Microbiology

with Diseases by Taxonomy

FIFTH EDITION

Robert W. Bauman

Pearson

Invest in your future:

Microbiology Matters

Engage with compelling healthcare applications

NEW! Micro Matters

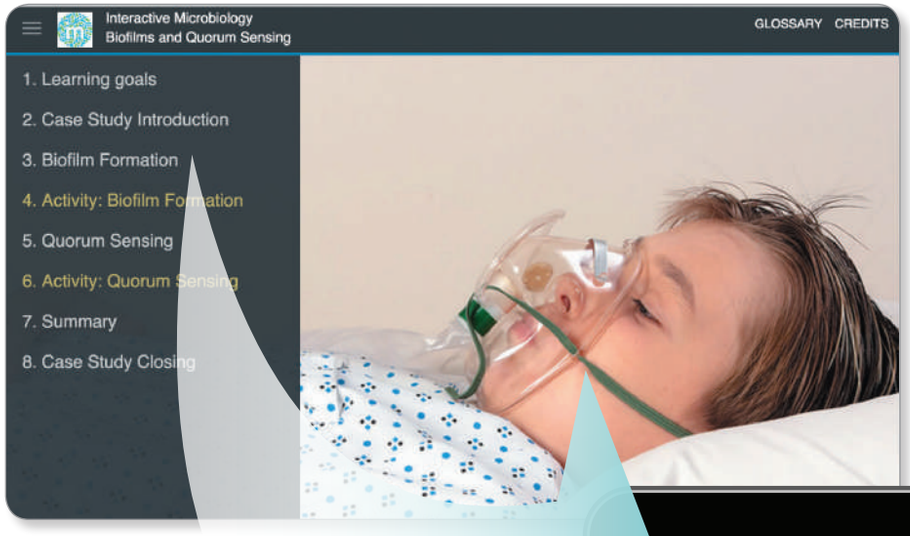
Video Cases animate and connect concepts across chapters and emphasize the clinical importance of foundational material. Micro Matters videos are accessible via QR codes in select chapters and are also assignable in MasteringMicrobiology.

MICRO MATTERS

Make the connection between Chapters 11, 12, and 13. Scan this QR code to see how *Micro Matters*.

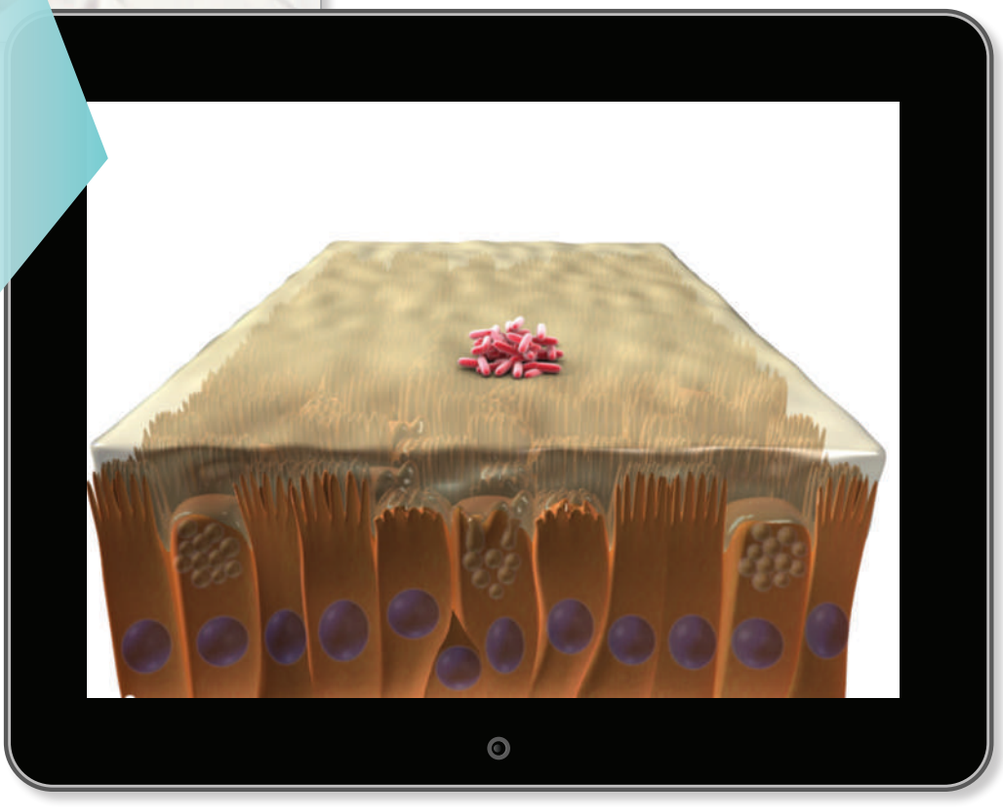
Visit the **MasteringMicrobiology Study Area** to challenge your understanding with practice tests, animation quizzes, and clinical case studies!

MasteringMicrobiology®

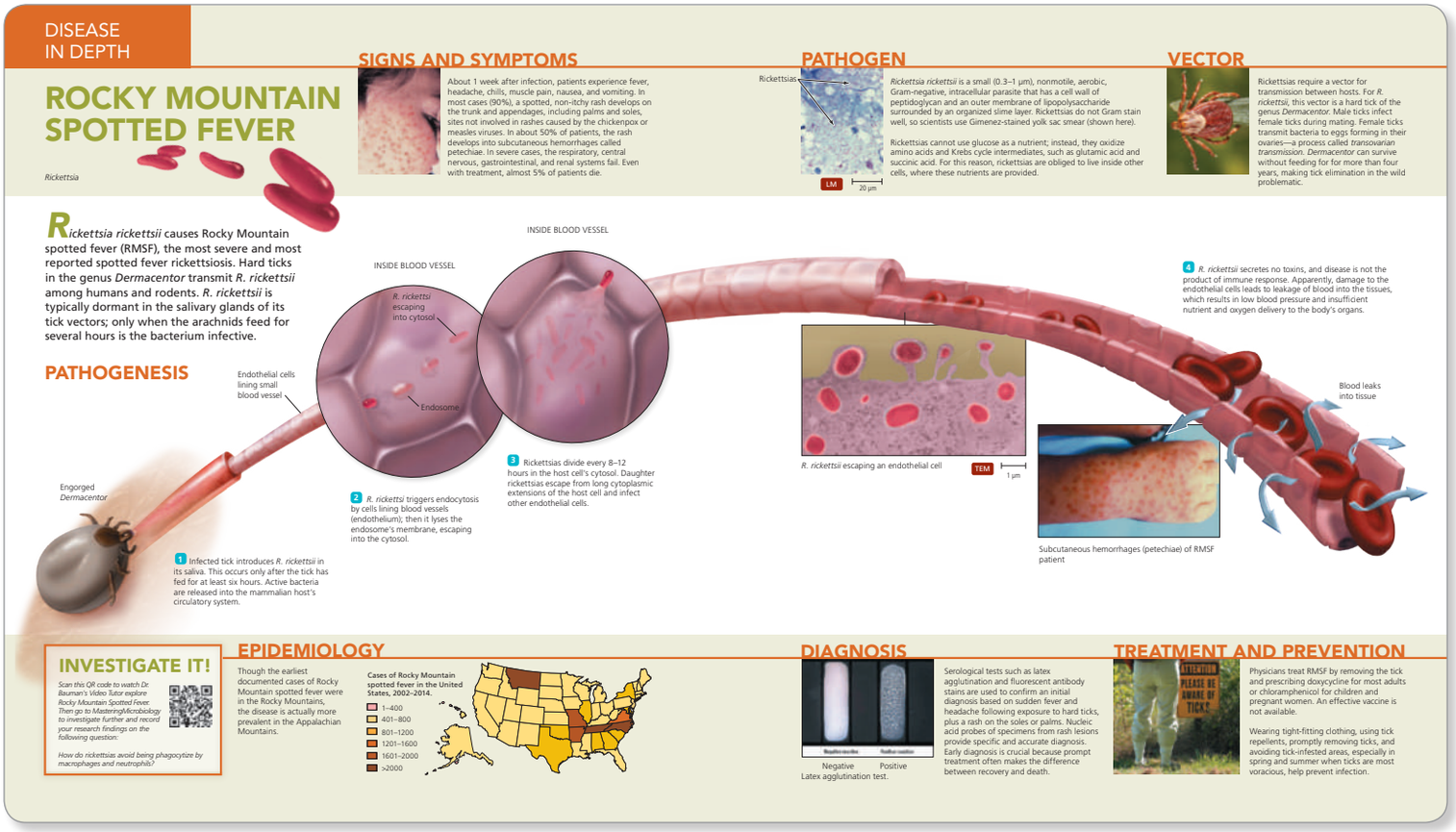


NEW! Interactive Microbiology

is a dynamic suite of interactive tutorials and animations that teach key concepts in microbiology including Operons; Biofilms and Quorum Sensing; Complement; Antibiotic Resistance, Mechanisms and Selection; Aerobic Respiration in Prokaryotes, and more. Each tutorial presents the concept within a real healthcare scenario and allows you to learn from manipulating variables, predicting outcomes, and answering assessment questions.



NEW! Disease in Depth One- or two-page spreads feature important and representative diseases. These highly visual spreads contain illustrations, micrographs, and infographics, providing in-depth overviews of selected diseases for comprehensive study and review.



Disease in Depth Video Tutors walk through the presented disease, concluding with an "Investigate It!" question for independent research, furthering your understanding of microbiology's relevancy and importance. Dr. Bauman also includes video tutors to coach students through key process art figures in the book.

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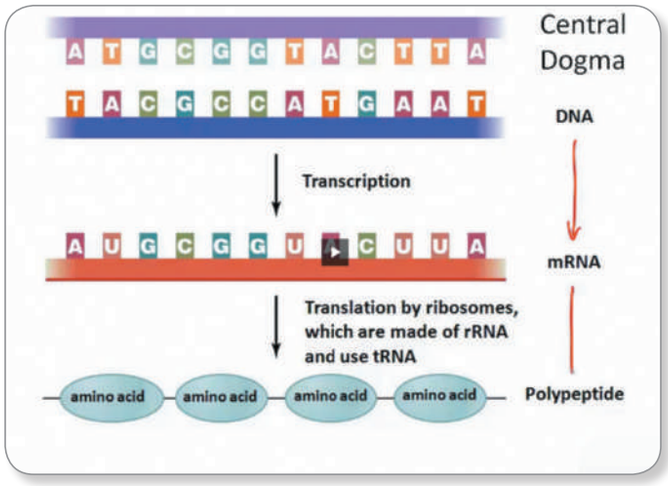
NEW! Disease in Depth Coaching Activities feature personalized hints and feedback and provide guidance through each disease, prompting students to explore further with independent research.

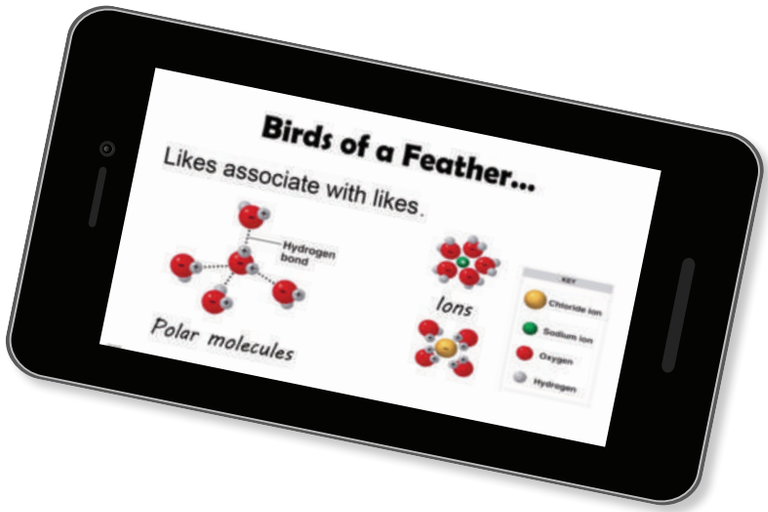
NEW! Connecting Concepts Coaching Activities reinforce a "big picture" understanding of microbiology by showing how concepts in a particular chapter connect across other chapters in the text.

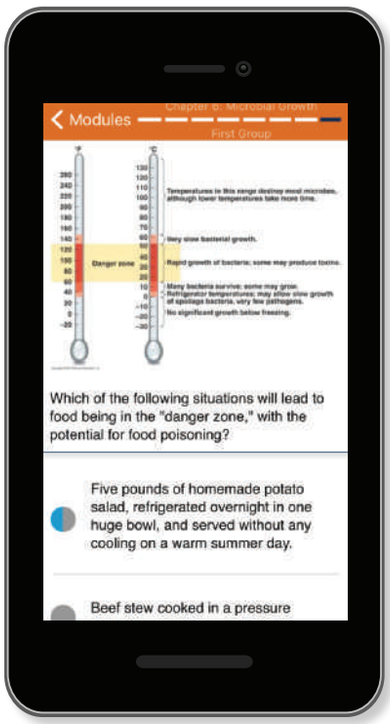


Master Microbiology **at your own pace**, wherever you go!

MasteringMicrobiology®

NEW! MicroBoosters offer a mobile-friendly way for you to review (or learn for the first time) foundational concepts that are important in order to understand Microbiology, including Study Skills, Basic General and Organic Chemistry, Cell Biology, and more. MicroBoosters can be assigned through MasteringMicrobiology and are available for self-study as Dynamic Study Modules.





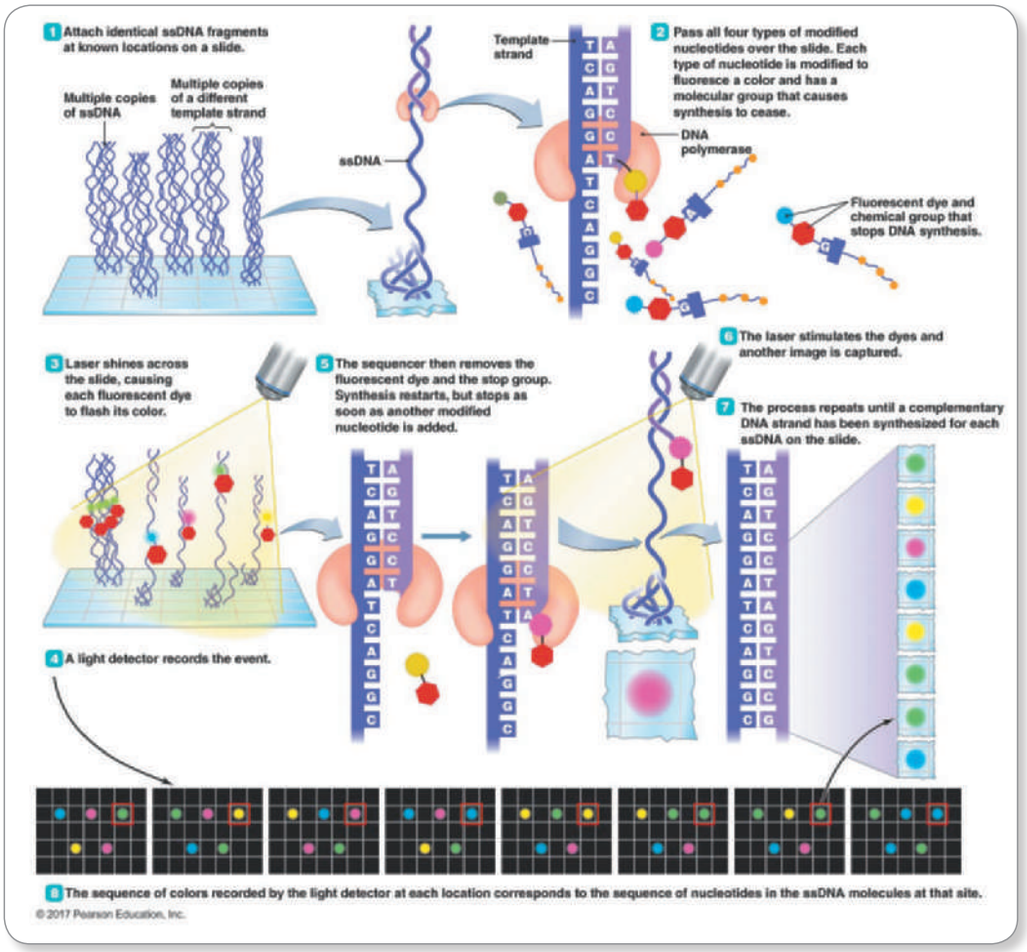
NEW! Mobile-friendly Dynamic Study Modules help students acquire, retain, and recall information faster and more effectively than ever before. These flashcard-style modules are available as a self-study tool or can be assigned by instructors.

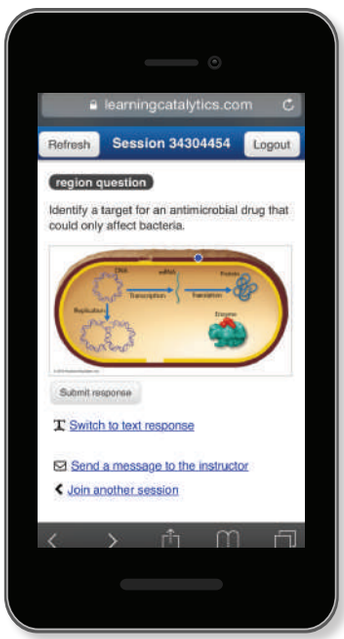
NEW! Adaptive Follow-Up Assignments in MasteringMicrobiology are based on each student's performance on the original homework assignment and, when assigned, provide additional coaching and practice.

EXPANDED! Dr. Bauman's Video Tutors, developed and narrated by the author, carefully teach key concepts using textbook art, bringing the illustrations to life and helping you visualize and understand complex topics and important processes. The Fifth Edition includes new video tutors on key concepts as well as the Disease in Depth overviews. You can quickly access the video tutors by scanning QR codes with a mobile device for on-the-go tutoring; instructors may also assign them as coaching activities in MasteringMicrobiology.

Learn how **today's microbiologists think.**

UPDATED! Every chapter has been revised to reflect the current **State of the Science**, including the latest research and technology. Highlights of content updates include extensive discussions on the impact of genomics in understanding disease diagnosis and treatment options.





Develop **higher-level thinking skills** and conceptual understanding

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NEW! Learning Catalytics is a "bring your own device" (laptop, smartphone, or tablet) classroom system for student engagement and assessment. With Learning Catalytics, instructors can assess students in real time using open-ended tasks to probe student understanding.

NEW! ASM Curriculum Guidelines pre-test and post-test assessments are assignable in MasteringMicrobiology to facilitate efficient and customizable assessment of the six underlying concepts and 22 related topics of lasting importance in undergraduate microbiology courses as determined by the American Society of Microbiology.

Connect Lecture and Lab

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MicroLab Tutors help instructors and students get the most out of lab time and make the connection between microbiology concepts, lab techniques, and real-world applications.

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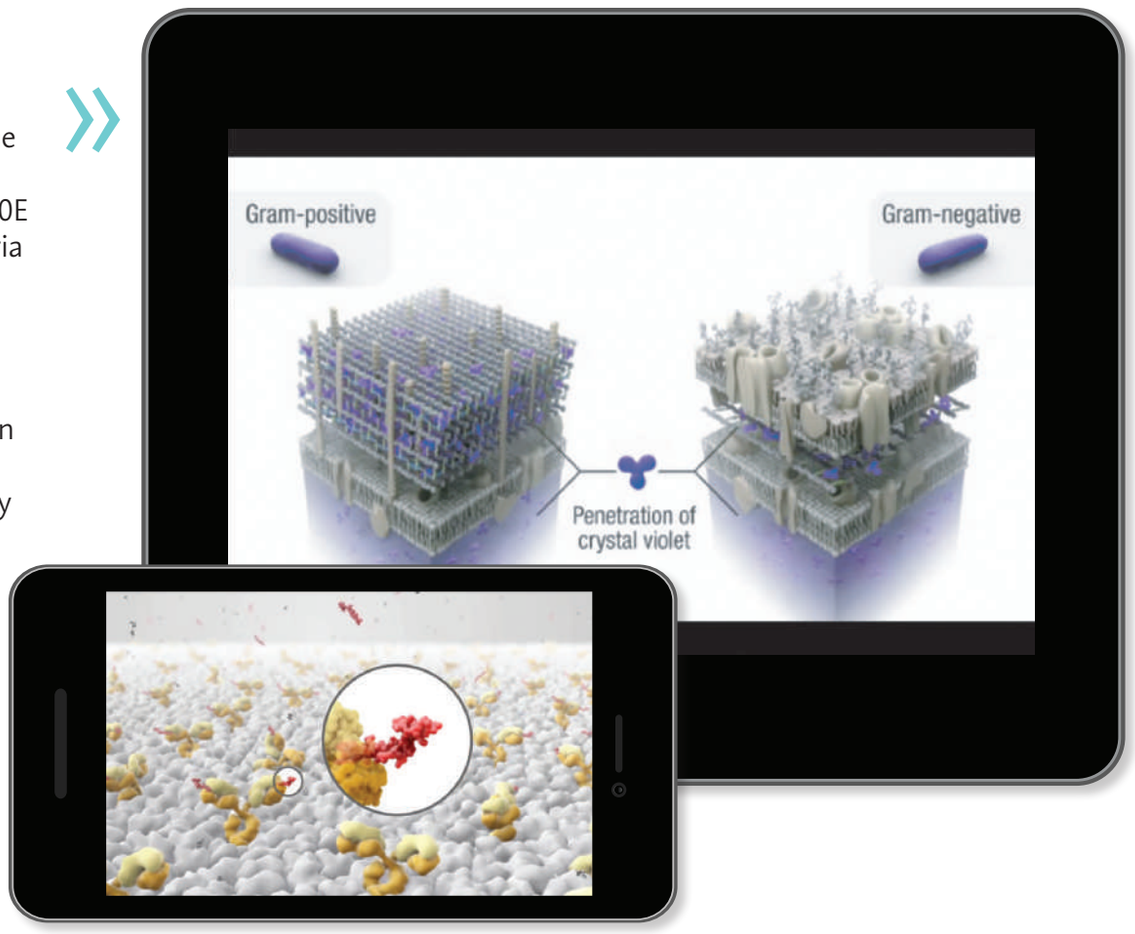
MicroLab Tutor Coaching Activities include the following topics:

- Use and Application of the Acid-Fast Stain
- Multitest Systems—API 20E
- Aseptic Transfer of Bacteria
- ELISA
- Gram Stain
- Use and Application of Microscopy
- Polymerase Chain Reaction (PCR)
- Safety in the Microbiology Laboratory
- Quantifying Bacteria with Serial Dilutions and Pour Plates
- Smear Preparation and Fixation
- Streak Plate Technique
- Survey of Protozoa
- Identification of Unknown Bacteria



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Lab Technique Videos give students an opportunity to see techniques performed correctly and quiz themselves on lab procedures both before and after lab time.

Lab Technique videos can be assigned as pre-lab quizzes in MasteringMicrobiology and include coaching and feedback on the following techniques:

- **NEW!** The Scientific Method
- **NEW!** How to Write a Lab Report
- Acid-Fast Staining
- Amylase Production
- Carbohydrate Catabolism
- Compound Microscope
- Differential and Selective Media
- Disk-Diffusion Assay
- ELISA
- Gram Stain
- Hydrogen Sulfide Production
- Litmus Milk Reactions
- Negative Staining
- Respiration
- Serial Dilutions
- Simple Staining
- Smear Preparation
- Structural Stains
- Safety in the Microbiology Laboratory

Also Available for the Microbiology Lab Course

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The Eleventh Edition of this popular laboratory manual has been thoroughly revised with easy-to-adapt Lab Reports and the latest protocols from governing agencies including the EPA, ASM, and AOAC, along with two new lab exercises: one on Food Safety, and another covering the BSL 1 Biological Safety Level.

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MasteringMicrobiology is the most effective and widely used online homework, tutorial, and assessment system for the sciences, delivering self-paced tutorials that focus on your course objectives, provide individualized coaching, and respond to your students' progress.

Instructor's Resource Material

The Instructor's Resource Material offers a wealth of instructor media resources, including presentation art, lecture outlines, test items, and answer keys—all in one convenient location. These resources help instructors prepare for class—and create dynamic lectures—in half the time! The Instructor's Resource Materials include:

- All figures from the text with and without labels in both JPEG and PowerPoint® formats
- All figures from the book with the Label Edit feature and selected "process" figures from the text with the Step Edit feature in PowerPoint format
- All tables from the text
- PowerPoint lecture outlines, including figures and tables from the book and links to the animations and videos

All items provided on the IRC can also be downloaded from the "Instructor Resources" area of MasteringMicrobiology, which also includes: Video Tutors, MicroFlix™ Animations, Microbiology Animations, Microbiology Videos, Lab Technique Videos, and more.

NEW! Learning Catalytics is a "bring your own device" (laptop, smartphone, or tablet) classroom system for student engagement and assessment. With Learning Catalytics, instructors can assess students in real time using open-ended tasks to probe student understanding.

Test Bank (Download Only)

by Robert W. Bauman, Nichol Dolby

The Fifth Edition Test Bank includes hundreds of multiple choice, true/false, and short answer/essay questions that are correlated to the book's Learning Outcomes and Bloom's Taxonomy rankings. Available electronically in the "Instructor Resources" area of MasteringMicrobiology, in both Microsoft Word® and in TestGen formats.

Instructor's Manual (Download Only)

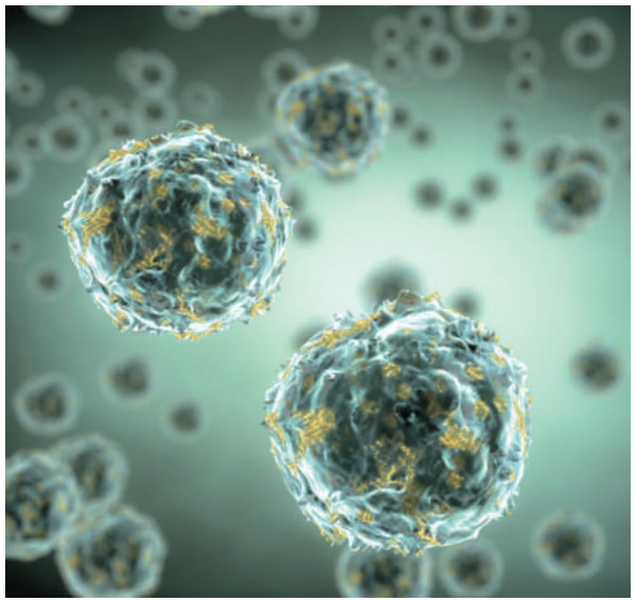
by Robert W. Bauman, Nichol Dolby

This guide can be downloaded from the "Instructor Resources" area of MasteringMicrobiology and includes a detailed chapter outline and summary for each chapter as well as answers to in-text Clinical Case Studies, "Tell Me Why" questions, Critical Thinking questions, and end-of-chapter Questions for Review.

FIFTH EDITION
GLOBAL EDITION

MICROBIOLOGY

WITH DISEASES BY TAXONOMY



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To Michelle:
My best friend, my closest confidant, my cheerleader, my partner, my love. Thirty-four years! I love you more now than then.

—Robert

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About the Author

ROBERT W. BAUMAN is a professor of biology and past chairman of the Department of Biological Sciences at Amarillo College in Amarillo, Texas. He has taught microbiology, human anatomy and physiology, and botany. In 2004, the students of Amarillo College selected Dr. Bauman as the recipient of the John F. Mead Faculty Excellence Award and he has been nominated for the one-time award every year since. He received an M.A. degree in botany from the University of Texas at Austin and a Ph.D. in biology from Stanford University. His research interests have included the morphology and ecology of freshwater algae, the cell biology of marine algae (particularly the deposition of cell walls and intercellular communication), environmentally triggered chromogenesis in butterflies, and terrestrial oil pollution remediation by naturally occurring bacteria. He is a member of the American Society of Microbiology (ASM) where he has held national offices, Texas Community College Teachers Association (TCCTA) where he serves in a statewide position of leadership, American Association for the Advancement of Science (AAAS), Human Anatomy and Physiology Society (HAPS), and The Lepidopterists' Society. When he is not writing books, he enjoys spending time with his family: gardening, hiking, camping, rock climbing, backpacking, cycling, skiing, and reading by a crackling fire in the winter and in a gently swaying hammock in the summer.

TODD P. PRIMM (contributor) is an associate professor at Sam Houston State University, where he teaches pre-nursing microbiology. He also serves as Director of the Professional and Academic Center for Excellence, which focuses on improving teaching and learning on campus. In 2010, he was Distinguished Alumnus of the Graduate School of Biomedical Sciences of Baylor College of Medicine, where he earned a Ph.D. in Biochemistry in 1997. He received a B.S. from Texas A&M University in 1992. He is very active in the American Society for Microbiology and received the Texas Branch 2015 Faculty Teaching Award. He was chair of the organizing committee for the 2013 ASM Conference for Undergraduate Educators, participated in the 2012 Research Residency of the ASM/NSF Biology Scholars Program, and currently serves on the editorial board for the *Journal of Microbiology and Biology Education*. He is also an affiliate staff member with the international organization Cru. He loves teaching and mentoring students and spending time with his wonderful wife of 23 years and four children.

About the Clinical Consultants

CECILY D. COSBY is nationally certified as both a family nurse practitioner and physician assistant. She is a professor of nursing, currently teaching at Samuel Merritt University in Oakland, California, and has been in clinical practice since 1980. She received her Ph.D. and M.S. from the University of California, San Francisco; her BSN from California State University, Long Beach; and her P.A. certificate from the Stanford Primary Care program. She is the Director of Samuel Merritt University's Doctor of Nursing Practice Program.

JEAN E. MONTGOMERY is a registered nurse formerly teaching in the associate degree nursing program at Austin Community College in Texas. She received her MSN from the University of Texas Health Science Center at San Antonio, Texas.

Preface

The reemergence of whooping cough, mumps, and measles and the emergence of snail fever, spotted fever rickettsiosis, Middle East respiratory syndrome, and other diseases; the cases of strep throat, MRSA, and tuberculosis; the progress of cutting-edge research into microbial genetics; the challenge of increasingly drug-resistant pathogens; the continual discovery of microorganisms previously unknown—these are just a few examples of why exploring microbiology has never been more exciting, or more important. Welcome!

I have taught microbiology to undergraduates for over 27 years and witnessed firsthand how students struggle with the same topics and concepts year after year. To address these challenging topics, I have created 14 new Video Tutors: three in addition to those already incorporated into the first 18 chapters of the text and 11 that cover the Disease in Depth features. The Video Tutors and Disease in Depth features walk students through key concepts in microbiology, bringing the art of the textbook to life and important concepts into view. In creating this textbook, my aim was to help students see complex topics of microbiology—especially metabolism, genetics, and immunology—in a way that they can understand, while at the same time presenting a thorough and accurate overview of microbiology. I also wished to highlight the many positive effects of microorganisms on our lives, along with the medically important microorganisms that cause disease.

New to This Edition

In approaching the fifth edition, my goal was to build upon the strengths and success of the previous editions by updating it with the latest scientific and educational research and data available and by incorporating the many terrific suggestions I have received from colleagues and students alike. The feedback from instructors who adopted previous editions has been immensely gratifying and is much appreciated. The Microbe at a Glance features have been widely praised by instructors and students, so I, along with art editor Kelly Murphy, developed 11 new Disease in Depth features, most as two-page spreads, that use compelling art and photos to provide a detailed, visually unsurpassed overview of a specific disease. Each Disease in Depth feature includes an Investigate It! question with a QR code directing students to a Video Tutor that explores the topic and encourages further, independent research. These activities are assignable in MasteringMicrobiology®. Another goal for this edition was to provide additional instruction on important foundational concepts and processes. To that end, I developed and narrated three new core concept Video Tutors, accessible via QR codes in the textbook and assignable in MasteringMicrobiology.

The result is, once again, a collaborative effort of educators, students, editors, and top scientific illustrators: a textbook that, I hope, continues to improve upon conventional explanations and illustrations in substantive and effective ways.

In this new edition:

- **NEW Disease in Depth** features highlight important and representative diseases for each body system, extending the visual impact of the art program as well as the highly praised Microbe at a Glance features. Each of these 11 visual features contains infographics, provides in-depth coverage of the selected disease, and includes a QR code and Investigate It! question that directs students to a Video Tutor exploring the topic and prompting further inquiry and critical thinking.

New assignable Disease in Depth coaching activities in MasteringMicrobiology® encourage students to apply and test their understanding of key concepts.

