzymes speed up reactions by lowering the energy needed to start them p. 85

20. **Activation energy** is the amount of energy required to start a reaction. **Enzymes** are **catalysts**—compounds that accelerate chemical reactions without themselves being permanently changed or consumed. Enzymes promote chemical reactions by lowering the activation energy needed. *(Figure 2–9)*
21. **Exergonic** reactions release energy. **Endergonic** reactions absorb energy.

### 2-5 Inorganic compounds lack carbon, and organic compounds contain carbon p. 86

22. **Nutrients** are the essential elements and molecules normally obtained from the diet. **Metabolites**, on the other hand, are molecules that can be synthesized or broken down by chemical reactions inside our bodies. Nutrients and metabolites can be broadly categorized as either **inorganic** or **organic compounds**.

### 2-6 Physiological systems depend on water p. 86

23. Water is the most important constituent of the body.
24. A **solution** is a uniform mixture of two or more substances. It consists of a medium, or **solvent**, in which atoms, ions, or molecules of another substance, or **solute**, are individually dispersed. In *aqueous solutions*, water is the solvent. *(Figure 2–10)*

> Pearson Mastering A&P™ Access more chapter study tools online in the Pearson Mastering A&P Study Area:
> - Chapter Quizzes, Chapter Practice Test, MP3 Tutor Sessions, and Clinical Case Studies
> - Practice Anatomy Lab PAL™ 3.0
> - Interactive Physiology IP2™
> - A&P Flix A&PFlix™
> - PhysioEx PhysioEx™ 9.1

25. Many inorganic substances, called **electrolytes**, undergo **dissociation**, or **ionization**, in water to form ions. Molecules that interact readily with water molecules are called **hydrophilic**. Those that do not are called **hydrophobic**. *(Figure 2–10; Table 2–2)*

### 2-7 Body fluid pH is vital for homeostasis p. 89

26. The **pH** of a solution indicates the concentration of hydrogen ions it contains. Solutions are classified as **neutral**, **acidic**, or **basic** *(alkaline)* on the basis of pH. *(Figure 2–11)*

### 2-8 Acids, bases, and salts have important physiological roles p. 90

27. An **acid** releases hydrogen ions. A **base** removes hydrogen ions from a solution. *Strong acids* and *strong bases* ionize completely. In the case of *weak acids* and *weak bases*, only some of the molecules ionize.
28. A **salt** is an electrolyte whose cation is not a hydrogen ion ($OH^+$) and whose anion is not a hydroxide ion ($OH^-$).
29. **Buffers** remove or replace hydrogen ions in solution. Buffers and *buffer systems* in body fluids maintain the pH within normal limits.

### 2-9 Living things contain organic compounds made up of monomers, polymers, and functional groups p. 91

30. Carbon and hydrogen are the main constituents of **organic compounds**, which generally contain oxygen as well. Identical **monomers** join together through *dehydration synthesis* reactions and form long complex chains called **polymers**. Organic polymers include carbohydrates, lipids, proteins, and nucleic acids.
31. The properties of the different classes of organic monomers and polymers are a result of the presence of *functional groups* of atoms. *(Table 2–3)*

### 2-10 Carbohydrates contain carbon, hydrogen, and oxygen in a 1:2:1 ratio p. 91

32. **Carbohydrates** are most important as an energy source for metabolic processes. The three major types of carbohydrates are **monosaccharides** *(simple sugars)*, **disaccharides**, and **polysaccharides**. Disaccharides and polysaccharides form from monosaccharide monomers by **dehydration synthesis**. *(Figures 2–12 to 2–14; Table 2–4)*

### 2-11 Lipids often contain a carbon-to-hydrogen ratio of 1:2 p. 93

33. **Lipids** include *fats*, *oils*, and *waxes*. Most are insoluble in water. The five important classes of lipids are **fatty acids**, **eicosanoids**, **glycerides**, **steroids**, and **phospholipids** and **glycolipids**. *(Figures 2–15 to 2–19; Table 2–5)*
34. **Triglycerides** *(neutral fats)* consist of three fatty acid molecules attached by dehydration synthesis to a molecule of **glycerol**. **Diglycerides** consist of two fatty acids and glycerol. **Monoglycerides** consist of one fatty acid plus glycerol. Fatty acids and glycerol are lipid monomers. *(Figure 2–17)*
35. Steroids (1) are components of plasma membranes, (2) include sex hormones and hormones regulating metabolic activities, and (3) are important in lipid digestion. *(Figure 2–18)*
36. **Phospholipids** and **glycolipids** are structural lipids that are components of *micelles* and plasma membranes *(Figure 2–19)*.

### 2-12 Proteins contain carbon, hydrogen, oxygen, and nitrogen and are formed from amino acids p. 97

37. **Proteins** perform a variety of essential functions in the body. Seven important types of proteins are *structural proteins*, *contractile proteins*, *transport proteins*, *buffering proteins*, *enzymes*, *hormones*, and *antibodies*.
38. Proteins are organic polymers made up of chains of **amino acids**. Each amino acid monomer consists of an *amino group*, a *carboxyl group*, a *hydrogen atom*, and an *R group (side chain)* attached to a central carbon atom. A **polypeptide** is a linear sequence of amino acids held together by **peptide bonds**; **proteins** are polypeptides containing over 100 amino acids. *(Figures 2–20, 2–21)*
39. The four levels of protein structure are **primary structure** (amino acid sequence), **secondary structure** (amino acid interactions, such as hydrogen bonds), **tertiary structure** (complex folding, disulfide bonds, and interaction with water molecules), and **quaternary structure** (formation of protein complexes from individual subunits). **Globular proteins**, such as *myoglobin* and *hemoglobin*, are generally rounded and water soluble. **Fibrous proteins**, such as *collagen* and *keratin*, are elongated, tough, durable, and generally insoluble. *(Figure 2–22)*
40. The reactants in an enzymatic reaction, called **substrates**, interact to yield a product by binding to the enzyme's **active site**. **Cofactors** are ions or molecules that must bind to the enzyme before the substrates can bind. **Coenzymes** are organic cofactors commonly derived from *vitamins*. *(Figure 2–23)*
41. The shape of a protein determines its functional characteristics. Each protein works best at an optimal combination of temperature and pH and will undergo temporary or permanent **denaturation**, or change in shape, at temperatures or pH values outside the normal range.

### 2-13 DNA and RNA are nucleic acids p. 103

42. **Nucleic acids** store and process information at the molecular level. The two kinds of nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. *(Figures 2–24, 2–25; Table 2–6)*
43. Nucleic acids are organic polymers made up of chains of **nucleotides**. Each nucleotide contains a sugar, a phosphate group, and a **nitrogenous base**. The sugar is *ribose* in RNA and *deoxyribose* in DNA. DNA is a two-stranded double helix containing the nitrogenous bases **adenine**, **guanine**, **cytosine**, and **thymine**. RNA consists of a single strand and contains **uracil** instead of thymine.

### 2-14 ATP is a high-energy compound used by cells p. 105

44. Cells store energy in the *high-energy bonds* of **high-energy compounds**. The most important high-energy compound is **ATP (adenosine triphosphate)**. Cells make ATP by adding a phosphate group to **ADP (adenosine diphosphate)** through **phosphorylation**. When ATP is broken down to ADP and phosphate, energy is released. Cells can use this energy to power essential activities. *(Figure 2–26; Table 2–7)*

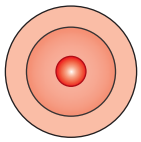
# Review Questions

See the blue Answers tab at the back of the book.



## LEVEL 1 Reviewing Facts and Terms

1. An oxygen atom has eight protons. **(a)** Sketch in the arrangement of electrons around the nucleus of the oxygen atom in the following diagram. **(b)** How many more electrons will it take to fill the outermost energy level?



Oxygen atom

2. What is the following type of synthesis reaction called?

$$AH + BOH \longrightarrow AB + H_2O$$

3. The mass of an atom is determined primarily by the number of **(a)** protons, **(b)** neutrons, **(c)** electrons, **(d)** protons and neutrons.
4. Isotopes of an element differ from each other in the number of **(a)** protons in the nucleus, **(b)** neutrons in the nucleus, **(c)** electrons in the outer shells, **(d)** a, b, and c are all correct.
5. The number and arrangement of electrons in an atom's outer energy level (valence shell) determine the atom's **(a)** atomic weight, **(b)** atomic number, **(c)** molecular weight, **(d)** chemical properties.
6. In the human body, the element that constitutes the highest percentage of the total body weight is **(a)** hydrogen, **(b)** carbon, **(c)** oxygen, **(d)** calcium, **(e)** nitrogen.
7. A substance containing atoms of different elements that are bonded together is called a(n) **(a)** molecule, **(b)** compound, **(c)** mixture, **(d)** isotope, **(e)** solution.
8. Decomposition reactions of complex molecules in the cells and tissues of the human body are collectively referred to as **(a)** metabolism, **(b)** catabolism, **(c)** anabolism, **(d)** equilibrium.
9. Which of the following chemical equations illustrates a typical decomposition reaction?
   **(a)** $A + B \longrightarrow AB$
   **(b)** $AB + CD \longrightarrow AD + CB$
   **(c)** $2A_2 + B_2 \longrightarrow 2A_2B$
   **(d)** $AB \longrightarrow A + B$
10. The speed, or rate, of a chemical reaction is influenced by **(a)** the presence of catalysts, **(b)** the temperature, **(c)** the concentration of the reactants, **(d)** a, b, and c are all correct.
11. A pH of 7.8 in the human body typifies a condition referred to as **(a)** acidosis, **(b)** alkalosis, **(c)** dehydration, **(d)** homeostasis.
12. A(n) _____ is a solute that dissociates to release hydrogen ions, and a(n) _____ is a solute that removes hydrogen ions from solution. **(a)** base, acid, **(b)** salt, base, **(c)** acid, salt, **(d)** acid, base.
13. Enzymes, which speed up chemical reactions in the human body, are _____. **(a)** polysaccharides, **(b)** lipids, **(c)** pyrimidines, **(d)** purines, **(e)** proteins.
14. Which of the following is *not* a function of a protein? **(a)** support, **(b)** transport, **(c)** metabolic regulation, **(d)** storage of genetic information, **(e)** movement.
15. A characteristic of DNA is that it has **(a)** paired strands coiled in a double helix, **(b)** 50,000 or fewer nucleotides, **(c)** uracil, **(d)** ribose.
16. What are the three subatomic particles in atoms?
17. What four major classes of organic compounds (polymers) are found in the body?
18. List three important functions of triglycerides (neutral fats) in the body.
19. List seven major functions performed by proteins.
20. **(a)** What three basic components make up a nucleotide of DNA? **(b)** What three basic components make up a nucleotide of RNA?
21. What are the most important methods of storing and releasing energy in our cells?

## LEVEL 2 Reviewing Concepts

22. If a polypeptide contains 10 peptide bonds, how many amino acids does it contain? **(a)** 9, **(b)** 10, **(c)** 11, **(d)** 12.
23. A dehydration synthesis reaction between glycerol and a single fatty acid would yield a(n) **(a)** micelle, **(b)** omega-3 fatty acid, **(c)** triglyceride, **(d)** monoglyceride, **(e)** diglyceride.
24. Explain how enzymes function in chemical reactions.
25. What is a buffer? What is the significance of buffers in biochemical reactions?
26. What is the difference between potential energy and kinetic energy?.
27. In an endergonic reaction, **(a)** the amount of energy released is greater than that of the activation energy, **(b)** enzymes are always needed, **(c)** large molecules are broken down into smaller ones, **(d)** the reaction as a whole absorbs energy, **(e)** heat is generated to maintain body temperature.
28. The hydrogen bonding that occurs in water is responsible for all of the following *except* **(a)** the high boiling point of water, **(b)** the low freezing point of water, **(c)** the ability of water to dissolve nonpolar substances, **(d)** the ability of water to dissolve inorganic salts, **(e)** the surface tension of water.
29. A sample that contains an organic molecule has the following constituents: carbon, hydrogen, oxygen, nitrogen, and phosphorus. Is the molecule more likely to be a carbohydrate, a lipid, a protein, or a nucleic acid?

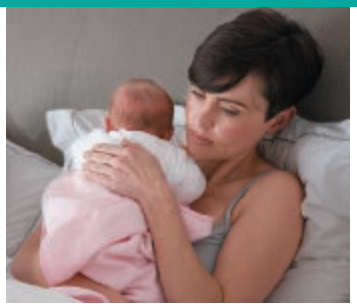
## LEVEL 3 Critical Thinking and Clinical Applications

30. An atom of the element magnesium has 12 protons and 12 neutrons. Determine the following information about magnesium: **(a)** number of electrons, **(b)** atomic number, **(c)** atomic weight, **(d)** number of electrons in each energy level.
31. A certain reaction pathway consists of four steps. How would decreasing the amount of enzyme that catalyzes the second step affect the amount of product produced at the end of the pathway?
32. An important buffer system in the human body involves carbon dioxide ($CO_2$) and bicarbonate ion ($HCO_3^-$) in the reversible reaction

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

If a person becomes excited and exhales large amounts of $CO_2$, how will the pH of the person's body be affected?

## CLINICAL CASE Wrap-Up What Is Wrong with My Baby?



Baby Sean has *cystic fibrosis (CF),* a life-threatening genetic disease. He inherited a defective gene from each parent. This faulty gene adversely affects the transport of salt—sodium chloride (NaCl)—into and out of cells. As a result, thick, sticky secretions are produced in both the digestive and respiratory systems.

In someone with CF, the digestive juices produced are so thick they clog in the pancreas and cannot get into the small intestine. Digestive juices contain enzymes that break down carbohydrates, lipids, and proteins in food so that they can be absorbed and used by cells. Without these enzymes, Sean's food passes right through him without being digested, leading to weight loss and fatty stools. In addition, the abnormal secretions clog the lungs, making Sean short of breath, wheezy, and susceptible to repeated lung infections. Finally, CF makes his skin taste very salty because of salt being lost in the sweat.

The diagnosis of cystic fibrosis is made with a sweat test. A sweat-producing chemical is applied to an area of Sean's skin, and the sweat is collected and tested for chloride concentration.