- **NEW Video Tutors** developed and narrated by the author walk students through key concepts. New to this edition are Video Tutors on glycolysis, protein translation, and antigen processing. These Video Tutors bring the textbook art to life and help students visualize and understand tough topics and important processes. Thirty-two video tutorials are accessible via QR codes in the textbook and are accompanied by multiple-choice questions, assignable in MasteringMicrobiology®.
- **NEW Tell Me Why** critical thinking questions end every main section within each chapter. These questions strengthen the pedagogy and organization of each chapter and *consistently* provide stop-and-think opportunities for students as they read.
- **NEW Expanded coverage of helminths** is provided in new Highlight features, and an **emphasis on virulence factors** is included the Disease in Depth features.
- **The genetics chapters (Chapters 7–8)** have been reviewed and revised by genetics specialists. These now reflect the most current understanding of this rapidly evolving field, including new discussion of next-generation DNA sequencing.
- **Over 330 NEW and revised micrographs, photos, and figures** enhance student understanding of the text and boxed features.
- **NEW and EXPANDED MasteringMicrobiology** includes new Interactive Microbiology animations and tutorials; new MicroBooster remedial video tutorials; new Disease in Depth coaching activities; new Video Tutors with assessments; new MicroCareers and Clinical Case Study coaching activities; and a plethora of microbiology lab resources. **NEW** Interactive Microbiology is a dynamic suite of interactive tutorials and animations that teach key concepts in the context of a clinical setting. Students actively engage with each topic and learn from manipulating variables, predicting outcomes, and answering formative and summative assessments. Topics include Operons; Complement; Biofilms and Quorum Sensing; Antibiotic Resistance, Mechanisms; Antibiotic Resistance, Selection; Aerobic Respiration in Prokaryotes; and Human Microbiota. **NEW** MicroBoosters are a suite of brief video tutorials that cover key concepts that students often need to review, including Study Skills, Math, Basic Chemistry, Cell Biology, Basic Biology and more! The Micro Lab resources include MicroLab Tutors, which use lab technique videos, 3-D molecular animations, and step-by-step tutorials to help students make connections between lecture and lab; Lab Technique Videos and pre-lab quizzes to ensure that students come prepared for lab time; and Lab Practical and post-lab quizzes to reinforce what students have learned.

MasteringMicrobiology offers students access to Dynamic Study Modules to help them acquire, retain, and recall information faster and more efficiently than ever before with textbook-specific explanations and art. Dynamic Study Modules are available for use as a self-study tool or as assignments. Instructors also now have the option to give Adaptive Follow-Up assignments that provide student-specific additional coaching and practice. These question sets continuously adapt to each student's needs, making efficient use of homework time.

MasteringMicrobiology also includes Learning Catalytics—a "bring your own device" student engagement, assessment, and classroom intelligence system. With Learning Catalytics, instructors can assess students in real time using open-ended tasks to probe student understanding using Pearson's library of questions or designing their own.

The following section provides a detailed outline of this edition's chapter-by-chapter revisions.

Chapter-by-Chapter Revisions

CHAPTER 1 A BRIEF HISTORY OF MICROBIOLOGY

- Added three Tell Me Why critical thinking questions to text
- Added three new photos (chapter opener, Fig. 1.6b, Highlight box on MERS)
- Updated map showing countries having transmission of variant Creutzfeldt-Jakob disease (vJCD)
- Added CDC-preferred term "healthcare-associated infection (HAI)" (formerly nosocomial infection)
- Added introductory coverage of normal microbiota and of agar in micro labs
- Clarified the use of *controls* in Pasteur's experiment to disprove spontaneous generation
- Clarified industrial use of microbes in making yogurt and pest control
- Introduced the success of gene therapy to treat several inherited immune deficiencies
- Updated box: "The New Normal": The Challenge of Emerging and Reemerging Diseases to include Middle East respiratory syndrome (MERS), Ebola, chikungunya, and measles
- Added to list of current problems in microbiology: biofilms, tests for infections, and persistent antimicrobial-drug resistance
- Added three critical thinking questions to Emerging Disease Case Study: Variant Creutzfeldt-Jacob Disease
- New end-of-chapter, short-answer question on healthcare-associated (nosocomial) infections
- Added fill-in Concept Map over types of microbes and some of their major characteristics

CHAPTER 2 THE CHEMISTRY OF MICROBIOLOGY

- Added five Tell Me Why critical thinking questions to text
- Eleven figures revised for better pedagogy (Figs. 2.2, 2.3, 2.6, 2.11, 2.15, 2.17, 2.19, 2.21, 2.22, 2.23; amino group in Table 2.3)
- New Learning Outcomes concerning terms regarding elements, valence electrons and chemical bonding, organic compounds, contrasting ionic and covalent bonds, and lipids
- New figure legend question for enhanced pedagogy (Fig. 2.3)
- Expanded coverage of term "nucleoside" because nucleoside analogs treat many diseases
- Added fill-in Concept Map over nucleotide structure and function

CHAPTER 3 CELL STRUCTURE AND FUNCTION

- Added 12 Tell Me Why critical thinking questions to text
- Two new photos (Figs. 3.5b, 3.8a)
- Revised and enhanced artwork in 14 figures for enhanced pedagogy (Figs. 3.4, 3.8b, 3.9, 3.12, 3.14, 3.15, 3.17, 3.18, 3.19, 3.20, 3.21, 3.22, 3.24, 3.35)
- Added one new figure (structure of glucose versus NAG and NAM) (Fig. 3.13)
- Enhanced discussion of flagella and cilia structure and function, comparison and contrast between the outer and cytoplasmic membranes of Gram-negative cells, and movement across cell membranes

CHAPTER 4 MICROSCOPY, STAINING, AND CLASSIFICATION

- Added four Tell Me Why critical thinking questions to text
- Revised two figures for enhanced pedagogy (Figs. 4.4, 4.6)
- Revised Learning Outcome regarding simple stains, which now include Gomori methenamine silver stain and hematoxylin and eosin stains
- Added fill-in-the-blank Concept Map about Gram stain and cell wall structure to end-of-chapter review
- Revised coverage of history of taxonomy
- Expanded discussion of resolution, immersion oil, mordants, definition of microbial species, and role of George Fox in the discovery of the archaea and three domains of life
- Revised section on microbial taxonomy to more fully address genomic techniques in taxonomy
- At request of reviewers and instructors, removed detailed figures for dark field, phase, and scanning electron microscopy so as to reduce complexity and chapter length
- Added three critical thinking questions and a new photo to Emerging Disease Case Study: Necrotizing Fasciitis

CHAPTER 5 MICROBIAL METABOLISM

- Added six Tell Me Why critical thinking questions to text
- Added two new figure questions (Figs. 5.4, 5.13)
- Added one new end-of-chapter fill-in-the-blank question
- Revised 14 figures for greater clarity and better pedagogy (Figs. 5.5, 5.6, 5.10, 5.11, 5.12, 5.13, 5.14, 5.16, 5.17, 5.18, 5.19, 5.26, 5.30; end-of-chapter critical thinking question 1)
- Clarified and expanded discussion of enzymatic activation through allosteric sites and competitive and noncompetitive inhibition of enzyme activity
- Added fill-in Concept Map over aerobic respiration

CHAPTER 6 MICROBIAL NUTRITION AND GROWTH

- Added three Tell Me Why critical thinking questions to text
- Revised five figures for greater clarity and better pedagogy (Figs. 6.7, 6.8, 6.9, 6.17, 6.20)
- Added two new photos (Figs. 6.13, 6.24b)
- Expanded discussion of singlet oxygen and superoxide radicals as oxidizing agents
- Clarified the method of counting microbes using a cell counter
- Added fill-in Concept Map over culture media

CHAPTER 7 MICROBIAL GENETICS

- Added four Tell Me Why critical thinking questions to text
- Upgraded 20 figures for greater clarity, accuracy, ease of reading, and better pedagogy (Figs. 7.1, 7.5, 7.6, 7.7, 7.9, 7.10, 7.11, 7.13, 7.20, 7.21, 7.22, 7.23, 7.26, 7.27, 7.28, 7.30, 7.34, 7.35, 7.36, 7.37)
- Updated text to discuss the smallest cellular genome at 112,091 bp (candidatus *Nasuia deltocephalinicola*)
- Included recent discovery that chloroplast chromosomes are linear rather than circular
- Increased discussion of use of RNA as enzymes (ribozymes)

- Expanded table comparing and contrasting DNA replication, transcription, and translation
- Discussed codon and tRNA for 21st amino acid, selenocysteine
- Enhanced and clarified discussion of *lac* and *trp* operons and of the action of cAMP and CAP as activators
- Expanded and reorganized discussion of DNA repair systems
- Clarified and updated information on the events in conjugation, particularly with Hfr cells
- Expanded coverage of nucleotides and pyrophosphate (diphosphate)
- Added critical thinking questions to Emerging Disease Case Study: *Vibrio vulnificus* Infection
- Revised the chapter to better explain differences between archaeal, bacterial, and eukaryotic genetics
- Added fill-in Concept Map over point mutations

CHAPTER 8 RECOMBINANT DNA TECHNOLOGY

- Added five Tell Me Why critical thinking questions to text
- Added six Learning Outcomes concerning uses of synthetic nucleic acids, PCR, fluorescent *in situ* hybridization (FISH), functional genomics, Sanger sequencing, and next-generation sequencing
- Added one new figure (Fig. 8.10)
- Modified Fig. 8.7 for better pedagogy
- Deleted figures for Southern blots and Sanger automated DNA sequencing as these techniques are historical and less-commonly used today
- Added discussion of real-time PCR (RT-PCR), Sanger sequencing methods, next-generation DNA sequencing (NGS), including pyrosequencing and fluorescent methods, functional genomics, microbiomes, and biomedical animal models
- New Highlight boxes: How Do You Fix a Mosquito? on controlling dengue and The Human Microbiome Project

CHAPTER 9 CONTROLLING MICROBIAL GROWTH IN THE ENVIRONMENT

- Added four Tell Me Why critical thinking questions to text
- Revised five figures for better accuracy, currency, and pedagogy (Figs. 9.2, 9.7, 9.13, 9.15, 9.16)
- Two new photos (Fig. 9.9, Beneficial Microbes)
- Updated techniques for deactivation of prions, coverage of thimerosal in vaccines, and activity of AOAC International in developing disinfection standards
- Added three critical thinking questions to Emerging Disease Case Study: *Acanthamoeba* Keratitis
- Added critical thinking question concerning salmonellosis pandemic from smoked salmon
- Added fill-in Concept Map over moist heat applications to control microbes

CHAPTER 10 CONTROLLING MICROBIAL GROWTH IN THE BODY: ANTIMICROBIAL DRUGS

- Added four Tell Me Why critical thinking questions to text
- Updated and revised tables of antimicrobials to include all new antimicrobials mentioned in disease chapters, including carbapenems and capreomycin (antibacterials); enfuvirtide (newly approved anti-HIV-1); ciclopirox (antifungal); and bithionol (anthelmintic); updated sources of drugs, modes of action, clinical considerations, and methods of resistance
- Updated adverse effects of aminoglycosides
- Updated the mechanism of resistance against quinolone antibacterial drugs
- Removed amantadine as a treatment for influenza A
- Revised seven figures for greater clarity, accuracy, ease of reading, and better pedagogy (Figs. 10.2, 10.3, 10.6, 10.8, 10.13, 10.15; map of worldwide, community-associated MRSA)
- Three new photos (Highlight, Fig. 10.10, Clinical Case Study)
- Added three critical thinking questions to Emerging Disease Case Study: Community-Associated MRSA and updated map with newly published data

CHAPTER 11 CHARACTERIZING AND CLASSIFYING PROKARYOTES

- Added four Tell Me Why critical thinking questions to text
- Six new Learning Outcomes (for proteobacteria, including newly discovered zetaproteobacteria)
- Thirteen new photos (Figs. 11.1, 11.2a, 11.5, 11.7, 11.11a, 11.16, 11.17, 11.19, 11.21, 11.22, 11.23, 11.24b, 11.27b)
- Ten revised figures for better pedagogy (Figs. 11.1, 11.3, 11.4, 11.6, 11.10, 11.14, 11.17, 11.21, 11.26, 11.27)
- Clarified and expanded coverage of (1) "snapping division," which is a distinctive characteristic of corynebacteria, including *C. diphtheriae*, (2) floc formation and its use in sewage treatment, and (3) methicillin-resistant strains of *Staphylococcus aureus*
- Updated with new discoveries in bacterial and archaeal systematics: six classes of proteobacteria rather than four and five phyla of archaea (rather than two)
- Removed box on Botox and box on the possible link between cyanobacteria and brain disease to make room for new material
- Three new critical thinking questions over pertussis as a reemerging disease
- Added fill-in Concept Map over domain Archaea

CHAPTER 12 CHARACTERIZING AND CLASSIFYING EUKARYOTES

- Added six Tell Me Why critical thinking questions to text
- Eight new photos (Figs. 12.11, 12.12a and b, 12.13c, 12.14, 12.20, 12.25, 12.27)
- Seven revised figures for more accurate and lucid pedagogy (Figs. 12.1, 12.3, 12.7, 12.8, 12.17, 12.23; map for aspergillosis)
- As reviewers requested, shortened chapter by eliminating detailed discussion and artwork of ciliate (*Paramecium*) conjugation and of sexual reproduction by zygomycetes, ascomycetes, and basidiomycetes
- Updated algal, fungal, protozoan, water mold, and slime mold taxonomy
- Clarified and expanded coverage of (1) meiosis, (2) alveoli in protists, and (3) use of radiation as an energy source for some fungi
- Added new critical thinking questions: three about the emerging disease aspergillosis and two at end of chapter about genomics in relationship to metabolism in various environments
- Added fill-in Concept Map over eukaryotic microorganisms

CHAPTER 13 CHARACTERIZING AND CLASSIFYING VIRUSES, VIROIDS, AND PRIONS

- Added four Tell Me Why critical thinking questions to text
- Four new photos (Figs. 13.1b, 13.21, 13.24; bacteriophage box)
- Upgraded eight figures for better pedagogy and currency (Figs. 13.5, 13.8, 13.12, 13.13, 13.14, 13.16, 13.18, 13.22)
- One new figure showing prion templating (Fig. 13.23)
- Two new Learning Outcomes concerning (1) structures of viruses and (2) control of prions
- Updated viral nomenclature to correspond to changes approved by the International Committee on Taxonomy of Viruses (ICTV) in 2014

- Added discussion on the benefits and costs to a virus of having an envelope versus being naked
- Clarified and expanded text concerning lytic cycle of phage replication; use of phage typing; replication of animal viruses, particularly ssDNA viruses; link between viruses and human cancers; viroids; and prions
- Updated techniques for deactivation of prions and treatment of prion disease
- Updated Emerging Disease Case Study: Chikungunya; added three critical thinking questions to the discussion

CHAPTER 14 INFECTION, INFECTIOUS DISEASES, AND EPIDEMIOLOGY

- Added eight Tell Me Why critical thinking questions to text
- Changed eight figures for better pedagogy, timeliness, or clarity (Figs. 14.3, 14.4, 14.5, 14.9, 14.10, 14.14, 14.16, 14.20)
- Revised and updated coverage of (1) number of human cells in a body and the number of cellular microbiota, (2) microbiome, and (3) symbioses (added terms *symbiont* and *amensalism*)
- Updated to replace term *nosocomial* with *healthcare-associated* (in all chapters)
- Updated epidemiology charts, tables, and graphs
- Updated list of nationally notifiable infectious diseases
- Three new critical thinking questions added to the discussion of *Hantavirus* as an emerging disease
- Added fill-in Concept Map over transmission of diseases

CHAPTER 15 INNATE IMMUNITY

- Added two Tell Me Why critical thinking questions to text
- Modified nine figures for enhanced clarity and better pedagogy (Figs. 15.4, 15.6, 15.7, 15.8, 15.9, 15.11, 15.12, 15.13, 15.14)
- Three new photos (Figs. 15.1, 15.5b)
- Updated and expanded coverage of the action of antimicrobial peptides (defensins), Toll-like receptor 10 (TLR10), complement activation, complement cascade, and membrane attack complexes
- Expanded and clarified discussion of inflammatory mediators

CHAPTER 16 SPECIFIC DEFENSE: ADAPTIVE IMMUNITY

- Added three Tell Me Why critical thinking questions to text
- Revised and clarified (1) function and structure of tonsils, (2) flow of lymph, and (3) mucosa-associated lymphoid tissue
- Reordered the discussion of topics in adaptive immunity to better align with the way events occur; for example, MHC and antigen processing are discussed before T cells and cell-mediated immunity, which are discussed before B cells and antibody-mediated immunity
- Removed discussion of T-independent antibody immunity as it was too advanced for beginning students
- Revised three pieces of art for enhanced pedagogy (Figs. 16.2, 16.3, 16.10)
- Added three critical thinking questions and updated incidence map for the discussion of microsporidiosis
- Added fill-in Concept Map over antibodies

CHAPTER 17 IMMUNIZATION AND IMMUNE TESTING

- Added a Tell Me Why critical thinking question to text
- Updated to newly revised CDC 2015 vaccination schedule for children, adolescents, and adults
- Updated table of vaccine-preventable diseases in the United States
- Enhanced discussion of development of attenuated viral vaccines
- Added two points to chapter summary about recombinant gene technology and vaccine production and about vaccine safety
- Revised five figures for better pedagogy (Figs. 17.2, 17.3, 17.6, 17.11, 17.14)

CHAPTER 18 HYPERSENSITIVITIES, AUTOIMMUNE DISEASES, AND IMMUNE DEFICIENCIES

- Added three Tell Me Why critical thinking questions to text
- Revised one figure for greater clarity and accuracy (Fig. 18.7)
- Expanded coverage of type III hypersensitivity, the relationship between hypersensitivities and autoimmune disorders
- Removed figure and text for a very rare disease, immune thrombocytopenic purpura, to make room for new material in Chapter 19

CHAPTER 19 PATHOGENIC GRAM-POSITIVE BACTERIA

- Added nine Tell Me Why critical thinking questions to text
- Added three Disease in Depth visual presentations of disease: necrotizing fasciitis, listeriosis, and tuberculosis
- Twenty-five new photos (Figs. 19.1, 19.12, 19.17, 19.19, 19.20, 19.21)
- Seven revisions to figures for consistency, currency, accuracy, and better pedagogy (Figs. 19.5, 19.23; Disease in Depth: Necrottizing Fasciitis, Listeriosis, and Tuberculosis; Microbe at a Glance: *Streptococcus* and *Clostridium*)
- Updated all diagnoses and incidence data
- Revised two Learning Outcomes for better pedagogy (19.10, 19.13)
- Revised Chapter Summary for better pedagogy (for *Staphylococcus*; *Streptococcus*; *Enterococcus*, *Bacillus*; *Clostridium*; *Listeria*; *Mycoplasma*; *Corynebacterium*; *Mycobacterium*)
- Updated definitions for multi-drug-resistant (MDR) and extensively drug-resistant (XDR) tuberculosis
- Updated treatment regimen for inhalation anthrax, bioterrorist anthrax, botulism, tetanus, listeriosis, mycoplasmal pneumonia, nongonococcal urethritis, and tuberculosis
- Updated and enhanced discussion of mycolic acids, role of *Streptococcus mutans* in tooth decay, and anthrax vaccine
- Added a figure question regarding snapping division in corynebacteria
- Added three critical thinking questions and updated incidence maps for the discussion of Buruli ulcer
- Added Clinical Case Study regarding tuberculosis

CHAPTER 20 PATHOGENIC GRAM-NEGATIVE COCCI AND BACILLI

- Added three Tell Me Why critical thinking questions to text
- Added one Disease in Depth visual presentation of disease on urinary tract infections
- Updated all diagnoses and incidence data, including maps
- Updated to replace term *nosocomial* with *healthcare-associated*
- Revised Chapter Summary for better pedagogy (Pathogenic, Gram-Negative, Facultatively Anaerobic Bacilli; Pathogenic, Gram-Negative, Aerobic Bacilli; Pathogenic, Gram-Negative, Anaerobic Bacilli)
- Updated treatment regimen for gonorrhea, meningococcus meningitis, bubonic plague, bartonellosis, brucellosis, and Legionnaires' disease
- Added one new figure (Fig. 20.1) and figure question on the potential effects of lipid A
- Revised nine figures for better pedagogy (Microbe at a Glance: *Neisseria gonorrhoeae;* Figs. 20.2, 20.3, 20.14, 20.18, 20.19, 20.22, 20.23, 20.28)
- Added three critical thinking questions and updated incidence maps for the discussion of melioidosis

CHAPTER 21 RICKETTSIAS, CHLAMYDIAS, SPIROCHETES, AND VIBRIOS

- Added three Tell Me Why critical thinking questions to text
- New Disease in Depth: Spotted Fever Rickettsiosis
- Updated all diagnoses and incidence data
- Modified/updated nine figures (Figs. 21.1, 21.2, 21.3, 21.5, 21.8, 21.12, 21.13, 21.17, 21.20)
- Two new photos (Figs. 21.11, 21.19)
- Updated treatment regimen for rickettsial spotted fever (Rocky Mountain spotted fever, RMSF), murine typhus, scrub typhus, human monocytic ehrlichiosis, anaplasmosis (formerly called human granulocytic ehrlichiosis), lymphogranuloma venereum, trachoma, cholera, and gastric ulcers
- Updated and expanded coverage of epidemic typhus, murine typhus, scrub typhus, spotted fever rickettsioses (RMSF), ehrlichiosis, anaplasmosis, lymphogranuloma venereum, urethritis, yaws, *Borrelia*, and cholera

CHAPTER 22 PATHOGENIC FUNGI

- Added five Tell Me Why critical thinking questions to text
- Added new Disease in Depth: Candidiasis
- Updated all diagnoses and incidence data
- New Learning Outcomes: antifungal vaccines, mycetomas
- Added one new photo for enhanced pedagogy (Fig. 22.19)
- Updated treatment regimen for paracoccidioidomycosis, *Pneumocystis* pneumonia, candidiasis, aspergillosis, *Malassezia* infections, mycetoma, and sporotrichosis
- Enhanced discussion of dearth of antifungal vaccines
- Added three critical thinking questions and updated incidence maps for the discussion of blastomycosis
- Added fill-in Concept Map over systemic mycoses

CHAPTER 23 PARASITIC PROTOZOA, HELMINTHS, AND ARTHROPOD VECTORS

- Added four Tell Me Why critical thinking questions to text
- Added two new Disease in Depth spreads: Giardiasis and Malaria
- Rearranged the chapter to cover vectors first; expanded coverage of vectors
- New Learning Outcomes: parasitology, definitive versus intermediate hosts, biological versus mechanical vectors, ascariasis, hookworm infestations, pinworms, anisakiasis
- Updated all diagnoses and incidence data
- Updated treatment regimen for *Acanthamoeba* keratitis, leishmaniasis, trichomoniasis, malaria, *Cryptosporidium* enteritis, and infestation with *Fasciola*
- Added mention of emerging human pathogen of malaria: *Plasmodium knowlesi*
- Updated stages in life cycle of *Toxoplasma*
- Simplified discussion of life cycles of *Trypanosoma cruzi* and of *T. brucei*
- Added roundworm *Anisakis* and its disease anisakiasis at teachers' requests
- Twenty-four new, more engaging photos (Figs. 23.2, 23.10, 23.12, 23.13, 23.18; Disease in Depth: Giardiasis; Disease in Depth: Malaria; Emerging Disease Case Study: Babesiosis)
- Eight revised, updated, enhanced, and pedagogically more effective figures (Figs. 23.1, 23.3, 23.5, 23.6, 23.9, 23.14, 23.17, 23.24)
- Added three critical thinking questions and updated incidence maps for the discussions of babesiosis and of schistosomiasis
- Added fill-in Concept Map over intestinal protozoan parasites

CHAPTER 24 PATHOGENIC DNA VIRUSES

- Added five Tell Me Why critical thinking questions to text
- Updated all diagnoses and incidence data
- Updated treatment regimen for shingles, history of smallpox vaccination, and the effect of adenovirus 36 on obesity
- Four new photos (Figs. 24.3, 24.15, 24.16c, 24.22)
- Reformatted one figure for better pedagogy (Fig. 24.21)
- Added three critical thinking questions and updated incidence maps for the discussion of monkeypox
- New Disease in Depth: Papillomas with three new photos and three new figures

CHAPTER 25 PATHOGENIC RNA VIRUSES

- Added six Tell Me Why critical thinking questions to text
- Updated all diagnoses and incidence data
- Updated treatment regimen for colds, hepatitis E, hepatitis C, AIDS, measles, respiratory syncytial virus infection, and Lassa hemorrhagic fever
- Updated, revised, and expanded discussion of coronavirus respiratory syndromes, Nipah virus encephalitis, hepatitis E virus, and respiratory syncytial viral disease
- Clarified definition of zoonosis
- Added Learning Outcome about mumps
- Sixteen figures revised, updated, or enhanced for better pedagogy (Figs. 25.2, 25.9, 25.10, 25.11, 25.12, 25.14, 25.17, 25.18, 25.19, 25.21, 25.23, 25.24, 25.26, 25.28, 25.29, 25.36)
- Thirteen new photos (chapter opener; Figs. 25.1, 25.7, 25.16b, 25.22b, 25.27, 25.30, 25.32; Highlight box on bats and Nipah virus)
- New Microbe at a Glance box on measles virus
- Two new Emerging Disease Case Study boxes on norovirus gastroenteritis and tick-borne encephalitis
- Two new Disease in Depth features on Ebola hemorrhagic fever and influenza
- Added three critical thinking questions to the box on influenza H1N1

CHAPTER 26 INDUSTRIAL AND ENVIRONMENTAL MICROBIOLOGY

- Added four Tell Me Why critical thinking questions to text
- Added Learning Outcome on eutrophication
- Three figures revised, updated, or enhanced for better pedagogy (Figs. 26.6, 26.8, 26.15)
- Revised and clarified water contamination and water pollution
- Updated list of bioterrorist threats to include the additions to category C
- New Emerging Disease Case Study regarding primary amebic meningoencephalitis (*Naegleria fowleri* infection)

Reviewers for the **Fifth Edition**

I wish to thank the hundreds of instructors and students who participated in reviews, class tests, and focus groups for earlier editions of the textbook. Your comments have informed this book from beginning to end, and I am deeply grateful. For the fifth edition, I extend my deepest appreciation to the following reviewers.

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Amarillo, Texas

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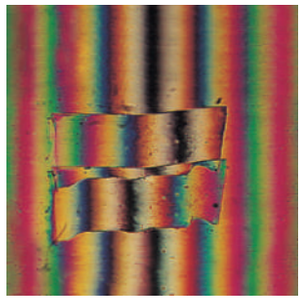
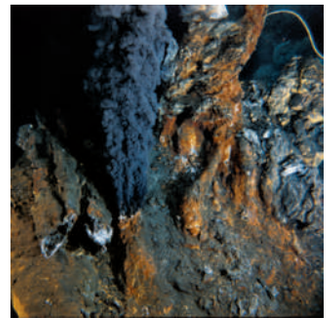
Table of Contents





7

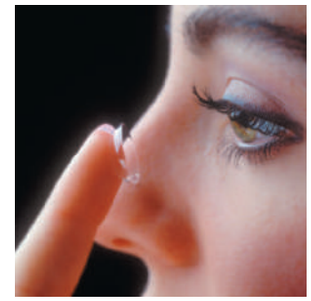
Microbial Genetics 220

8

Recombinant DNA Technology 265

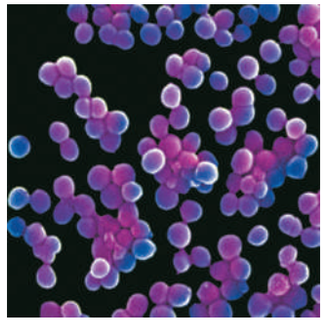
9

Controlling Microbial Growth in the Environment 288



10

Controlling Microbial Growth in the Body: Antimicrobial Drugs 313



11

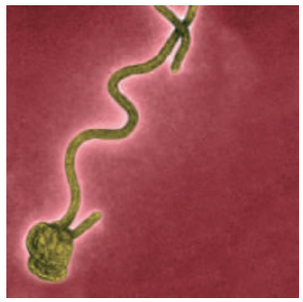
Characterizing and Classifying Prokaryotes 347

12

Characterizing and Classifying Eukaryotes 376

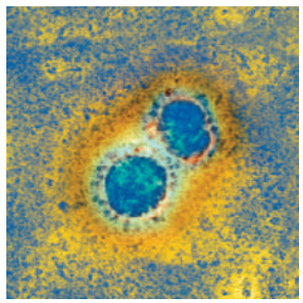
13

Characterizing and Classifying Viruses, Viroids, and Prions 407



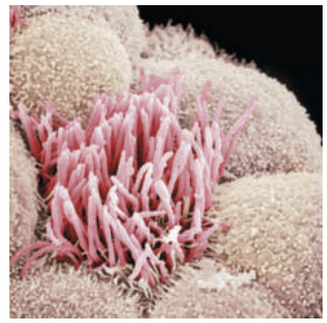
14

Infection, Infectious Diseases, and Epidemiology 435



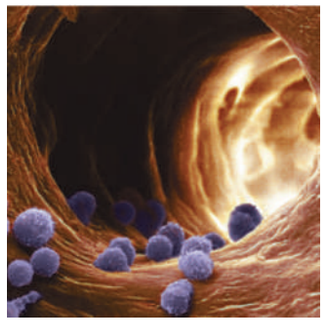
15

Innate Immunity 469



16

Adaptive Immunity 494



17

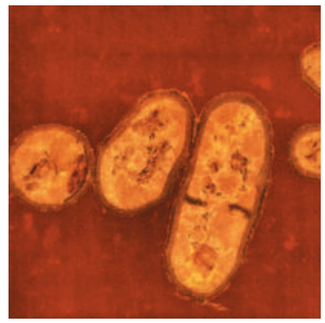
Immunization and Immune Testing 525

18

Immune Disorders 547

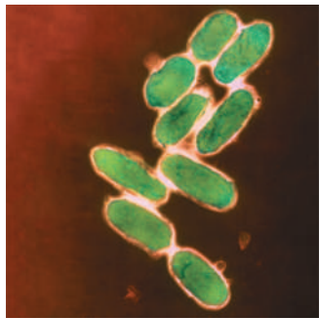
19

Pathogenic Gram-Positive Bacteria 568



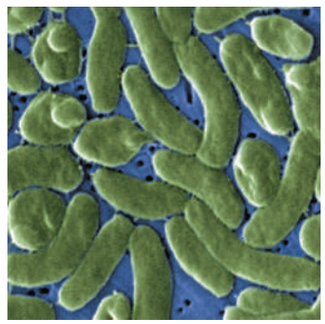
20

Pathogenic Gram-Negative Cocci and Bacilli 608



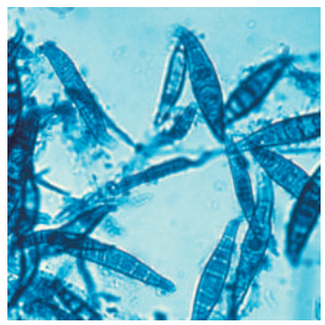
21

Rickettsias, Chlamydias, Spirochetes, and Vibrios 641



22

Pathogenic Fungi 668

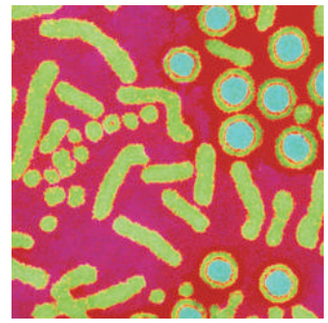


23

Parasitic Protozoa, Helminths, and Arthropod Vectors 696

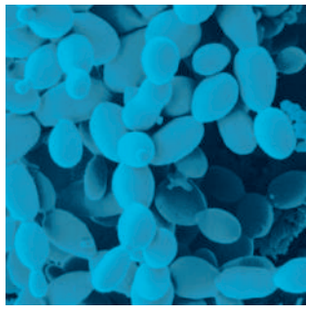
24

Pathogenic DNA Viruses 730



25

Pathogenic RNA Viruses 755



Feature Boxes

BENEFICIAL MICROBES

HIGHLIGHT

EMERGING DISEASE CASE STUDY

CLINICAL CASE STUDY

MICROBE AT A GLANCE

DISEASE IN DEPTH

1

A Brief History of Microbiology

Aquatic microorganisms, such as these, thrilled early microscopists with their beauty and antics.

LIFE AS WE KNOW IT WOULD NOT EXIST without microorganisms. Plants depend on microorganisms to help them obtain the nitrogen they need for survival. Animals such as cows and sheep need microbes in order to digest the carbohydrates in their plant-based diets. Ecosystems rely on microorganisms to enrich soil, degrade wastes, and support life. We use microorganisms to make wine and cheese and to develop vaccines and antibiotics. Through recombinant DNA technology (genetic engineering), we are now able to harness the power of these small microbes to do big jobs like mass producing important pharmaceuticals such as blood-clotting factor VIII and insulin for patients who desperately need them.