Sean's treatment starts immediately. His parents give him digestive enzymes before each feeding so that he can absorb nutrients. Sean's parents learn chest physical therapy: For 20–60 minutes, twice per day, they percuss (clap forcefully with a cupped hand) and vibrate (shake with an open hand) his chest to loosen the thick mucus so he can cough it up and out. Soon Sean gains weight and begins to thrive, but this therapy will be lifelong.

1. What undigested substances would have made Sean's stools greasy and foamy?
2. Why are digestive enzymes necessary for life?

See the blue Answers tab at the back of the book.

## Related Clinical Terms

**artificial sweetener:** Organic molecules that can stimulate taste buds and provide a sweet taste to foods without adding substantial amounts of calories to the diet.

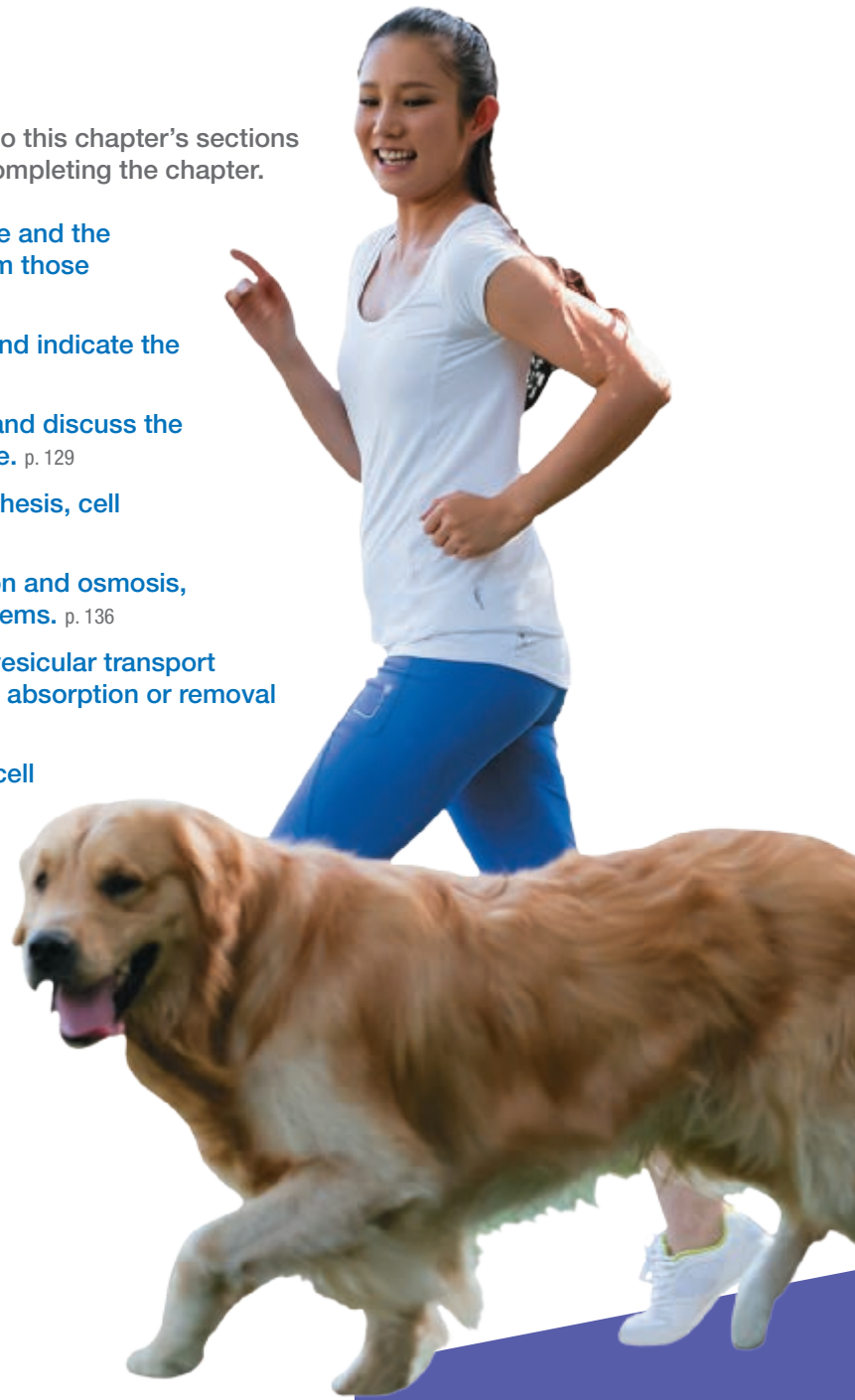
**heavy metal:** The term used for a group of elements on the "heavier" end of the periodic table of elements. Some heavy metals—cobalt, copper, iron, manganese, molybdenum, vanadium, strontium, and zinc—are essential to health in trace amounts. Others are nonessential and can be harmful to health in excessive amounts. These include cadmium, antimony, chromium, mercury, lead, and arsenic.

# 3 The Cellular Level of Organization

## Learning Outcomes

These Learning Outcomes correspond by number to this chapter's sections and indicate what you should be able to do after completing the chapter.

- 3-1 ■ List the functions of the plasma membrane and the structural features that enable it to perform those functions. p. 112
- 3-2 ■ Describe the organelles of a typical cell, and indicate the specific functions of each. p. 117
- 3-3 ■ Explain the functions of the cell nucleus, and discuss the nature and importance of the genetic code. p. 129
- 3-4 ■ Summarize the role of DNA in protein synthesis, cell structure, and cell function. p. 131
- 3-5 ■ Describe the processes of cellular diffusion and osmosis, and explain their role in physiological systems. p. 136
- 3-6 ■ Describe carrier-mediated transport and vesicular transport mechanisms used by cells to facilitate the absorption or removal of specific substances. p. 140
- 3-7 ■ Explain the origin and significance of the cell membrane potential. p. 145
- 3-8 ■ Describe the stages of the cell life cycle, including interphase, mitosis, and cytokinesis, and explain their significance. p. 148
- 3-9 ■ Discuss the regulation of the cell life cycle. p. 149
- 3-10 ■ Discuss the relationship between cell division and cancer. p. 153
- 3-11 ■ Define cellular differentiation, and explain its importance. p. 155



## CLINICAL CASE The Beat Must Go On!



Five-year-old Jackson comes home from kindergarten with yet another ear infection. He is a happy child with a great appetite, but he can't seem to stay healthy. His nose is constantly plugged, and he always has a cough. Sometimes he coughs so hard he vomits.

Jackson tested negative for cystic fibrosis, a genetic disease that produces thick, sticky mucus. There are no pets or cigarette smokers in the home.

Because this cough has gone on so long, Jackson is now getting a chest x-ray. The x-ray technician asks if she can take another film, carefully checking to be sure she has the "right" marker on Jackson's right side.

"Now that's funny," the tech says. "It looks like this x-ray is backward, but I know I took it correctly. Jackson's heart must be on the wrong side." **What clue has the technician discovered that might explain Jackson's chronic infections and cough? To find out, turn to the Clinical Case Wrap-Up on p. 159.**

## An Introduction to Cells

In this chapter we will see how combinations of chemicals form *cells*, the smallest living units in the human body. We will also look at the chemical events that sustain life, which occur mostly inside cells.

Much of anatomy and physiology cannot be seen with the naked (unaided) eye, because cells are very small. The unaided human eye can see objects only about 0.1 mm in diameter. A typical cell is much smaller than that. As a result, no one could actually examine the structure of a cell until effective microscopes were invented about 400 years ago and the field of *microscopy* (investigating objects using a microscope) was born. Microscopes have evolved from the compound light microscope, which magnifies objects up to 1000 times, to the scanning electron microscope, which can magnify an object from 10 to 500,000 times!

Over time, the work of scientists in this area has led to the development of the *cell theory* in its current form. We can summarize its basic concepts as follows:

- Cells are the building blocks of all organisms.
- All cells come from the division of preexisting cells.
- Cells are the smallest units that carry out life's essential physiological functions.
- Each cell maintains homeostasis at the cellular level. Homeostasis at the level of the tissue, organ, organ system, and organism reflects the combined and coordinated actions of many cells.

The human body contains trillions of cells. All our activities—from running to thinking—result from these combined and coordinated actions of millions or even billions of cells. Many insights into human physiology arose from studies of the functioning of individual cells. What we have learned over the years has given us a new understanding of cellular physiology and the mechanisms of homeostatic control. Today, the study of cellular structure and function, or **cytology**, is part of the broader discipline of **cell biology**, which integrates aspects of biology, chemistry, and physics.

The human body contains two general classes of cells: sex cells and somatic cells. **Sex cells** (also called *germ cells* or *reproductive cells*) are either the *sperm* of males or the *oocytes* (Ō-ō-sītz), or immature ova ("eggs"), of females. The fusion of a sperm and an oocyte at fertilization is the first step in the development of a new individual. **Somatic cells** (*soma*, body), or body cells, include all the other cells. In this chapter, we focus on somatic cells. We discuss sex cells in Chapters 28 and 29.

In the rest of this chapter, we describe the structure of a typical somatic cell, consider some of the ways in which cells interact with their environment, and discuss how somatic cells reproduce. Keep in mind that the "typical" somatic cell is like the "average" person: Any description masks many individual variations. **Spotlight Figure 3–1** summarizes the anatomy of a typical (representative) cell.

## 3-1 The plasma membrane separates the cell from its surrounding environment and performs various functions

**Learning Outcome** List the functions of the plasma membrane and the structural features that enable it to perform those functions.

When you view a cell through a microscope, the first structure you encounter is its outer boundary, called the **plasma membrane**, or **cell membrane**. Membranes are neither rigid nor uniform in structure. At each location, the inner and outer surfaces of the plasma membrane may differ in important ways. For example, some enzymes are found only on the inner surface of

the membrane, and some receptor molecules are found only on the outer surface. In general, plasma membranes have these functions:

- *Physical Isolation.* The plasma membrane is a physical barrier that separates the inside of the cell, or *cytoplasm*, from the surrounding extracellular fluid. For example, the plasma membrane keeps enzymes and structural proteins inside the cell. Conditions inside and outside the cell are very different, and those differences must be maintained to preserve homeostasis.
- *Regulation of Exchange with the Environment.* The plasma membrane acts as a kind of gatekeeper. It controls the entry of ions and nutrients, the elimination of wastes, and the release of secretions.
- *Sensitivity to the Environment.* The plasma membrane is the first part of the cell affected by changes in the composition, concentration, or pH of the extracellular fluid. It also contains a variety of special structural molecules known as *receptors* that allow the cell to recognize and respond to specific molecules in its environment. For instance, the plasma membrane may receive chemical signals from other cells. The binding of just one molecule to a receptor may trigger the activation or deactivation of enzymes that affect many cellular activities.
- *Structural Support.* Specialized connections between plasma membranes, or between membranes and extracellular materials, give tissues stability. For example, the cells at the surface of the skin are tightly bound together, while those in the deepest layers are attached to extracellular protein fibers in underlying tissues.

The plasma membrane is extremely thin, ranging from 6 to 10 nm in thickness. The membrane contains lipids, proteins, and carbohydrates.

## Membrane Lipids

Lipids form most of the surface area of the plasma membrane, but they make up only about 42 percent of its weight. The plasma membrane is called a **phospholipid bilayer**, because the phospholipid molecules in it form two layers (Figure 3–2).

Recall from Chapter 2 that a phospholipid has both a hydrophilic end (the phosphate portion) and a hydrophobic end (the lipid portion). ↩ p. 97 In each half of the bilayer, the phospholipids lie with their hydrophilic heads at the membrane surface and their hydrophobic tails on the inside. In this arrangement, the hydrophilic ("water-loving") heads of the two layers are in contact with the watery environments on both sides of the membrane—the extracellular fluid outside the cell and the intracellular fluid, or *cytosol*, inside the cell. (The cytosol is the fluid component of the cytoplasm.) The hydrophobic ("water-fearing") tails form the interior of the membrane.

The lipid bilayer also contains cholesterol and other steroids, small quantities of other lipids, proteins, and glycolipids. Cholesterol is an important component of plasma membranes, with almost one cholesterol molecule for each phospholipid molecule. ↩ p. 96 Cholesterol "stiffens" the plasma membrane, making it less fluid and less permeable.

Note the similarities in lipid organization between the plasma membrane and a micelle (look back at Figure 2–19c, p. 98). Ions and water-soluble compounds cannot enter a micelle, because the lipid tails of the phospholipid molecules are hydrophobic and will not associate with water molecules. For the same reason, such substances cannot cross the lipid portion of the plasma membrane. In this way, the hydrophobic center of the membrane isolates the cytoplasm from the surrounding fluid environment.

## Membrane Proteins

Proteins, which are much denser than lipids, account for about 55 percent of the weight of a plasma membrane. There are two general structural classes of membrane proteins based on their location, integral and peripheral (see Figure 3–2). **Integral proteins** are part of the plasma membrane structure and cannot be easily separated from it without damaging or destroying the membrane. Most integral proteins span the width of the membrane one or more times, and are known as *transmembrane proteins.* These proteins contain hydrophobic portions embedded within the hydrophobic lipid bilayer, with their hydrophilic portions extended into the extracellular environment and cytosol. **Peripheral proteins** are bound to the inner or outer surface of the membrane and (like sticky notes) are easily separated from it. Integral proteins greatly outnumber peripheral proteins.

Various types of membrane proteins carry out particular specialized functions. Here are some examples of important types of membrane proteins:

- *Anchoring Proteins.* **Anchoring proteins** attach the plasma membrane to other structures and stabilize its position. Inside the cell, membrane proteins are bound to the *cytoskeleton*, a network of supporting filaments in the cytoplasm. Outer membrane proteins may attach the cell to extracellular protein fibers or to another cell.
- *Recognition Proteins (Identifiers).* The cells of the immune system recognize other cells as normal or abnormal based on the presence or absence of characteristic **recognition proteins**. Many important recognition proteins are glycoproteins. ↩ p. 103 (We discuss one group, the MHC proteins involved in the immune response, in Chapter 22.)