The human body is home to trillions of microorganisms, many of which help keep us healthy. Microorganisms are an essential part of our lives. Of course, some microorganisms do cause harm to us, from the common cold to more serious diseases such as tuberculosis, malaria, and AIDS. The threats of bioterrorism and new or re-emerging infectious diseases are real.

This textbook explores the roles—both beneficial and harmful—that microorganisms play in our lives, as well as their sophisticated structures and processes. This chapter will explore not only the history of microbiology, but how new discoveries have led to a number of new disciplines within the field of microbiology. We begin with the invention of crude microscopes that revealed, for the first time, the existence of this miraculous, miniature world.

Science is the study of nature that proceeds by posing questions about observations. Why are there seasons? What is the function of the nodules at the base of this plant? Why does this bread taste sour? What does plaque from between teeth look like when magnified? What causes the spread of diseases?

Many early written records show that people have always asked questions like these. For example, the Greek physician Hippocrates (ca. 460–ca. 377 B.C.) wondered whether there is a link between environment and disease, and the Greek historian Thucydides (ca. 460–ca. 404 B.C.) questioned why he and other survivors of the plague could have close contact with victims and not fall ill again. For many centuries, the answers to these and other fundamental questions about the nature of life remained largely unanswered. But about 350 years ago, the invention of the microscope began to provide some clues.

In this chapter, we'll see how one man's determination to answer a fundamental question about the nature of life—What does life really look like?—led to the birth of a new science called *microbiology*. We'll then see how the search for answers to other questions, such as those concerning spontaneous generation, the reason fermentation occurs, and the cause of disease, prompted advances in this new science. Finally, we'll look briefly at some of the key questions microbiologists are asking today.

The Early Years of Microbiology

The early years of microbiology brought the first observations of microbial life and the initial efforts to organize them into logical classifications.

What Does Life Really Look Like?

LEARNING OUTCOMES

1.1 Describe the world-changing scientific contributions of Leeuwenhoek.
1.2 Define microbes in the words of Leeuwenhoek and as we know them today.

A few people have changed the world of science forever. We've all heard of Galileo, Newton, and Einstein, but the list also includes Antoni van Leeuwenhoek (lā´vĕn-huk; 1632–1723), a Dutch tailor, merchant, and lens grinder, and the man who first discovered the bacterial world **(FIGURE 1.1)**.

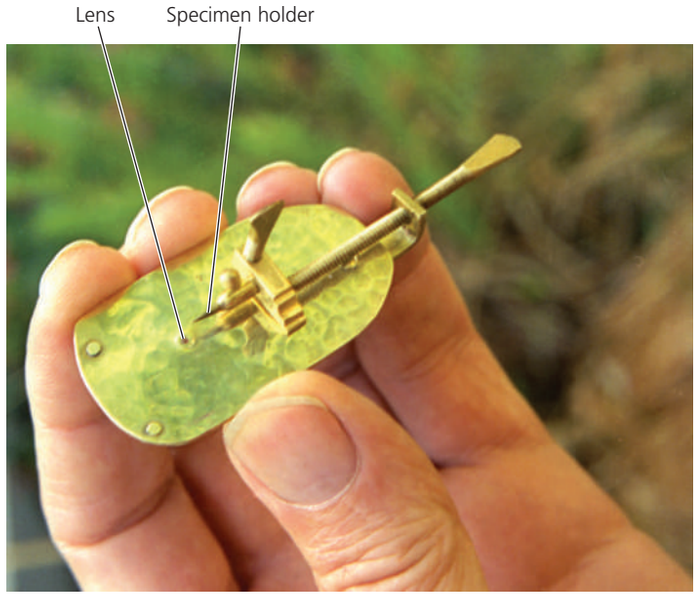
Leeuwenhoek was born in Delft, the Netherlands, and lived most of his 90 years in the city of his birth. What set Leeuwenhoek apart from many other men of his generation was an insatiable curiosity coupled with an almost stubborn desire to do everything for himself. His journey to fame began simply enough, when as a cloth merchant he needed to examine the quality of cloth. Rather than merely buying a magnifying lens, he learned to make glass lenses of his own **(FIGURE 1.2)**. Soon he began asking, "What does it really look like?" of everything in his world: the stinger of a bee, the brain of a fly, the leg of a louse, a drop of blood, flakes of his own skin. To find answers,

▲ **FIGURE 1.1 Antoni van Leeuwenhoek.** Leeuwenhoek reported the existence of protozoa in 1674 and of bacteria in 1676. *Why did Leeuwenhoek discover protozoa before bacteria?*

Figure 1.1 *Protozoa are generally larger than bacteria.*

he spent hours examining, reexamining, and recording every detail of each object he observed.

Making and looking through his simple microscopes, really no more than magnifying glasses, became the overwhelming passion of his life. His enthusiasm and dedication are evident from the fact that he sometimes personally extracted the metal



▲ **FIGURE 1.2 Reproduction of Leeuwenhoek's microscope.** This simple device is little more than a magnifying glass with screws for manipulating the specimen, yet with it, Leeuwenhoek changed the way we see our world. The lens, which is convex on both sides, is about the size of a pinhead. The object to be viewed was mounted either directly on the specimen holder or inside a small glass tube, which was then mounted on the specimen holder.

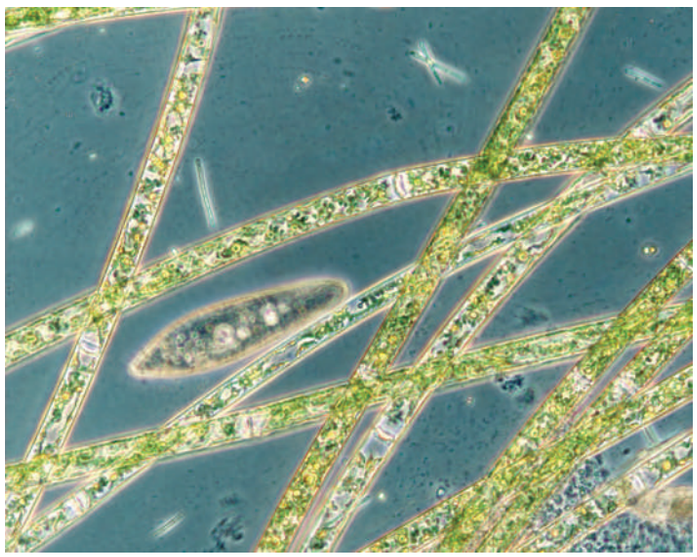
for a microscope from ore. Further, he often made a new microscope for each specimen, which remained mounted so that he could view it again and again. Then one day, he turned a lens onto a drop of water. We don't know what he expected to see, but certainly he saw more than he had anticipated. As he reported to the Royal Society of London[1] in 1674, he was surprised and delighted by

> some green streaks, spirally wound serpent-wise, and orderly arranged. . . . Among these there were, besides, very many little animalcules, some were round, while others a bit bigger consisted of an oval. On these last, I saw two little legs near the head, and two little fins at the hind most end of the body. . . . And the motion of most of these animalcules in the water was so swift, and so various, upwards, downwards, and round about, that 'twas wonderful to see.[2]

Leeuwenhoek had discovered the previously unknown microbial world, which today we know to be populated with tiny animals, fungi, algae, and single-celled protozoa **(FIGURE 1.3)**. In a later report to the Royal Society, he noted that

> the number of these animals in the plaque of a man's teeth, are so many that I believe they exceed the number of men in a kingdom. . . . in a quantity of matter no bigger than the 1/100 part of a [grain of] sand.

From the figure accompanying his report and the precise description of the size of these organisms from between his teeth, we know that Leeuwenhoek was reporting the existence of bacteria. By the end of the 19th century, Leeuwenhoek's "beasties," as he sometimes dubbed them, were called **microorganisms,** and today we also know them as **microbes.**



▲ **FIGURE 1.3 The microbial world.** Leeuwenhoek reported seeing a scene very much like this, full of numerous fantastic, cavorting creatures.

[1]The Royal Society of London for the Promotion of Natural Knowledge, granted a royal charter in 1662, is one of the older and more prestigious scientific groups in Europe.
[2]Antony von Leeuwenhoek, in a letter to the Royal Society of London for the Promotion of Natural Knowledge.

Both terms include all organisms that are too small to be seen without a microscope.

Because of the quality of his microscopes, his profound observational skills, his detailed reports over a 50-year period, and his report of the discovery of many types of microorganisms, Antoni van Leeuwenhoek was elected to the Royal Society in 1680. He was one of the more famous scientists of his time.

How Can Microbes Be Classified?

LEARNING OUTCOMES

1.3 List six groups of microorganisms.
1.4 Explain why protozoa, algae, and nonmicrobial parasitic worms are studied in microbiology.
1.5 Differentiate prokaryotic from eukaryotic organisms.

Shortly after Leeuwenhoek made his discoveries, the Swedish botanist Carolus Linnaeus (1707–1778) developed a **taxonomic system**—a system for naming plants and animals and grouping similar organisms together. For instance, Linnaeus and other scientists of the period grouped all organisms into either the animal kingdom or the plant kingdom. Today, biologists still use this basic system, but they have modified Linnaeus's scheme by adding categories that more realistically reflect the relationships among organisms. For example, scientists no longer classify yeasts, molds, and mushrooms as plants but instead as fungi. (We examine taxonomic schemes in more detail in Chapter 4.)

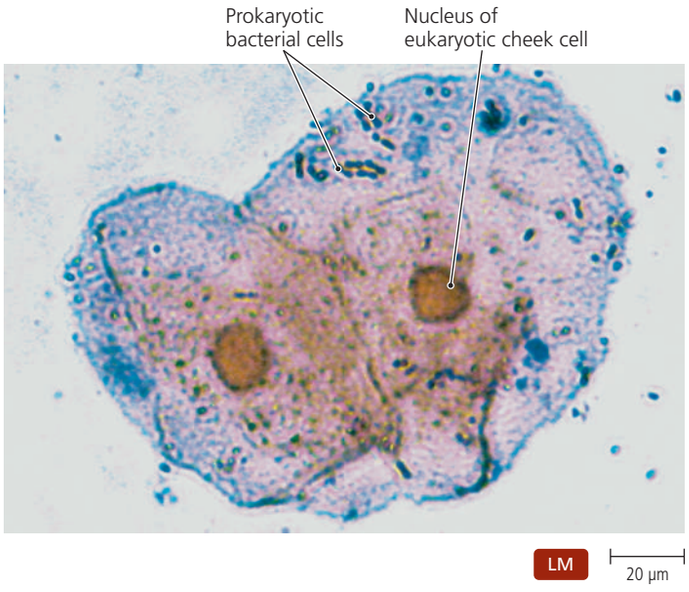
The microorganisms that Leeuwenhoek described can be grouped into six basic categories: bacteria, archaea, fungi, protozoa, algae, and small multicellular animals. The only types of microbes not described by Leeuwenhoek are *viruses*,[3] which are too small to be seen without an electron microscope. We briefly consider organisms in the first five categories in the following sections.

Bacteria and Archaea

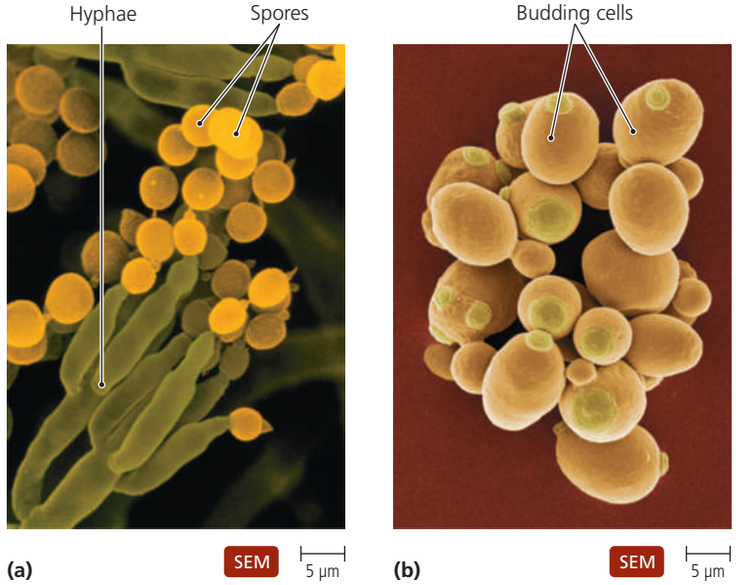
Bacteria and **archaea** are **prokaryotic,**[4] meaning that their cells lack nuclei; that is, their genes are not surrounded by a membrane. Bacterial cell walls are composed of a polysaccharide called *peptidoglycan,* though some bacteria lack cell walls. The cell walls of archaea lack peptidoglycan and instead are composed of other chemicals. Members of both groups reproduce asexually. (Chapters 3, 4, and 11 examine other differences between bacteria and archaea, and Chapters 19–21 discuss pathogenic [disease-causing] bacteria.)

Most archaea and bacteria are much smaller than eukaryotic cells **(FIGURE 1.4)**. They live singly or in pairs, chains, or clusters in almost every habitat containing sufficient moisture. Archaea are often found in extreme environments, such as the highly saline and arsenic-rich Mono Lake in California, acidic

[3]Technically, viruses are not "organisms," because they neither replicate themselves nor carry on the chemical reactions of living things.
[4]From Greek *pro,* meaning "before," and *karyon,* meaning "kernel" (which, in this case, refers to the nucleus of a cell).



▲ **FIGURE 1.4 Cells of the bacterium *Streptococcus* (dark blue) and two human cheek cells.** Notice the size difference.



▲ **FIGURE 1.5 Fungi. (a)** The mold *Penicillium chrysogenum*, which produces penicillin, has long filamentous hyphae that intertwine to form its body. It reproduces by spores. **(b)** The yeast *Saccharomyces cerevisiae*. Yeasts are round to oval and typically reproduce by budding.

hot springs in Yellowstone National Park, and oxygen-depleted mud at the bottom of swamps. No archaea are known to cause disease.

Though bacteria may have a poor reputation in our world, the great majority do not cause disease in animals, humans, or crops. Indeed, bacteria are beneficial to us in many ways. For example, without beneficial bacteria, our bodies would be much more susceptible to disease. Also, bacteria (and fungi) degrade dead plants and animals to release phosphorus, sulfur, nitrogen, and carbon back into the air, soil, and water to be used by new generations of organisms. Without microbial recyclers, the world would be buried under the corpses of uncountable dead organisms.

Fungi

Fungi (fŭn´jī)[5] are **eukaryotic;**[6] that is, each of their cells contains a nucleus composed of genetic material surrounded by a distinct membrane. Fungi are different from plants because fungi obtain their food from other organisms (rather than making it for themselves). They differ from animals by having cell walls.

Microscopic fungi include some molds and yeasts. **Molds** are typically multicellular organisms that grow as long filaments that intertwine to make up the body of the mold. Molds reproduce by sexual and asexual spores, which are cells that produce a new individual without fusing with another cell **(FIGURE 1.5a)**. The cottony growths on cheese, bread, and jams are molds. *Penicillium chrysogenum* (pen-i-sil´ē-ŭm krī-so´jĕn-ŭm) is a mold that produces penicillin.

Yeasts are unicellular and typically oval to round. They reproduce asexually by *budding*, a process in which a daughter cell grows off the mother cell. Some yeasts also produce sexual spores. An example of a useful yeast is *Saccharomyces cerevisiae* (sak-ă-rō-mī´sēz se-ri-vis´ē-ī; **FIGURE 1.5b**), which causes bread to rise and produces alcohol from sugar (see **Beneficial Microbes: Bread, Wine, and Beer** on p. 37). Another example of a yeast is *Candida albicans* (kan´did-ă al´bi-kanz), which causes most cases of yeast infections in women. (Chapters 12, 22, and 26 discuss fungi and their significance in the environment, in food production, and as agents of human disease.)

Protozoa

Protozoa are single-celled eukaryotes that are similar to animals in their nutritional needs and cellular structure. In fact, *protozoa* is Greek for "first animals," though scientists today classify them in their own groups rather than as animals. Most protozoa are capable of locomotion, and one way scientists categorize protozoa is according to their locomotive structures: *pseudopods*,[7] *cilia*,[8] or *flagella*.[9] Pseudopods are extensions of a cell that flow in the direction of travel **(FIGURE 1.6a)**. Cilia are numerous short protrusions of a cell that beat rhythmically to propel the protozoan through its environment **(FIGURE 1.6b)**. Flagella are also extensions of a cell but are fewer, longer, and more whiplike than cilia **(FIGURE 1.6c)**. Some protozoa, such as the malaria-causing *Plasmodium* (plazmō´dē-ŭm), are nonmotile in their mature forms.

Many protozoa live freely in water, but some live inside animal hosts, where they can cause disease. Most protozoa reproduce asexually, though some are sexual as well. (Chapters 12 and 23 further examine protozoa and some diseases they cause.)

[5]Plural of the Latin *fungus*, meaning "mushroom."
[6]From Greek *eu*, meaning "true," and *karyon*, meaning "kernel."
[7]Plural Greek *pseudes*, meaning "false," and *podos*, meaning "foot."
[8]Plural of the Latin *cilium*, meaning "eyelid."
[9]Plural of the Latin *flagellum*, meaning "whip."

▶ **FIGURE 1.6 Locomotive structures of protozoa.** **(a)** Pseudopods are cellular extensions used for locomotion and feeding, as seen in *Amoeba proteus*. **(b)** *Blepharisma americana* moves by means of cilia. **(c)** Flagella are whiplike extensions that are less numerous and longer than cilia, as seen in *Peranema*. *How do cilia and flagella differ?*

FIGURE 1.6 *Cilia are short, numerous, and often cover the cell, whereas flagella are long and relatively few in number.*

Algae

Algae[10] are unicellular or multicellular *photosynthetic* eukaryotes; that is, like plants, they make their own food from carbon dioxide and water using energy from sunlight. They differ from plants in the relative simplicity of their reproductive structures. Algae are categorized on the basis of their pigmentation and the composition of their cell walls.

Large algae, commonly called seaweeds and kelps, are common in the world's oceans. Manufacturers use gelatinous chemicals from the cell walls of some large algae as thickeners and emulsifiers in many foods and cosmetics. Scientists use the algae-derived chemical called *agar* to solidify laboratory media.

Unicellular algae **(FIGURE 1.7)** are common in freshwater ponds, streams, and lakes and in the oceans as well. They are the major food of small aquatic and marine animals and provide most of the world's oxygen as a by-product of photosynthesis. The glasslike cell walls of diatoms provide grit for many polishing compounds. (Chapter 12 discusses other aspects of the biology of algae.)

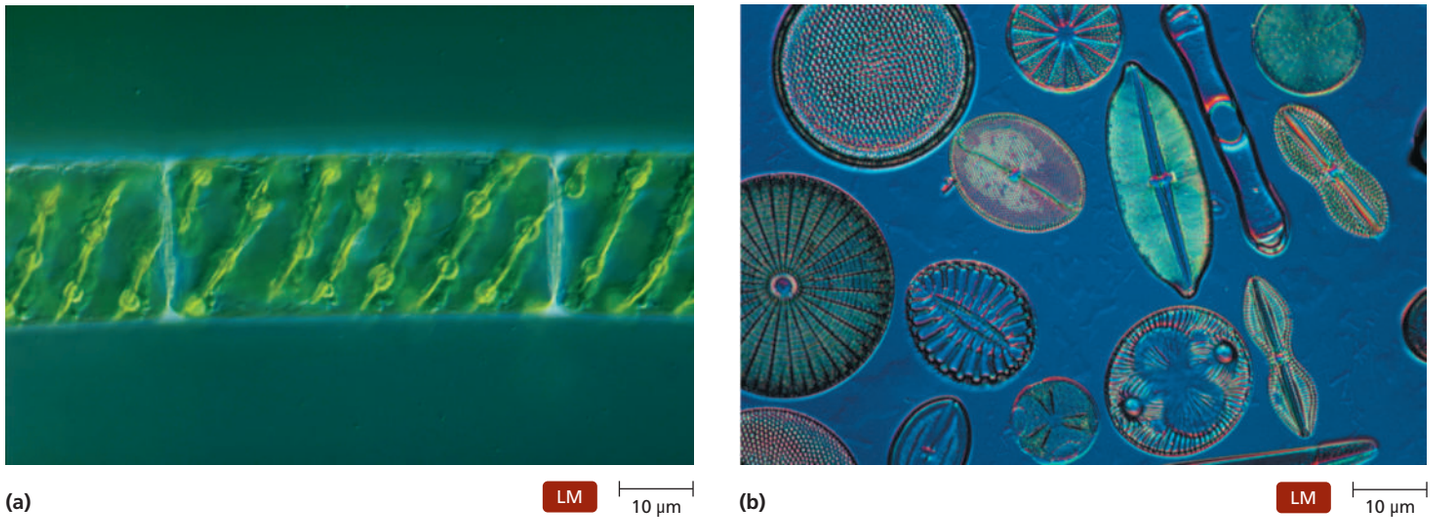
Other Organisms of Importance to Microbiologists

Microbiologists also study parasitic worms, which range in size from microscopic forms **(FIGURE 1.8)** to adult tapeworms over 10 meters (approximately 33 feet) in length. Even though most parasitic worms are not microscopic as adults, many of them cause diseases that were studied by early microbiologists, so microbiology books and classes often discuss parasitic worms. Further, laboratory scientists diagnose infections of parasitic worms by finding microscopic eggs and immature stages in blood, fecal, urine, and lymph specimens. (Chapter 23 discusses parasitic worms.)

The only type of microbe that remained hidden from Leeuwenhoek and other early microbiologists was the virus, which is typically much smaller than the smallest prokaryote and is not usually visible by light microscopy **(FIGURE 1.9)**. Viruses were not seen until the electron microscope was invented in 1932. All viruses are acellular (not composed of cells) obligatory parasites composed of small amounts of genetic material (either DNA or RNA) surrounded by a protein coat. (Chapter 13 examines the general characteristics of viruses, and Chapters 24 and 25 discuss specific viral pathogens.)

Leeuwenhoek first reported the existence of most types of microorganisms in the late 1600s, but microbiology did not

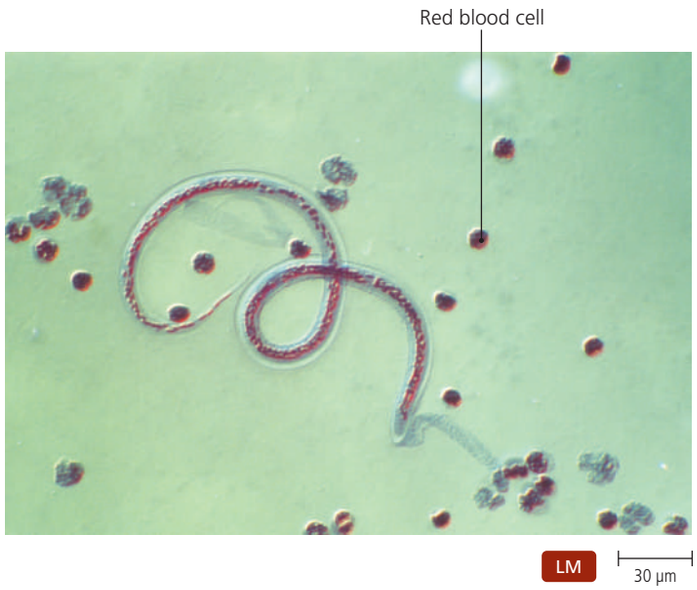
[10]Plural of the Latin *alga*, meaning "seaweed."



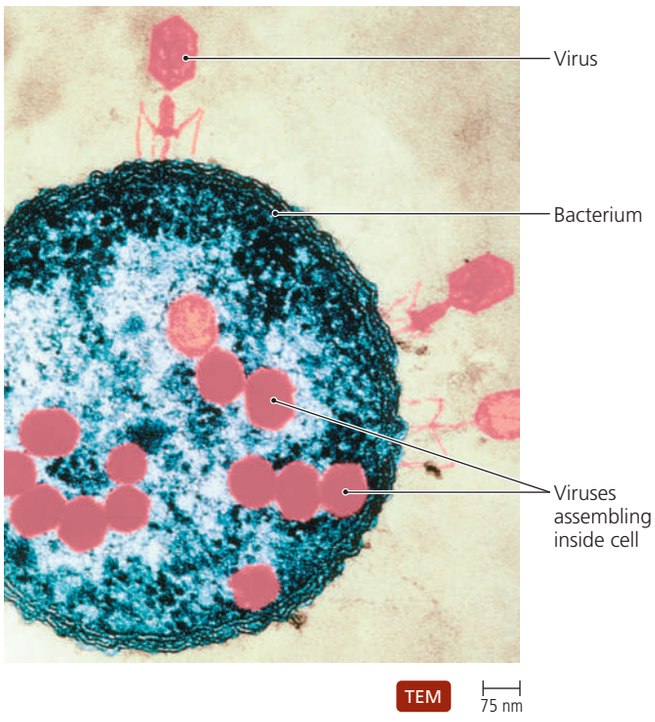
▲ **FIGURE 1.7 Algae. (a)** *Spirogyra.* These microscopic algae grow as chains of cells containing helical photosynthetic structures. **(b)** Diatoms. These beautiful algae have glasslike cell walls.

develop significantly as a field of study for almost two centuries. There were a number of reasons for this delay. First, Leeuwenhoek was a suspicious and secretive man. Though he built over 400 microscopes, he never trained an apprentice, and he never sold or gave away a microscope. In fact, he never let *anyone*—not his family or such distinguished visitors as the czar of Russia—so much as peek through his very best instruments. When Leeuwenhoek died, the secret of creating superior microscopes was lost. It took almost 100 years for scientists to make microscopes of equivalent quality.

Another reason that microbiology was slow to develop as a science is that scientists in the 1700s considered microbes to be curiosities of nature and insignificant to human affairs. But in the late 1800s, scientists began to adopt a new philosophy, one that demanded experimental evidence rather than mere acceptance of traditional knowledge. This fresh philosophical foundation, accompanied by improved microscopes, new laboratory techniques, and a drive to answer a series of pivotal questions, propelled microbiology to the forefront as a scientific discipline.



▲ **FIGURE 1.8 An immature stage of a parasitic worm in blood.**



▲ **FIGURE 1.9 A colorized electron microscope image of viruses infecting a bacterium.** Viruses, which are acellular obligatory parasites, are generally too small to be seen with a light microscope. Notice how small the viruses are compared to the bacterium.

TELL ME WHY

Some people consider Leeuwenhoek the "Father of Microbiology." Explain why this moniker makes sense.

The Golden Age of Microbiology

LEARNING OUTCOME

1.6 List and answer four questions that propelled research in what is called the "Golden Age of Microbiology."

For about 50 years, during what is sometimes called the "Golden Age of Microbiology," scientists and the blossoming field of microbiology were driven by the search for answers to the following four questions:

- Is spontaneous generation of microbial life possible?
- What causes fermentation?
- What causes disease?
- How can we prevent infection and disease?

Competition among scientists who were striving to be the first to answer these questions drove exploration and discovery in microbiology during the late 1800s and early 1900s. These scientists' discoveries and the fields of study they initiated continue to shape the course of microbiological research today.

In the next sections, we consider these questions and how the great scientists accumulated the experimental evidence that answered them.

Does Microbial Life Spontaneously Generate?

LEARNING OUTCOMES

1.7 Identify the scientists who argued in favor of spontaneous generation.
1.8 Compare and contrast the investigations of Redi, Needham, Spallanzani, and Pasteur concerning spontaneous generation.
1.9 List four steps in the scientific method of investigation.

A dry lake bed has lain under the relentless North African desert sun for eight long months. The cracks in the baked, parched mud are wider than a man's hand. There is no sign of life anywhere in the scorched terrain. With the abruptness characteristic of desert storms, rain falls in a torrent, and a raging flood of roiling water and mud crashes down the dry streambed and fills the lake. Within hours, what had been a lifeless, dry mudflat becomes a pool of water teeming with billions of shrimp; by the next day it is home to hundreds of toads. Where did these animals come from?

Many philosophers and scientists of past ages thought that living things arose via three processes: through asexual

BENEFICIAL MICROBES

Bread, Wine, and Beer

Microorganisms play important roles in people's lives; for example, pathogens have undeniably altered the course of history. However, what may be the most important microbiological event—one that has had a greater impact on culture and society than that of any disease or epidemic—was the domestication of the yeast used by bakers and brewers. Its scientific name, *Saccharomyces cerevisiae*, translates from Latin as "sugar fungus [that makes] beer."

The earliest record of the use of yeast comes from Persia (modern Iran), where archaeologists have found the remains of grapes and wine preservatives in pottery vessels more than 7000 years old. Brewing of beer likely started even earlier, its beginnings undocumented. The earliest examples of leavened bread are from Egypt and show that bread making was routine about 6000 years ago. Before that time, bread was unleavened and flat.

It is likely that making wine and brewing beer occurred earlier than the use of leavened bread because *Saccharomyces* is naturally found on grapes, which can begin to ferment while still on the vine. Historians hypothesize that early bakers may have exposed bread dough to circulating air, hoping that the invisible and inexplicable "fermentation principle" would inoculate the bread. Another hypothesis is that bakers learned to add small amounts of beer or wine to the bread, intentionally inoculating the dough with yeast. Of course, all those years before Leeuwenhoek and Pasteur, no one knew that the fermenting ingredient of wine was a living organism.

Besides its role in baking and in making alcoholic beverages, *S. cerevisiae* is an important tool for the study of cells. Scientists use yeast to delve into the mysteries of cellular function, organization, and genetics, making *Saccharomyces* the most intensely studied eukaryote. In fact, molecular biologists published the complete sequence of the genes of *S. cerevisiae* in 1996—the first complete sequence published for any eukaryotic cell.

Today, scientists are working toward using *S. cerevisiae* in novel ways. For example, some nutritionists and gastroenterologists are examining the use of *Saccharomyces* as a *probiotic*, that is, a microorganism intentionally taken to ward off disease and promote good health. Research suggests that the yeast helps treat diarrhea and colitis and may even help prevent these and other gastrointestinal diseases.

reproduction, through sexual reproduction, or from nonliving matter. The appearance of shrimp and toads in the mud of what so recently was a dry lake bed was seen as an example of the third process, which came to be known as *abiogenesis*,[11] or **spontaneous generation.** The theory of spontaneous generation as promulgated by Aristotle (384–322 B.C.) was widely accepted for over 2000 years because it seemed to explain a variety of commonly observed phenomena, such as the appearance of maggots on spoiling meat. However, the validity of the theory came under challenge in the 17th century.

Redi's Experiments

In the late 1600s, the Italian physician Francesco Redi (1626–1697) demonstrated by a series of experiments that when decaying meat was kept isolated from flies, maggots never developed, whereas meat exposed to flies was soon infested with maggots **(FIGURE 1.10)**. As a result of experiments such as these, scientists began to doubt Aristotle's theory and adopt the view that animals come only from other animals.

Needham's Experiments

The debate over spontaneous generation was rekindled when Leeuwenhoek discovered microbes and showed that they appeared after a few days in freshly collected rainwater. Though scientists agreed that larger animals could not arise spontaneously, they disagreed about Leeuwenhoek's "wee animalcules"; surely they did not have parents, did they? They must arise spontaneously.

▲ **FIGURE 1.10 Redi's experiments.** When the flask remained unsealed, maggots covered the meat within a few days. When the flask was sealed, flies were kept away, and no maggots appeared on the meat. When the flask opening was covered with gauze, flies were kept away, and no maggots appeared on the meat, although a few maggots appeared on top of the gauze.

The proponents of spontaneous generation pointed to the careful demonstrations of British investigator John T. Needham (1713–1781). He boiled beef gravy and infusions[12] of plant material in vials, which he then tightly sealed with corks. Some days later, Needham observed that the vials were cloudy, and examination revealed an abundance of "microscopical animals of most dimensions." As he explained it, there must be a "life force" that causes inanimate matter to spontaneously come to

[11]From Greek *a,* meaning "not"; *bios,* meaning "life"; and *genein,* meaning "to produce."

[12]Infusions are broths made by heating water containing plant or animal material.

HIGHLIGHT

Emerging and Reemerging Diseases: "The New Normal"

Middle East respiratory syndrome (MERS). West Nile encephalitis. Chikungunya. Ebola! These and diseases like them are emerging diseases—ones that have been diagnosed in a population for the first time or are rapidly increasing in incidence or geographic range. Among them are Middle East respiratory syndrome (MERS), a highly fatal, viral disease ostensibly acquired from camels and mosquito-born chikungunya, which causes severe joint pain. Indeed, unfamiliar diseases have become "the new normal" for health care workers, according to the Centers for Disease Control and Prevention (CDC) in Atlanta, Georgia.

Meanwhile, diseases once thought to be near eradication, such as measles, whooping cough, and tuberculosis, have reemerged in troubling outbreaks. Other near-vanquished pathogens such as smallpox or anthrax could become potential weapons in bioterrorist attacks.

How do emerging and reemerging diseases arise? Some are introduced to humans as we move into remote jungles and contact infected animals, some are carried by insects whose range is spreading as climate changes, and some take advantage of the AIDS crisis, infecting immunocompromised patients. In other cases, previously harmless microbes acquire new genes that allow them to be infective and cause disease. Some emerging pathogens spread with the speed of jet planes carrying infected people around the globe, and still others arise when previously treatable microbes develop resistance to our antibiotics.

MERS virus may be transmitted from camels to people.

However they arise, emerging and reemerging diseases that may develop into the next generation of high-profile infectious diseases are being monitored by scientists. Throughout this text, you will encounter many boxed discussions of such emerging and reemerging diseases.

life because he had heated the vials sufficiently to kill everything. Needham's experiments so impressed the Royal Society that they elected him a member.

Spallanzani's Experiments

Then, in 1799, the Italian Catholic priest and scientist Lazzaro Spallanzani (1729–1799) reported results that contradicted Needham's findings. Spallanzani boiled infusions for almost an hour and sealed the vials by melting their slender necks closed. His infusions remained clear unless he broke the seal and exposed the infusion to air, after which they became cloudy with microorganisms. He concluded three things:

- Needham either had failed to heat his vials sufficiently to kill all microbes or had not sealed them tightly enough.
- Microorganisms exist in the air and can contaminate experiments.
- Spontaneous generation of microorganisms does not occur; all living things arise from other living things.

Although Spallanzani's experiments would appear to have settled the controversy once and for all, it proved difficult to dethrone a theory that had held sway for 2000 years, especially when so notable a man as Aristotle had propounded it. One of the criticisms of Spallanzani's work was that his sealed vials did not allow enough air for organisms to thrive; another objection was that his prolonged heating destroyed the "life force." The debate continued until the French chemist Louis Pasteur **(FIGURE 1.11)** conducted experiments that finally laid the theory of spontaneous generation to rest.

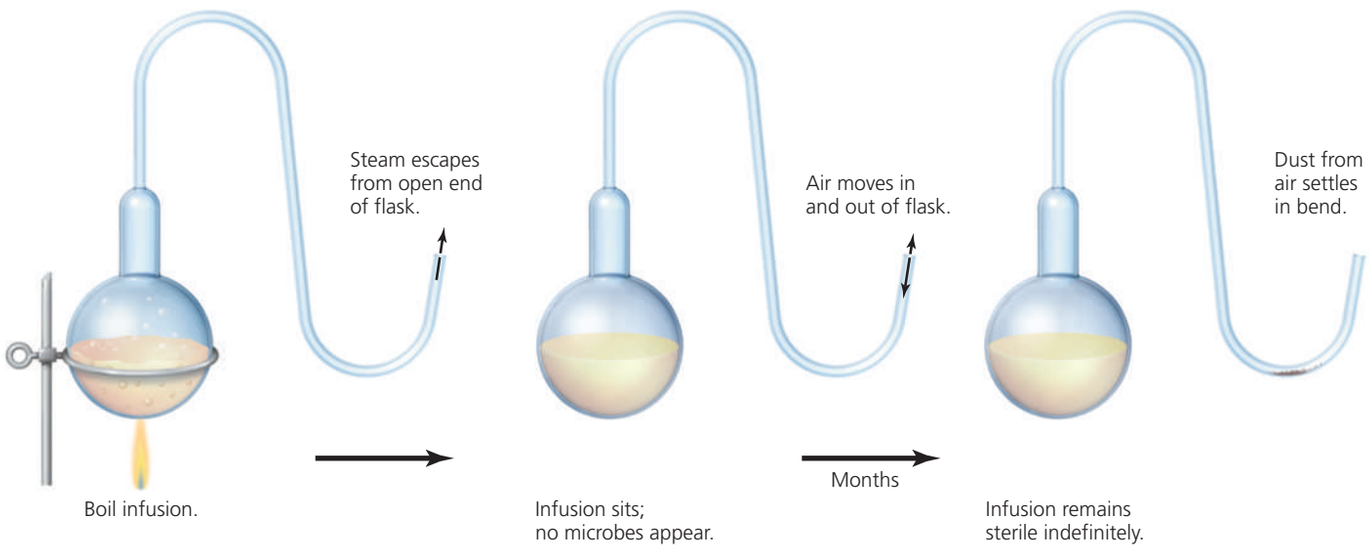
Pasteur's Experiments

Louis Pasteur (1822–1895) was an indefatigable worker who pushed himself as hard as he pushed others. As he wrote his sisters, "To *will* is a great thing dear sisters, for Action and Work usually follow Will, and almost always Work is accompanied by Success. These three things, Work, Will, Success, fill human existence. Will opens the door to success both brilliant and happy; Work passes these doors, and at the end of the journey Success comes to crown one's efforts." When his wife complained about his long hours in the laboratory, he replied, "I will lead you to fame."

▲ **FIGURE 1.11 Louis Pasteur.** Often called the Father of Microbiology, he disproved spontaneous generation. In this depiction, Pasteur examines some bacterial cultures.

Pasteur's determination and hard work are apparent in his investigations of spontaneous generation. Like Spallanzani, he boiled infusions long enough to kill everything. But instead of sealing the flasks, he bent their necks into an S-shape, which allowed air to enter while preventing the introduction of dust and microbes into the broth **(FIGURE 1.12)**.

Crowded for space and lacking funds, he improvised an incubator in the opening under a staircase. Day after day, he



▲ **FIGURE 1.12 Pasteur's experiments with "swan-necked flasks."** As long as the flask remained upright, no microbial growth appeared in the infusion.

crawled on hands and knees into this incommodious space and examined his flasks for the cloudiness that would indicate the presence of living organisms. In 1861, he reported that his "swan-necked flasks" remained free of microbes even 18 months later. Because the flasks contained all the nutrients (including air) known to be required by living things, he concluded, "Never will spontaneous generation recover from the mortal blow of this simple experiment."

Pasteur followed this experiment with demonstrations that microbes in the air were the "parents" of Needham's microorganisms. He broke the necks off some flasks, exposing the liquid in them directly to the air, and he carefully tilted others so that the liquid touched the dust that had accumulated in their necks. The next day, all of these flasks were cloudy with microbes. He concluded that the microbes in the liquid were the progeny of microbes that had been on the dust particles in the air.

The Scientific Method

The debate over spontaneous generation led in part to the development of a generalized **scientific method** by which questions are answered through observations of the outcomes of carefully controlled experiments instead of by conjecture or according to the opinions of any authority figure. The scientific method, which provides a framework for conducting an investigation rather than a rigid set of specific "rules," consists of four basic steps **(FIGURE 1.13)**:

1. A group of observations leads a scientist to ask a question about some phenomenon.
2. The scientist generates a hypothesis—that is, a potential answer to the question.
3. The scientist designs and conducts an experiment to test the hypothesis.
4. Based on the observed results of the experiment, the scientist either accepts, rejects, or modifies the hypothesis.

The scientist then returns to earlier steps in the method, either modifying hypotheses and then testing them or repeatedly testing accepted hypotheses until the evidence for a hypothesis is convincing (Figure 1.13). Accepted hypotheses that explain many observations and are repeatedly verified by numerous scientists over many years are called *theories* or *laws*.

Note that for the scientific community to accept experiments (and their results) as valid, they must include appropriate *control groups*—groups that are treated exactly the same as the other groups in the experiment except for the one variable that the experiment is designed to test. In Pasteur's experiments on spontaneous generation, for example, his "control flasks" were the sterile infusion composed of all the nutrients living things need as well as air made available through the flasks' "swan necks." His "experimental flasks" for testing his hypothesis were exposed to exactly the same conditions *plus* contact with the dust in the bend in the neck. Because exposure to the dust was the *only* difference between the control and experimental groups, Pasteur was able to conclude that the microbes growing in the infusion arrived on the dust particles.

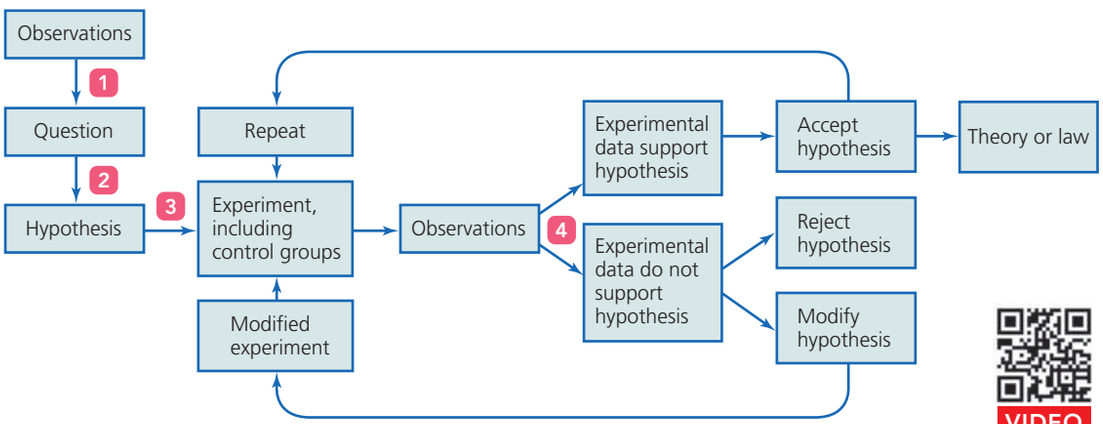
What Causes Fermentation?

LEARNING OUTCOMES

- **1.10** Discuss the significance of Pasteur's fermentation experiments to our world today.
- **1.11** Explain why Pasteur may be considered the Father of Microbiology.
- **1.12** Identify the scientist whose experiments led to the field of biochemistry and the study of metabolism.

The controversy over spontaneous generation was largely a philosophical exercise among men who conducted research to gain basic scientific knowledge and not to apply the knowledge they gained. However, the second question that moved microbial studies forward in the 1800s had tremendous practical applications.

Our story resumes in 19th-century France, where spoiled, acidic wine was threatening the livelihood of many grape growers. This led to a fundamental question, "What causes the fermentation of grape juice into wine?" This question was so



▲ **FIGURE 1.13** The scientific method, which forms a framework for scientific research.

important to vintners that they funded research concerning fermentation, hoping scientists could develop methods to promote the production of alcohol and prevent spoilage by acid during fermentation.

Pasteur's Experiments

Scientists of the 1800s used the word *fermentation* to mean not only the formation of alcohol from sugar but also other chemical reactions, such as the formation of lactic acid, the putrefaction of meat, and the decomposition of waste. Many scientists asserted that air caused fermentation reactions; others insisted that living organisms were responsible.

The debate over the cause of fermentation reactions was linked to the debate over spontaneous generation. Some scientists proposed that the yeasts observed in fermenting juices were nonliving globules of chemicals and gases. Others thought that yeasts were alive and were spontaneously generated during fermentation. Still others asserted that yeasts not only were living organisms but also caused fermentation.

Pasteur conducted a series of careful observations and experiments that answered the question, "What causes fermentation?" First, he observed yeast cells growing and budding in grape juice and conducted experiments showing that they arise only from other yeast cells. Then, by sealing some sterile flasks containing grape juice and yeast and by leaving others open to the air, he demonstrated that yeast could grow with or without oxygen; that is, he discovered that yeasts are *facultative anaerobes*[13]—organisms that can live with or without oxygen. Finally, by introducing bacteria and yeast cells into different flasks of sterile grape juice, he proved that bacteria ferment grape juice to produce acids and that yeast cells ferment grape juice to produce alcohol **(FIGURE 1.14)**.

Pasteur's discovery that *anaerobic* bacteria fermented grape juice into acids suggested a method for preventing the spoilage of wine. His name became a household word when he developed *pasteurization,* a process of heating the grape juice just enough to kill most contaminating bacteria without changing the juice's basic qualities. After pasteurization, wine makers added yeast to ensure that alcohol fermentation occurred. Pasteur thus began the field of **industrial microbiology** (or **biotechnology**) in which microbes are intentionally used to manufacture products (**TABLE 1.1** on p. 43; see also Chapter 26). Today, pasteurization is used routinely on milk to eliminate pathogens that cause such diseases as bovine tuberculosis and brucellosis; it is also used to eliminate pathogens in juices and other beverages.

These are just a few of the many experiments Pasteur conducted with microbes. Although a few of Pasteur's successes can be attributed to the superior microscopes available in the late 1800s, his genius is clearly evident in his carefully designed and straightforward experiments. Because of his many, varied, and significant accomplishments in working with microbes, Pasteur may be considered the Father of Microbiology.

Buchner's Experiments

Studies on fermentation began with the idea that fermentation reactions were strictly chemical and did not involve living organisms. This idea was supplanted by Pasteur's work showing that fermentation proceeded only when living cells were present and that different types of microorganisms growing under varied conditions produced different end products.

In 1897, the German scientist Eduard Buchner (1860–1917) resurrected the chemical explanation by showing that fermentation does not require living cells. Buchner's experiments demonstrated the presence of *enzymes,* which are cell-produced proteins that promote chemical reactions. Buchner's work began the field of **biochemistry** and the study of **metabolism,** a term that refers to the sum of all chemical reactions within an organism.

What Causes Disease?

LEARNING OUTCOMES

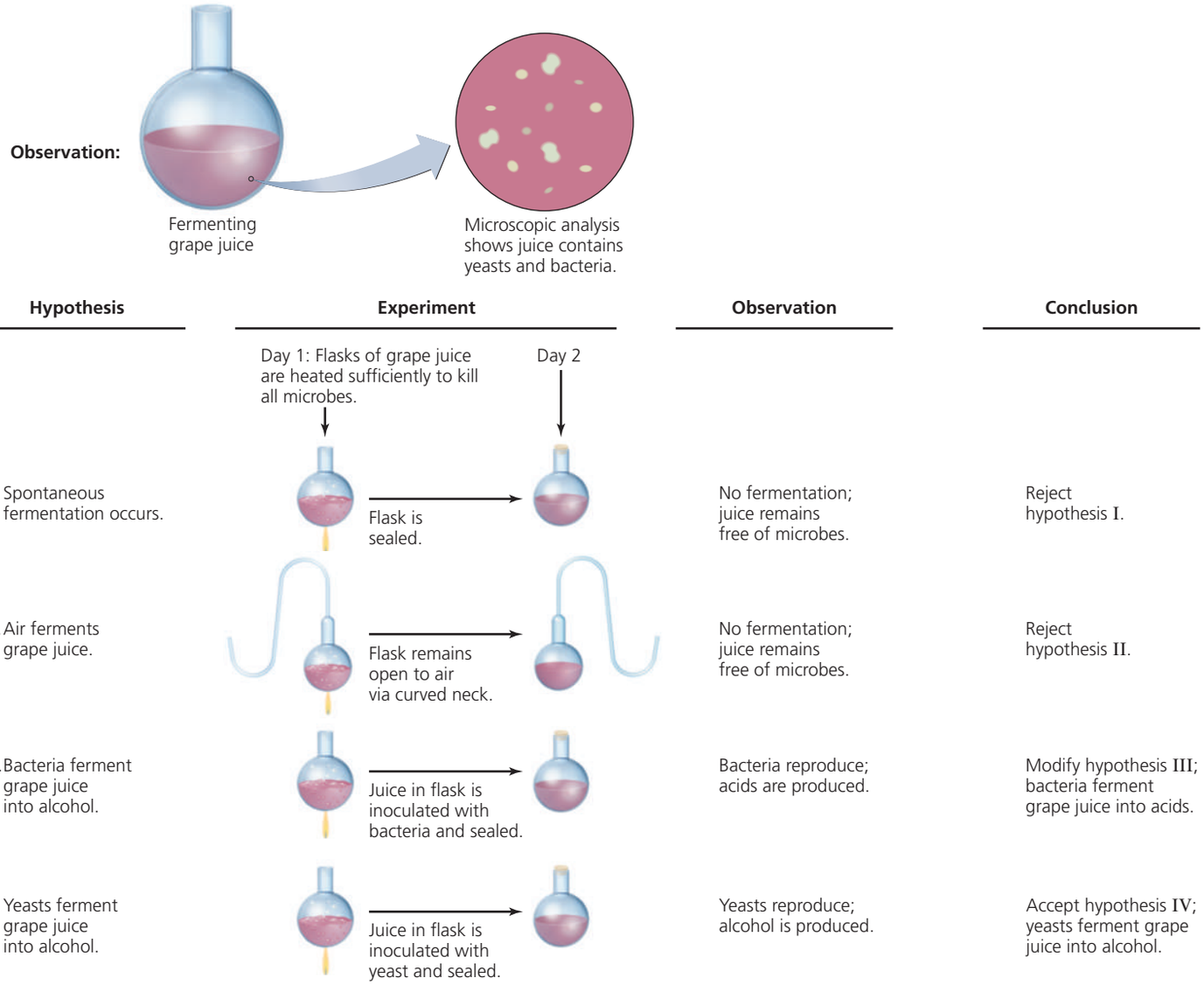
1.13 List at least seven contributions made by Koch to the field of microbiology.
1.14 List the four steps that must be taken to prove the cause of an infectious disease.
1.15 Describe the contribution of Gram to the field of microbiology.

You are a physician in London, and it is August 1854. It is past midnight, and you have been visiting patients since before dawn. As you enter the room of your next patient, you observe with frustration and despair that this case is like hundreds of others you and your colleagues have attended in the neighborhood over the past month.

A five-year-old boy with a vacant stare lies in bed listlessly. As you watch, he is suddenly gripped by severe abdominal cramps, and his gastrointestinal tract empties in an explosion of watery diarrhea. The voided fluid is clear, colorless, odorless, and streaked with thin flecks of white mucus, reminiscent of water poured off a pot of cooking rice. His anxious mother changes his bedclothes as his father gives him a sip of water, but it is of little use. With a heavy heart, you confirm the parents' fear—their child has cholera, and there is nothing you can do. He will likely die before morning. As you despondently turn to go, the question that has haunted you for two months is foremost in your mind: What causes such a disease?

The third question that propelled the advance of microbiology concerned disease, defined generally as any abnormal condition in the body. Prior to the 1800s, disease was attributed to various factors, including evil spirits, astrological signs, imbalances in body fluids, and foul vapors. Although the Italian philosopher Girolamo Fracastoro (1478–1553) conjectured as early as 1546 that "germs[14] of contagion" cause disease, the idea that

[13]From Greek *an,* meaning "not"; *aer,* meaning "air" (i.e., oxygen); and *bios,* meaning "life."
[14]From Latin *germen,* meaning "sprout."



▲ FIGURE 1.14 How Pasteur applied the scientific method in investigating the nature of fermentation. After observing that fermenting grape juice contained both yeasts and bacteria, Pasteur hypothesized that these organisms cause fermentation. On eliminating the possibility that fermentation could occur spontaneously or be caused by air (hypotheses I and II), he concluded that fermentation requires the presence of living cells. The results of additional experiments (those testing hypotheses III and IV) indicated that bacteria ferment grape juice to produce acids and that yeasts ferment grape juice to produce alcohol. *Which of Pasteur's flasks was the control?*

Figure 1.14 *The sealed flask that remained free of microorganisms served as the control.*

germs might be invisible living organisms awaited Leeuwenhoek's investigations 130 years later.

Pasteur's discovery that bacteria are responsible for spoiling wine led naturally to his hypothesis in 1857 that microorganisms are also responsible for diseases. This idea came to be known as the **germ theory of disease.** Because a particular disease is typically accompanied by the same symptoms in all affected individuals, early investigators suspected that diseases such as cholera, tuberculosis, and anthrax are each caused by a specific germ, called a **pathogen.**[15] Today, we know that some diseases are genetic and that allergic reactions and environmental toxins cause others, so the germ theory applies only to *infectious*[16] *diseases.*

Just as Pasteur was the chief investigator in disproving spontaneous generation and determining the cause of fermentation, so Robert Koch (1843–1910) dominated **etiology**[17] (disease causation) **(FIGURE 1.15)**.

[15]From Greek *pathos,* meaning "disease," and *genein,* meaning "to produce."
[16]From Latin *inficere,* meaning "to taint" (i.e., with a pathogen).
[17]From Greek *aitia,* meaning "cause," and *logos,* meaning "word" or "study."

TABLE 1.1 Some Industrial Uses of Microbes

Product or Process	Contribution of Microorganism
Foods and Beverages	
Cheese	Flavoring and ripening produced by bacteria and fungi; flavors dependent on the source of milk and the type of microorganism
Alcoholic beverages	Alcohol produced by bacteria or yeast by fermentation of sugars in fruit juice or grain
Soy sauce	Produced by fungal fermentation of soybeans
Vinegar	Produced by bacterial fermentation of sugar
Yogurt	Produced by certain bacteria growing in milk
Sour cream	Produced by bacteria growing in cream
Artificial sweetener	Amino acids synthesized by bacteria from sugar
Bread	Rising of dough produced by action of yeast; sourdough results from bacteria-produced acids
Other Products	
Antibiotics	Produced by bacteria and fungi
Human growth hormone, human insulin	Produced by genetically engineered bacteria
Laundry enzymes	Isolated from bacteria
Vitamins	Isolated from bacteria
Diatomaceous earth (in polishes and buffing compounds)	Composed of cell walls of microscopic algae
Pest control chemicals	Insect pests killed or inhibited by insect-destroying bacteria
Drain opener	Protein-digesting and fat-digesting enzymes produced by bacteria

Koch's Experiments

Koch was a country doctor in Germany when he began a race with Pasteur to discover the cause of anthrax, which is a potentially fatal disease, primarily of animals, in which toxins produce ulceration of the skin. Anthrax, which can spread to humans, caused untold financial losses to farmers and ranchers in the 1800s.

Koch carefully examined the blood of infected animals, and in every case he identified rod-shaped bacteria[18] in chains. He observed the formation of resting stages *(endospores)* within the bacterial cells and showed that the endospores always produced anthrax when they were injected into mice. This was the first time that a bacterium was proven to cause a disease. Koch published his findings in 1876. As a result of his successful work on anthrax, Koch moved to Berlin and was given facilities and funding to continue his research.

Heartened by his success, Koch turned his attention to other diseases. He had been fortunate when he chose anthrax for his initial investigations, because anthrax bacteria are quite large and easily identified with the microscopes of that time. However, most bacteria are very small, and different types exhibit few or no visible differences. Koch was puzzled regarding how he was to distinguish among these bacteria.

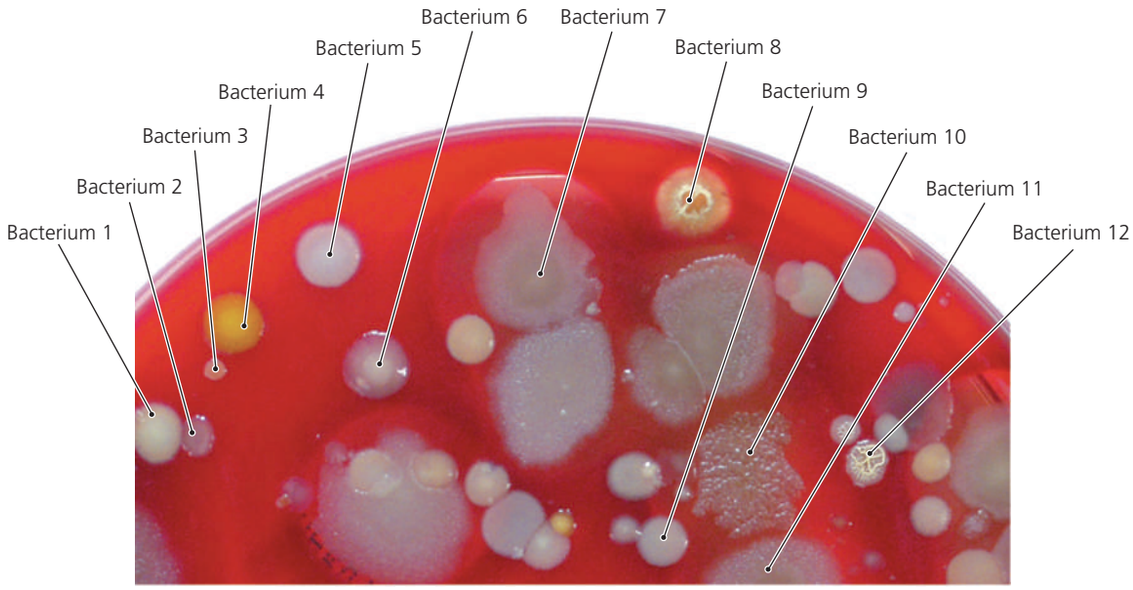
▲ **FIGURE 1.15 Robert Koch.** Koch was instrumental in modifying the scientific method to prove that a given pathogen caused a specific disease.

He solved the problem by taking specimens (e.g., blood, pus, or sputum) from disease victims and then smearing the specimens onto a solid surface such as a slice of potato or a gelatin medium. He then waited for bacteria and fungi present in the specimen to multiply and form distinct colonies **(FIGURE 1.16)**. Koch hypothesized that each colony consisted of the progeny of a single cell. He then inoculated samples from each colony into laboratory animals to see which caused disease. Koch's method of isolation is a standard technique in microbiological and medical labs to this day, though *agar* derived from red algae is used instead of gelatin or potato.

Koch and his colleagues are also responsible for many other advances in laboratory microbiology, including the following:

- Simple staining techniques for bacterial cells and flagella
- The first photomicrograph of bacteria
- The first photograph of bacteria in diseased tissue
- Techniques for estimating the number of bacteria in a solution based on the number of colonies that form after inoculation onto a solid surface
- The use of steam to sterilize growth media
- The use of Petri[19] dishes to hold solid growth media
- Laboratory techniques such as transferring bacteria between media using a metal wire that has been heat-sterilized in a flame
- Elucidation of bacteria as distinct species

[18]Now known as *Bacillus anthracis*—Latin for "the rod of anthrax."
[19]Named for Richard Petri, Koch's coworker, who invented them in 1887.



◀ FIGURE 1.16 Bacterial colonies on a solid surface (agar). Differences in colony size, shape, and color indicate the presence of different species. Such differences allowed Koch to isolate specific types of microbes that could be tested for their ability to cause disease.

Koch's Postulates

After discovering the anthrax bacterium, Koch continued to search for disease agents. In two pivotal scientific publications in 1882 and 1884, he announced that the cause of tuberculosis was a rod-shaped bacterium, *Mycobacterium tuberculosis* (mī´kō-bak-tēr´ē-ŭm too-ber-kyū-lō´sis). In 1905, he received the Nobel Prize in Physiology or Medicine for this work.

In his publications on tuberculosis, Koch elucidated a series of steps that must be taken to prove the cause of any infectious disease. These steps, now known as **Koch's postulates,** are one of his important contributions to microbiology. His postulates (which we discuss in more detail in Chapter 14) are the following:

1. The suspected causative agent must be found in every case of the disease and be absent from healthy hosts.
2. The agent must be isolated and grown outside the host.
3. When the agent is introduced to a healthy, susceptible host, the host must get the disease.
4. The same agent must be found in the diseased experimental host.

We use the term *suspected causative agent* because it is merely "suspected" until the postulates have been fulfilled, and "agent" can refer to any fungus, protozoan, bacterium, virus, or other pathogen. There are practical and ethical limits in the application of Koch's postulates, but in almost every case they must be satisfied before the cause of an infectious disease is proven.

During microbiology's "Golden Age," other scientists used Koch's postulates and laboratory techniques introduced by Koch and Pasteur to discover the causes of most protozoan and bacterial diseases as well as some viral diseases. For example, Charles Laveran (1845–1922) showed that a protozoan is the cause of malaria, and Edwin Klebs (1834–1913) described the bacterium that causes diphtheria. Dmitri Ivanovsky (1864–1920) and Martinus Beijerinck (1851–1931) discovered that a certain disease in tobacco plants is caused by a pathogen that passes through filters with such extremely small pores that bacteria cannot pass through. Beijerinck, recognizing that the pathogen was not bacterial, called it a *filterable virus.* Now such pathogens are simply called *viruses.* As previously noted, viruses could not be seen until electron microscopes were invented in 1932. The American physician Walter Reed (1851–1902) proved in 1900 that viruses can cause such diseases as yellow fever in humans. (Chapter 13 deals with *virology,* and Chapters 24 and 25 deal with viral diseases.)

A partial list of scientists and the pathogens they discovered is provided in **TABLE 1.2**.

Gram's Stain

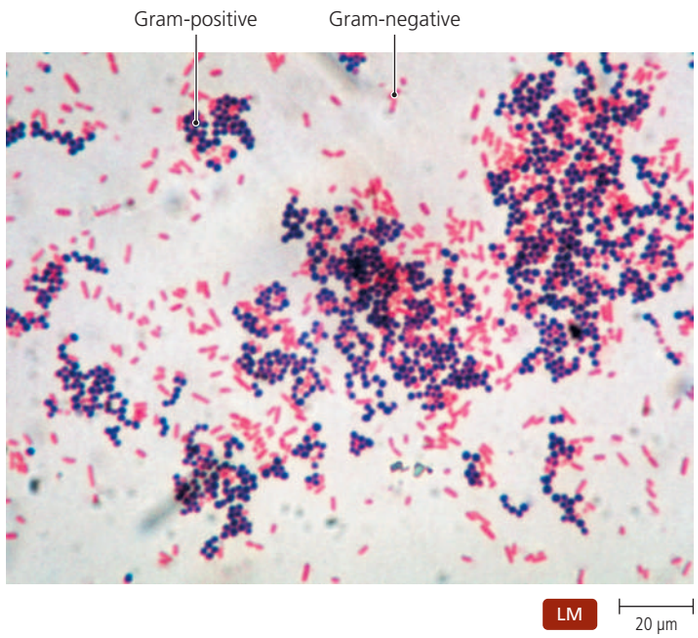
The first of Koch's postulates demands that the suspected agent be found in every case of a given disease, which presupposes that minute microbes can be seen and identified. However, because most microbes are colorless and difficult to see, scientists began to use dyes to stain them and make them more visible under the microscope.

Though Koch reported a simple staining technique in 1877, the Danish scientist Hans Christian Gram (1853–1938) developed a more important staining technique in 1884. His procedure, which involves the application of a series of dyes, leaves some microbes purple and others pink. We now label the purple cells as *Gram positive* and the pink ones as *Gram negative,* and we use the Gram procedure to separate bacteria into these two large groups **(FIGURE 1.17)**.

The **Gram stain** is still the most widely used staining technique. It is one of the first steps carried out when bacteria are being identified, and it is one of the procedures you will learn in microbiology lab. (Chapter 4 discusses the full procedure.)

TABLE 1.2 Other Notable Scientists of the "Golden Age of Microbiology" and the Agents of Disease They Discovered

Scientist	Year	Disease	Agent
Albert Neisser	1879	Gonorrhea	*Neisseria gonorrhoeae* (bacterium)
Charles Laveran	1880	Malaria	*Plasmodium* species (protozoa)
Carl Eberth	1880	Typhoid fever	*Salmonella enterica* serotype Typhi (bacterium)
Edwin Klebs	1883	Diphtheria	*Corynebacterium diphtheriae* (bacterium)
Theodor Escherich	1884	Traveler's diarrhea Bladder infection	*Escherichia coli* (bacterium)
Albert Fraenkel	1884	Pneumonia	*Streptococcus pneumoniae* (bacterium)
David Bruce	1887	Undulant fever (brucellosis)	*Brucella melitensis* (bacterium)
Anton Weichselbaum	1887	Meningococcal meningitis	*Neisseria meningitidis* (bacterium)
A. A. Gartner	1888	Salmonellosis (form of food poisoning)	*Salmonella* species (bacterium)
Shibasaburo Kitasato	1889	Tetanus	*Clostridium tetani* (bacterium)
Dmitri Ivanovsky and	1892	Tobacco mosaic disease	*Tobamovirus tobacco mosaic virus*
Martinus Beijerinck	1898		
William Welch and George Nuttall	1892	Gas gangrene	*Clostridium perfringens* (bacterium)
Alexandre Yersin and Shibasaburo Kitasato	1894	Bubonic plague	*Yersinia pestis* (bacterium)
Kiyoshi Shiga	1898	Shigellosis (a type of severe diarrhea)	*Shigella dysenteriae* (bacterium)
Walter Reed	1900	Yellow fever	*Flavivirus yellow fever virus*
Robert Forde and Joseph Dutton	1902	African sleeping sickness	*Trypanosoma brucei gambiense* (protozoan)



▲ **FIGURE 1.17 Results of Gram staining.** Gram-positive cells (in this case, *Staphylococcus aureus*) are purple; Gram-negative cells (in this case, *Escherichia coli*) are pink.