# SPOTLIGHT

Figure 3–1
## Anatomy of a Model Cell

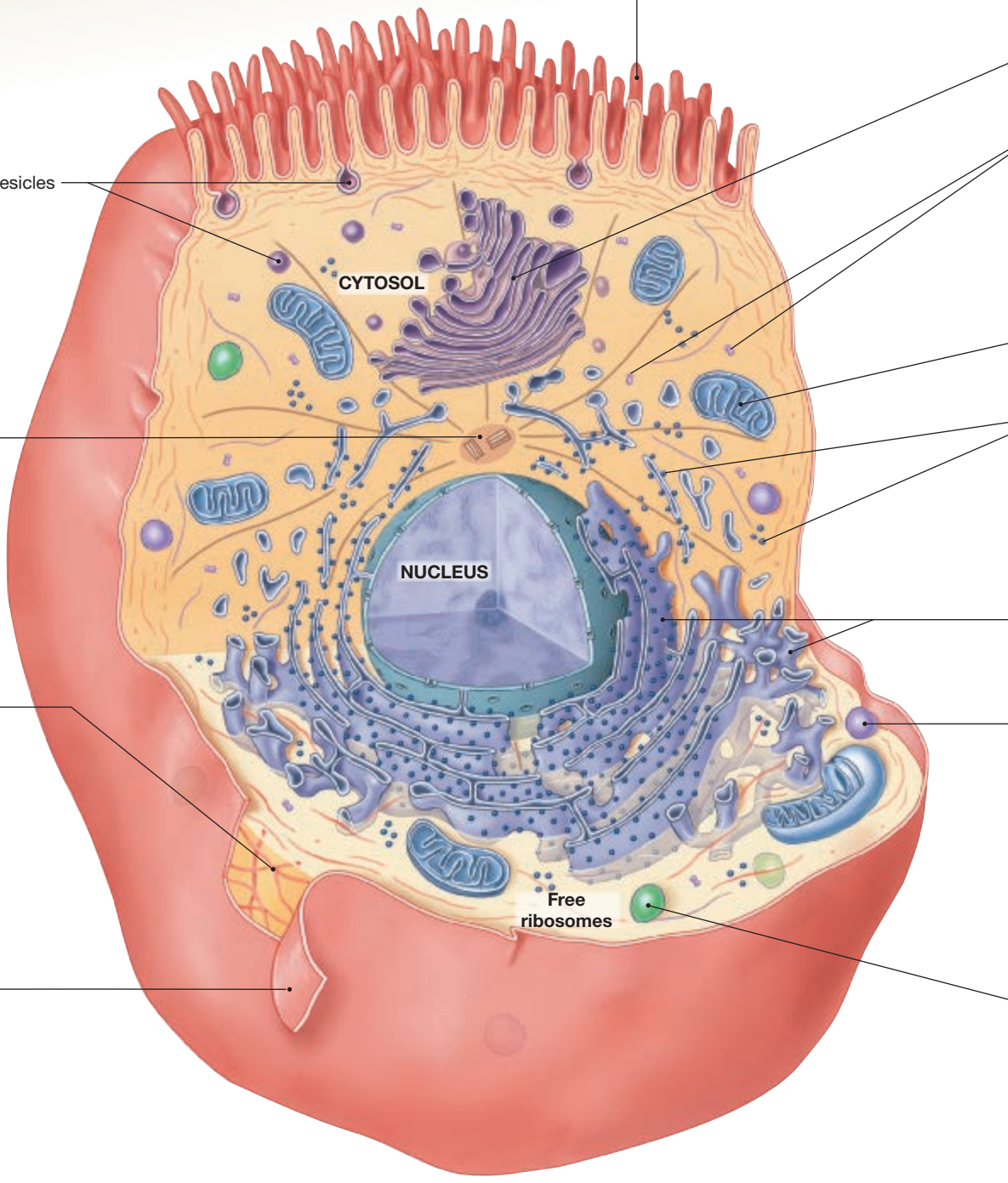
In our model cell, a *plasma membrane* separates the cell contents, called the *cytoplasm*, from its surroundings. The cytoplasm can be subdivided into the *cytosol*, a fluid, and intracellular structures collectively known as *organelles* (or-ga-NELZ). Organelles are structures suspended within the cytosol that perform specific functions within the cell. They can be subdivided into membranous and nonmembranous organelles. Cells are surrounded by a watery medium known as the **extracellular fluid**. The extracellular fluid in most tissues is called **interstitial** (in-ter-STISH-ul) **fluid**.

= Plasma membrane
= Nonmembranous organelles
= Membranous organelles

### Microvilli

Microvilli are extensions of the plasma membrane containing microfilaments.

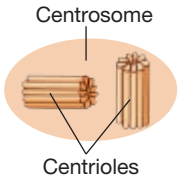
**Function**
Increase surface area to facilitate absorption of extracellular materials




### Centrosome and Centrioles

Cytoplasm containing two centrioles at right angles; each centriole is composed of 9 microtubule triplets in a 9 + 0 array

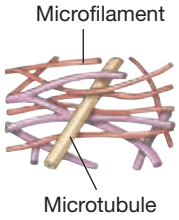
**Functions**
Essential for movement of chromosomes during cell division; organization of microtubules in cytoskeleton




### Cytoskeleton

Proteins organized in fine filaments or slender tubes

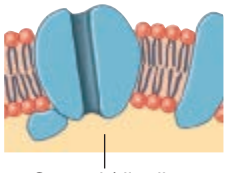
**Functions**
Strength and support; movement of cellular structures and materials




### Plasma Membrane

Lipid bilayer containing phospholipids, steroids, proteins, and carbohydrates

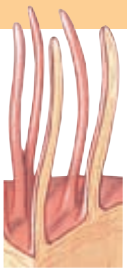
**Functions**
Isolation; protection; sensitivity; support; controls entry and exit of materials



### Cilia

Cilia are long extensions of the plasma membrane containing microtubules. There are two types: primary and motile.

**Functions**
A primary cilium acts as a sensor. Motile cilia move materials over cell surfaces



### Proteasomes

Hollow cylinders of proteolytic enzymes with regulatory proteins at their ends

**Functions**
Breakdown and recycling of damaged or abnormal intracellular proteins

### Ribosomes

RNA + proteins; fixed ribosomes bound to rough endoplasmic reticulum; free ribosomes scattered in cytoplasm

**Function**
Protein synthesis

### Peroxisomes

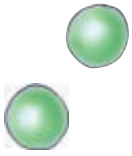
Vesicles containing degradative enzymes

**Functions**
Catabolism of fats and other organic compounds; neutralization of toxic compounds generated in the process

### Lysosomes

Vesicles containing digestive enzymes

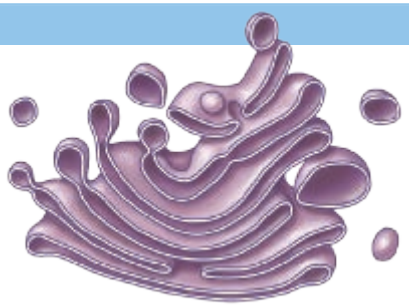
**Function**
Intracellular removal of damaged organelles or pathogens



### Golgi apparatus

Stacks of flattened membranes (cisternae) containing chambers

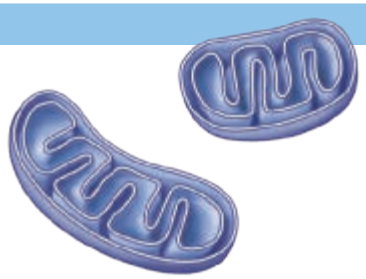
**Functions**
Storage, alteration, and packaging of secretory products and lysosomal enzymes



### Mitochondria

Double membrane, with inner membrane folds (cristae) enclosing important metabolic enzymes

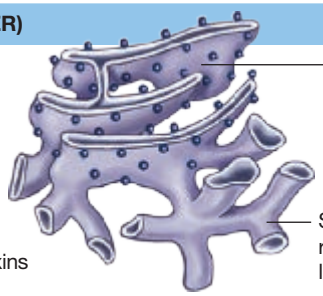
**Function**
Produce 95% of the ATP required by the cell



### Endoplasmic reticulum (ER)

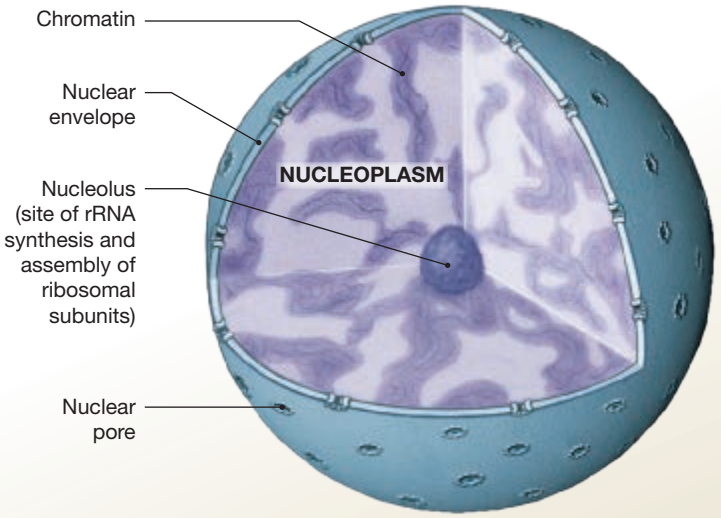
Network of membranous channels extending throughout the cytoplasm

**Functions**
Synthesis of secretory products; intracellular storage and transport; detoxification of drugs or toxins



Rough ER has ribosomes, and it modifies and packages newly synthesized proteins

Smooth ER does not have ribosomes and synthesizes lipids and carbohydrates

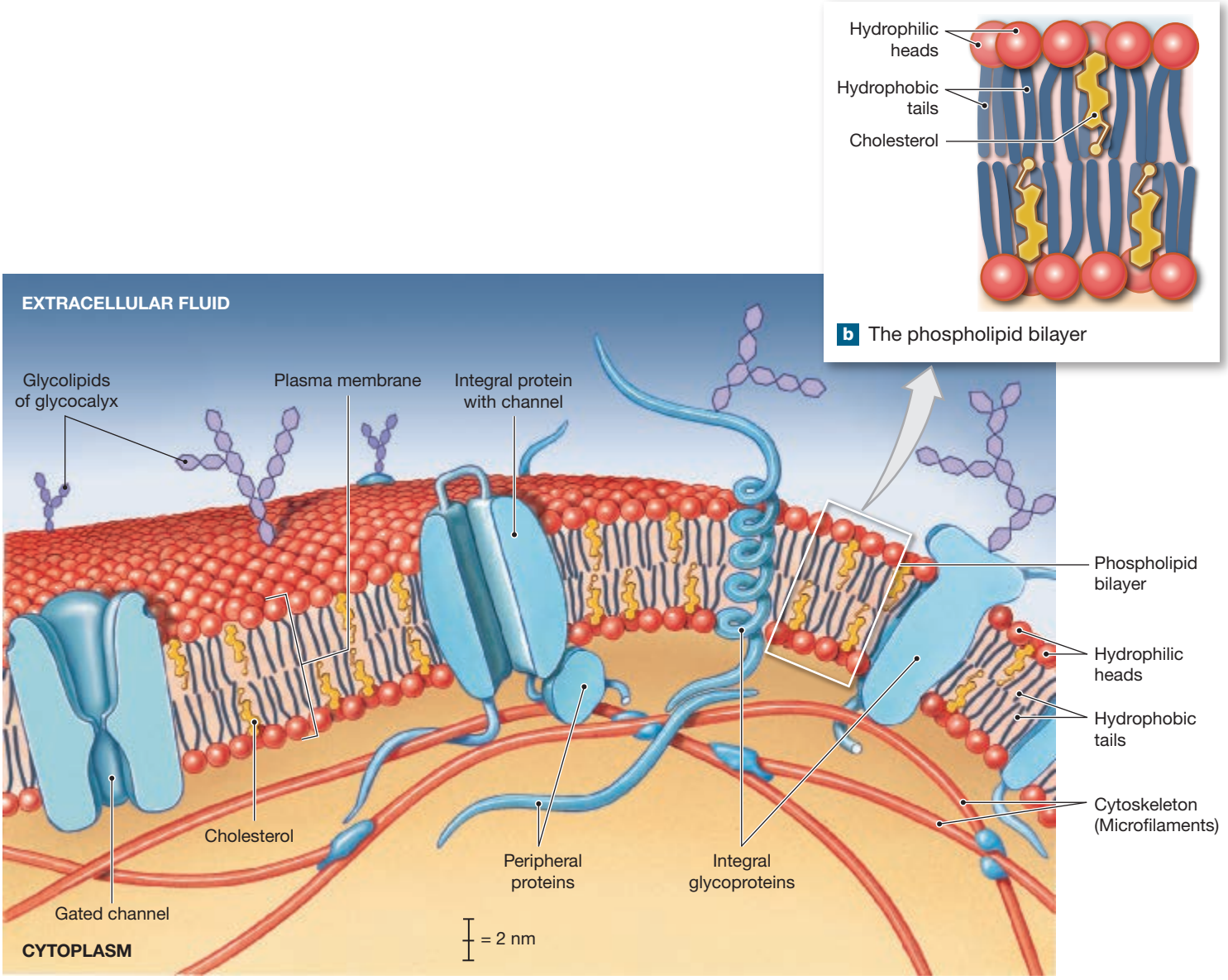



### NUCLEUS

Nucleoplasm containing nucleotides, enzymes, nucleoproteins, and chromatin; surrounded by a double membrane, the nuclear envelope

**Functions**
Control of metabolism; storage and processing of genetic information; control of protein synthesis

**Figure 3–2** The Plasma Membrane.




- *Enzymes.* Enzymes in plasma membranes may be integral or peripheral proteins. They catalyze reactions in the extracellular fluid or in the cytosol, depending on their location. For example, dipeptides are broken down into amino acids by enzymes on the extracellular membrane surfaces of cells that line the intestinal tract.
- *Receptor Proteins.* **Receptor proteins** in the plasma membrane are sensitive to the presence of specific extracellular ions or molecules called **ligands** (LĪ-gandz). A ligand can be anything from a small ion, such as a calcium ion, to a relatively large and complex hormone. When a ligand binds to the appropriate receptor, that binding may trigger changes in the activity of the cell. For example, the binding of the hormone *insulin* to a specific membrane receptor protein is the key step that leads to an increase in the cell's rate of glucose absorption. Plasma membranes differ in the type and number of receptor proteins they contain, and these differences account for a cell's sensitivity to specific hormones and other ligands.
- *Carrier Proteins.* **Carrier proteins** bind solutes and transport them across the plasma membrane. Carrier proteins may require ATP as an energy source. ↩ p. 105 For example,

virtually all cells have carrier proteins that bring glucose into the cytoplasm without expending ATP. Yet these cells must use ATP to transport ions such as sodium ($Na^+$) and calcium ($Ca^{2+}$) out of the cytoplasm and across the plasma membrane.