How Can We Prevent Infection and Disease?

LEARNING OUTCOMES

1.16 Identify six health care practitioners who did pioneering research in the areas of public health microbiology and epidemiology.
1.17 Name two scientists whose work with vaccines began the field of immunology.
1.18 Describe the quest for a "magic bullet."

The last great question that drove microbiological research during the "Golden Age" was how to prevent infectious diseases. Though some methods of preventing or limiting disease were discovered even before it was understood that microorganisms caused contagious diseases, great advances occurred after Pasteur and Koch showed that life comes from life and that microorganisms can cause diseases.

In the mid-1800s, modern principles of hygiene, such as those involving sewage and water treatment, personal cleanliness, and pest control, were not widely practiced. Typically, medical personnel and health care facilities lacked adequate

CLINICAL CASE STUDY

Remedy for Fever or Prescription for Death?

In the late 18th century, Philadelphia was one of the larger and wealthier cities in the United States and served as the capital. That changed in 1793. The city had an unusually wet spring, which left behind stagnant pools that became breeding grounds for mosquitoes. At about the same time, refugees from the slave revolution in Haiti fled to Philadelphia, carrying the yellow fever virus. In late August 1793, a female *Aedes aegypti* mosquito bit an infected refugee and then bit a healthy Philadelphian. This began a yellow fever epidemic that killed 10% of the city's population within three months and led another 30% to flee for their lives. Victims suffered from high fever, nausea, skin eruptions, black vomit, and jaundice.

The treatment for yellow fever in the 18th century was often worse than the disease: physicians administered potions to purge the victims' intestines and drained up to four-fifths of their patients' blood in the mistaken belief the bloodletting would stem fever. These attempted remedies often left patients tired, weak, and unable to fight the virus. Without effective treatments, the epidemic stopped only when the first frost arrived.

1. People who left the city seemed to have milder cases of yellow fever or avoided the infection altogether. Explain why.
2. The story mentions that the coming of the first frost brought an end to the epidemic. Discuss the possible reasons why this would provide at least temporary relief from the epidemic.

cleanliness. **Healthcare-associated infections** (**HAI,** formerly called *nosocomial*[20] *infections*) were rampant. For example, surgical patients frequently succumbed to gangrene acquired while under their doctor's care, and many women who gave birth in hospitals died from puerperal[21] fever. Six health care practitioners who were especially instrumental in changing health care delivery methods were Semmelweis, Lister, Nightingale, Snow, Jenner, and Ehrlich.

Semmelweis and Handwashing

Ignaz Semmelweis (1818–1865) was a physician on the obstetric ward of a teaching hospital in Vienna. In about 1848, he observed that women giving birth in the wing where medical students were trained died from puerperal fever at a rate 20 times higher than the mortality rates of either women attended by midwives in an adjoining wing or women who gave birth at home.

Though Pasteur had not yet elaborated his germ theory of disease, Semmelweis hypothesized that medical students carried "cadaver particles" from their autopsy studies into the delivery rooms and that these "particles" resulted in puerperal fever. Semmelweis gained support for his hypothesis when a doctor who sliced his finger during an autopsy died after showing symptoms similar to those of puerperal fever. Today, we know that the primary cause of puerperal fever is a bacterium in the genus *Streptococcus* (strep-tō-kok´ŭs; see Figure 1.4), which is usually harmless on the skin or in the mouth but causes severe complications when it enters the blood.

Semmelweis began requiring medical students to wash their hands with chlorinated lime water, a substance long used to eliminate the smell of cadavers. Mortality in the subsequent year dropped from 18.3% to 1.3%. Despite his success, Semmelweis was ridiculed by the director of the hospital and eventually was forced to leave. He returned to his native Hungary, where his insistence on handwashing met with general approval when it continued to produce higher patient survival rates.

Though his impressive record made it easier for later doctors to institute changes, Semmelweis was unsuccessful in gaining support for his method from most European doctors. He became severely depressed and was committed to a mental hospital, where he died from an infection of *Streptococcus,* the very organism he had fought for so long.

Lister's Antiseptic Technique

Shortly after Semmelweis was rejected in Vienna, the English physician Joseph Lister (1827–1912) modified and advanced the idea of *antisepsis*[22] in health care settings. As a surgeon, Lister was aware of the dreadful consequences that resulted from the infection of wounds. Therefore, he began spraying wounds, surgical incisions, and dressings with carbolic acid (phenol), a chemical that had previously proven effective in reducing odor and decay in sewage. Like Semmelweis, he initially met with some resistance, but when he showed that it reduced deaths among his patients by two-thirds, his method was accepted into common practice. In this manner, Lister vindicated Semmelweis, became the founder of antiseptic surgery, and opened new fields of research into antisepsis and disinfection.

Nightingale and Nursing

Florence Nightingale (1820–1910) **(FIGURE 1.18)** was a dedicated English nurse who introduced cleanliness and other antiseptic techniques into nursing practice. She was instrumental

[20]From Greek *nosos,* meaning "disease," and *komein,* meaning "to care for" (relating to a hospital).
[21]From Latin *puerperus,* meaning "childbirth."
[22]From Greek *anti,* meaning "against," and *sepein,* meaning "putrefaction."

▲ **FIGURE 1.18 Florence Nightingale.** The founder of modern nursing, she was influential in introducing antiseptic technique into nursing practice.

in setting standards of hygiene that saved innumerable lives during the Crimean War of 1854–1856. One of her first requisitions in the military hospital was for 200 scrubbing brushes, which she and her assistants used diligently in the squalid wards. She next arranged for each patient's filthy clothes and dressings to be replaced or cleaned at a different location, thus removing many sources of infection. She thoroughly documented statistical comparisons to show that poor food and unsanitary conditions in the hospitals were responsible for the deaths of many soldiers.

After the war, Nightingale returned to England, where she actively exerted political pressure to reform hospitals and implement public health policies. Perhaps her greatest achievements were in nursing education. For example, she founded the Nightingale School for Nurses—the first of its kind in the world.

Snow and Epidemiology

Another English physician, John Snow (1813–1858), also played a key role in setting standards for good public hygiene to prevent the spread of infectious diseases. Snow had been studying the propagation of cholera and suspected that the disease was spread by a contaminating agent in water. In 1854, he mapped the occurrence of cholera cases during an epidemic in London and showed that they centered around a public water supply on Broad Street.

Though Snow did not know the cause of cholera, his careful documentation of the epidemic highlighted the critical need for adequate sewage treatment and a pure water supply. His study was the foundation for two branches of microbiology—**infection control** and **epidemiology,**[23] which is the study of the occurrence, distribution, and spread of disease in humans.

Jenner's Vaccine

In 1796, the English physician Edward Jenner (1749–1823) tested the hypothesis that a mild disease called cowpox provided protection against potentially fatal smallpox. After he intentionally inoculated a boy with pus collected from a milkmaid's cowpox lesion, the boy developed cowpox and survived. When Jenner then infected the boy with smallpox pus, he found that the boy had become immune[24] to smallpox. (Today, experiments that intentionally expose human subjects to deadly pathogens are unethical.) In 1798, Jenner reported similar results from additional experiments, demonstrating the validity of the procedure he named *vaccination* after *Vaccinia virus,*[25] the virus that causes cowpox. Because vaccination stimulates a long-lasting response by the body's protective immune system, the term *immunization* is often used synonymously today. Jenner began the field of **immunology**—the study of the body's specific defenses against pathogens. (Chapters 16–18 discuss immunology.)

Pasteur later capitalized on Jenner's work by producing weakened strains of various pathogens for use in preventing the serious diseases they cause. In honor of Jenner's work with cowpox, Pasteur used the term *vaccine* to refer to all weakened, protective strains of pathogens. He subsequently developed successful vaccines against fowl cholera, anthrax, and rabies.

Ehrlich's "Magic Bullets"

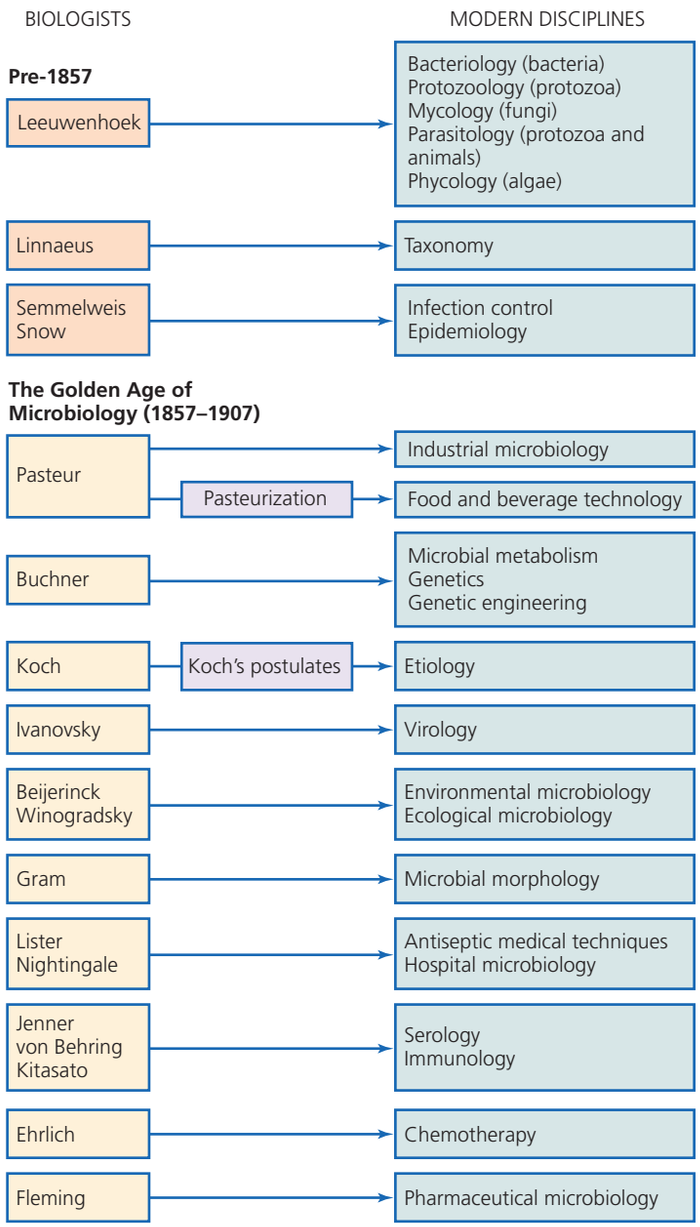
Gram's discovery that stained bacteria could be differentiated into two types by color suggested to the German microbiologist Paul Ehrlich (1854–1915) that chemicals could be used to kill microorganisms differentially. To investigate this idea, Ehrlich undertook an exhaustive survey of chemicals to find a "magic bullet" that would destroy pathogens while remaining nontoxic to humans. By 1908, he had discovered a chemical active against the causative agent of syphilis, though the arsenic-based drug can have serious side effects in humans. His discoveries began the branch of medical microbiology known as **chemotherapy.**

In summary, the Golden Age of Microbiology was a time when researchers proved that living things come from other living things, that microorganisms can cause fermentation and disease, and that certain procedures and chemicals can limit, prevent, and cure infectious diseases. These discoveries were made by scientists who applied the scientific method to biological investigation, and they led to an explosion of knowledge in a number of scientific disciplines **(FIGURE 1.19)**.

TELL ME WHY

Some people consider Pasteur or Koch to be the Father of Microbiology, rather than Leeuwenhoek. Why might they be correct?

[23]From Greek *epi,* meaning "upon"; *demos,* meaning "people"; and *logos,* meaning "word" or "study."
[24]From Latin *immunis,* meaning "free."
[25]From Latin *vacca,* meaning "cow."



▲ **FIGURE 1.19** **Some of the many scientific disciplines and applications that arose from the pioneering work of scientists just before and around the time of the golden age of microbiology.**

The Modern Age of Microbiology

LEARNING OUTCOME

1.19 List four major questions that drive microbiological investigations today.

The vast increase in the number of microbiological investigations and in scientific knowledge during the 1800s opened new fields of science, including disciplines called environmental microbiology, immunology, epidemiology, chemotherapy, and genetic engineering **(TABLE 1.3)**. Microorganisms played a significant role in the development of these disciplines because microorganisms are relatively easy to grow, take up little space, and are available by the trillions. Much of what has been learned about microbes also applies to other organisms, including humans. In the rest of this text we examine advances made in these branches of microbiology, though it would require thousands of books this size to deal with all that is known.

Once the developing science of microbiology had successfully answered questions about spontaneous generation, fermentation, and disease, additional questions arose in each branch of the new science. In this section, we briefly consider some of the 20th century's overarching questions in both basic and applied research. The chapter concludes with a look at some of the questions that might propel microbiological research for the next 50 years.

What Are the Basic Chemical Reactions of Life?

Biochemistry is the study of metabolism—that is, the chemical reactions that occur in living organisms. Biochemistry began with Pasteur's work on fermentation by yeast and bacteria and with Buchner's discovery of enzymes in yeast extract, but by the early 1900s, many scientists thought that the metabolic reactions of microbes had little to do with the metabolism of plants and animals.

In contrast, microbiologists Albert Kluyver (1888–1956) and his student C. B. van Niel (1897–1985) proposed that basic biochemical reactions are shared by all living things, that these reactions are relatively few in number, and that their primary feature is the transfer of electrons and hydrogen ions. In adopting this view, scientists could use microbes as model systems to answer questions about metabolism in all organisms. Research during the 20th century validated this approach to understanding basic metabolic processes, but scientists have also documented an amazing metabolic diversity. (Chapter 5 discusses basic metabolic processes, and Chapter 6 considers metabolic diversity.)

Basic biochemical research has many practical applications, including the following:

- The design of herbicides and pesticides that are specific in their action and have no long-term adverse effects on the environment.
- The diagnosis of illnesses and the monitoring of a patient's responses to treatment. For example, physicians routinely monitor liver disease by measuring blood levels of certain enzymes and products of liver metabolism.
- The treatment of metabolic diseases. One example is treating phenylketonuria, a disease resulting from the inability to properly metabolize the amino acid phenylalanine, by eliminating foods containing phenylalanine from the diet.
- The design of drugs to treat leukemia, gout, bacterial infections, malaria, herpes, AIDS, asthma, and heart attacks.

How Do Genes Work?

Genetics, the scientific study of inheritance, started in the mid-1800s as an offshoot of botany, but scientists studying microbes made most of the great advances in this discipline.

TABLE 1.3 Fields of Microbiology

Disciplines	Subject(s) of Study
Basic Research	
Microbe Centered	
Bacteriology	Bacteria and archaea
Phycology	Algae
Mycology	Fungi
Protozoology	Protozoa
Parasitology	Parasitic protozoa and parasitic animals
Virology	Viruses
Process Centered	
Microbial metabolism	Biochemistry: chemical reactions within cells
Microbial genetics	Functions of DNA and RNA
Environmental microbiology	Relationships between microbes and among microbes, other organisms, and their environment
Applied Microbiology	
Medical Microbiology	
Serology	Antibodies in blood serum, particularly as an indicator of infection
Immunology	Body's defenses against specific diseases
Epidemiology	Frequency, distribution, and spread of disease
Etiology	Causes of disease
Infection control	Hygiene in health care settings and control of nosocomial infections
Chemotherapy	Development and use of drugs to treat infectious diseases
Applied Environmental Microbiology	
Bioremediation	Use of microbes to remove pollutants
Public health microbiology	Sewage treatment, water purification, and control of insects that spread disease
Agricultural microbiology	Use of microbes to control insect pests
Industrial Microbiology (Biotechnology)	
Food and beverage technology	Reduction or elimination of harmful microbes in food and drink
Pharmaceutical microbiology	Manufacture of vaccines and antibiotics
Recombinant DNA technology (genetic engineering)	Alteration of microbial genes to synthesize useful products

Microbial Genetics

While working with the bacterium *Streptococcus pneumoniae* (strep-tō-kok´ŭs nū-mō´nē-ī), Oswald Avery (1877–1955), Colin MacLeod (1909–1972), and Maclyn McCarty (1911–2005) determined that genes are contained in molecules of DNA. In 1958, George Beadle (1903–1989) and Edward Tatum (1909–1975), working with the bread mold *Neurospora crassa* (noo-ros´pōr-ă kras´ă), established that a gene's activity is related to the function of the specific protein coded by that gene. Other researchers, also working with microbes, determined the exact way in which genetic information is translated into a protein, the rates and mechanisms of genetic mutation, and the methods by which cells control genetic expression. (Chapter 7 examines all these aspects of microbial genetics.)

Over the past 40 years, advances in microbial genetics developed into several new disciplines that are among the faster-growing areas of scientific research today, including *molecular biology, recombinant DNA technology,* and *gene therapy.*

Molecular Biology

Molecular biology combines aspects of biochemistry, cell biology, and genetics to explain cell function at the molecular level. Molecular biologists are particularly concerned with *genome*[26] *sequencing*. Using techniques perfected on microorganisms, molecular biologists have sequenced the genomes of many organisms, including humans and many of their pathogens. It is hoped that a fuller understanding of the genomes of organisms will result in practical ways to limit disease, repair genetic defects, and enhance agricultural yield.

The American Nobel Prize winner Linus Pauling (1901–1994) proposed in 1965 that gene sequences could provide a means of understanding evolutionary relationships and processes, establishing taxonomic categories that more closely reflect these relationships, and identifying the existence of microbes that have never been cultured in a laboratory. Two examples illustrate such uses of gene sequencing data:

- In the 1970s, Carl Woese (1928–2012) and George Fox (1945–) discovered that significant differences in nucleic acid sequences among organisms clearly reveal that cells belong to one of *three* major groups—bacteria, archaea, or eukaryotes—and not merely two groups (prokaryotes and eukaryotes), as previously thought.
- Scientists showed in 1990 that cat scratch disease is caused by a bacterium that had not been cultured. The bacterium was discovered by comparing the sequence of a portion of its ribonucleic acid with ribonucleic acid sequences from all other known bacteria. This is a standard technique in modern bacterial identification.

Recombinant DNA Technology

Molecular biology is applied in **recombinant DNA technology,**[27] commonly called *genetic engineering,* which was first developed using microbial models. Geneticists manipulate genes in microbes, plants, and animals for practical applications. For instance, once scientists have inserted the gene for a human blood-clotting factor into the bacterium *Escherichia coli* (esh-ĕ-rik´ē-ă kō´lī), the bacterium produces the factor in a pure form. This technology is a benefit to hemophiliacs, who previously depended on clotting factor derived from donated blood, which was possibly contaminated by life-threatening viral pathogens.

[26] A genome is the total genetic information of an organism.
[27] Recombinant DNA is DNA composed of genes from more than one organism.

Gene Therapy

An exciting new area of study is the use of recombinant DNA technology for **gene therapy,** a process that involves inserting a missing gene or repairing a defective one in human cells. In such procedures, researchers insert a desired gene into host cells, where it is incorporated into a chromosome and begins to function normally. Doctors have successfully treated several inherited immune deficiencies with gene therapy. (Chapter 8 examines recombinant DNA technology and gene therapy in more detail.)

What Roles Do Microorganisms Play in the Environment?

LEARNING OUTCOMES

1.20 Identify the field of microbiology that studies the role of microorganisms in the environment.
1.21 Name the fastest-growing scientific disciplines in microbiology today.

Ever since Koch and Pasteur, most research in microbiology has focused on pure cultures of individual species; however, microorganisms are not alone in the "real world." Instead, they live in natural microbial communities in the soil, water, the human body, and other habitats, and these communities play critical roles in such processes as the production of vitamins and *bioremediation*—the use of living bacteria, fungi, and algae to detoxify polluted environments.

Microbial communities also play an essential role in the decay of dead organisms and the recycling of chemicals such as carbon, nitrogen, and sulfur. Martinus Beijerinck discovered bacteria capable of converting nitrogen gas (N_2) from the air into nitrate (NO_3), the form of nitrogen used by plants, and the Russian microbiologist Sergei Winogradsky (1856–1953) elucidated the role of microorganisms in the recycling of sulfur. Together these two microbiologists developed laboratory techniques for several important aspects of **environmental microbiology.**

Another role of microbes in the environment is the causation of disease. Although most microorganisms are not pathogenic, in this book (particularly in Chapters 19–25), we focus on pathogenic microbes because of the threat they pose to human health. We examine their characteristics and the diseases they cause as well as the steps we can take to limit their abundance and control their spread in the environment, such as sewage treatment, water purification, disinfection, pasteurization, and sterilization.

How Do We Defend Against Disease?

Why do some people get sick during the flu season while their close friends and family remain well? The germ theory of disease showed not only that microorganisms can cause diseases, but also that the body can defend itself—otherwise, everyone would be sick most of the time.

The work of Jenner and Pasteur on vaccines showed that the body can protect itself from repeated diseases by the same organism. The German bacteriologist Emil von Behring (1854–1917) and the Japanese microbiologist Shibasaburo Kitasato (1852–1931), working in Koch's laboratory, reported the existence in the blood of chemicals and cells that fight infection. Their studies developed into the fields of *serology,* the study of blood serum[28]—specifically, the chemicals in the liquid portion of blood that fight disease—and *immunology,* the study of the body's defense against specific pathogens. (Chapters 15–18

EMERGING DISEASE CASE STUDY

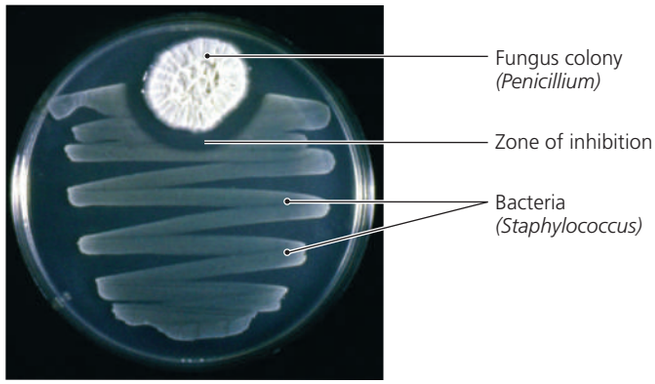
Variant Creutzfeldt-Jakob Disease

Ellen screamed obscenities as she staggered from the room and collapsed in the hallway, jerking uncontrollably and unable to stand. Her parents were shocked that their kind, considerate, and lovable daughter had changed so drastically during the past year. Sadly, she couldn't even remember her siblings' names.

Ellen had joined the nearly 200 Europeans and one Canadian afflicted with variant Creutzfeldt-Jakob disease (vCJD; what the media call "mad cow disease" because most humans with the condition acquired the pathogen from eating infected beef). Because vCJD affects the brain by slowly eroding nervous tissue and leaving the brain full of spongelike holes, the signs and symptoms of vCJD are neurological. Ellen's disease started with insomnia, depression, and confusion, but eventually it led to uncontrollable emotional and verbal outbursts, inability to coordinate movements, coma, and death. Typically, the disease lasts about a year, and there is no treatment.

Variant CJD resembles the rare genetic disorder Creutzfeldt-Jakob disease (named for its discoverers), which is caused by a mutation and occurs in the elderly. The difference is that the variant form of CJD results from an acquired infection and often strikes and kills college-aged people, like Ellen in our story. For more about vCJD, see pp. 428–430.

1. The vCJD pathogen is primarily transmitted when a person or animal consumes nervous tissue (brains). How could cattle become infected?
2. Why is vCJD called *variant*?
3. What effect does this pathogen have on cattle?



▲ **FIGURE 1.20 The effects of penicillin on a bacterial "lawn" in a Petri dish.** The clear area (zone of inhibition) surrounding the fungus colony, which is producing the antibiotic, is where the penicillin prevented bacterial growth.

cover these aspects of microbiology, which are of utmost importance to physicians, nurses, and other health care practitioners.)

Ehrlich introduced the idea of a "magic bullet" that would kill pathogens, but it was not until Alexander Fleming (1881–1955) discovered penicillin **(FIGURE 1.20)** in 1929 and Gerhard Domagk (1895–1964) discovered sulfa drugs in 1935 that medical personnel finally had drugs effective against a wide range of bacteria. (We study chemotherapy and some physical and chemical agents used to control microorganisms in the environment in Chapters 9 and 10.)

What Will the Future Hold?

Science is built on asking and answering questions. What began with the questioning curiosity of a dedicated lens grinder in the Netherlands has come far in the past 350 years, expanding into disciplines as diverse as immunology, recombinant DNA technology, and bioremediation. However, the adage remains true: *The more questions we answer, the more questions we have.*

What will microbiologists discover next? Among the questions for the next 50 years are the following:

- How can we develop successful programs to control or eradicate diseases such as tuberculosis, malaria, AIDS, and Ebola?
- What is it about the physiology of life forms known only by their nucleic acid sequences that has prevented researchers from growing them in the laboratory?
- Can bacteria and archaea be used in ultraminiature technologies, such as living computer circuit boards?
- How can an understanding of microbial *biofilms*—aggregates of microbial cells growing together on a surface—help us understand aspects of microbial action in preventing and curing diseases, recycling nutrients, degrading pollutants, and moderating climate change?
- How can we reduce the threat from microbes resistant to antimicrobial drugs, particularly so-called *persistent* cells that resist antimicrobial treatment without acquiring genetic changes?
- Can we develop inexpensive, rapid, accurate, and simple tests for infections?
- Can microorganisms that grow normally in the body bolster our ability to fight disease, lose weight, and maintain good mental health?
- Can microorganisms or their genes be used to develop sustainable fuels or bioremediate synthetic chemicals?

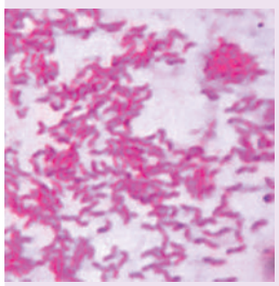
TELL ME WHY

Why are so many modern questions in microbiology related to genetics?

[28]Latin, meaning "whey." Serum is the liquid that remains after blood coagulates.

CLINICAL CASE STUDY

Can Spicy Food Cause Ulcers?



Ramona is a young mom who takes care of her two children during the day and takes pre-nursing classes at night. Juggling the needs of her family and her studies means a hectic schedule, late nights, very little sleep, and eating on the run. Ramona particularly loves spicy food, and she eats a lot of it. She adds hot sauce to nearly every meal, which tends to be Mexican fast food. She also likes to drink wine with dinner on the weekends, and sneaks an occasional cigarette when her children aren't watching.

One night, Ramona notices a burning pain in her upper abdomen. It disappears after a few minutes but then comes back a couple of nights later. Pretty soon, she is feeling the pain every night—sometimes accompanied by nausea. She mentions her symptoms to her best friend, who suggests that she might have an ulcer. Her friend knows about Ramona's love of spicy food and advises her to cut back on the hot sauce to see if that improves her symptoms. Ramona takes the advice, but the pain and nausea continue. A physician finds the pictured bacteria in her stomach. The cells lack nuclei.

1. How would Koch have determined if ulcers are caused by a microbe?
2. How can Ramona tell if these cells are prokaryotes, fungi, algae, or protozoa?
3. The cells have been stained with the procedure developed by Gram. How would you describe them to Ramona, as Gram positive or Gram negative?

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CHAPTER SUMMARY

The Early Years of Microbiology (pp. 32–37)

1. Leeuwenhoek's observations of **microbes** introduced most types of **microorganisms** to the world. His discoveries were named and classified by Linnaeus in his **taxonomic system.**
2. Small **prokaryotes**—**bacteria** and **archaea**—live in a variety of communities and in most habitats. Even though some cause disease, most are beneficial.
3. Relatively large microscopic **eukaryotic fungi** include **molds** and **yeasts.**
4. Animal-like **protozoa** are single-celled eukaryotes. Some cause disease.
5. Plantlike eukaryotic **algae** are important providers of oxygen, serve as food for many marine animals, and make chemicals used in microbiological growth media.
6. Parasitic worms, the largest organisms studied by microbiologists, are often visible without a microscope, although their immature stages are microscopic.
7. Viruses, the smallest microbes, are so small they can be seen only by using an electron microscope.

The Golden Age of Microbiology (pp. 37–48)

1. The study of the Golden Age of Microbiology includes a look at the men who proposed or refuted the theory of **spontaneous generation:** Aristotle, Redi, Needham, Spallanzani, and Pasteur (the Father of Microbiology). The **scientific method** that emerged then remains the accepted sequence of study today.

2. The study of fermentation by Pasteur and Buchner led to the fields of **industrial microbiology (biotechnology)** and **biochemistry** and to the study of **metabolism.**
3. Koch, Pasteur, and others proved that **pathogens** cause infectious diseases, an idea that is known as the **germ theory of disease. Etiology** is the study of the causation of diseases.
4. Koch initiated careful microbiological laboratory techniques in his search for disease agents. **Koch's postulates,** the logical steps he followed to prove the cause of an infectious disease, remain an important part of microbiology today.
5. The procedure for the **Gram stain** was developed in the 1880s and is still used to differentiate bacteria into two categories: Gram positive and Gram negative.
6. The investigations of Semmelweis, Lister, Nightingale, and Snow are the foundations on which **infection control,** including control of **healthcare-associated infections (HAI),** and **epidemiology** are built.
7. Jenner's use of a cowpox-based vaccine for preventing smallpox began the field of **immunology.** Pasteur significantly advanced the field.
8. Ehrlich's search for "magic bullets"—chemicals that differentially kill microorganisms—laid the foundations for the field of **chemotherapy.**

The Modern Age of Microbiology (pp. 48–51)

1. Microbiology in the modern age has focused on answering questions regarding **biochemistry,** which is the study of metabolism; microbial genetics, which is the study of inheritance in microorganisms; and **molecular biology,** which involves investigations of cell function at the molecular level.
2. Scientists have applied knowledge from basic research to answer questions in **recombinant DNA technology** and **gene therapy.**
3. The study of microorganisms in their natural environment is **environmental microbiology.**
4. The discovery of chemicals in the blood that are active against specific pathogens advanced immunology and began the field of serology.
5. Advancements in chemotherapy were made in the 1900s with the discovery of numerous substances, such as penicillin and sulfa drugs, that inhibit pathogens.

QUESTIONS FOR REVIEW

Answers to the Questions for Review (except Short Answer questions) begin on p. 835.

Multiple Choice

1. Which of the following microorganisms does *not* cause diseases?
   a. archaea
   b. bacteria
   c. fungi
   d. protozoa
2. Which of the following microorganisms produces penicillin?
   a. bacteria
   b. molds
   c. algae
   d. yeasts
3. Which of the following diseases is caused by archaea?
   a. cat scratch
   b. variant CJD
   c. brucellosis
   d. none of the above
4. Of the following scientists, who first discovered the causative agent of pneumonia?
   a. David Bruce
   b. Charles Laveran
   c. Edwin Klebs
   d. Albert Fraenkel

5. Of the following scientists, who studied *Streptococcus* and later died of an infection caused by it?
   a. Joseph Lister
   b. Ignaz Semmelweis
   c. Robert Koch
   d. Louis Pasteur
6. Which scientist first hypothesized that medical personnel can infect patients with pathogens?
   a. Edward Jenner
   b. Joseph Lister
   c. John Snow
   d. Ignaz Semmelweis
7. Which of the following types of microbes was not described by Leeuwenhoek?
   a. bacteria
   b. molds
   c. archaea
   d. viruses
8. Which of the following favored the theory of spontaneous generation?
   a. Spallanzani
   b. Needham
   c. Pasteur
   d. Koch
9. A scientist who studies the occurrence, distribution, and spread of diseases in humans is a(n) _____.
   a. genetic technologist
   b. earth microbiologist
   c. epidemiologist
   d. environmental microbiologist
10. The laboratory of Robert Koch contributed which of the following to the field of microbiology?
    a. simple staining technique
    b. use of Petri dishes
    c. first photomicrograph of bacteria
    d. all of the above

Fill in the Blanks

Fill in the blanks with the name(s) of the scientist(s) whose investigations led to the following fields of study in microbiology.

1. Environmental microbiology _____ and _____
2. Biochemistry _____ and _____
3. Chemotherapy _____
4. Immunology _____
5. Infection control _____
6. Etiology _____
7. Epidemiology _____
8. Biotechnology _____
9. Food microbiology _____

Short Answer

1. Why was the theory of spontaneous generation a hindrance to the development of the field of microbiology?
2. Discuss the significant difference between the flasks used by Pasteur and Spallanzani. How did Pasteur's investigation settle the dispute about spontaneous generation?
3. List six types of microorganisms.
4. Defend this statement: "The investigations of Antoni van Leeuwenhoek changed the world forever."
5. Why would a *macro*scopic tapeworm be studied in *micro*biology?
6. Describe what has been called the "Golden Age of Microbiology" with reference to four major questions that propelled scientists during that period.
7. List four major questions that drive microbiological investigations today.
8. Refer to the four steps in the scientific method in describing Pasteur's fermentation experiments.
9. List Koch's postulates and explain why they are significant.
10. Name the bacterium that causes puerperal fever. How did Semmelweis's hypothesis help to control this bacterium from spreading?