- *Channels.* Some integral proteins contain a **channel**, or central pore, that forms a passageway completely through the plasma membrane. Such channels permit water and small solutes to move across the plasma membrane. Ions do not dissolve in lipids, so they cannot cross the phospholipid bilayer. For this reason, ions and other small water-soluble substances can cross the membrane only by passing through channels. Most of the communication between the interior and exterior of the cell occurs through these channels. Some of the channels are called **gated channels** because they can open or close to regulate the passage of substances. Channels account for about 0.2 percent of the total surface area of the plasma membrane, but they are extremely important in physiological processes such as muscle contraction and nerve impulse transmission, as we discuss in Chapters 10 and 12.

Some integral and peripheral proteins are always confined to specific areas of the plasma membrane. These areas, called *rafts*, mark the location of anchoring proteins and some kinds of receptor proteins. Yet because membrane phospholipids are fluid at body temperature, many other integral proteins drift across the surface of the membrane like ice cubes in a bowl of punch. In addition, the composition of the entire plasma membrane can change over time as large areas of the membrane surface are removed and recycled in the ongoing process of metabolic turnover. A table listing the turnover times of the organic components of representative cells is found in the Appendix.

## Membrane Carbohydrates

Carbohydrates account for about 3 percent of the weight of a plasma membrane. The carbohydrates in the plasma membrane are parts of complex molecules such as *proteoglycans*, *glycoproteins*, and *glycolipids*. ↩ pp. 97, 103 The carbohydrate portions of these large molecules extend beyond the outer surface of the membrane, forming a layer known as the **glycocalyx** (glī-kō-KĀ-liks; *calyx*, cup).

The glycocalyx has a variety of important functions, including the following:

- *Lubrication and Protection.* The glycoproteins and glycolipids form a viscous (thick and sticky) layer that lubricates and protects the plasma membrane.
- *Anchoring and Locomotion.* Because its components are sticky, the glycocalyx can help anchor the cell in place. It also takes part in the movement of specialized cells.
- *Specificity in Binding.* Glycoproteins and glycolipids can function as receptors, binding specific extracellular compounds. Such binding can change the properties of the cell surface and indirectly affect the cell's behavior.
- *Recognition.* Cells involved with the immune response recognize glycoproteins and glycolipids as normal or abnormal. The characteristics of the glycocalyx are genetically determined. The body's immune system recognizes its own membrane glycoproteins and glycolipids as "self" rather than as "foreign." This recognition system keeps your immune system from attacking your cells, and allows it to recognize and destroy invading pathogens (disease-causing agents).

The plasma membrane forms a barrier between the cytosol and the extracellular fluid. If the cell is to survive, dissolved substances and larger compounds must be permitted to cross this barrier. Nutrients must be able to enter the cell, and metabolic wastes must be able to leave. The structure of the plasma membrane is ideally suited to this need for selective transport. We will discuss selective transport and other membrane functions further, after we have completed our overview of cellular anatomy.

### Checkpoint

1. **List the general functions of the plasma membrane.**
2. **Identify the components of the plasma membrane that allow it to carry out its functions.**
3. **Which component of the plasma membrane is primarily responsible for the membrane's ability to form a physical barrier between the cell's internal and external environments?**
4. **Which type of integral protein allows water, ions, and small water-soluble solutes to pass through the plasma membrane?**

See the blue Answers tab at the back of the book.

# 3-2 Organelles within the cytoplasm perform particular functions

**Learning Outcome** Describe the organelles of a typical cell, and indicate the specific functions of each.

**Cytoplasm** is a general term for the material between the plasma membrane and the membrane that surrounds the nucleus. The cytoplasm has three major subdivisions: cytosol, organelles, and inclusions. **Cytosol** is also known as *intracellular fluid*. It is a mixture of water and various dissolved and insoluble materials, in which the organelles and inclusions are suspended. Cytosol is a colloid with a consistency that varies between that of thin maple syrup and almost-set gelatin. Cytosol contains many more proteins than does extracellular fluid, the watery medium that surrounds cells. ↩ p. 88 These proteins

are so important to the cell that they make up about 30 percent of a typical cell's weight.

**Organelles** ("little organs") are the internal structures of cells that perform most of the tasks that keep a cell alive and functioning normally. Each organelle has specific functions related to cell structure, growth, maintenance, and metabolism. We can divide cellular organelles into two broad categories, nonmembranous and membranous. **Nonmembranous organelles** are not completely enclosed by membranes, and all of their components are in direct contact with the cytosol. **Membranous organelles** are isolated from the cytosol by phospholipid membranes, just as the plasma membrane isolates the cytosol from the extracellular fluid. The *nucleus* is also surrounded by a membranous envelope—and is, strictly speaking, a membranous organelle. It has so many vital functions that we will consider it in a separate section.

**Inclusions** are masses of insoluble materials. Some inclusions are stored nutrients, such as glycogen granules in liver or in skeletal muscle cells and lipid droplets in fat cells. Others are pigment granules such as the brown skin pigment *melanin*, found in hair and skin cells.

## The Cytosol

Cytosol is different from extracellular fluid. Some important differences between cytosol and extracellular fluid are as follows:

- *Sodium and potassium concentrations differ.* The concentration of potassium ions ($K^+$) is higher in the cytosol than in the extracellular fluid, whereas the concentration of sodium ions ($Na^+$) is lower in the cytosol than in the extracellular fluid.
- *Suspended protein concentrations differ.* The cytosol contains a much higher concentration of suspended proteins than does extracellular fluid. Many of the proteins are enzymes that regulate metabolic operations. Others are associated with the various organelles. The consistency of the cytosol is determined in large part by the enzymes and cytoskeletal proteins.
- *Nutrient concentrations differ.* The cytosol usually contains smaller quantities of carbohydrates and lipids, and smaller reserves of amino acids than does the extracellular fluid. The extracellular fluid is a transport medium only, and no materials are stored there. The carbohydrates in the cytosol are broken down to provide energy. When carbohydrates are unavailable, lipids, in particular triglycerides, are used instead as a source of energy. The amino acids are primarily used to manufacture proteins.

## Nonmembranous Organelles

Nonmembranous organelles do not have a definite boundary. The cell's nonmembranous organelles include the *cytoskeleton*, *centrosome* with *centrioles*, *ribosomes*, and *proteasomes*. Some cells also have what are called cellular extensions, which include *microvilli*, *cilia*, and *flagella*.

### The Cytoskeleton

The **cytoskeleton** serves as the cell's skeleton. It is an internal protein framework that gives the cytosol strength and flexibility. The cytoskeleton of all cells is made of *microfilaments*, *intermediate filaments*, and *microtubules* (Figure 3–3). Muscle cells contain these cytoskeletal elements plus *thick filaments*. The filaments and microtubules of the cytoskeleton form a dynamic network whose continual reorganization affects cell shape and function. This network provides support for organelles, and keeps them in their proper positions. Interactions between cytoskeletal components are also important in moving organelles and in changing the shape of the cell.

We will consider only a few of the many functions of the cytoskeleton in this section. In addition to the functions we describe here, the cytoskeleton plays a role in the metabolic organization of the cell. It determines where in the cytoplasm key enzymatic reactions take place and where specific proteins are synthesized. For example, many enzymes (especially those involved with metabolism and energy production), ribosomes, and RNA molecules responsible for the synthesis of proteins are attached to the microfilaments and microtubules of the cytoskeleton. The varied metabolic functions of the cytoskeleton are now a subject of intensive research.

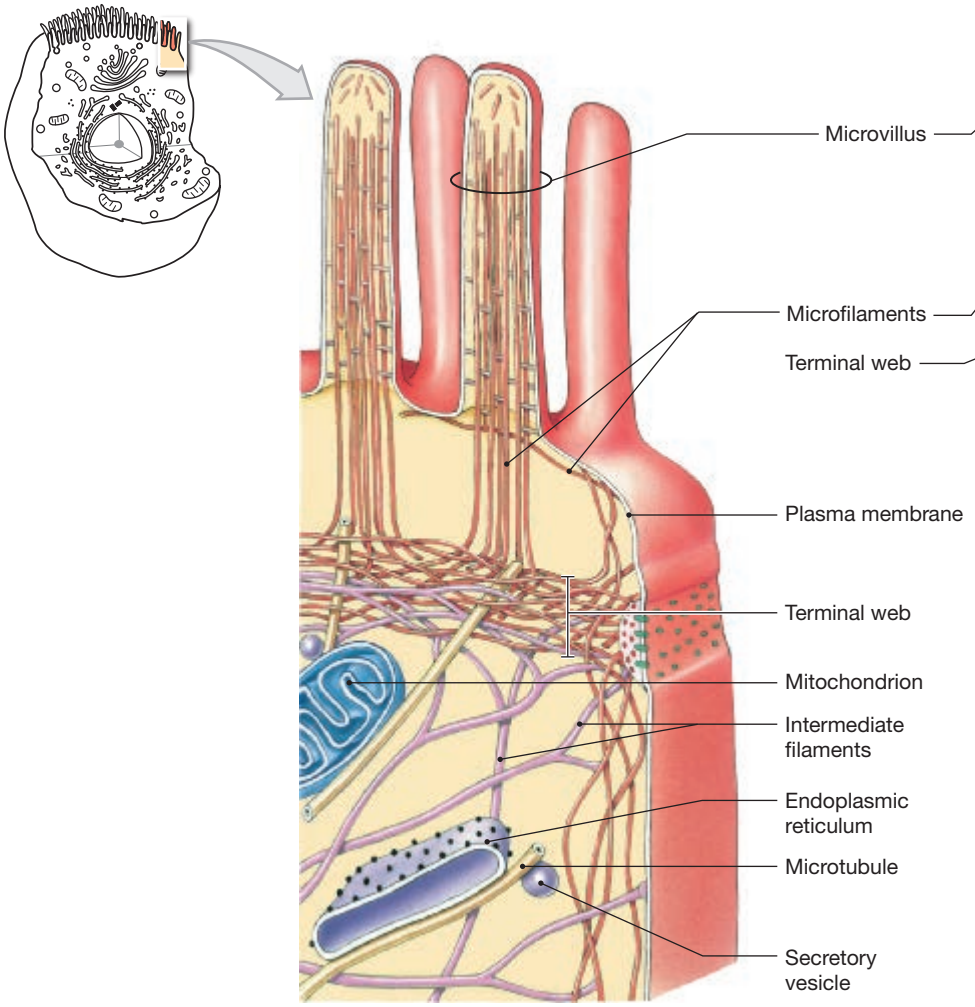
**Microfilaments.** The smallest cytoskeletal structures are the rod-shaped **microfilaments**. These protein strands are generally about 5 nm in diameter. Typical microfilaments are made of the protein **actin**. In skeletal muscle cells, the thin actin filaments interact with other protein strands of thick *myosin* filaments to cause contraction. In cells that form a layer or lining, such as the lining of the intestinal tract, actin filaments also form a layer, called the *terminal web*, just inside the plasma membrane at the exposed surface of the cell (Figure 3–3a).

Microfilaments have the following major functions:

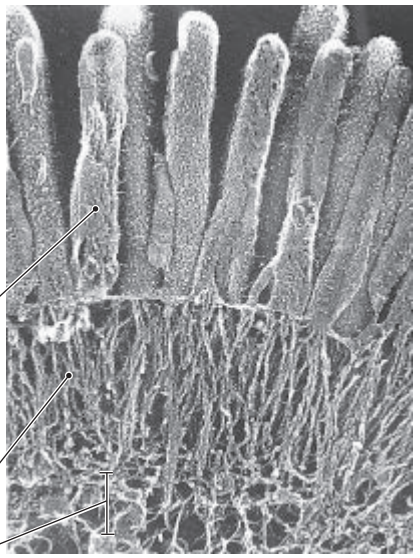
- *Microfilaments anchor the cytoskeleton* to integral proteins of the plasma membrane. They give the cell additional mechanical strength and attach the plasma membrane to the enclosed cytoplasm.
- *Microfilaments, interacting with other proteins, determine the consistency of the cytosol.* Where microfilaments form a dense, flexible network, the cytosol has a gelatinous consistency. Where they are widely dispersed, the cytosol is more fluid.

**Intermediate Filaments.** The protein composition of **intermediate filaments** varies among cell types. These filaments range from 9 to 11 nm in diameter. They are so named because they

**Figure 3–3** The Cytoskeleton.

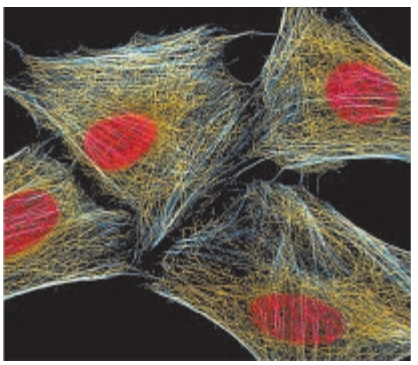



**a** The cytoskeleton provides strength and structural support for the cell and its organelles. Interactions between cytoskeletal components are also important in moving organelles and in changing the shape of the cell.



**Microfilaments and microvilli** SEM × 30,000

**b** The microfilaments and microvilli of an intestinal cell. Such an image, produced by a scanning electron microscope, is called a scanning electron micrograph (SEM).



**Microfilaments and microvilli** LM × 3200

**c** Microtubules (yellow) in living cells, as seen in a light micrograph (LM) after special fluorescent labeling.

**?** What are the three different components that make up the cytoskeleton in all body cells?

are intermediate in size between microfilaments and microtubules. Intermediate filaments, which are insoluble in the watery medium, are the most durable of the cytoskeletal elements.

Intermediate filaments (1) *strengthen the cell* and help maintain its shape, (2) *stabilize the positions of organelles*, and (3) *stabilize the position of the cell with respect to surrounding cells* through specialized attachments to the plasma membrane. Many cells contain specialized intermediate filaments with unique functions. For example, the keratin fibers in superficial layers of the skin are intermediate filaments that make these layers strong and able to resist stretching.