VISUALIZE IT!

1. On the photos below, label *cilium*, *flagellum*, *nucleus*, and *pseudopod*.

2. Show where microbes ended up in Pasteur's experiment.

Matching

Match each of the following descriptions with the person it best describes. An answer may be used more than once.

1. _____ Developed smallpox immunization
2. _____ First photomicrograph of bacteria
3. _____ Germ theory of disease
4. _____ Germs cause disease
5. _____ Sought a "magic bullet" to destroy pathogens
6. _____ Early epidemiologist
7. _____ Father of Microbiology
8. _____ Classification system
9. _____ Discoverer of bacteria
10. _____ Discoverer of protozoa
11. _____ Founder of antiseptic surgery
12. _____ Developed the most widely used bacterial staining technique

A. John Snow
B. Paul Ehrlich
C. Louis Pasteur
D. Antoni van Leeuwenhoek
E. Carolus Linnaeus
F. John Needham
G. Eduard Buchner
H. Robert Koch
I. Joseph Lister
J. Edward Jenner
K. Girolamo Fracastoro
L. Hans Christian Gram

CRITICAL THINKING

1. If Robert Koch had become interested in a viral disease, such as influenza, instead of anthrax (caused by a bacterium), how might his list of lifetime accomplishments be different? Why?
2. In 1911, the Polish scientist Casimir Funk proposed that a limited diet of polished white rice (rice without the husks) caused beriberi, a disease of the central nervous system. Even though history has proven him correct—beriberi is caused by a thiamine deficiency, which in his day resulted from unsophisticated milling techniques that removed the thiamine-rich husks—Funk was criticized by his contemporaries, who told him to find the microbe that caused beriberi. Explain how the prevailing scientific philosophy of the day shaped Funk's detractors' point of view.
3. *Haemophilus influenzae* does not cause flu, but it received its name because it was once thought to be the cause. Explain how a proper application of Koch's postulates would have prevented this error in nomenclature.
4. Just before winter break in early December, your roommate stocks the refrigerator with a gallon of milk, but both of you leave before opening it. When you return in January, the milk has soured. Your roommate is annoyed because the milk was pasteurized and thus should not have spoiled. Explain why your roommate's position is unreasonable.
5. Explain the significant role that control groups play in order to validate a scientific experiment.
6. The British General Board of Health concluded in 1855 that the Broad Street cholera epidemic discussed in the chapter (see p. 47) resulted from fermentation of "nocturnal clouds of vapor" from the polluted Thames River. How could an epidemiologist prove or disprove this claim?
7. Compare and contrast the investigations of Redi, Needham, Spallanzani, and Pasteur in relation to the idea of spontaneous generation.
8. If you were a career counselor directing a student in the field of medical microbiology, describe three possible disciplines you could suggest.
9. A few bacteria produce disease because they derive nutrition from human cells and produce toxic wastes. Algae do not typically cause disease. Why not?
10. Imagine that you discover a new microorganism. How will you determine which class of microorganisms it belongs to?
11. French microbiologists, led by Pasteur, tried to isolate a single bacterium by diluting liquid media until only a single type of bacterium could be microscopically observed in a sample of the

diluted medium. What advantages does Koch's method have over the French method?

12. Why aren't Koch's postulates always useful in proving the cause of a given disease? Consider a variety of diseases, such as cholera, pneumonia, Alzheimer's, AIDS, Down syndrome, and lung cancer.

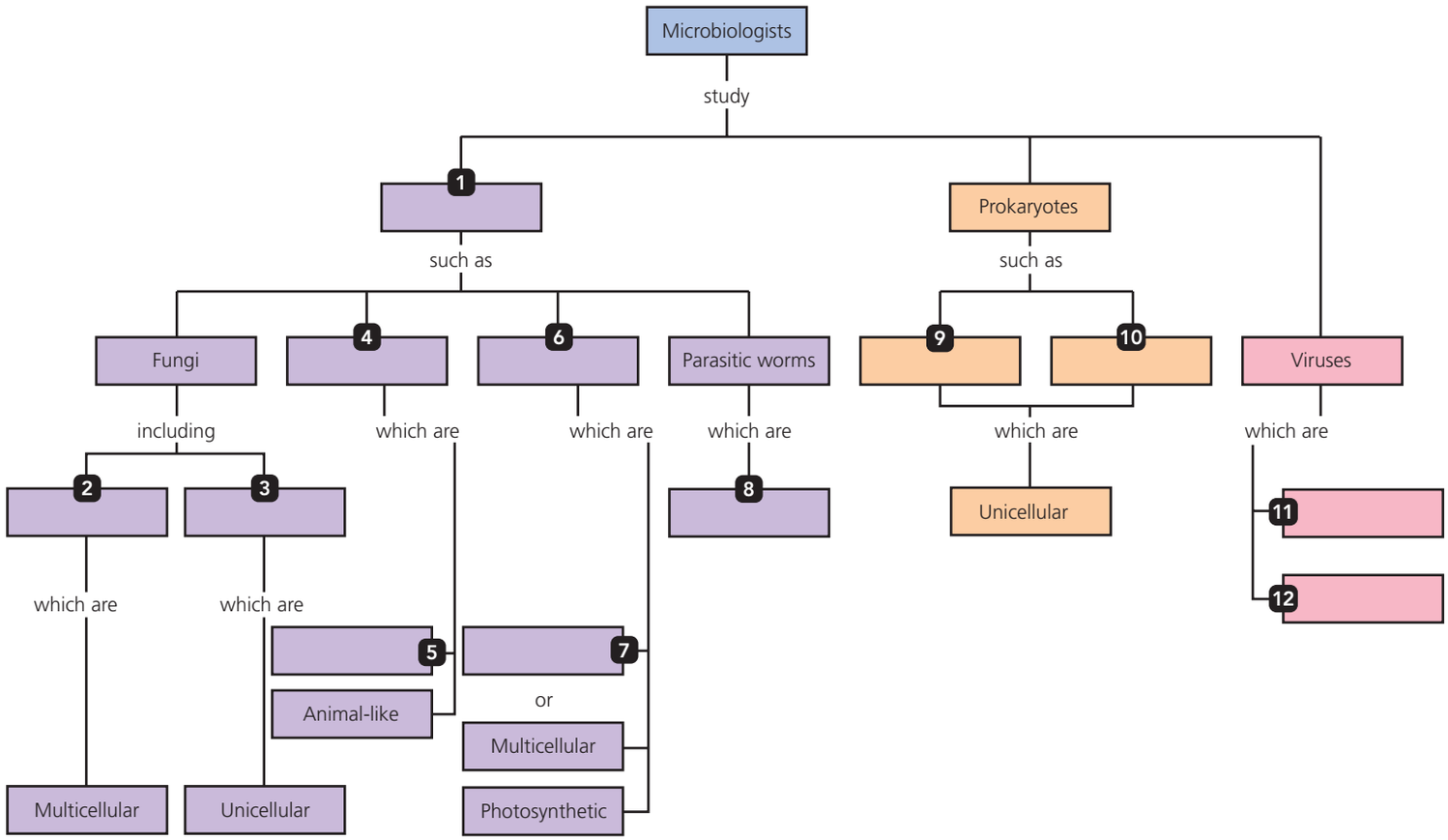
13. Albert Kluyver said, "From elephant to . . . bacterium—it is all the same!" What did he mean?

14. The ability of farmers around the world to produce crops such as corn, wheat, and rice is often limited by the lack of nitrogen-based fertilizer. How might scientists use Beijerinck's discovery to increase world supplies of grain?

CONCEPT MAPPING

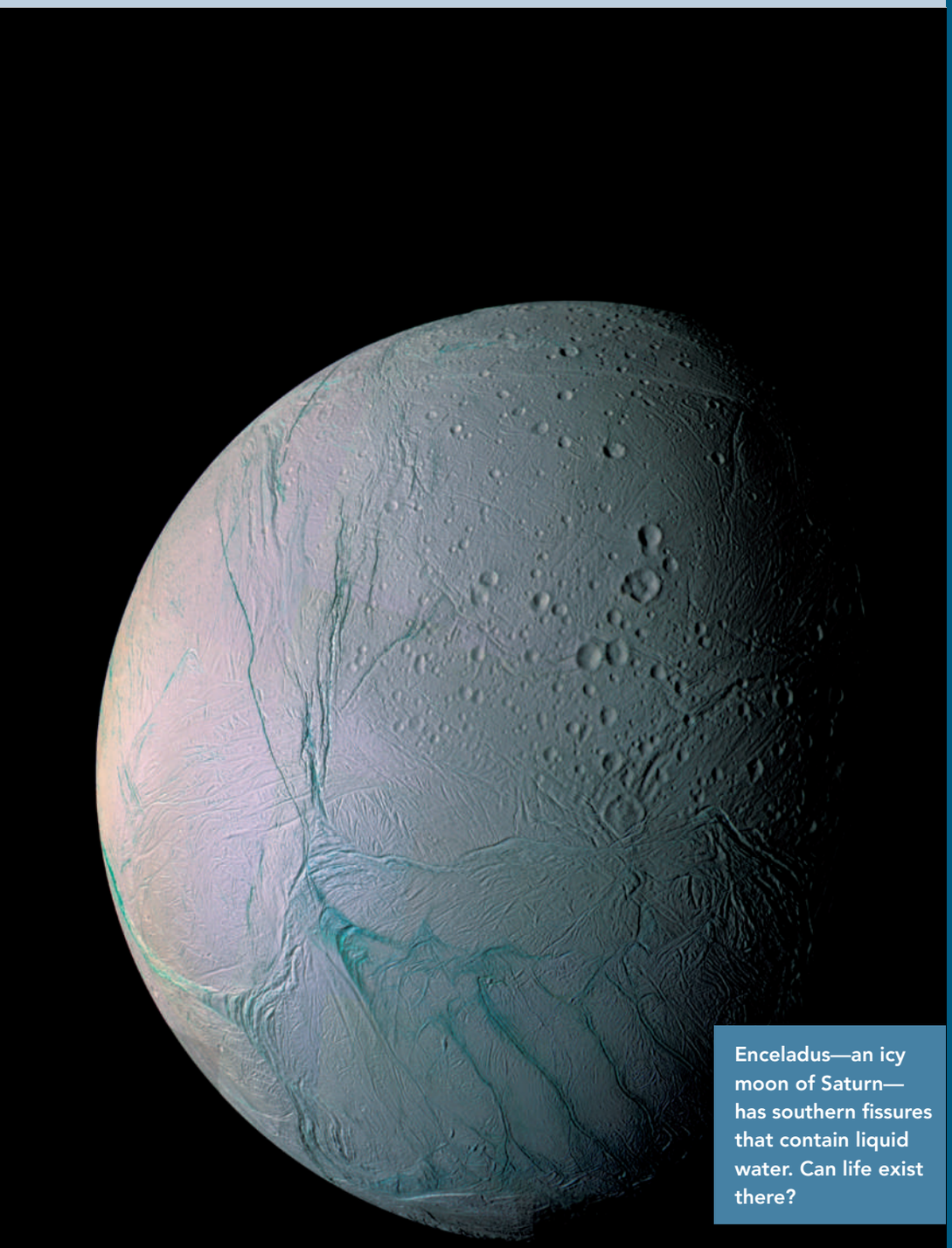
Using the following terms, fill in the following concept map that describes what microbiologists study. You can also complete this and other concept maps online by going to the MasteringMicrobiology Study Area.

Acellular
Algae
Animal-like
Archaea
Bacteria
Eukaryotes
Fungi
Molds
Multicellular
Obligate intracellular parasites
Parasitic worms
Photosynthetic
Prokaryotes
Protozoa
Unicellular (2)
Viruses
Yeasts



2

The Chemistry of Microbiology



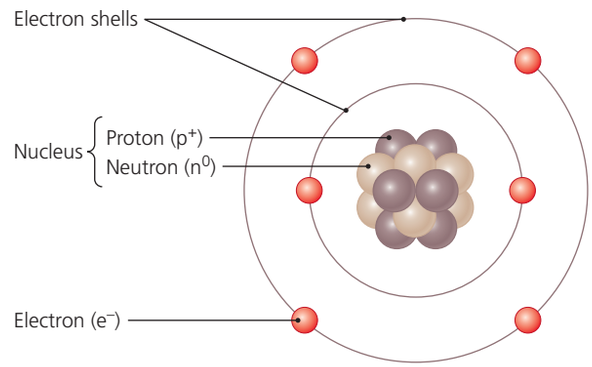
Enceladus—an icy moon of Saturn—has southern fissures that contain liquid water. Can life exist there?

IS THERE MICROBIAL LIFE ELSEWHERE in the solar system? Using telescopic observations and space probes of some of our nearest neighbors, we have identified chemicals necessary for life. For example, both Venus and Mars have water and carbon, in the form of carbon dioxide (CO_2); however, Enceladus, a small moon circling Saturn, is an even stronger candidate for life beyond Earth. Enceladus has warm liquid water beneath its frozen exterior; carbon is available in CO_2 and in organic molecules such as methane and propane; nitrogen is dissolved in the water. Thus, Enceladus has carbon, hydrogen, nitrogen, oxygen, and liquid water. The south pole of Enceladus has fissures that spew water and dissolved chemicals hundreds of kilometers into space. These fissures are similar to oceanic hydrothermal vents that support life in the depths of Earth's oceans.

How does an understanding of the chemistry of microbial life matter to our everyday lives? One way involves the concept of selective toxicity, the idea that because of chemical differences between the harmful microbes and us, drugs can be toxic to them and relatively harmless to us. Understanding these chemical differences and action of antimicrobial drugs begins with an understanding of basic chemistry—the subject of this chapter.

Learning or reviewing some basic concepts of chemistry will enable you to understand more fully the variety of interactions between microorganisms and their environment—which includes you. If you plan a career in health care, you will find microbial chemistry involved in the diagnosis of disease, the response of the immune system, the growth and identification of pathogenic microorganisms in the laboratory, and the function and selection of antimicrobial drugs. Understanding the fundamentals of chemistry will even help you preserve your own health.

In this chapter, we study atoms, which are the basic units of chemistry, and we consider how atoms react with one another to form chemical bonds and molecules. Then we examine the three major categories of chemical reactions. The chapter concludes with a look at the molecules of greatest importance to life: water, acids, bases, lipids, carbohydrates, proteins, nucleic acids, and ATP.



▲ **FIGURE 2.1 An example of a Bohr model of atomic structure.** This drawing is not to scale; for the electrons to be shown in scale with the greatly magnified nucleus, the electrons would have to occupy orbits located many miles from the nucleus. Put another way, the volume of an entire atom is about 100 trillion times the volume of its nucleus.

Atoms

LEARNING OUTCOME

2.1 Define *matter* and *atom* and explain how these terms relate to one another.

Matter is defined as anything that takes up space and has mass.[1] The smallest chemical units of matter are **atoms.** Atoms are extremely small, and only the very largest of them can be seen using the most powerful microscopes. Therefore, scientists have developed various models to conceptualize and illustrate the structure of atoms.

Atomic Structure

LEARNING OUTCOMES

2.2 Draw and label an atom, showing the parts of the nucleus and orbiting electrons.
2.3 Define *element*, *atomic number*, *atomic mass*, and *dalton* and explain how these terms relate to one another.

In 1913, the Danish physicist Niels H. D. Bohr (1885–1962) proposed a simple model in which negatively charged subatomic particles called **electrons** orbit a centrally located nucleus like planets in a miniature solar system **(FIGURE 2.1)**. A nucleus is composed of both uncharged **neutrons** and positively charged **protons.** (The only exception is the nucleus of a normal hydrogen atom, which is composed of only a single proton and no neutrons.)

An **element** is matter that is composed of a single type of atom. For example, gold is an element because it consists of only gold atoms. In contrast, the ink in your pen is not an element because it is composed of many different kinds of atoms.

Elements differ from one another in their **atomic number,** which is the number of protons in their nuclei. For example, the atomic numbers of hydrogen, carbon, and oxygen are 1, 6, and 8, respectively, because all hydrogen nuclei contain a single proton, all carbon nuclei have six protons, and all oxygen nuclei have eight protons.

The **atomic mass** of an atom (sometimes called its *atomic weight*) is the sum of the masses of its protons, neutrons, and electrons. Protons and neutrons each have a mass of approximately 1 *atomic mass unit*,[2] which is also called a *dalton*.[3] An electron is much less massive, with a mass of about 0.00054 dalton. Electrons are often ignored in discussions of atomic mass because their contribution to the overall mass is negligible. Therefore, the sum of the number of protons and neutrons approximates the atomic mass of an atom.

There are 93 naturally occurring elements known;[4] however, organisms typically utilize only about 20 elements, each of which has its own symbol that is derived from its English or Latin name (**TABLE 2.1** on p. 58).

Isotopes

LEARNING OUTCOME

2.4 List at least four ways that radioactive isotopes are useful.

Every atom of an element has the same number of protons, but atoms of a given element can differ in the number of neutrons in their nuclei. Atoms that differ in this way are called **isotopes.** For example, there are three naturally occurring isotopes of carbon, each having six protons and six electrons **(FIGURE 2.2)**. Over 95% of carbon atoms also have six neutrons. Because these carbon atoms have six protons and six neutrons, the atomic mass of this isotope is about 12 daltons, and it is known as carbon-12, symbolized as ^{12}C. Atoms of carbon-13 (^{13}C) have seven neutrons per nucleus, and ^{14}C atoms each have eight neutrons.

[1] *Mass* and *weight* are sometimes confused. Mass is the quantity of material in something, whereas weight is the effect of gravity on mass. Even though an astronaut is weightless in space, his mass is the same in space as on Earth.

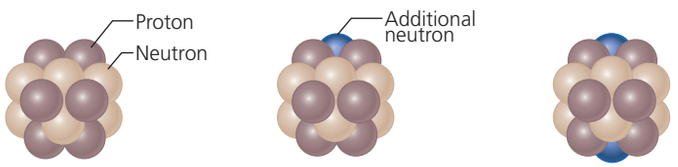
[2] An atomic mass unit (dalton) is 1/597,728,630,000,000,000,000,000, or 1.673×10^{-24}, grams.
[3] Named for John Dalton, the British chemist who helped develop atomic theory around 1800.
[4] For many years, scientists thought that there were only 92 naturally occurring elements, but natural plutonium was discovered in Africa in 1997.

TABLE 2.1 Common Elements of Life

Element	Symbol	Atomic Number	Atomic Mass[a] (daltons)	Biological Significance
Hydrogen	H	1	1	Component of organic molecules and water; H^+ released by acids
Boron	B	5	11	Essential for plant growth
Carbon	C	6	12	Backbone of organic molecules
Nitrogen	N	7	14	Component of amino acids, proteins, and nucleic acids
Oxygen	O	8	16	Component of many organic molecules and water; OH^- released by bases; necessary for aerobic metabolism
Sodium (Natrium)	Na	11	23	Principal cation outside cells
Magnesium	Mg	12	24	Component of many energy-transferring enzymes
Silicon	Si	14	28	Component of cell wall of diatoms
Phosphorus	P	15	31	Component of nucleic acids and ATP
Sulfur	S	16	32	Component of proteins
Chlorine	Cl	17	35	Principal anion outside cells
Potassium (Kalium)	K	19	39	Principal cation inside cells; essential for nerve impulses
Calcium	Ca	20	40	Utilized in many intercellular signaling processes; essential for muscular contraction
Manganese	Mn	25	54	Component of some enzymes; acts as intracellular antioxidant; used in photosynthesis
Iron (Ferrum)	Fe	26	56	Component of energy-transferring proteins; transports oxygen in the blood of many animals
Cobalt	Co	27	59	Component of vitamin B_{12}
Copper (Cuprum)	Cu	29	64	Component of some enzymes; used in photosynthesis
Zinc	Zn	30	65	Component of some enzymes
Molybdenum	Mo	42	96	Component of some enzymes
Iodine	I	53	127	Component of many brown and red algae

[a]Rounded to nearest whole number.

Unlike carbon-12 and carbon-13, the nucleus of carbon-14 is unstable because of the ratio of its protons and neutrons. Unstable atomic nuclei release energy and subatomic particles such as neutrons, protons, and electrons in a process called *radioactive decay*. Atoms that undergo radioactive decay are *radioactive isotopes*. Radioactive decay and radioactive isotopes play important roles in microbiological research, medical diagnosis, the treatment of disease, and the complete destruction of contaminating microbes (sterilization) of medical equipment and chemicals.



(a) Carbon-12 6 Protons 6 Neutrons

(b) Carbon-13 6 Protons 7 Neutrons

(c) Carbon-14 6 Protons 8 Neutrons

▲ FIGURE 2.2 Nuclei of the three naturally occurring isotopes of carbon. Each isotope also has six electrons, which are not shown. *What are the atomic number and atomic mass of each of these isotopes?*

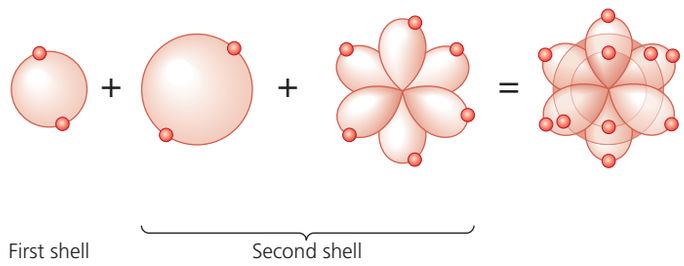
Figure 2.2 *The atomic number of all three is 6; their atomic masses are 12, 13, and 14, respectively.*

Electron Configurations

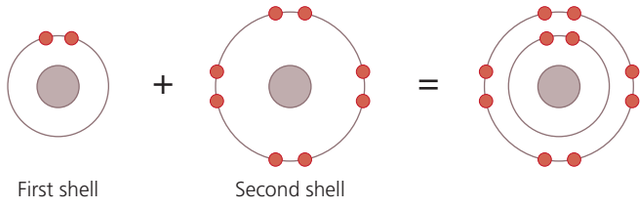
Although the nuclei of atoms determine their identities, it is electrons that determine an atom's *chemical behavior*. Nuclei of different atoms almost never come close enough together to interact.[5] Typically, only the electrons of atoms interact. Thus, because all of the isotopes of carbon (for example) have the same number of electrons, all these isotopes behave the same way in chemical reactions, even though their nuclei are different.

Scientists know that electrons do not really orbit the nucleus in a two-dimensional circle, as indicated by a Bohr model; instead, they speed around a nucleus 100 quadrillion times per second in three-dimensional *electron shells* or *clouds* that assume unique shapes dependent on the energy of the electrons **(FIGURE 2.3a)**. More accurately put, an electron shell depicts the *probable* locations of electrons at a given time; nevertheless, it is simpler and more convenient to draw electron shells as circles **(FIGURE 2.3b)**.

[5]Except during nuclear reactions, such as occur in nuclear power plants.



(a) Electron shells of neon: three-dimensional view



(b) Electron shells of neon: two-dimensional view

▲ **FIGURE 2.3 Electron configurations.** **(a)** Three-dimensional model of the electron shells of neon. In this model, the first shell is a small sphere, whereas the second shell consists of a larger sphere plus three pairs of ellipses that extend from the nucleus at right angles. Larger shells (not shown) are even more complex. **(b)** Two-dimensional model (Bohr diagram) of the electron shells of neon. *How many shells does a sodium atom need to hold its 11 electrons?*

Figure 2.3 *Three shells: two electrons in the first shell, eight in the second, and a single electron in the third.*

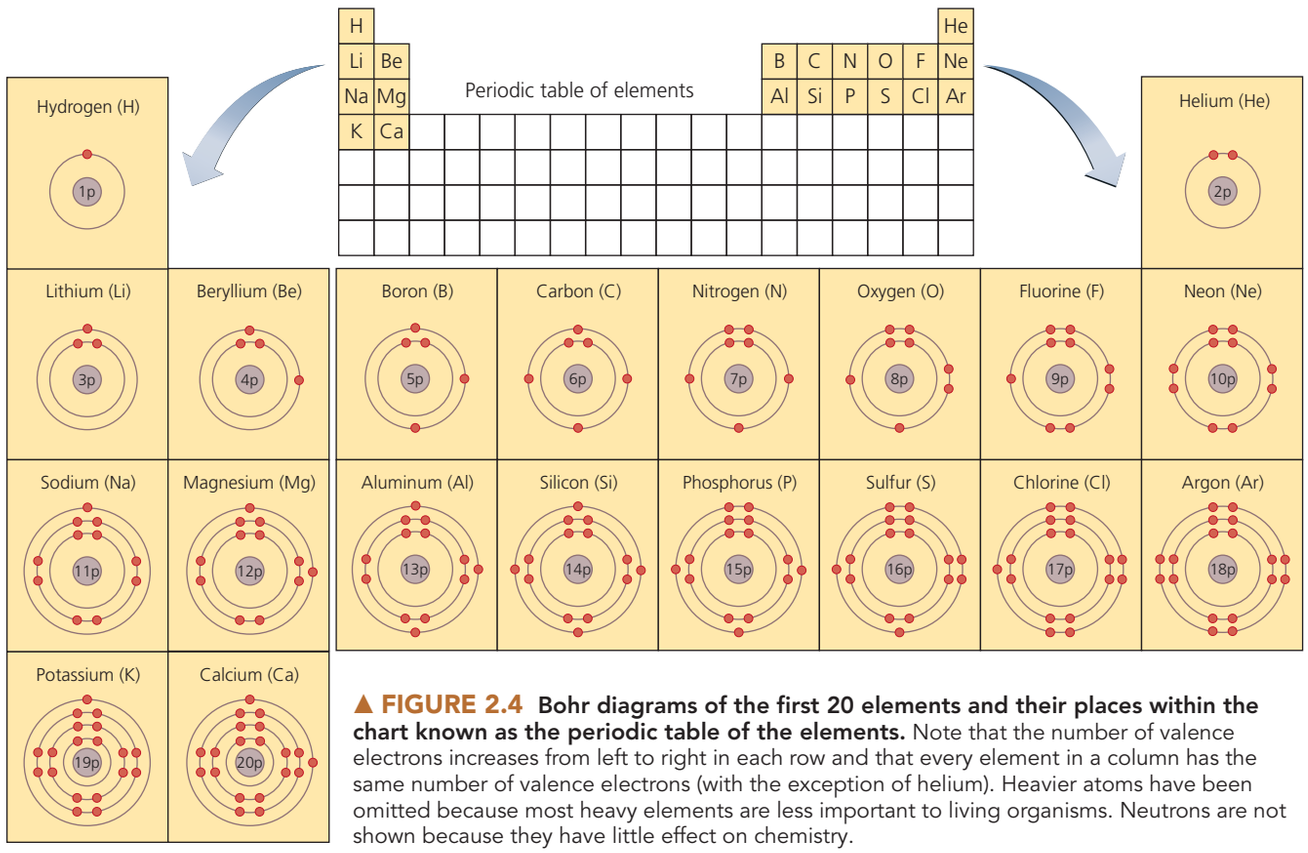
Each electron shell can hold only a certain maximum number of electrons. For example, the first shell (the one nearest the nucleus) can accommodate a maximum of two electrons, and the second shell can hold no more than eight electrons. Atoms of hydrogen and helium have one and two electrons, respectively; thus, these two elements have only a single electron shell. A lithium atom, which has three electrons, has two shells.

Atoms with more than 10 electrons require more shells. The third shell holds up to eight electrons when it is the outermost shell, though its capacity increases to 18 when the fourth shell contains two electrons. Heavier atoms have even more shells, but these atoms do not play significant roles in the processes of life.

Electrons in the outermost shell of atoms are called *valence electrons*. **FIGURE 2.4** depicts the electron configurations of atoms of some elements important to microbial life. Notice that except for helium, atoms of all elements in a given column of the periodic table of elements have the same number of valence electrons. Helium is placed in the far right-hand column with the other inert gases because its outer shell is full, though it has two rather than eight valence electrons. Valence electrons are critical for interactions between atoms. Next, we consider these interactions, which are called chemical bonds.

TELL ME WHY

Electrons zip around the nucleus at about 5 million miles per hour. Why don't they fly off?



▲ **FIGURE 2.4 Bohr diagrams of the first 20 elements and their places within the chart known as the periodic table of the elements.** Note that the number of valence electrons increases from left to right in each row and that every element in a column has the same number of valence electrons (with the exception of helium). Heavier atoms have been omitted because most heavy elements are less important to living organisms. Neutrons are not shown because they have little effect on chemistry.

Chemical Bonds

LEARNING OUTCOMES

2.5 Describe the configuration of electrons in a stable atom and explain how valence electrons form chemical bonds.
2.6 Contrast molecules and compounds.

Outer electron shells are stable when they contain eight electrons (except for the first electron shell, which is stable with only two electrons, because that is its maximum number). When atoms' outer shells are not filled with eight electrons, they either have room for more electrons or have "extra" electrons, depending on whether it is easier for them to gain electrons or lose electrons. For example, an oxygen atom, with six electrons in its outer shell, has two "unfilled spaces" (see Figure 2.4) because it requires less energy for the oxygen atom to gain two electrons than to lose six electrons. A calcium atom, by contrast, has two "extra" electrons in its outer (fourth) shell because it requires less energy to lose these two electrons than to gain six new ones. When a calcium atom loses two electrons, its third shell, which is then its outer shell, is full and stable with eight electrons.

As previously noted, an atom's outermost electrons are called valence electrons, and thus the outermost shell of an atom is the *valence shell*. An atom's **valence,**[6] defined as its combining capacity, is considered to be positive if its valence shell has extra electrons to give up and to be negative if its valence shell has spaces to fill. Thus, a calcium atom, with two electrons in its valence shell, has a valence of +2, whereas an oxygen atom, with two spaces to fill in its valence shell, has a valence of –2.

Atoms combine with one another by either sharing or transferring valence electrons in such a way as to fill their valence shells. Such interactions between atoms are called **chemical bonds.** Two or more atoms held together by chemical bonds form a **molecule.** A molecule that contains atoms of more than one element is a **compound.** Two hydrogen atoms bonded together form a hydrogen molecule, which is not a compound because only one element is involved. However, two hydrogen atoms bonded to an oxygen atom form a molecule of water (H_2O), which is a compound.

In this section, we discuss the three principal types of chemical bonds: *nonpolar covalent bonds*, *polar covalent bonds*, and *ionic bonds*. We also consider *hydrogen bonds*, which are weak forces that act with polar covalent bonds to give certain large chemicals their characteristic three-dimensional shapes.

Nonpolar Covalent Bonds

LEARNING OUTCOMES

2.7 Contrast nonpolar covalent, polar covalent, and ionic bonds.
2.8 Define *organic compound*.

A **covalent**[7] **bond** is the sharing of a pair of electrons between two atoms. Consider, for example, what happens when two hydrogen atoms approach one another. Each hydrogen atom consists of a single proton orbited by a single electron. Because the valence shell of each hydrogen atom requires two electrons in order to be full, each atom shares its single electron with the other, forming a hydrogen molecule in which both atoms have full shells **(FIGURE 2.5a)**. Similarly, two oxygen atoms can share electrons, but they must share *two* pairs of electrons for their valence shells to be full **(FIGURE 2.5b)**. Because two pairs of electrons are involved, oxygen atoms form two covalent bonds, or a *double covalent bond*, with one another.

The attraction of an atom for electrons is called its **electronegativity.** The more electronegative an atom, the greater the pull its nucleus exerts on electrons. Note in **FIGURE 2.6**, which displays the electronegativities of atoms of several elements, that electronegativities tend to increase from left to right in the chart. The reason is that elements toward the right of the chart have more protons and thus exert a greater pull on electrons. Electronegativities of elements decrease from top to bottom in the chart because the distance between the nucleus and the valence shell increases as elements get larger.

Atoms with equal or nearly equal electronegativities, such as two hydrogen atoms or a hydrogen and a carbon, share electrons equally or nearly equally. In chemistry and physics, "poles" are opposed forces, such as north and south magnetic poles or positive and negative terminals of a battery. In the case of atoms with similar electronegativities, the shared electrons tend to spend an equal amount of time around each nucleus of the pair, and no poles exist; therefore, the bond between them is a **nonpolar covalent bond.** (The covalent bonds illustrated in Figure 2.5a–c are nonpolar; formaldehyde, shown in Figure 2.5d, is polar.)