**Microtubules.** Most cells contain **microtubules**, hollow tubes built from the globular protein **tubulin**. Microtubules are the largest components of the cytoskeleton, with diameters of about 25 nm. Microtubules extend outward into the periphery of the cell from a region near the nucleus called the *centrosome* (see **Spotlight Figure 3–1**).

Each microtubule forms by the aggregation of tubulin molecules, growing out from its origin at the centrosome. The entire structure persists for a time and then disassembles into individual tubulin molecules again.

Microtubules have the following functions:

- *Microtubules form the main portions of the cytoskeleton*, giving the cell strength, maintaining its shape, and anchoring the position of major organelles.
- *Microtubules change the shape of the cell, and may assist in cell movement*, through the assembly and disassembly of microtubules.
- *Microtubules can serve as a kind of monorail system to move vesicles or other organelles within the cell.* Proteins called **motor proteins** create the movement. These motor proteins bind to both the structure being moved and to a microtubule and then move along its length. The direction of movement depends on the particular motor protein involved. For example, the proteins *kinesin* and *dynein* (DĪ-nēn) carry materials in opposite directions on a microtubule: Kinesin moves toward one end, dynein toward the other. Regardless of the direction of transport or the nature of the motor, the process requires ATP and is essential to normal cellular function.
- *During cell division, microtubules distribute duplicated chromosomes containing DNA* to opposite ends of the dividing cell by forming a network of microtubules called the *spindle apparatus.* We look at this process in more detail in Section 3-8.
- *Microtubules form structural components of organelles,* such as *centrioles* and *cilia.*

## Microvilli

Many cells have small, finger-shaped projections of the plasma membrane on their exposed surfaces (**Figure 3–3b**). These nonmotile projections, called **microvilli** (singular, *microvillus*), greatly increase the surface area of the cell exposed to the extracellular environment. Accordingly, they cover the surfaces of cells that are actively absorbing materials, such as the cells lining the digestive tract. Microvilli have extensive connections with the cytoskeleton. A core of microfilaments stiffens each microvillus and anchors it to the cytoskeleton at the terminal web.

## Centrosome and Centrioles

The **centrosome** is a region of cytoplasm located next to the nucleus in a cell. It is the *microtubule-organizing center* of animal cells, and the heart of the cytoskeletal system. Microtubules of the cytoskeleton generally begin at the centrosome and radiate out through the cytoplasm. In all animal cells capable of undergoing cell division, the centrosome surrounds a pair of cylindrical structures called **centrioles**. The centrioles lie perpendicular to each other and are composed of short microtubules. The microtubules form nine groups, three in each group. Each of these nine "triplets" is connected to its nearest neighbors on either side. Because there are no central microtubules, this organization is called a *9 + 0 array* (**Figure 3–4a**).

During cell division, the centrioles aid the formation of the spindle apparatus needed for the movement of chromosomes. Mature red blood cells, skeletal muscle cells, cardiac muscle cells, and typical neurons have no centrioles, and as a result, these cells cannot divide. The centrioles also form the *basal bodies* found at the base of some cellular extensions.

## Cilia and Flagella

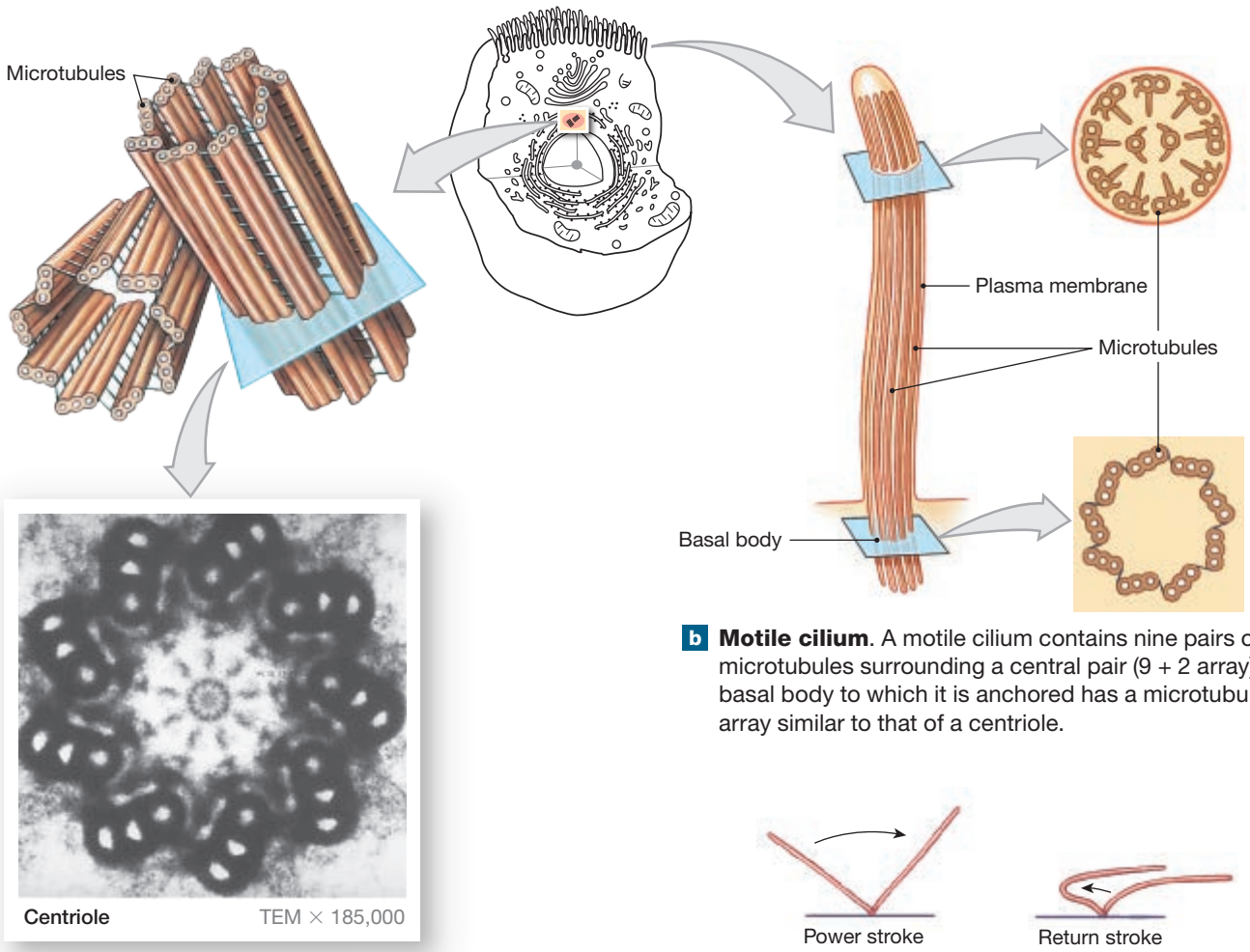
**Cilia** (singular, *cilium*) are fairly long, slender extensions of the plasma membrane. Two types of cilia are found in human cells, *nonmotile* and *motile*.

A single, nonmotile **primary cilium** is found on the cells of a wide variety of tissues in the body. Its structure is similar to the 9 + 0 microtubule organization of a centriole. The nonmotile primary cilium acts as a signal sensor, detecting environmental stimuli and coordinating activities such as embryonic development and homeostasis at the tissue level.

Multiple **motile cilia** are found on cells lining both the respiratory and reproductive tracts, and at various other locations in the body. Motile cilia have an internal arrangement similar to that of centrioles. However, in cilia, nine *pairs* of microtubules (rather than triplets) surround a central pair (**Figure 3–4b**)—an organization known as a *9 + 2 array*. The microtubules are anchored to a compact **basal body** situated just beneath the cell surface. The organization of microtubules in the basal body resembles the array of a centriole: nine triplets with no central pair.

Motile cilia are important because they "beat" rhythmically to move fluids or secretions across the cell surface (**Figure 3–4c**). A motile cilium is relatively stiff during the *power stroke* and flexible during the *return stroke.* For example, the ciliated cells along your trachea beat their cilia in synchronized waves to move sticky mucus and trapped dust particles toward the throat and away from delicate respiratory surfaces. If the cilia are damaged or immobilized by heavy smoking or a metabolic problem, this cleansing action is lost. When irritants are no longer removed, a chronic cough and respiratory infections develop. Ciliated cells also move oocytes along the uterine tubes, and sperm from the testes into the male reproductive tract. Defective primary cilia are known to be responsible for a wide range of human disorders, collectively known as *ciliopathies.*

**Figure 3–4** Centrioles and Cilia.




**a** **Centriole**. A centriole consists of nine microtubule triplets (known as a 9 + 0 array). A pair of centrioles oriented at right angles to one another occupies the centrosome. This micrograph, produced by a transmission electron microscope, is called a TEM.

**b** **Motile cilium**. A motile cilium contains nine pairs of microtubules surrounding a central pair (9 + 2 array). The basal body to which it is anchored has a microtubule array similar to that of a centriole.

**c** **Ciliary movement**. Action of a single motile cilium. During the power stroke, the cilium is relatively stiff. During the return stroke, it bends and returns to its original position.

A **flagellum** (plural, *flagella*) is a whip-like extension of the plasma membrane. Flagella have the same 9 + 2 microtubule organization as motile cilia, but are much longer and beat in a wavelike fashion. The only human cell with a flagellum is a sperm, and there is only one flagellum per cell. Sperm with more than one flagellum are abnormal and cannot fertilize an oocyte.

## Ribosomes

Now let's turn to how proteins are produced within cells, using information provided by the DNA of the nucleus. **Ribosomes** are the organelles responsible for protein synthesis. The number of ribosomes in a particular cell varies with the type of cell and its demand for new proteins. For example, liver cells, which manufacture blood proteins, contain far more ribosomes than do fat cells, which primarily synthesize lipids.

Individual ribosomes are not visible with a light microscope. In an electron micrograph, they appear as dense granules approximately 25 nm in diameter. Each ribosome is about 60 percent RNA and 40 percent protein.

A functional ribosome consists of two subunits that are normally separate and distinct. One is called a **small ribosomal subunit** and the other a **large ribosomal subunit**. These subunits contain special proteins and **ribosomal RNA (rRNA)**, one of the RNA types introduced in Chapter 2. Before protein synthesis can begin, a small and a large ribosomal subunit in the cytoplasm must join together with a strand of *messenger RNA* (*mRNA*), another type of RNA. Protein synthesis then begins in the cytoplasm.

The two major types of functional ribosomes in cells are free ribosomes and fixed ribosomes. **Free ribosomes** are scattered throughout the cytoplasm. The proteins they manufacture directly enter the cytosol. Ribosomes synthesizing proteins with destinations other than the cytosol become temporarily bound, or fixed, to the *endoplasmic reticulum (ER)*, a membranous organelle. Proteins manufactured by such **fixed ribosomes** enter the ER, where they are modified and packaged for use within the cell or they are secreted from the cell. We look at ribosomal structure and functions when we discuss the endoplasmic reticulum and protein synthesis in later sections.

## Proteasomes

**Proteasomes** are organelles that contain an assortment of protein-digesting (proteolytic) enzymes, or *proteases.* They are smaller than free ribosomes and their job is to remove proteins from the cytoplasm. Cytoplasmic enzymes attach chains of *ubiquitin*, a molecular "tag," to proteins destined for recycling. Tagged proteins are quickly transported into a proteasome. Once inside, they are rapidly disassembled into amino acids and small peptides, which are released into the cytoplasm.

Proteasomes remove and recycle damaged or denatured proteins. They also break down abnormal proteins, such as those produced within cells infected by viruses. Proteasomes also play a key role in the immune response, as we will see in Chapter 22.

Check **Spotlight Figure 3–1** for a review of the characteristics of nonmembranous organelles before reading about membranous organelles in the next section.

# Membranous Organelles

Membranous organelles include the *endoplasmic reticulum*, the *Golgi apparatus*, *lysosomes*, *peroxisomes*, and *mitochondria.*

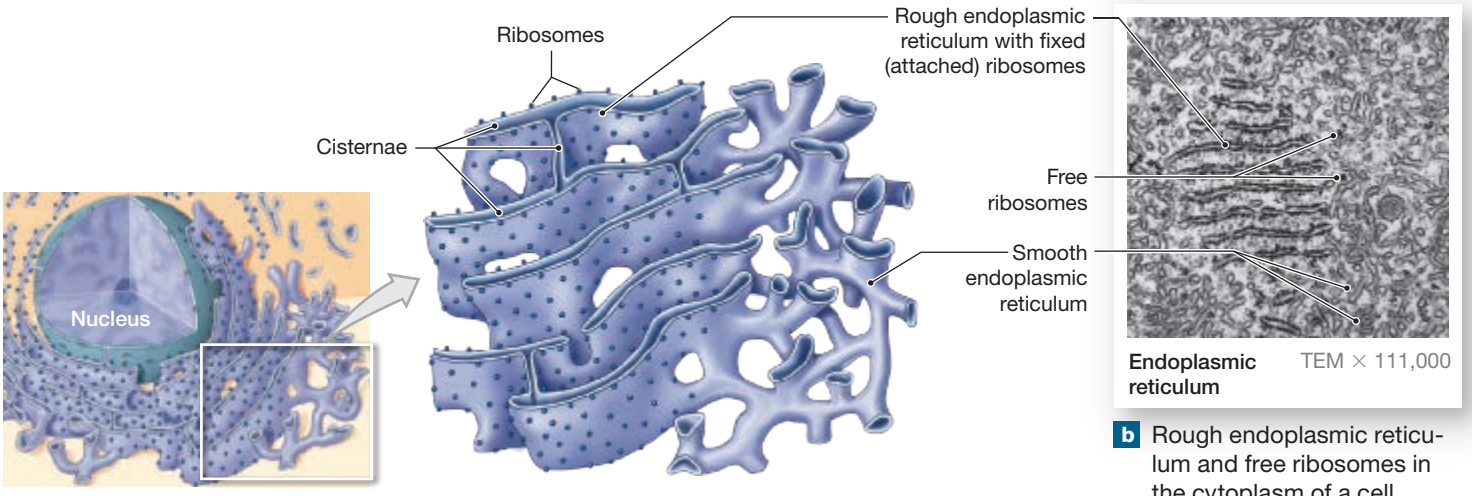
## The Endoplasmic Reticulum

The **endoplasmic reticulum** (en-dō-PLAZ-mik re-TIK-ū-lum), or **ER**, is a network of intracellular membranes continuous with the *nuclear envelope*, which surrounds the nucleus. The name *endoplasmic reticulum* is very descriptive. *Endo-* means "within," *plasm* refers to the cytoplasm, and a *reticulum* is a network. The ER has the following major functions:

- *Synthesis.* Specialized regions of the ER synthesize proteins, carbohydrates, and lipids.
- *Storage.* The ER can store synthesized molecules or materials absorbed from the cytosol without affecting other cellular operations.
- *Transport.* Materials can travel from place to place within the ER.
- *Detoxification.* The ER can absorb drugs or toxins and neutralize them with enzymes.