A hydrogen molecule can be symbolized a number of ways:

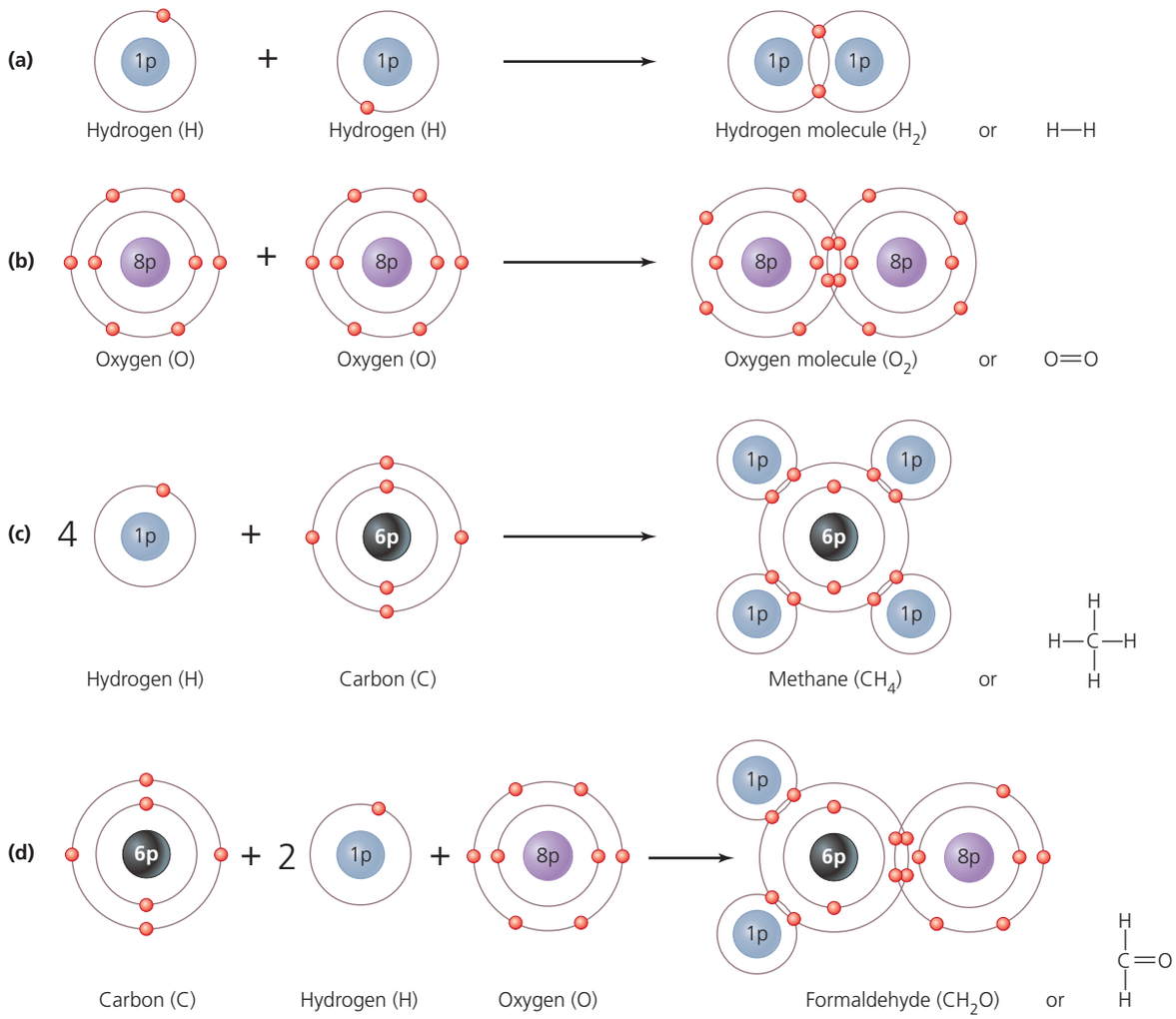
$$H—H \qquad H{:}H \qquad H_2$$

In the first symbol, the dash represents the chemical bond between the atoms. In the second symbol, the dots represent the electron pair of the covalent bond. These two symbols are known as *structural formulas*. In the third symbol, known as a *molecular formula*, the subscript "2" indicates the number of hydrogen atoms that are bonded, not the number of shared electrons. Each of these symbols indicates the same thing—two hydrogen atoms are sharing a pair of electrons.

Many atoms need more than one electron to fill their valence shell. For instance, a carbon atom has four valence electrons and needs to gain four more if it is to have eight in its valence shell. **FIGURE 2.5c** illustrates a carbon atom sharing with four hydrogen atoms. As before, a line in the structural formula represents a covalent bond formed from the sharing of two electrons. Two covalent bonds are formed between an oxygen atom and a carbon atom in formaldehyde **(FIGURE 2.5d)**. This fact is represented by a double line, which indicates that the carbon atom shares four electrons with the oxygen atom.

Carbon atoms are critical to life. Because a carbon atom has four electrons in its valence shell, it has equal tendencies to either lose four electrons or gain four electrons. Either event produces

[6]From Latin *valentia*, meaning "strength."
[7]From Latin *co*, meaning "with" or "together," and *valentia*, meaning "strength."



▲ **FIGURE 2.5** **Four molecules formed by covalent bonds.** **(a)** Hydrogen. Each hydrogen atom needs another electron to have a full valence shell. The two atoms share their electrons, forming a covalent bond. **(b)** Oxygen. Oxygen atoms have six electrons in their valence shells; thus, they need two electrons each. When they share with each other, two covalent bonds are formed. Note that the valence electrons of oxygen atoms are in the second shell. **(c)** A methane molecule, which has four single covalent bonds. **(d)** Formaldehyde. The carbon atom forms a double bond with the oxygen atom and single bonds with two hydrogen atoms. *Which of these molecules are also compounds? Why?*

Figure 2.5 *Methane and formaldehyde molecules are also compounds because they are composed of more than one element.*

a full outer shell. The result is that carbon atoms tend to share electrons and form four covalent bonds with one another and with many other types of atoms. Each carbon atom in effect acts as a four-way intersection where different components of a molecule can attach. One result of this feature is that carbon atoms can form very large chains that constitute the "backbone" of many biologically important molecules. Carbon chains can be branched or unbranched, and some even close back on themselves to form rings. Compounds that contain carbon and hydrogen atoms are called **organic compounds.** Among the many biologically important organic compounds are proteins and carbohydrates, which are discussed later in the chapter.

Polar Covalent Bonds

LEARNING OUTCOME

2.9 Explain the relationship between electronegativity and the polarity of a covalent bond.

If two covalently bound atoms have significantly different electronegativities, their electrons will not be shared equally. Instead, the electron pair will spend more time orbiting the nucleus of the atom with greater electronegativity. This type of bond, in which there is unequal sharing of electrons, is a **polar covalent bond.**

I	II	III	IV	V	VI	VII	Inert gases
H 2.1							He 0.0
Li 1.0	Be 1.5	B 2.0	C 2.5	N 3.0	O 3.5	F 4.0	Ne 0.0
Na 0.9	Mg 1.2	Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0	Ar 0.0
K 0.8	Ca 1.0	Ga 1.6	Ge 1.8	As 2.0	Se 2.4	Br 2.8	Kr 0.0

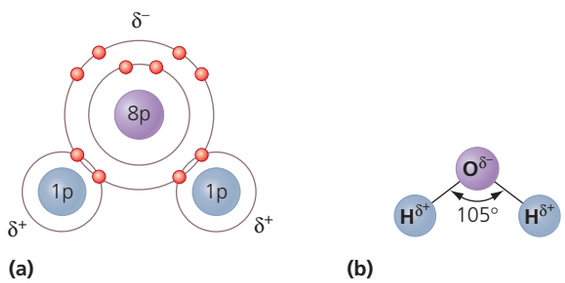
▲ FIGURE 2.6 Electronegativity values of selected elements. The values are expressed according to the Pauling scale, named for the Nobel Prize–winning chemist Linus Pauling, who based the scale on bond energies. Pauling chose to compare the electronegativity of each element to that of fluorine, to which he assigned a value of 4.0.

An example of a molecule with polar covalent bonds is water **(FIGURE 2.7a)**.

Because oxygen is more electronegative than hydrogen, the electrons spend more time near the oxygen nucleus than near the hydrogen nuclei, and thus the oxygen atom acquires a transient (partial) negative charge (symbolized as δ^-). Each of the hydrogen nuclei has a corresponding transient positive charge (δ^+). The covalent bond between an oxygen atom and a hydrogen atom is called polar because the atoms have opposite partial electrical charges.

Polar covalent bonds can form between many different elements. Generally, molecules with polar covalent bonds are water soluble, and nonpolar molecules are not. The most important polar covalent bonds for life are those that involve hydrogen because they allow hydrogen bonding, which we discuss shortly.

Both nonpolar and polar covalent bonds form angles between atoms such that the distances between electron orbits are maximized. The bond angle for water is shown in **FIGURE 2.7b**.



▲ FIGURE 2.7 Polar covalent bonding in a water molecule. **(a)** A Bohr model of a water molecule, which has two polar covalent bonds. When the electronegativities of two atoms are significantly different, the shared electrons of covalent bonds spend more time around the more electronegative atom, giving it a transient negative charge (δ^-). Its partner has a transient positive charge (δ^+). **(b)** The bond angle in a water molecule. Atoms maximize the distances between electron orbitals in polar and nonpolar covalent bonds.

However, it is more convenient to simply draw molecules as if all the atoms were in one plane; for example, H—O—H.

Ionic Bonds

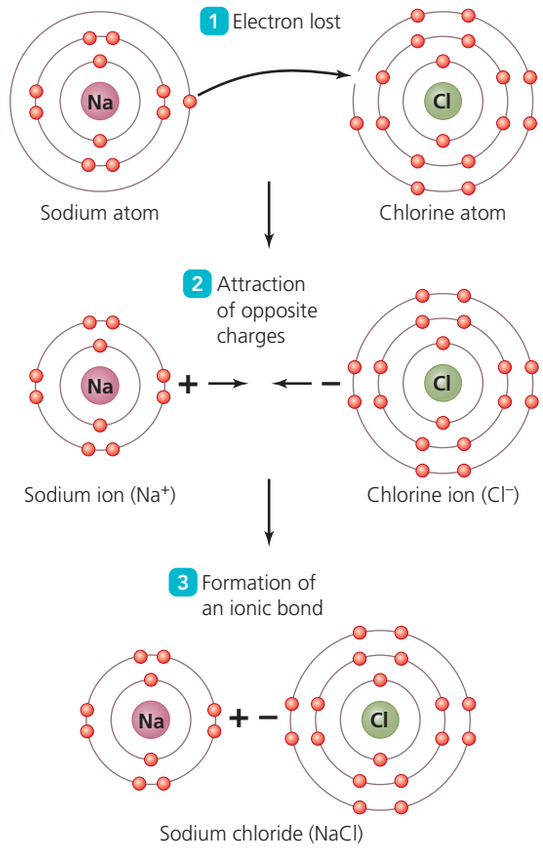
LEARNING OUTCOMES

2.10 Define *ionization* using the terms *cation* and *anion*.
2.11 Contrast the formation of an ionic bond with that of a covalent bond.

Consider what happens when two atoms with vastly different electronegativities—for example, sodium, with one electron in its valence shell and an electronegativity of 0.9, and chlorine, with seven electrons in its valence shell and an electronegativity of 3.0—come together **(FIGURE 2.8)**. Chlorine has such a higher electronegativity that it very strongly attracts sodium's single valence electron, and the result is that the sodium loses that electron to chlorine 1.

Now that the chlorine atom has one more electron than it has protons, it has a full negative charge, and the sodium atom, which has lost an electron, now has a full positive charge 2. An atom or group of atoms that has either a full negative charge or a full positive charge is called an *ion*. Positively charged ions are called **cations,** whereas negatively charged ions are called **anions.**

Because of their opposite charges, cations and anions attract each other and form what is termed an **ionic bond** 3.

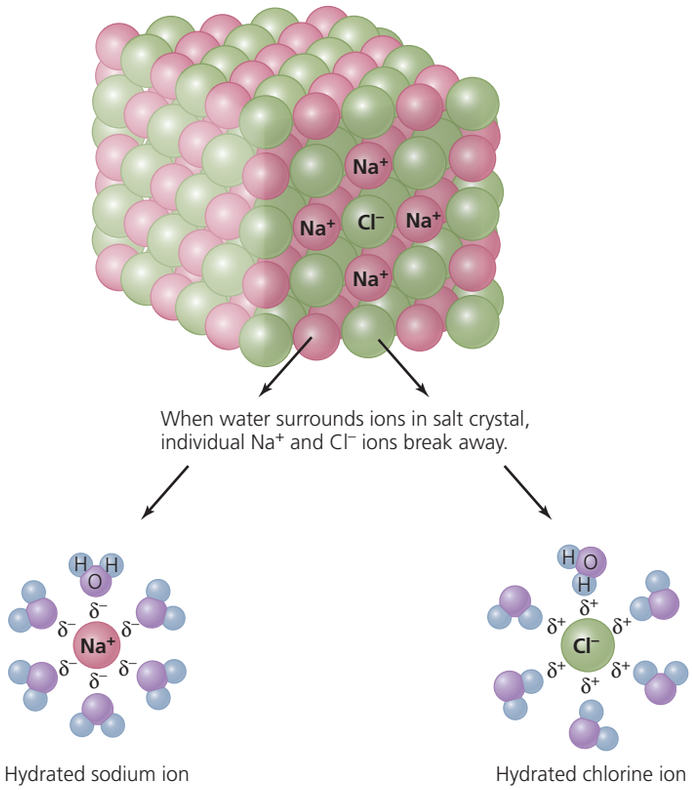


▲ FIGURE 2.8 The interaction of sodium and chlorine to form an ionic bond.

They form crystalline compounds composed of metallic and nonmetallic ions. These compounds are known as **salts,** such as sodium chloride (NaCl), also known as table salt, and potassium chloride (KCl, sodium-free table salt). Ionic bonds differ from covalent bonds in that ions do not share electrons. Instead, the bond is formed from the attraction of opposite electrical charges.

The polar bonds of water molecules interfere with the ionic bonds of salts, causing *dissociation* (also called *ionization*) **(FIGURE 2.9)**. This occurs as the partial negative charge on the oxygen atom of water attracts cations, and the partial positive charge on hydrogen atoms attracts anions. The presence of polar bonds interferes with the attraction between the cation and anion.

When cations and anions dissociate from one another and become surrounded by water molecules (are hydrated), they are called **electrolytes** because they can conduct electricity through the solution. Electrolytes are critical for life because they stabilize a variety of compounds, act as electron carriers, and allow electrical gradients to exist within cells. We examine these functions of electrolytes in later chapters.



▲ **FIGURE 2.9 Dissociation of NaCl in water.** When water surrounds the ions in a NaCl crystal, the partial charges on water molecules are attracted to charged ions, and the water molecules hydrate the ions by surrounding them. The partial negative charges (δ^-) on oxygen atoms are attracted to cations (in this case, the sodium ions), and the partial positive charges (δ^+) on hydrogen atoms are attracted to anions (the chlorine ions). Because the ions no longer attract one another, the salt crystal dissolves. Hydrated ions are called electrolytes.

In nature, chemical bonds range from nonpolar bonds to polar bonds to ionic bonds. The important thing to remember is that electrons are shared between atoms in covalent bonds and transferred from one atom to another in ionic bonds.

Hydrogen Bonds

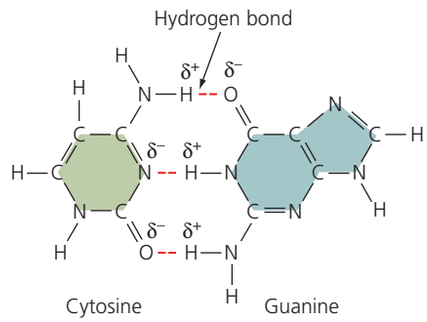
LEARNING OUTCOME

2.12 Describe hydrogen bonds and discuss their importance in living organisms.

As we have seen, hydrogen atoms bind to oxygen atoms by means of polar covalent bonds, resulting in transient positive charges on the hydrogen atoms. Hydrogen atoms form polar covalent bonds with atoms of other elements as well.

The electrical attraction between a partially charged hydrogen atom and a full or partial negative charge on either a different region of the same molecule or another molecule is called a **hydrogen bond (FIGURE 2.10)**. Hydrogen bonds can be likened to weak ionic bonds in that they arise from the attraction of positive and negative charges. Notice also that although they are a consequence of polar covalent bonds between hydrogen atoms and other, more electronegative atoms, hydrogen bonds themselves are not covalent bonds—they do not involve the sharing of electrons.

As we have seen, covalent bonds are essential for life because they strongly link atoms together to form molecules. Hydrogen bonds, though weaker than covalent bonds, are also essential. The cumulative effect of numerous hydrogen bonds is to stabilize the three-dimensional shapes of large molecules. For example, the familiar double-helix shape of DNA is due in part to the stabilizing effects of thousands of hydrogen bonds holding the molecule together. Hydrogen bonds play a role in the recognition of target cells by pathogens and also play a role in maintaining the exact shape of enzymes, antibodies, and intercellular chemical messengers, which is critical for their correct function. Further, because hydrogen bonds are weak, they can be overcome when necessary. For example, the two



▲ **FIGURE 2.10 Hydrogen bonds.** The transient positive charge (symbolized δ^+) on a hydrogen atom is attracted to a transient negative charge (δ^-) on another atom. Such attraction is a hydrogen bond. Hydrogen bonds can hold together portions of the same molecule or hold two different molecules together. In this case, three hydrogen bonds are holding molecules of cytosine and guanine together.

TABLE 2.2 Characteristics of Chemical Bonds

Type of Bond	Description	Relative Strength
Nonpolar covalent bond	Pair of electrons is nearly equally shared between two atoms	Strong
Polar covalent bond	Electrons spend more time around the more electronegative of two atoms	Strong
Ionic bond	Electrons are stripped from a cation by an anion	Weaker than covalent in aqueous environments
Hydrogen bond	Partial positive charges on hydrogen atoms are attracted to full and partial negative charges on other molecules or other regions of the same molecule	Weaker than ionic

complementary halves of a DNA molecule are held together primarily by hydrogen bonds, and they can be separated for DNA replication and other processes (see Chapter 7; Figure 7.6).

TABLE 2.2 summarizes some characteristics of chemical bonds.

TELL ME WHY

Chlorine and potassium atoms form ionic bonds, carbon atoms form nonpolar covalent bonds with nitrogen atoms, and oxygen forms polar covalent bonds with phosphorus. Explain why these bonds are the types they are.

Chemical Reactions

LEARNING OUTCOME

2.13 Describe three general types of chemical reactions found in living things.

You are already familiar with many consequences of chemical reactions: you add yeast to bread dough, and it rises; enzymes in your laundry detergent remove grass stains; and gasoline burned in your car releases energy to speed you on your way. What exactly is happening in these reactions? What is the precise definition of *chemical reaction*?

We have discussed how bonds are formed via the sharing of electrons or the attraction of positive and negative charges. Scientists define **chemical reactions** as the making or breaking of such chemical bonds. All chemical reactions begin with **reactants**—the atoms, ions, or molecules that exist at the beginning of a reaction. Similarly, all chemical reactions result in **products**—the atoms, ions, or molecules left after the reaction is complete. *Biochemistry* involves the chemical reactions of living things.

Reactants and products may have very different physical and chemical characteristics. For example, hydrogen and oxygen are gases and have very different properties from water, which is composed of hydrogen and oxygen atoms. However, the numbers and types of atoms never change in a chemical reaction; atoms are neither destroyed nor created, only rearranged.

Now let's turn our attention to three general categories of biochemical reactions (reactions that occur in organisms): *synthesis*, *decomposition*, and *exchange reactions*.

Synthesis Reactions

LEARNING OUTCOMES

2.14 Give an example of a synthesis reaction that involves the formation of a water molecule.
2.15 Contrast endothermic and exothermic chemical reactions.

Synthesis reactions involve the formation of larger, more complex molecules. Synthesis reactions can be expressed symbolically as

$$\text{Reactant} + \text{Reactant} \rightarrow \text{Product(s)}$$

The arrow indicates the direction of the reaction and the formation of new chemical bonds. For example, algae make their own glucose (sugar) using the following reaction:

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

The reaction is read, "Six molecules of water plus six molecules of carbon dioxide yield one molecule of glucose and six molecules of oxygen." Notice that the total number and kind of atoms are the same on both sides of the reaction.

A common synthesis reaction in biochemistry is a **dehydration synthesis,** in which two smaller molecules are joined together by a covalent bond, and a water molecule is also formed **(FIGURE 2.11a)**. The word *dehydration* in the name of this type of reaction refers to the fact that one of the products is a water molecule formed when a hydrogen ion (H^+) from one reactant combines with a hydroxyl ion (OH^-) from another reactant.

Synthesis reactions require energy to break bonds in the reactants and to form new bonds to make products. Reactions that require energy are said to be **endothermic**[8] **reactions** because they trap energy within new molecular bonds. An energy supply for fueling synthesis reactions is one common requirement of all living things (Chapter 6).

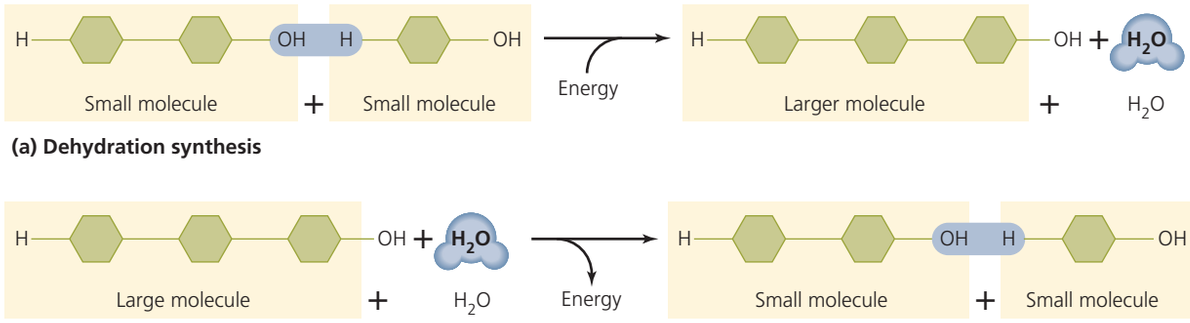
Taken together, all of the synthesis reactions in an organism are called **anabolism.**

Decomposition Reactions

LEARNING OUTCOME

2.16 Give an example of a decomposition reaction that involves breaking the bonds of a water molecule.

[8]From Greek *endon*, meaning "within," and *thermos*, meaning "heat" (energy).



▲ FIGURE 2.11 Two types of chemical reactions in living things. (a) Dehydration synthesis. In this energy-requiring reaction, a hydroxyl ion (OH^-) removed from one reactant and a hydrogen ion (H^+) removed from another reactant combine to form hydrogen hydroxide (HOH), which is water. **(b)** Hydrolysis, an energy-yielding reaction that is the reverse of a dehydration synthesis reaction. *What are the scientific words meaning "energy-requiring" and "energy-releasing"?*

Figure 2.11 Endothermic *means "energy-requiring," and* exothermic *means "energy-releasing."*

Decomposition reactions are the reverse of synthesis reactions in that they break bonds within larger molecules to form smaller atoms, ions, and molecules. These reactions release energy and are therefore **exothermic reactions.**[9] In general, decomposition reactions can be represented by the following formula:

$$\text{Reactant} \rightarrow \text{Product} + \text{Product}$$

An example of a biologically important decomposition reaction is the aerobic decomposition of glucose to form carbon dioxide and water:

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

Note that this reaction is exactly the reverse of the synthesis reaction in algae that we examined previously. Synthesis and decomposition reactions are often reversible in living things.

A common type of decomposition reaction in biochemistry is **hydrolysis,**[10] the reverse of dehydration synthesis **(FIGURE 2.11b)**. In hydrolytic reactions, a covalent bond in a large molecule is broken, and the ionic components of water (H^+ and OH^-) are added to the products.

Collectively, all of the decomposition reactions in an organism are called **catabolism.**

Exchange Reactions

LEARNING OUTCOME

2.17 Compare exchange reactions to synthesis and decomposition reactions.

Exchange reactions (also called *transfer reactions*) have features similar to both synthesis and decomposition reactions. For instance, they involve breaking and forming covalent bonds, and they involve both endothermic and exothermic steps. As the name suggests, atoms are moved from one molecule to another. In general, these reactions can be represented as either

$$A + BC \rightarrow AB + C$$

or

$$AB + CD \rightarrow AD + BC$$

An important exchange reaction within organisms is the phosphorylation of glucose:

$$C_6H_{12}O_6 + A\text{–}\textcircled{P}\text{–}\textcircled{P}\text{–}\textcircled{P} \longrightarrow C_6H_{11}O_6\text{–}\textcircled{P} + A\text{–}\textcircled{P}\text{–}\textcircled{P} + H^+$$

Glucose — Adenosine triphosphate — Glucose phosphate — Adenosine diphosphate

The sum of all of the chemical reactions in an organism, including catabolic, anabolic, and exchange reactions, is called **metabolism.** (Chapter 5 examines metabolism in more detail.)

TELL ME WHY

Why are decomposition reactions exothermic, that is, energy releasing?

Water, Acids, Bases, and Salts

As previously noted, living things depend on organic compounds, those that contain carbon and hydrogen atoms. Living things also require a variety of **inorganic chemicals,** which typically lack carbon. Such inorganic substances include water, oxygen molecules, metal ions, and many acids, bases, and salts. In this section, we examine the characteristics of some of these inorganic substances.

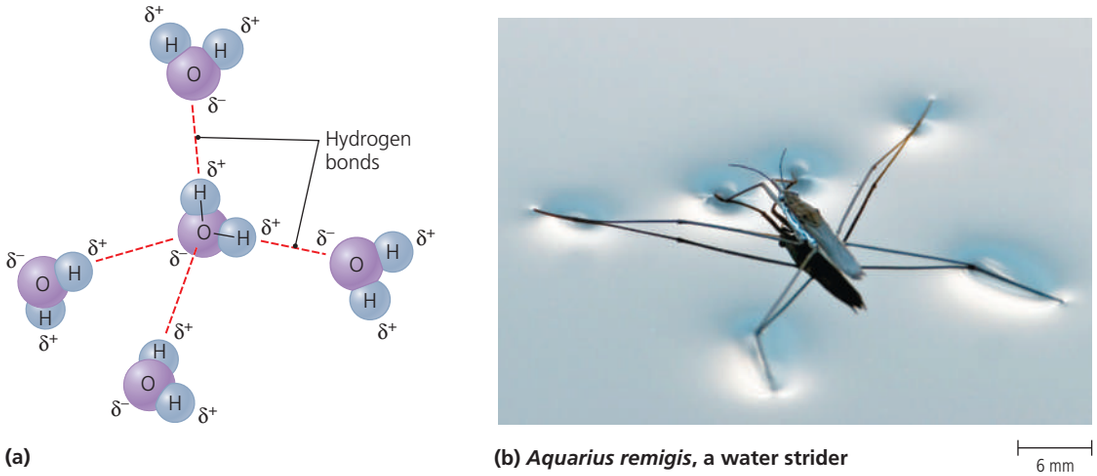
Water

LEARNING OUTCOME

2.18 Describe five qualities of water that make it vital to life.

Water is the most abundant substance in organisms, constituting 50% to 99% of their mass. Most of the special characteristics

[9]From Greek *exo*, meaning "outside," and *thermos*, meaning "heat" (energy).
[10]From Greek *hydor*, meaning "water," and *lysis*, meaning "loosening."



(a) (b) *Aquarius remigis*, a water strider

▲ **FIGURE 2.12 The cohesiveness of liquid water.** **(a)** Water molecules are cohesive because hydrogen bonds cause them to stick to one another. **(b)** One result of cohesiveness in water is surface tension, which can be strong enough to support the weight of insects known as water striders.

that make water vital result from the fact that a water molecule has two polar covalent bonds, which allow hydrogen bonding between water molecules and their neighbors. Among the special properties of water are the following:

- Water molecules are cohesive; that is, they tend to stick to one another through hydrogen bonding **(FIGURE 2.12)**. This property generates many special characteristics of water, including *surface tension*, which allows water to form a thin layer on the surface of cells. This aqueous layer is necessary for the transport of dissolved materials into and out of a cell.
- Water is an excellent *solvent;* that is, it dissolves salts and other electrically charged molecules because it is attracted to both positive and negative charges (see Figure 2.9).
- Water remains a liquid across a wider range of temperatures than other molecules of its size. This is critical because living things require water in liquid form.
- Water can absorb significant amounts of heat energy without itself changing temperature. Further, when heated water molecules eventually evaporate, they take much of this absorbed energy with them. These properties moderate temperature fluctuations that would otherwise damage organisms.
- Water molecules participate in many chemical reactions within cells both as reactants in hydrolysis and as products of dehydration synthesis.

Acids and Bases

LEARNING OUTCOME

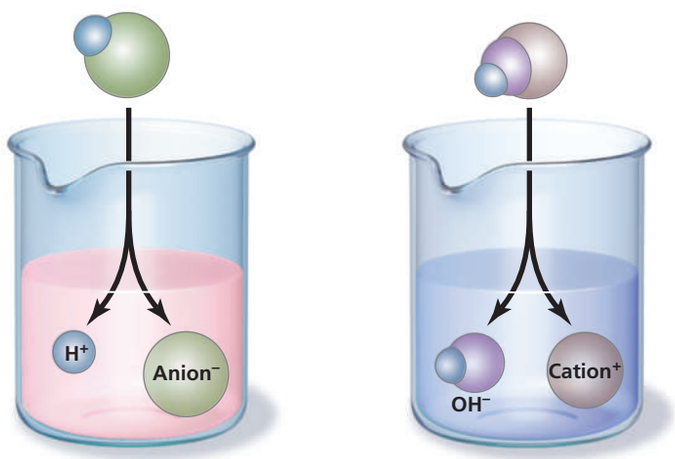
2.19 Contrast acids, bases, and salts and explain the role of buffers.

As we have seen, the polar bonds of water molecules dissociate salts into their component cations and anions. A similar process occurs with substances known as acids and bases.

An **acid** is a substance that dissociates into one or more hydrogen ions (H^+) and one or more anions **(FIGURE 2.13a)**. Acids can be inorganic molecules, such as hydrochloric acid (HCl) and sulfuric acid (H_2SO_4), or organic molecules, such as amino acids and nucleic acids. Familiar organic acids are found in lemon juice, black coffee, and tea. Of course, the anions of organic acids contain carbon, whereas those of inorganic acids do not.

A **base** is a molecule that binds with H^+ when dissolved in water. Some bases dissociate into cations and *hydroxyl ions* (OH^-) **(FIGURE 2.13b)**, which then combine with hydrogen ions to form water molecules:

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



(a) Acid (b) Base

▲ **FIGURE 2.13 Acids and bases.** **(a)** Acids dissociate in water into hydrogen ions and anions. **(b)** Many bases dissociate into hydroxyl ions and cations.

Other bases, such as household ammonia (NH_3), directly accept hydrogen ions and become compound ions such as NH_4^+ (ammonium). Another common household base is baking soda (sodium bicarbonate, $NaHCO_3$).

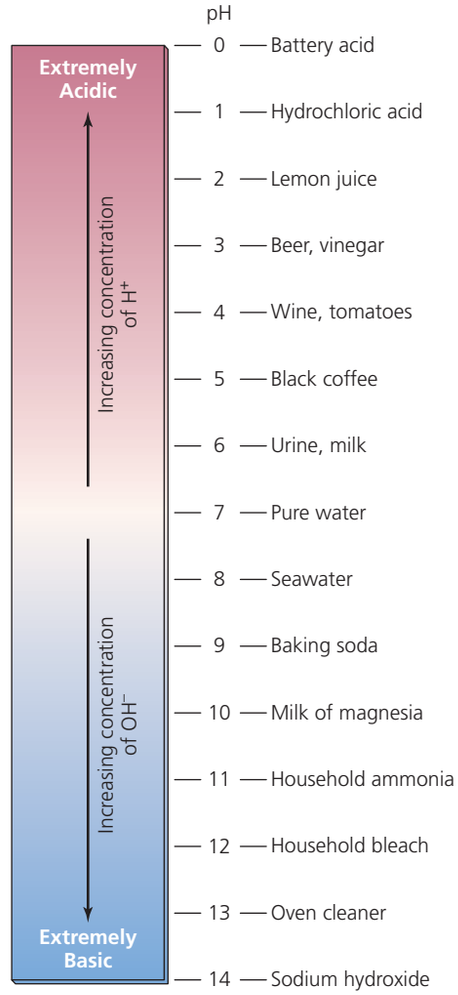
Metabolism requires a relatively constant balance of acids and bases because hydrogen ions and hydroxyl ions are involved in many chemical reactions. Further, many complex molecules such as proteins lose their functional shapes when acidity changes. If the concentration of either hydrogen ions or hydroxyl ions deviates too far from normal, metabolism ceases.