The ER forms hollow tubes, flattened sheets, and chambers called **cisternae** (sis-TUR-nē; singular, *cisterna*, a reservoir for water). Two types of ER exist: *smooth endoplasmic reticulum (SER)* and *rough endoplasmic reticulum (RER)* (**Figure 3–5**). The term *smooth* refers to the fact that no fixed ribosomes are associated with the smooth endoplasmic reticulum, while the fixed ribosomes on the outer surface of the rough endoplasmic reticulum give it a beaded, grainy, or rough appearance.

**Figure 3–5** The Endoplasmic Reticulum.




**a** The three-dimensional relationships between the rough and smooth endoplasmic reticula are shown here.

**b** Rough endoplasmic reticulum and free ribosomes in the cytoplasm of a cell.

The amount of endoplasmic reticulum and the proportion of RER to SER vary with the type of cell and its ongoing activities. For example, pancreatic cells that manufacture digestive enzymes contain an extensive RER, but the SER is relatively small. The situation is just the reverse in the cells of reproductive organs that synthesize steroid hormones.

**Smooth Endoplasmic Reticulum.** The **smooth endoplasmic reticulum (SER)** is involved with the synthesis of lipids, fatty acids, and carbohydrates; the sequestering of calcium ions; and the detoxification of drugs. Important functions of the SER include the following:

- *synthesis of the phospholipids and cholesterol* needed for maintenance and growth of the plasma membrane, ER, nuclear membrane, and Golgi apparatus in all cells;
- *synthesis of steroid hormones,* such as *androgens* and *estrogens* (the dominant sex hormones in males and in females, respectively) in the reproductive organs;
- *synthesis and storage of glycerides, especially triacylglycerides (triglycerides),* in liver cells and fat cells; and
- *synthesis and storage of glycogen* in skeletal muscle and liver cells.

In muscle cells, neurons, and many other types of cells, the SER also adjusts the composition of the cytosol by absorbing and storing ions, such as $Ca^{2+}$, or large molecules. In addition, the SER in liver and kidney cells detoxifies or inactivates drugs.

**Rough Endoplasmic Reticulum.** The **rough endoplasmic reticulum (RER)** functions as a combination workshop and shipping warehouse, because the fixed ribosomes on the RER synthesize proteins. Many of these newly synthesized proteins are then chemically modified in the RER and packaged for export to their next destination, the Golgi apparatus.

The new polypeptide chains produced at fixed ribosomes are released into the cisternae of the RER. Inside the RER, each protein assumes its secondary and tertiary structures. ↩ p. 101 Some of the proteins are enzymes that will function inside the endoplasmic reticulum. Other proteins are chemically modified by the attachment of carbohydrates, creating glycoproteins.

Most of the proteins and glycoproteins produced by the RER are packaged into small membranous sacs that pinch off from the tips of the cisternae. These **transport vesicles** then deliver their contents to the Golgi apparatus.

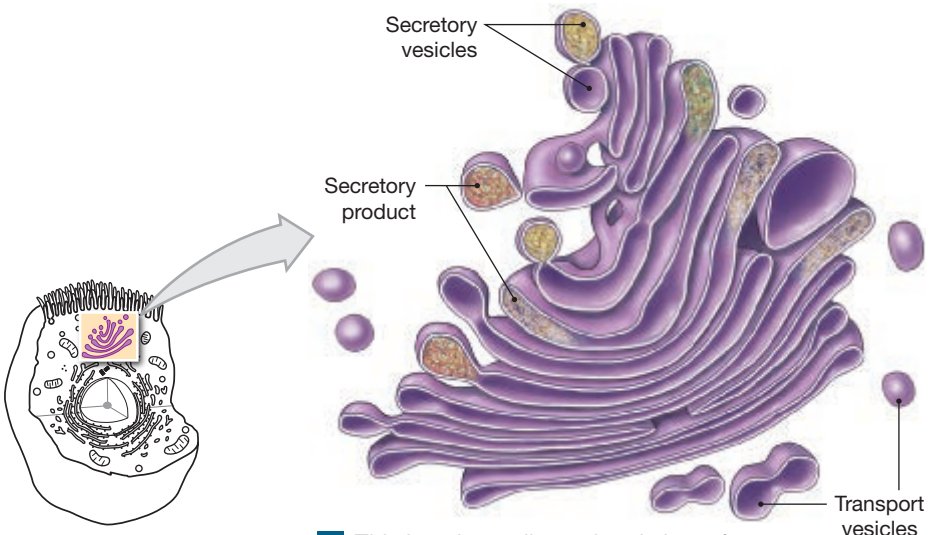
## The Golgi Apparatus

When a transport vesicle carries a newly synthesized protein or glycoprotein that is destined for export from the cell, it travels from the ER to the **Golgi** (GŌL-jē) **apparatus**, or **Golgi complex**, an organelle that looks a bit like a stack of dinner plates (Figure 3–6). This organelle typically consists of five or six flattened membranous discs called *cisternae.* A single cell may contain several of these organelles, most often near the nucleus.

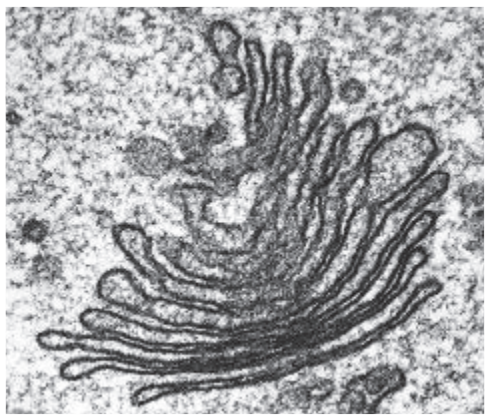
The Golgi apparatus has the following major functions (Spotlight Figure 3–7). It:

- *modifies and packages secretions*, such as hormones or enzymes, for release from the cell;
- *adds or removes carbohydrates to or from proteins* to change protein structure and thus function,
- *renews or modifies the plasma membrane*; and
- *packages special enzymes within vesicles (lysosomes)* for use in the cytoplasm.

**Figure 3–6** The Golgi Apparatus.




**a** This is a three-dimensional view of the Golgi apparatus with a cut edge.



Golgi apparatus TEM × 42,000

**b** This is a sectional view of the Golgi apparatus of an active secretory cell.

# SPOTLIGHT

Figure 3–7
## Protein Synthesis, Processing, and Packaging

The Golgi apparatus plays a major role in modifying and packaging newly synthesized proteins. Some proteins and glycoproteins synthesized in the rough endoplasmic reticulum (RER) are delivered to the Golgi apparatus by transport vesicles. Here's a summary of the process, beginning with DNA.

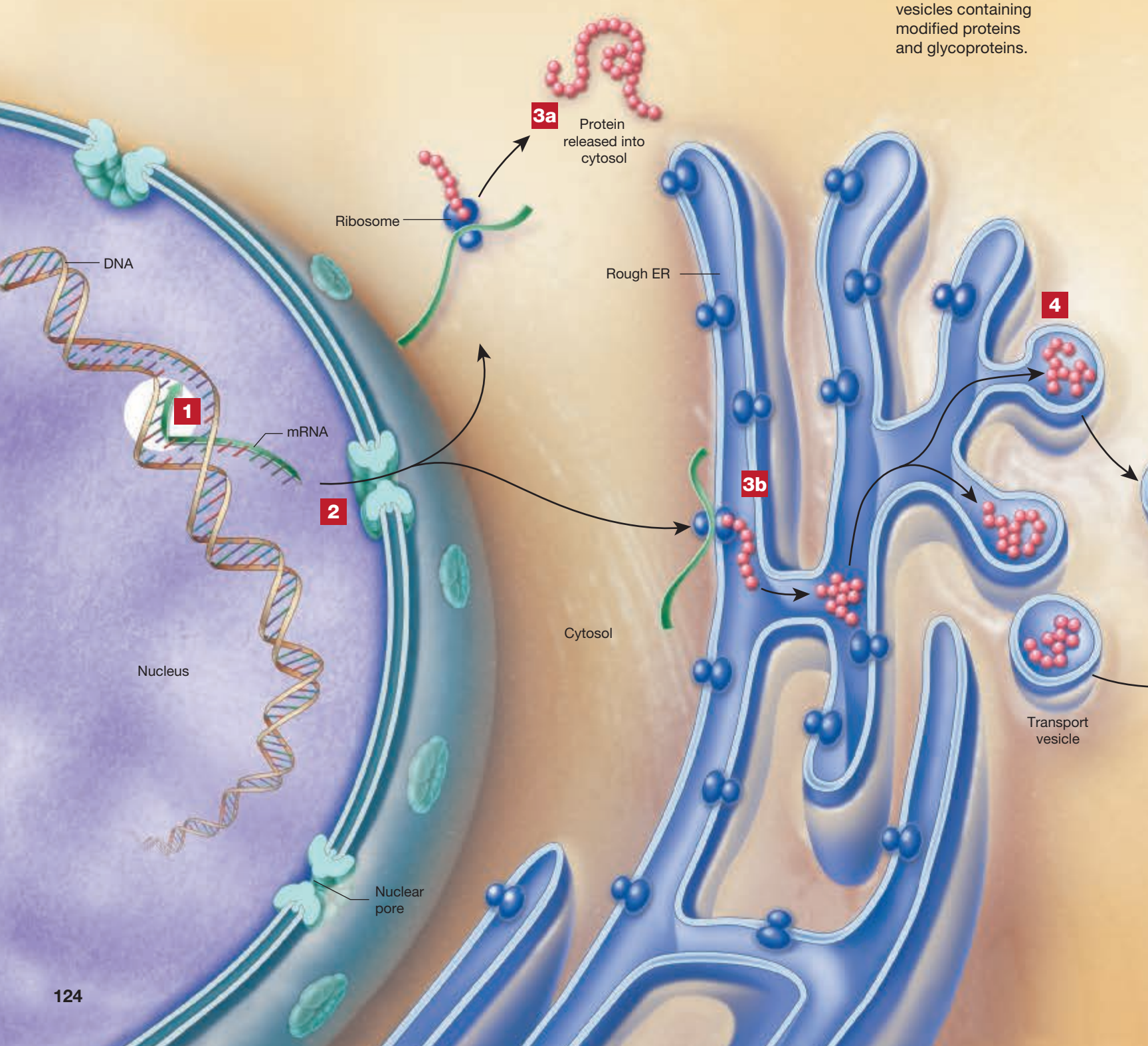
**1** Protein synthesis begins when a gene on DNA produces messenger RNA (mRNA), the template for protein synthesis.

**2** The mRNA leaves the nucleus and attaches to a free ribosome in the cytoplasm, or a fixed ribosome on the RER.

**3a** Proteins constructed on free ribosomes are released into the cytosol for use within the cell.

**3b** Protein synthesis on fixed ribosomes occurs at the RER. The newly synthesized protein folds into its three-dimensional shape.

**4** The proteins are then modified within the ER. Regions of the ER then bud off, forming transport vesicles containing modified proteins and glycoproteins.



**5** The transport vesicles carry the proteins and glycoproteins generated in the ER toward the Golgi apparatus. The transport vesicles then fuse to create the forming *cis* face ("receiving side") of the Golgi apparatus.

**6** Multiple transport vesicles combine to form cisternae on the *cis* face. Further protein and glycoprotein modification and packaging occur as the cisternae move toward the maturing (*trans*) face. Small transport vesicles return resident Golgi proteins to the forming cis face for reuse.

**7** The maturing *trans* face ("shipping side") generates vesicles that carry modified proteins away from the Golgi apparatus. One type of vesicle becomes a lysosome, which contains digestive enzymes.

**8** Two other types of vesicles proceed to the plasma membrane: secretory and membrane renewal. **Secretory vesicles** fuse with the plasma membrane and empty their products outside the cell by exocytosis. **Membrane renewal vesicles** add new lipids and proteins to the plasma membrane.

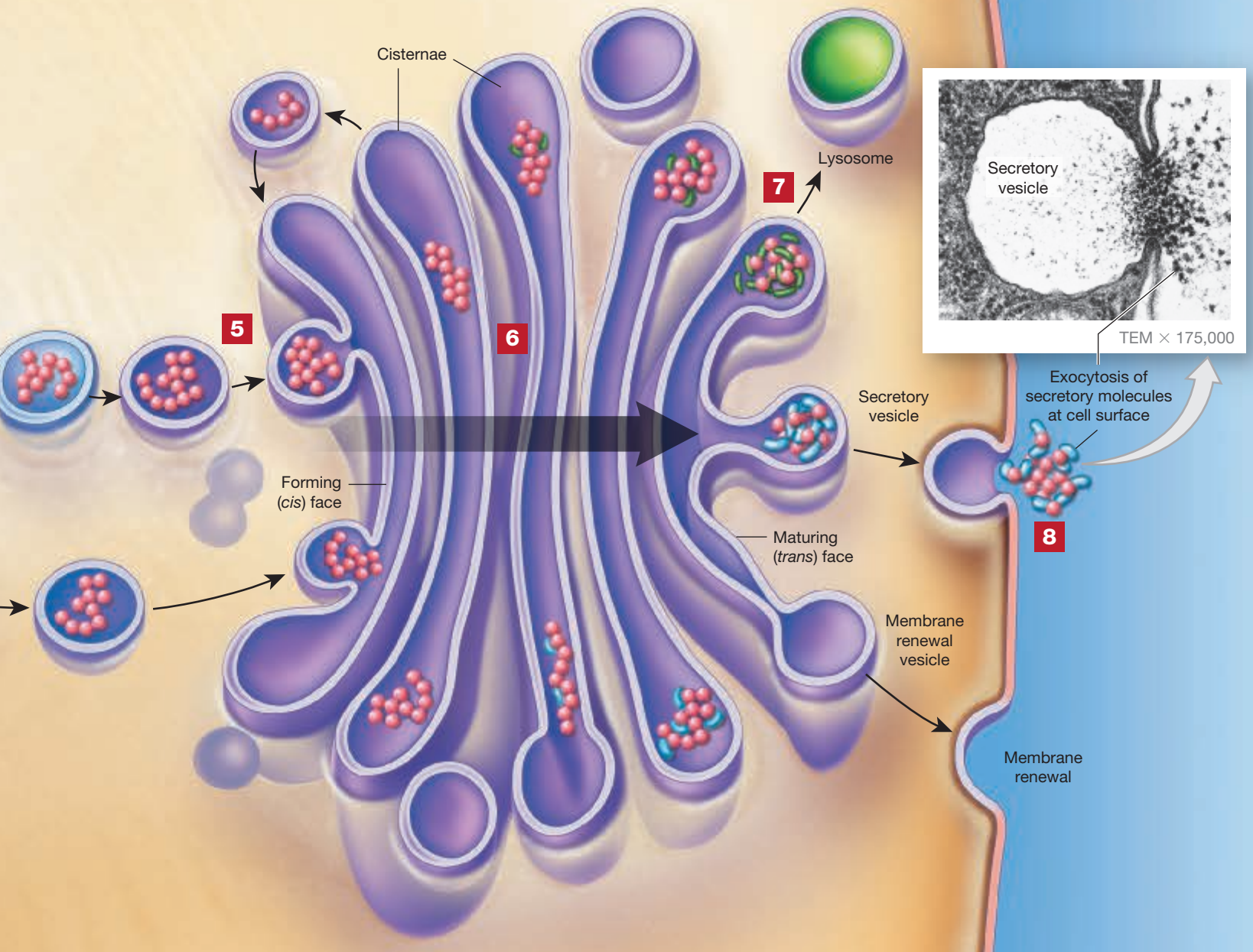
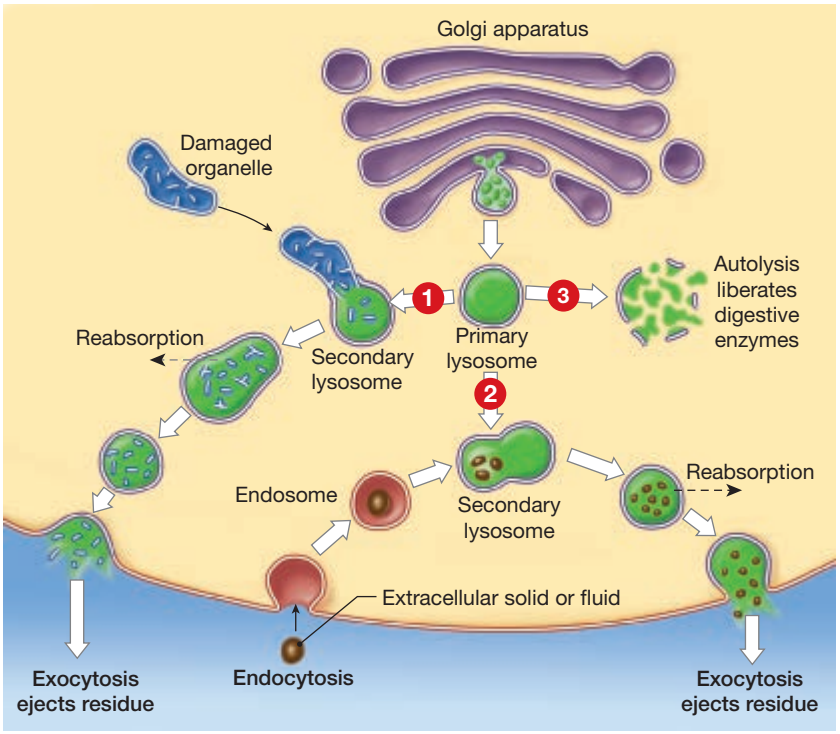


**Figure 3–8 Lysosome Functions.** Primary lysosomes, formed by the Golgi apparatus, contain inactive enzymes. They may be activated under any of the three basic conditions indicated here.




**Lysosome activation occurs when:**

1. A primary lysosome fuses with the membrane of another organelle, such as a mitochondrion
2. A primary lysosome fuses with an endosome containing fluid or solid materials from outside the cell
3. The lysosomal membrane breaks down during autolysis following cellular injury or death

## Lysosomes

Cells often need to break down and recycle large organic molecules and even complex structures like organelles. The breakdown process requires powerful enzymes, and it often generates toxic chemicals that could damage or kill the cell. **Lysosomes** (LĪ-sō-sōmz; *lyso-*, a loosening + *soma*, body) are vesicles that provide an isolated environment for potentially dangerous chemical reactions. These vesicles, produced by the Golgi apparatus, contain digestive enzymes that break organic polymers into monomers. Lysosomes are small, often spherical bodies with contents that look dense and dark in electron micrographs.

Lysosomes have several functions (Figure 3–8). One is to remove damaged organelles. *Primary lysosomes* contain inactive enzymes. When these lysosomes fuse with the membranes of damaged organelles (such as mitochondria or fragments of the ER), the enzymes are activated and *secondary lysosomes* are formed. The enzymes then break down the contents. The cytosol reabsorbs released nutrients, and the remaining material is expelled from the cell.

Lysosomes also destroy bacteria (as well as liquids and organic debris) that enter the cell from the extracellular fluid. The cell encloses these substances in a small portion of the plasma membrane, which is then pinched off to form a transport vesicle, or *endosome*, in the cytoplasm. (We discuss this method of transporting substances into the cell, called *endocytosis*, in Section 3-6.) Then a primary lysosome fuses with the vesicle, forming a secondary lysosome. Activated enzymes inside break down the contents and release usable substances, such as sugars or amino acids. In this way, the cell both protects itself against harmful substances and obtains valuable nutrients.

Lysosomes also do essential cleanup and recycling inside the cell. For example, when muscle cells are inactive, lysosomes gradually break down their contractile proteins. (This mechanism accounts for the reduction in muscle mass that accompanies aging.) The process is usually precisely controlled, but in a damaged or dead cell, the regulatory mechanism fails as lysosome membranes become increasingly permeable. Lysosomes then disintegrate, releasing enzymes that become activated within the cytosol. These enzymes rapidly destroy the cell's proteins and organelles in a process called **autolysis** (aw-TOL-i-sis; *auto-*, self). Although many factors appear to increase lysosome membrane permeability, we do not yet know how to control lysosomal activities.

## Peroxisomes

**Peroxisomes** are smaller than lysosomes and carry a different group of enzymes. In contrast to lysosomes, which are produced at the Golgi apparatus, new peroxisomes are produced by the growth and subdivision of existing peroxisomes. Their enzymes are produced at free ribosomes and transported from the cytosol into the peroxisomes by carrier proteins.

Peroxisomes absorb and break down fatty acids and other organic compounds. As they do so, peroxisomes generate hydrogen peroxide ($H_2O_2$), a potentially dangerous free radical. ↩ p. 81 Catalase, the most abundant enzyme within

### + Clinical Note Lysosomal Storage Diseases

Problems in producing lysosomal enzymes cause more than 30 serious diseases affecting children. In these conditions, called *lysosomal storage diseases*, the lack of a specific lysosomal enzyme results in the buildup of waste products and debris that lysosomes normally remove and recycle. Affected individuals may die when vital cells, such as those of the heart, can no longer function.

the peroxisome, then breaks down the hydrogen peroxide to oxygen and water. In this way, peroxisomes protect the cell from the potentially damaging effects of the free radicals produced during catabolism. Peroxisomes are present in all cells, but their numbers are highest in metabolically active cells, such as liver cells.

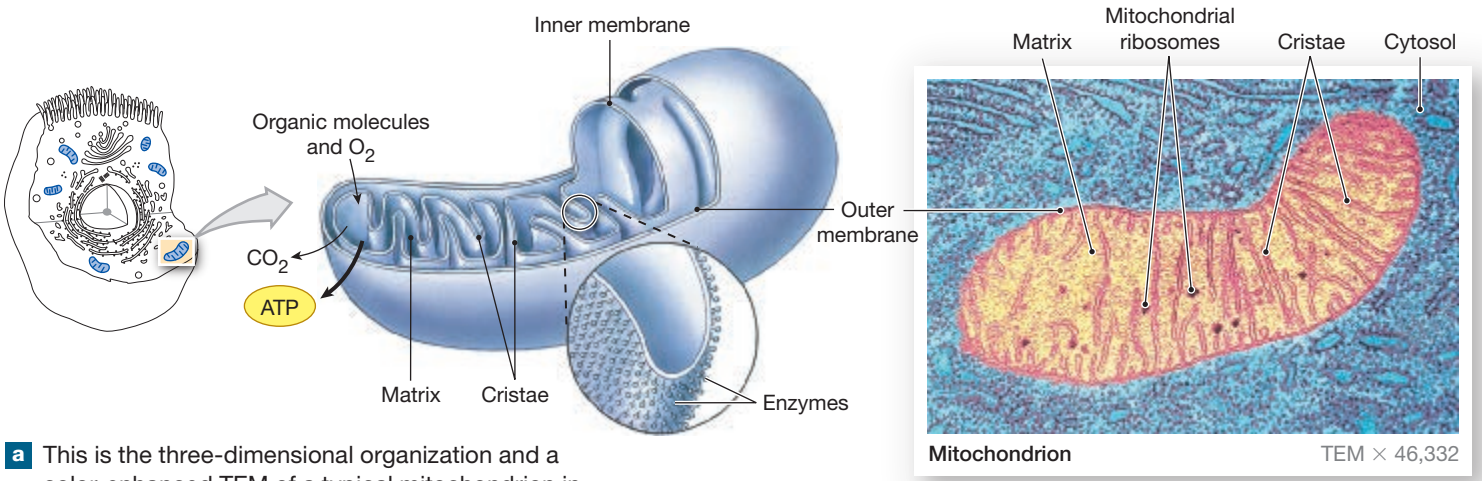
## Mitochondria

The cells of all living things require energy to carry out the functions of life. The organelles that produce energy in the form of ATP molecules are the **mitochondria** (mī-tō-KON-drē-ūh; singular, *mitochondrion*; *mitos*, thread + *chondrion*, granule). The number of mitochondria in a particular cell varies with the cell's energy demands. These organelles may account for 30 percent of the volume of a heart muscle cell, yet are absent in red blood cells.

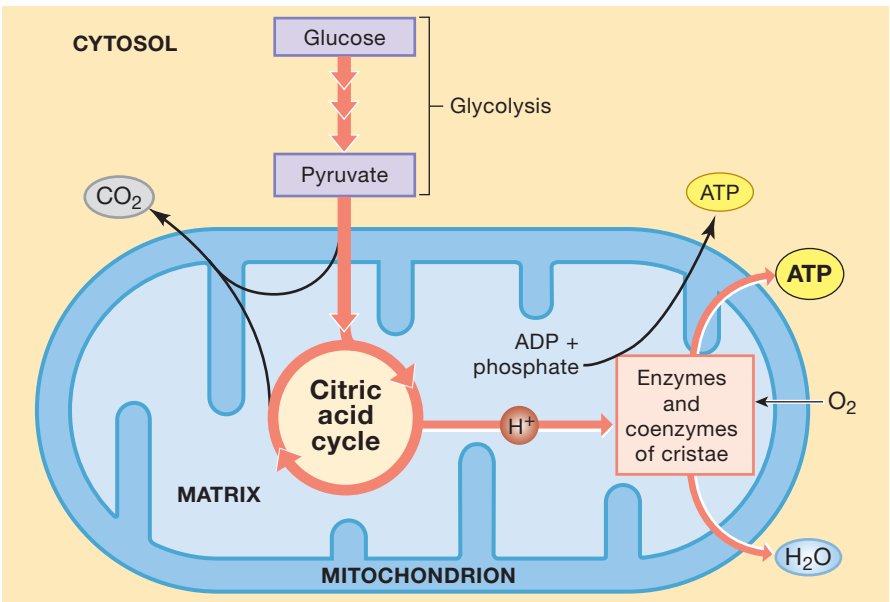
Mitochondria have an unusual double membrane (Figure 3–9a). The outer membrane surrounds the organelle. The inner membrane contains numerous folds called **cristae** (KRIS-tē), which surround the fluid contents, or **matrix**, of the mitochondrion. Cristae increase the membrane surface area

3

**Figure 3–9** Mitochondria.




**a** This is the three-dimensional organization and a color-enhanced TEM of a typical mitochondrion in longitudinal section.




**b** This is an overview of the role of mitochondria in energy production. Mitochondria absorb oxygen and short carbon chains, such as pyruvate, and they generate carbon dioxide, ATP, and water.

**?** What are the two reactants shown here that are necessary for energy production? What are the three products shown here as a result of this reaction?

in contact with the matrix and so allow more attached protein complexes and enzymes involved in making ATP from ADP and $P_i$ (inorganic phosphate). Metabolic enzymes in the matrix catalyze reactions that release carbon dioxide and provide some additional energy for cellular functions.

Mitochondria contain their own DNA (mtDNA) and ribosomes. The mtDNA codes for small numbers of RNA and polypeptide molecules. The polypeptides are used in enzymes required for energy production. Although mitochondria contain their own genetic system, their functions depend on imported proteins coded by nuclear DNA.

Most of the chemical reactions that release energy take place in the mitochondria, yet most of the cellular activities that require energy occur in the surrounding cytoplasm. For this reason, cells must store energy in a form that can be moved from place to place. Recall from Chapter 2 that cellular energy is stored and transferred in the form of *high-energy bonds.* The best example is the high-energy bond that attaches an inorganic phosphate ion ($P_i$) to adenosine diphosphate (ADP), forming the high-energy compound *adenosine triphosphate (ATP)*. Cells can then break this high-energy bond under controlled conditions, reconverting ATP to ADP and phosphate and releasing energy for the cell's use when and where it is needed.

Many cells generate ATP and other high-energy compounds as they break down carbohydrates, especially glucose. We examine the entire process in Chapter 25, but a few basic concepts now will help you follow discussions of muscle contraction, neuron function, and endocrine function in Chapters 10–18.

Most ATP is produced inside mitochondria, but the first steps take place in the cytosol (**Figure 3–9b**). A reaction sequence called **glycolysis** (*glycos*, sugar + *-lysis*, a loosening) breaks down a glucose molecule into two molecules of *pyruvate.* Mitochondria then absorb the pyruvate molecules.

In the mitochondrial matrix, a carbon dioxide ($CO_2$) molecule is removed from each absorbed pyruvate molecule. The remainder then enters the **citric acid cycle** (also known as the *Krebs cycle* and the *tricarboxylic acid cycle* or *TCA cycle*). The citric acid cycle is an enzymatic pathway that breaks down the absorbed pyruvate.

The remnants of pyruvate molecules contain carbon, oxygen, and hydrogen atoms. The carbon and oxygen atoms are released as carbon dioxide, which diffuses out of the cell. The hydrogen atoms are delivered to carrier protein complexes in the cristae. There the electrons are removed from the hydrogen atoms and passed along a chain of coenzymes and ultimately transferred to oxygen atoms. The energy released during these steps indirectly supports the enzymatic conversion of ADP to ATP. ↩ p. 105

Because mitochondrial activity requires oxygen, this method of ATP production is known as **aerobic metabolism** (*aer*, air + *bios*, life), or *cellular respiration.* Aerobic metabolism in mitochondria produces about 95 percent of the ATP needed to keep a cell alive. (Enzymatic reactions, including glycolysis, in the cytosol produce the rest.)

### + Clinical Note Free Radicals

Throughout a typical day or after exposure to pollution, cells generate free radicals. *Free radicals* are highly reactive atoms or molecules that contain an unpaired electron "seeking" the electrochemical stability of another electron. Common free radicals containing oxygen are known as reactive oxygen species (ROS). Free radicals such as ROS can damage proteins, DNA, and lipids. They prevent proteins from assuming their functional quaternary structure, DNA becomes cross-linked and unable to replicate, and the phospholipid bilayer of membranous organelles and the plasma membrane itself is pierced. Oxidative damage by free radicals underlies aging and numerous diseases such as Alzheimer's.

## Membrane Flow

When the temperature changes markedly, you change your clothes. Similarly, when a cell's environment changes, it changes the structure and properties of its plasma membrane. With the exception of mitochondria, all membranous organelles in the cell are either interconnected or in communication through the movement of vesicles. The membranes of the RER and SER are continuous and are connected to the nuclear envelope. Transport vesicles connect the ER with the Golgi apparatus, and secretory vesicles link the Golgi apparatus with the plasma membrane. Finally, vesicles forming at the exposed surface of the cell remove and recycle segments of the plasma membrane. This continuous movement and exchange of membrane segments is called **membrane flow**, or *membrane trafficking*. In an actively secreting cell, an area equal to the entire membrane surface may be replaced each hour. This process was shown in **Spotlight Figure 3–7**.

Membrane flow is an example of the dynamic nature of cells. It provides a way for cells to change the characteristics of their plasma membranes by altering their lipids and the proteins serving as receptors, channels, anchors, and enzymes—as they grow, mature, or respond to a specific environmental stimulus.

## ✓ Checkpoint

5. **Explain the difference between the cytoplasm and the cytosol.**
6. **What are the major differences between cytosol and extracellular fluid?**
7. **Identify the nonmembranous organelles, and cite a function of each.**

8. **Identify the membranous organelles, and cite their functions.**
9. **Explain why certain cells in the ovaries and testes contain large amounts of smooth endoplasmic reticulum.**
10. **What does the presence of many mitochondria imply about a cell's energy requirements?**

See the blue Answers tab at the back of the book.

## 3-3 The nucleus contains DNA and enzymes essential for controlling cellular activities

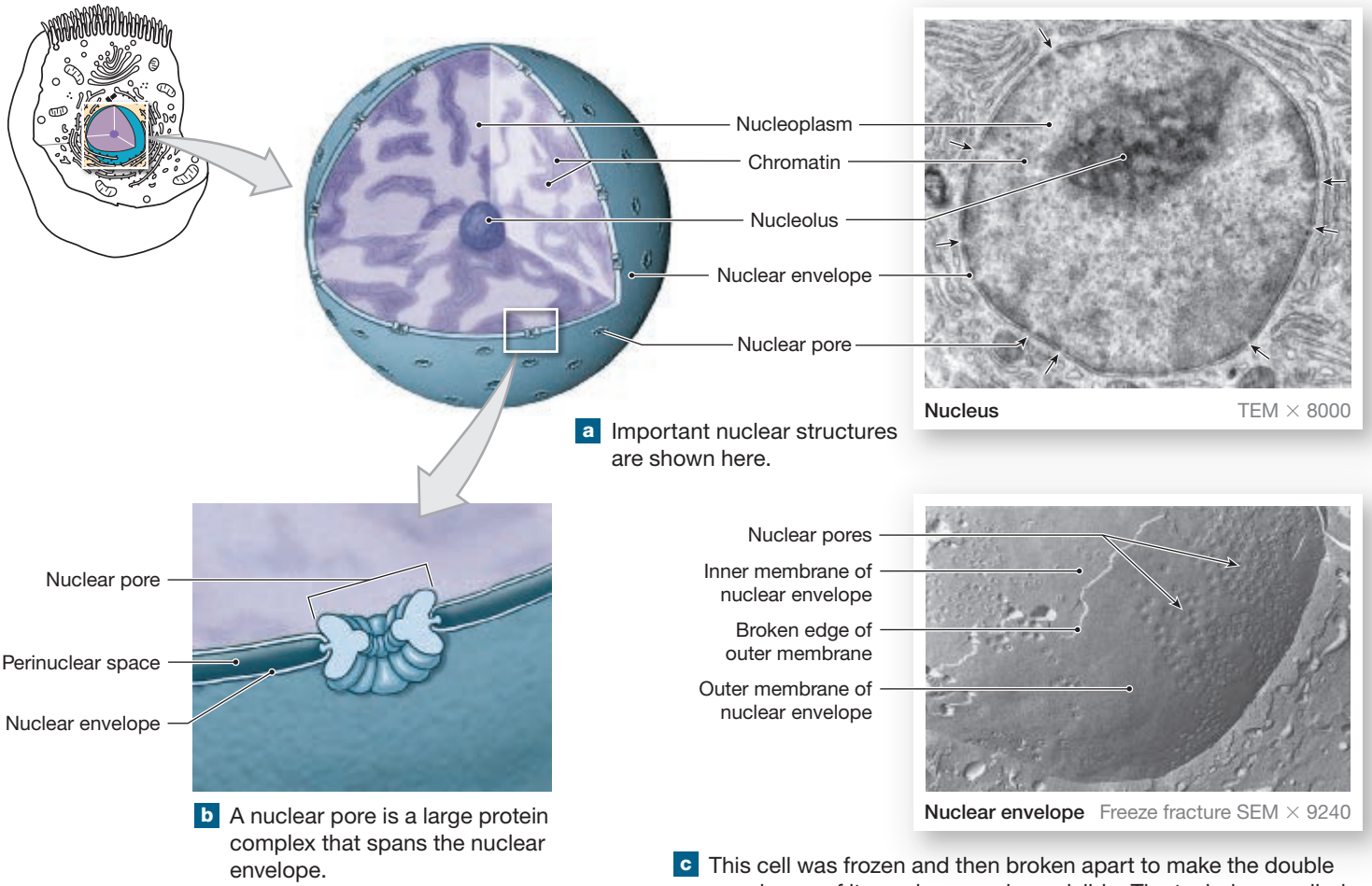
**Learning Outcome** Explain the functions of the cell nucleus, and discuss the nature and importance of the genetic code.

The **nucleus** is usually the largest and most conspicuous structure in a cell. If you look at a human cell under a light microscope, it may be the only organelle you can see. The nucleus is the control center for cellular operations. A single nucleus stores all the information needed to direct the synthesis of more than 100,000 different proteins in the human body. The nucleus determines the structure of the cell and what functions it can perform by controlling which proteins are synthesized, under what circumstances, and in what amounts. A cell without a nucleus cannot repair itself, so it will disintegrate within three or four months.

### Structure of the Nucleus

Most cells contain a single nucleus, but exceptions exist. For example, skeletal muscle cells have many nuclei, but mature red blood cells have none. Figure 3–10 details the structure of a typical nucleus. The nucleus is surrounded by a membranous nuclear envelope, which encloses its contents, including DNA.

**Figure 3–10** The Nucleus.




**a** Important nuclear structures are shown here.

**b** A nuclear pore is a large protein complex that spans the nuclear envelope.

**c** This cell was frozen and then broken apart to make the double membrane of its nuclear envelope visible. The technique, called *freeze fracture* or *freeze-etching*, provides a unique perspective on the internal organization of cells. The nuclear envelope and nuclear pores are visible. The fracturing process broke away part of the outer membrane of the nuclear envelope, and the broken edge of this membrane can be seen.

## Nuclear Envelope

Surrounding the nucleus and separating it from the cytosol is a **nuclear envelope**, a double membrane with its two layers separated by a narrow *perinuclear space* (*peri-*, around). At several locations, the nuclear envelope is connected to the rough endoplasmic reticulum (see **Spotlight Figure 3–1**).

To direct processes that take place in the cytoplasm, the nucleus must receive information about conditions and activities in other parts of the cell. Chemical communication between the nucleus and the cytoplasm takes place through openings in the nuclear envelope called **nuclear pores**. Each pore has about 50 associated proteins, forming a *nuclear pore complex*. Each nuclear pore complex regulates the transport of materials, such as RNA and other proteins, between the nucleus and the cytoplasm. They are large enough to allow ions and small molecules to enter or leave, but are too small for DNA to pass freely.

## Contents of the Nucleus

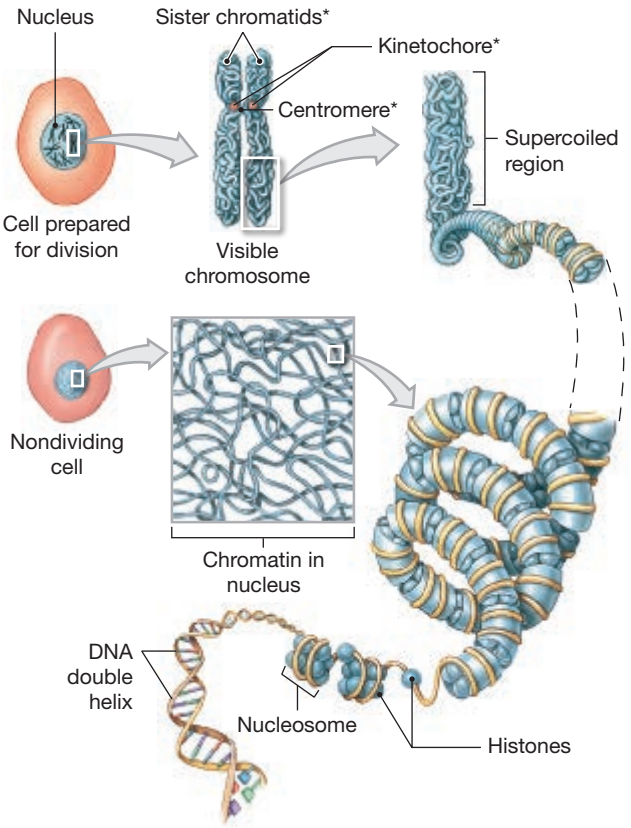
The fluid portion of the nucleus is called the *nucleoplasm* or *karyolymph* (*karyo-*, nucleus). The nucleoplasm contains the **nuclear matrix**, a network of fine filaments that provides structural support and may be involved in the regulation of genetic activity. The nucleoplasm also contains ions, enzymes, RNA and DNA nucleotides, small amounts of RNA, and DNA.

In addition, most nuclei contain several dark-staining areas called **nucleoli** (nū -KLĒ-ō-lī; singular, *nucleolus*). Nucleoli are transient nuclear organelles that synthesize ribosomal RNA. They also assemble the ribosomal subunits, which then enter the cytoplasm through nuclear pores. Nucleoli are composed of RNA, enzymes, and proteins called **histones**. The nucleoli form around portions of DNA that contain the instructions for producing ribosomal proteins and RNA when those instructions are being carried out. Nucleoli are most prominent in cells that manufacture large amounts of proteins, such as liver, nerve, and muscle cells, because those cells need large numbers of ribosomes.

The DNA in the nucleus stores the instructions for protein synthesis. Interactions between the DNA and the histones help determine which information is available to the cell at any moment. The organization of DNA within the nucleus of a nondividing cell and one preparing for cell division is shown in Figure 3–11. At intervals, the DNA strands wind around the histones, forming a complex known as a **nucleosome**. Such winding allows a great deal of DNA to be packaged in a small space.

The entire chain of nucleosomes may coil around other proteins. The degree of coiling varies, depending on whether cell division is under way. In cells that are not dividing, the nucleosomes are loosely coiled within the nucleus, forming a tangle of fine filaments known as **chromatin**. Chromatin gives the nucleus a clumped, grainy appearance. Just before cell division begins, the coiling becomes tighter, forming distinct structures called **chromosomes** (*chroma*, color). In humans, the nuclei of somatic cells contain 23 pairs of chromosomes. One member of each pair is derived from the mother, and one from the father.

**Figure 3–11 The Organization of DNA within the Nucleus.** DNA strands are coiled around histones to form nucleosomes. Nucleosomes form coils that may be very tight or rather loose. In cells that are not dividing, the DNA is loosely coiled, forming a tangled network known as chromatin. When the coiling becomes tighter, as it does in preparation for cell division, the DNA becomes visible as distinct structures called chromosomes. (Terms associated with cell division are highlighted with an asterisk [*] and discussed in **Spotlight Figure 3–23**.)




? How is DNA organized in the nucleus when the cell is prepared for division? How is DNA organized in the nucleus when the cell is not dividing?

## Information Storage in the Nucleus

As we saw in Chapter 2, each protein molecule consists of a unique sequence of amino acids. ↩ p. 99 Any "recipe" for a protein must specify the order of amino acids in the polypeptide chain. This information is stored in the chemical structure of the DNA strands in the nucleus. The chemical "language" the cell uses is known as the **genetic code**. An understanding of the genetic code has enabled researchers to learn how cells