The concentration of hydrogen ions in a solution is expressed using a logarithmic **pH scale** (FIGURE 2.14). The term *pH* comes from *potential hydrogen*, which is the negative of the logarithm of the concentration of hydrogen ions. In this logarithmic scale, it is important to notice that acidity increases as pH values decrease and that each decrease by a whole number in pH indicates a 10-fold increase in acidity (hydrogen ion concentration). For example, a glass of grapefruit juice, which has a pH of 3.0, contains 10 times as many hydrogen ions as the same volume of tomato juice, which has a pH of 4.0. Similarly, tomato juice is 1000 times more acidic than pure water, which has a pH of 7.0 (neutral). Water is neutral because it dissociates into one hydrogen cation and one hydroxyl anion:

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

Alkaline (basic) substances have pH values greater than 7.0. They reduce the number of free hydrogen ions by combining with them. For bases that produce hydroxyl ions, the concentration of hydroxyl ions is inversely related to the concentration of hydrogen ions.

Organisms can tolerate only a certain, relatively narrow pH range. Fluctuations outside an organism's preferred range inhibit its metabolism and may even be fatal. Most organisms contain natural **buffers**—substances, such as proteins,



▲ **FIGURE 2.14 The pH scale.** Values below 7 are acidic; values above 7 are basic.

BENEFICIAL MICROBES

Architecture-Preserving Bacteria

The Alhambra, a Moorish palace constructed of limestone and marble beginning in the 9th century, was built to last. But not even stone lasts forever. Wind and rain wear away the surface. Acid rain reacts with the calcite crystals in limestone and marble. As years pass, stone slowly crumbles.

Those who would preserve the Alhambra and other historic structures face a dilemma. The microscopic pores that riddle limestone and marble make these materials particularly susceptible to weathering and decay. Sealing the stone's pores can reduce weathering but can also lock in moisture that speeds the stone's decay.

With the help of *Myxococcus xanthus*, a bacterium commonly found in soil, a team of researchers led by mineralogist Carlos Rodríguez-Navarro of the University of Granada may have found a way to protect the stone of structures like the Alhambra.

The Alhambra

In many natural environments, bacteria instigate the formation of calcite crystals like the ones in limestone. In tests conducted using samples of the limestone commonly used in historic Spanish buildings, *M. xanthus* formed calcite crystals that lined the stone's pores rather than plugging them. The crystals formed by the bacteria are even more durable than the original stone, offering the potential for long-term protection.

that prevent drastic changes in internal pH by removing excess hydrogen and hydroxyl ions. In a laboratory culture, the metabolic activity of microorganisms can change the pH of microbial growth solutions as nutrients are taken up and wastes are released; therefore, pH buffers are often added to them. One common buffer used in microbiological media is KH_2PO_4 (potassium dihydrogen phosphate), which exists as either a weak acid or a weak base, depending on the pH of its environment. Under acidic conditions, KH_2PO_4 is a base that combines with H^+, neutralizing the acidic environment; in alkaline conditions, however, KH_2PO_4 acts as an acid, releasing hydrogen ions.

Microorganisms differ in their ability to tolerate various ranges of pH. Many grow best when the pH is between 6.5 and 8.5. Photosynthetic bacteria known as *cyanobacteria* grow well in more basic solutions. Fungi generally tolerate acidic environments better than most prokaryotes, though acid-loving prokaryotes, called *acidophiles*, require acidic conditions. Some bacteria are tolerant of acid. One such bacterium is *Propionibacterium acnes* (prō-pē-on-i-bak-tēr´ē-ŭm ak´nēz). This bacterium can cause acne in the skin, which normally has a pH of about 4.0. Another is *Helicobacter pylori* (hel´ĭ-kō-bak´ter pī´lō-rē),[11] a curved bacterium that has been shown to cause ulcers in the stomach, where pH can fall as low as 1.5 when acid is being actively secreted. **Clinical Case Study: Raw Oysters and Antacids: A Deadly Mix?** focuses on how the use of antacids may increase the survival rates of certain disease-causing bacteria in the stomach.

Microorganisms can change the pH of their environment by utilizing acids and bases and by producing acidic or basic wastes. For example, fermentative microorganisms form organic acids from the decomposition of sugar, and the bacterium *Thiobacillus* (thī-ō-bă-sil´ŭs) can reduce the pH of its environment to 0.0. Some mining companies rely on acid produced by this bacterium to dissolve uranium and copper from low-grade ore.

Scientists measure pH with a pH meter or with test papers impregnated with chemicals (such as litmus or phenol red) that change color in response to pH. In a microbiological laboratory, changes in color of such pH indicators incorporated into microbial growth media are commonly used to distinguish among bacterial genera.

Salts

As we have seen, a salt is a compound that dissociates in water into cations and anions other than H^+ and OH^-. Acids and hydroxyl-yielding bases neutralize each other during exchange reactions that produce water and salt. For instance, milk of magnesia (magnesium hydroxide) is an antacid used to neutralize excess stomach acid. The chemical reaction is

$$\underset{\text{Magnesium hydroxide}}{Mg(OH)_2} + \underset{\text{Hydrochloric acid}}{2\,HCl} \longrightarrow \underset{\text{Magnesium chloride (salt)}}{MgCl_2} + \underset{\text{Water}}{2H_2O}$$

[11]The name *pylori* refers to the pylorus, a region of the stomach.

CLINICAL CASE STUDY

Raw Oysters and Antacids: A Deadly Mix?

The highly acidic environment of the stomach kills most bacteria before they cause disease. One bacterium that can slightly tolerate conditions as it passes through the stomach is *Vibrio vulnificus*—a bacterium commonly ingested by eating raw tainted oysters. The bacterium cannot be seen, tasted, or smelled in food or water.

V. vulnificus is an emerging pathogen and a growing cause of food poisoning in the United States: it triggers vomiting, diarrhea, and abdominal pain. The pathogen can also infect the bloodstream, causing life-threatening illness characterized by fever, chills, skin lesions, and deadly loss of blood pressure. About 50% of patients with bloodstream infections die. *V. vulnificus* especially affects the immunocompromised and people with long-term liver disease.

Researchers have discovered that taking antacids may make people more susceptible to becoming ill from *V. vulnificus*. They found that antacids in a simulated gastric environment significantly increased the survival rate of *V. vulnificus*.

1. Why are patients who take antacids at greater risk for infections with *V. vulnificus*?
2. Will antacids raise or lower the pH of the stomach?
3. Other than refraining from antacids, what can people do to reduce their risk of infection?

Reference: Adapted from *MMWR* 45:621–624, 1996.

Cations and anions of salts are electrolytes. A cell uses electrolytes to create electrical differences between its inside and outside, to transfer electrons from one location to another, and as important components of many enzymes. Certain organisms also use salts such as calcium carbonate ($CaCO_3$) to provide structure and support for their cells.

TELL ME WHY

Why does the neutralization of an acid by a base often produce water?

Organic Macromolecules

Inorganic molecules play important roles in an organism's metabolism; however, water excluded, they compose only about 1.5% of its mass. Inorganic molecules are typically too

small and too simple to constitute an organism's basic structures or to perform the complicated chemical reactions required of life. These functions are fulfilled by organic molecules, which are generally larger and much more complex.

Functional Groups

LEARNING OUTCOME

2.20 Define *functional group* as it relates to organic chemistry.

As we have seen, organic molecules contain carbon and hydrogen atoms, and each carbon atom can form four covalent bonds with other atoms (see Figure 2.5c and d). Carbon atoms that are linked together in branched chains, unbranched chains, and rings provide the basic frameworks of organic molecules.

Atoms of other elements are bound to these carbon frameworks to form an unlimited number of compounds. Besides carbon and hydrogen, the most common elements in organic compounds are oxygen, nitrogen, phosphorus, and sulfur. Other elements, such as iron, copper, molybdenum, manganese, zinc, and iodine, are important in some proteins.

Atoms often appear in certain common arrangements called **functional groups** that are common in organic molecules. For example, —NH_2, the amino functional group, is found in all amino acids, and —OH, the hydroxyl functional group,[12] is common to all alcohols. When a class of organic molecules is discussed, the letter **R** (for *residue*) designates atoms in the compound that vary from one molecule to another. The symbol R—OH, therefore, represents the general formula for an alcohol. **TABLE 2.3** describes some common functional groups of organic molecules.

There is a great variety of organic compounds, but all organisms use certain basic types. These molecules—known as *macromolecules* because they are very large—are lipids, carbohydrates, proteins, and nucleic acids.

[12]Note that the hydroxyl *functional group* is not the same thing as the hydroxyl *ion*, because the former is covalently bonded to a carbon atom and the latter is unbound.

TABLE 2.3 Functional Groups of Organic Molecules and Some Classes of Compounds in Which They Are Found

Structure	Name	Class of Compounds
—OH	Hydroxyl	Alcohol Monosaccharide Amino acid
R—CH_2—O—CH_2—R′	Ether	Disaccharide Polysaccharide
R—C(=O)—R′	Internal carbonyl—a carbon atom (in R group) on each side	Ketone Carbohydrate
R—C(=O)—H	Terminal carbonyl—a carbon atom (in R group) on only one side	Aldehyde
R—C(=O)—O—H	Carboxyl	Amino acid Protein Fatty acid
R—C(H)(NH_2)—H	Amino	Amino acid Protein
R—C(=O)—O—R′	Ester	Fat Wax
R—CH_2—SH	Sulfhydryl	Amino acid Protein
R—CH_2—O—P(=O)(OH)—OH	Organic phosphate	Phospholipid Nucleotide ATP

Lipids

LEARNING OUTCOMES

2.21 Describe the structure of a molecule of fat (triglyceride), and compare it to that of phospholipids, waxes, and steroids.
2.22 Distinguish among saturated, unsaturated, and polyunsaturated fatty acids.

Lipids are a diverse group of organic macromolecules not composed of regular subunits. They have one common trait—they are **hydrophobic;**[13] that is, they are insoluble in water. Lipids have little or no affinity for water because they are composed almost entirely of carbon and hydrogen atoms linked by nonpolar covalent bonds. Because these bonds are nonpolar, they have no attraction to the polar bonds of water molecules. To look at it another way, the polar water molecules are attracted to each other and exclude the nonpolar lipid molecules. There are four major groups of lipids in cells: fats (triglycerides), phospholipids, waxes, and steroids.

Fats

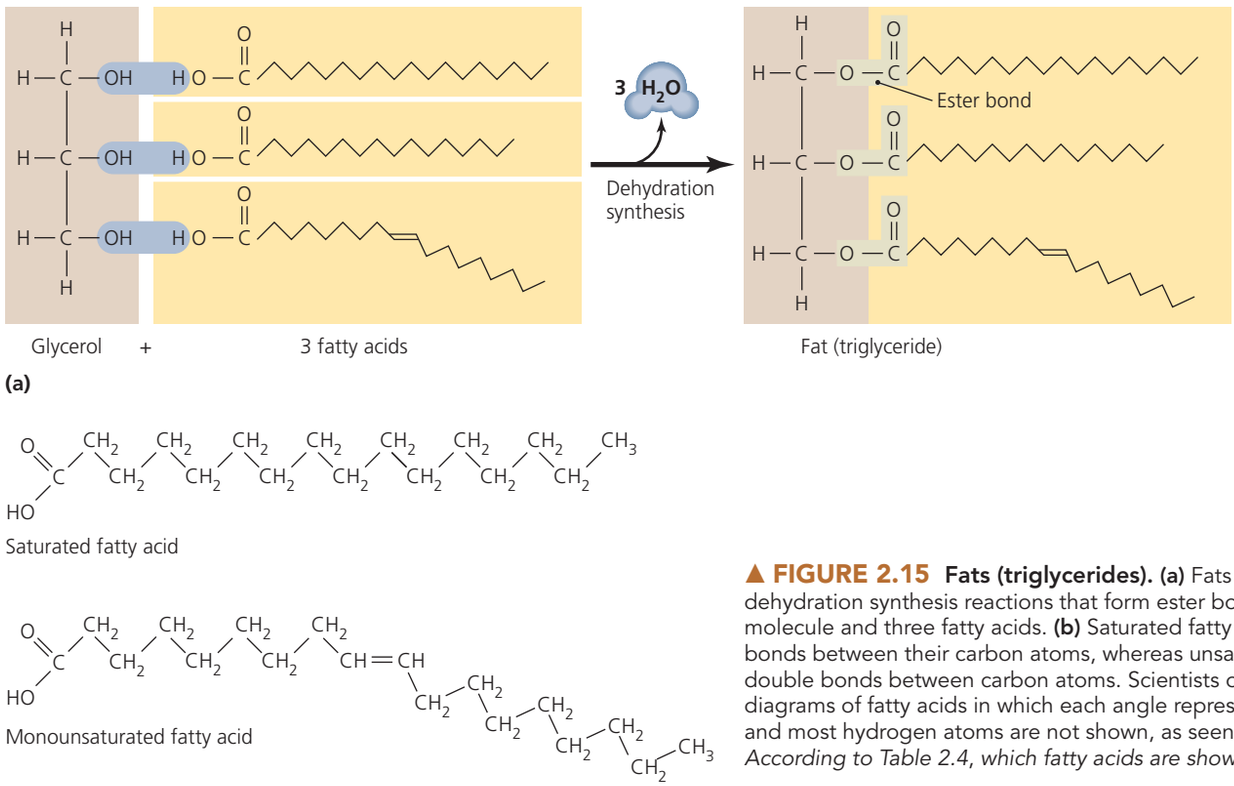
Organisms make **fats** via dehydration synthesis reactions that form *esters* between an alcohol named glycerol and three fatty acids, which are long hydrocarbon chains capped by a carboxyl functional group **(FIGURE 2.15a)**. Fats are also called *triglycerides* because they contain three fatty acid molecules linked to glycerol.

The three fatty acids in a fat molecule may be identical or different from one another, but each usually has 12–20 carbon atoms. An important difference among fatty acids is the presence and location of double bonds between carbon atoms. When carbon atoms are linked solely by single bonds, every carbon atom, with the exception of the terminal ones, is covalently linked to two hydrogen atoms. Such a fatty acid is **saturated** with hydrogen and is thus termed a **saturated fatty acid (FIGURE 2.15b)**. In contrast, **unsaturated fatty acids** contain one double bond between adjacent carbon atoms *(monounsaturated fatty acid)* or more than one double bond between carbon atoms *(polyunsaturated fatty acid)*. Triglycerides with at least one polyunsaturated fatty acid are polyunsaturated fats.

Saturated fats (composed solely of saturated fatty acids), like those found in animals, are usually solid at room temperature because their fatty acids can be packed closely together. Unsaturated fatty acids, by contrast, are bent at every double bond and so unsaturated fats cannot be packed tightly; they remain liquid at room temperature. Most fats in plants are unsaturated or polyunsaturated. **TABLE 2.4** compares the structures and melting points of four common fatty acids.

Fats contain an abundance of energy stored in their carbon-carbon covalent bonds. Indeed, a major role of fats in organisms is to store energy. Fats can be catabolized to provide energy for movement, synthesis, and transport (Chapter 5).

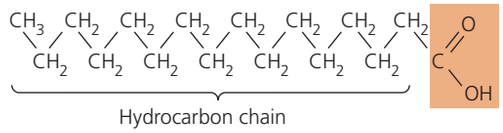
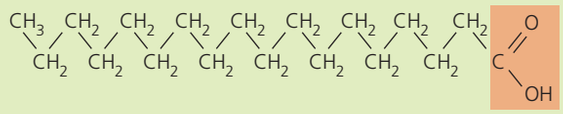
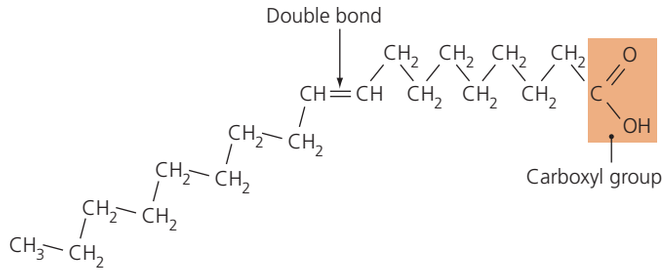
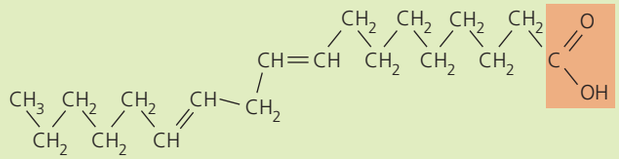
[13]From Greek *hydor*, meaning "water," and *phobos*, meaning "fear."



▲ **FIGURE 2.15 Fats (triglycerides). (a)** Fats are made in dehydration synthesis reactions that form ester bonds between a glycerol molecule and three fatty acids. **(b)** Saturated fatty acids have only single bonds between their carbon atoms, whereas unsaturated fatty acids have double bonds between carbon atoms. Scientists often use abbreviated diagrams of fatty acids in which each angle represents a carbon atom and most hydrogen atoms are not shown, as seen in part (a) of this figure. *According to Table 2.4, which fatty acids are shown in Figure 2.15a?*

Figure 2.15 *Stearic acid, palmitic acid, and oleic acid.*

TABLE 2.4 Common Fatty Acids in Fats and Cell Membranes

Numbers of Carbon Atoms: Double Bonds	Type of Fatty Acid	Structure and Formula	Common Name	Melting Point
16:0	Saturated	$CH_3(CH_2)_{14}COOH$ 	Palmitic acid	63°C
18:0	Saturated	$CH_3(CH_2)_{16}COOH$ 	Stearic acid	70°C
18:1	Monounsaturated	$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$ 	Oleic acid	16°C
18:2	Polyunsaturated	$CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6COOH$ 	Linoleic acid	−5°C

Phospholipids

Phospholipids are similar to fats, but they contain only two fatty acid chains instead of three. In phospholipids, the third carbon atom of glycerol is linked to a phosphate (PO_4) functional group instead of a fatty acid **(FIGURE 2.16a)**. Like fats, different phospholipids contain different fatty acids. Small organic groups linked to the phosphate group provide additional variety among phospholipid molecules.

The fatty acid "tail" portion of a phospholipid molecule is nonpolar and thus hydrophobic, whereas the phospholipid "head" is polar and thus **hydrophilic.**[14] As a result, phospholipids placed in a watery environment will always self-assemble into forms that keep the fatty acid tails away from water. One way they do this is to form a phospholipid bilayer **(FIGURE 2.16c)**. The fatty acid tails, which are hydrophobic, congregate in the water-free interior of bilayers. The polar phosphate heads, which are hydrophilic, orient toward the water on either side of the bilayer. Phospholipid bilayers make up the membranes surrounding cells as well as the internal membranes of plant, fungal, and animal cells.

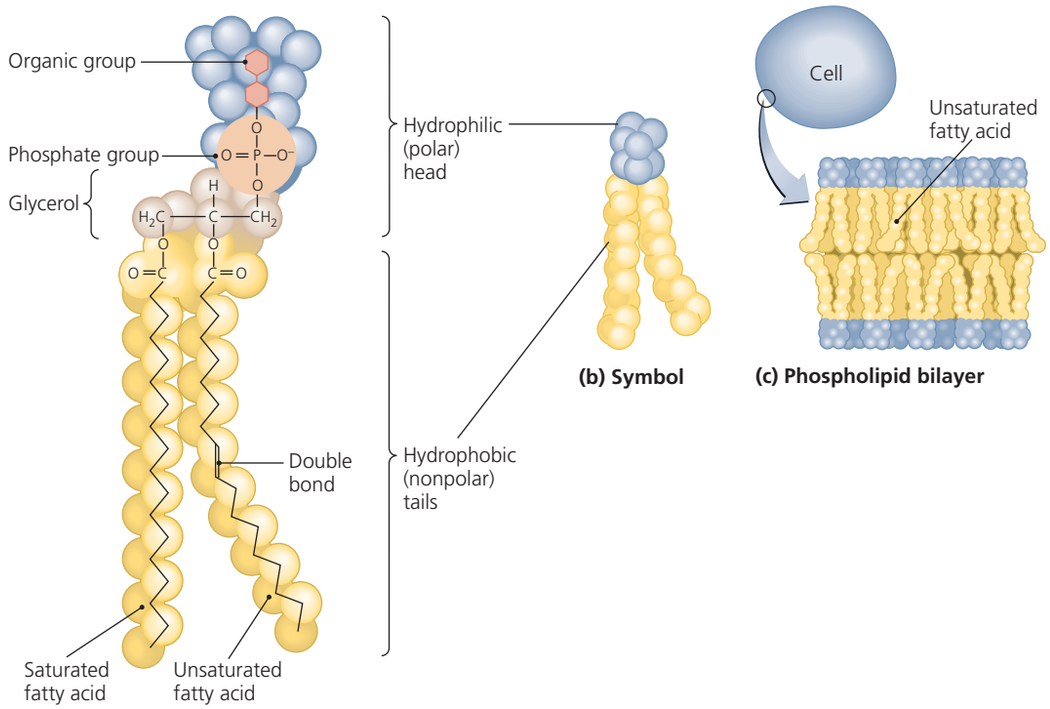
[14]From Greek *philos*, meaning "love."

Waxes

Waxes contain one long-chain fatty acid linked covalently to a long-chain alcohol by an ester bond. Waxes do not have hydrophilic heads; thus, they are completely water insoluble. Certain microorganisms, such as *Mycobacterium tuberculosis* (mī´kō-baktēr´ē-ŭm too-ber-kyū-lō´sis), are surrounded by a waxy wall, making them resistant to drying. Some marine microbes use waxes instead of fats as energy storage molecules.

Steroids

A final group of lipids are **steroids.** Steroids consist of four rings (each containing five or six carbon atoms) that are fused to one another and attached to various side chains and functional groups **(FIGURE 2.17a)**. Steroids play many roles in human metabolism. Some act as hormones; another steroid, *cholesterol*, is perhaps familiar to you as a less desirable component of food.



▲ **FIGURE 2.16 Phospholipids.** **(a)** A phospholipid is composed of a hydrophilic (polar) "head," which is composed of glycerol and a phosphate group, and two hydrophobic (nonpolar) fatty acid "tails." **(b)** The symbol used to represent phospholipids. **(c)** In water, phospholipids can self-assemble into spherical bilayers. Phospholipids containing unsaturated fatty acids do not pack together as tightly as those containing saturated fatty acids.

However, cholesterol is also an essential part of the phospholipid bilayer membrane surrounding an animal cell. Cells of fungi, plants, and one group of bacteria (mycoplasmas) have similar *sterol* molecules in their membranes. Sterols, which are steroids with an —OH functional group, interfere with the tight packing of the fatty acid chains of phospholipids **(FIGURE 2.17b)**. This keeps the membranes fluid and flexible at low temperatures. Without steroids such as cholesterol, the membranes of cells would become stiff and inflexible in the cold.

Carbohydrates, proteins, and nucleic acid macromolecules are composed of simpler subunits known as **monomers,**[15] which are basic building blocks. The monomers of these macromolecules are joined together to form chains of monomers called **polymers.**[16] Some macromolecular polymers are composed of hundreds of thousands of monomers.

Carbohydrates

LEARNING OUTCOME

2.23 Discuss the roles carbohydrates play in living systems.

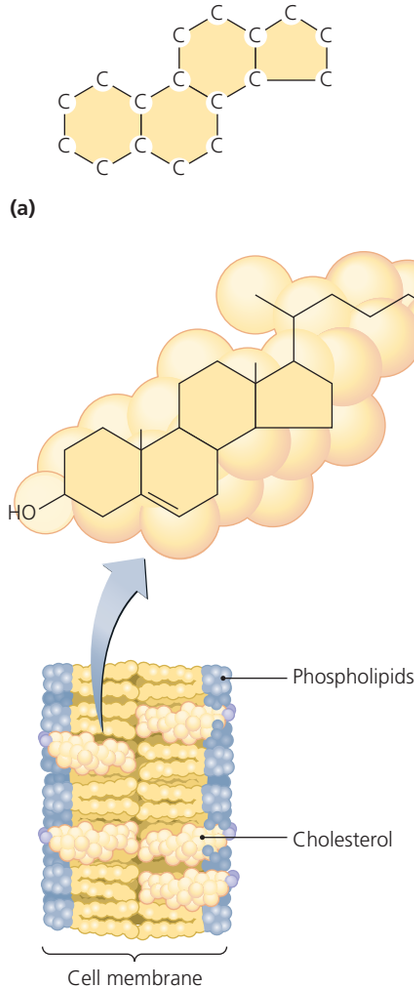
Carbohydrates are organic molecules composed solely of atoms of carbon, hydrogen, and oxygen. Most carbohydrate compounds contain an equal number of oxygen and carbon atoms and twice as many hydrogen atoms as carbon atoms, so the general formula for a carbohydrate is $(CH_2O)_n$, where n indicates the number of CH_2O units.

Carbohydrates play many important roles in organisms. Large carbohydrates, such as starch and glycogen, are used for the long-term storage of chemical energy, and smaller carbohydrate molecules serve as a ready energy source, form part of the backbones of DNA and RNA, and may be converted into amino acids. Additionally, polymers of carbohydrate form the cell walls of most fungi, plants, algae, and prokaryotes and are involved in intercellular interactions between animal cells.

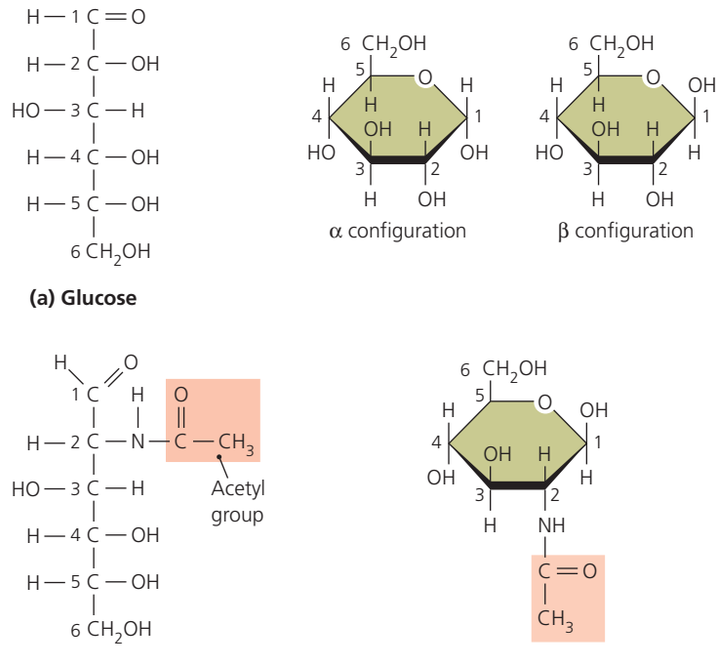
Monosaccharides

The simplest carbohydrates are **monosaccharides**[17]—simple sugars **(FIGURE 2.18)**. The general names for the classes of monosaccharides are formed from a prefix indicating the number of carbon atoms and from the suffix *-ose*. For example, *pentoses* are sugars with five carbon atoms, and *hexoses* are sugars with six carbon atoms. Pentoses and hexoses are particularly important in cellular metabolism. For example, deoxyribose, which is the sugar component of DNA, is a pentose. Glucose

[15]From Greek *mono*, meaning "one," and *meris*, meaning "part."
[16]From Greek *poly*, meaning "many," and *meris*, meaning "part."
[17]From Greek *sakcharon*, meaning "sugar."



▲ **FIGURE 2.17** **Steroids.** **(a)** Steroids are lipids characterized by four "fused" rings. **(b)** The steroid cholesterol, which has a short chain of atoms extending from the fourth ring, functions in animal and protozoan cell membranes to prevent packing of phospholipids, thereby keeping the membranes fluid at low temperatures.



▲ **FIGURE 2.18** **Monosaccharides (simple sugars).** Although simple sugars may exist as either linear molecules (at left) or rings (at right), energy dynamics in the watery cytoplasm of cells generally favor ring forms. **(a)** Glucose, a hexose, is the primary energy source for cellular metabolism and an important monomer in many larger carbohydrates. Chemists number the carbon atoms as shown. Alpha and beta ring configurations differ in the location of oxygen bound to carbon 1. **(b)** *N*-acetylglucosamine (NAG), a monomer in bacterial cell walls.

is a hexose and the primary energy molecule of cells, and fructose is a hexose found in fruit. Chemists assign numbers to the carbon atoms.

Monosaccharides may exist as linear molecules, but because of energy dynamics, each usually takes a cyclic (ring) form. In some cases, more than one cyclic structure may exist. For example, glucose can assume an alpha (a) configuration or a beta (b) configuration (see Figure 2.18a). As we will see, these configurations play important roles in the formation of different polymers.

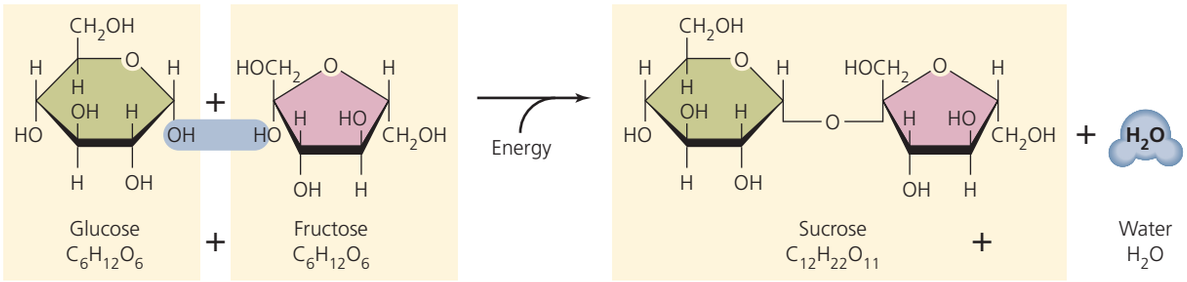
Disaccharides

When two monosaccharide molecules are linked together via dehydration synthesis, the result is a **disaccharide.** For example, the linkage of two hexoses, glucose and fructose, forms sucrose (table sugar) in a dehydration reaction **(FIGURE 2.19a)**. Other disaccharides include maltose (malt sugar) and lactose (milk sugar). Disaccharides can be broken down via hydrolysis into their constituent monosaccharides **(FIGURE 2.19b)**.

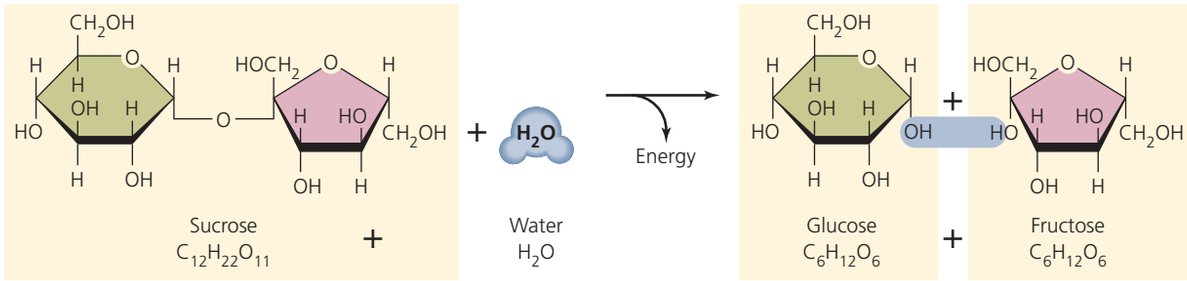
Polysaccharides

Polysaccharides are polymers composed of tens, hundreds, or thousands of monosaccharides that have been covalently linked in dehydration synthesis reactions. Even polysaccharides that contain only glucose monomers can be quite diverse because they can differ according to their monosaccharide monomer configurations (either alpha or beta) and their shapes (either branched or unbranched). Cellulose, the main constituent of the cell walls of plants and some green algae, is a long unbranched molecule that contains only β-monomers of glucose linked between carbons 1 and 4 of alternating monomers; such bonds are termed β-1,4 bonds **(FIGURE 2.20a)**. Amylose, a starch storage compound in plants, has only α-1,4 bonds and is unbranched **(FIGURE 2.20b)**; glycogen, a storage molecule formed in the liver and muscle cells of animals, is a highly branched molecule with both α-1,4 and α-1,6 bonds **(FIGURE 2.20c)**.

The cell walls of bacteria are composed of *peptidoglycan*, which is made of polysaccharides and amino acids (see Figure 3.15). Polysaccharides may also be linked to lipids to form glycolipids, which can form cell markers such as those involved in the ABO blood typing system in humans.



(a) Dehydration synthesis of sucrose



(b) Hydrolysis of sucrose

▲ **FIGURE 2.19 Disaccharides. (a)** Formation of the disaccharide sucrose via dehydration synthesis. **(b)** Breakdown of sucrose via hydrolysis.

Proteins

LEARNING OUTCOMES

2.24 Describe five general functions of proteins in organisms.
2.25 Sketch and label four levels of protein structure.

The most complex organic compounds are **proteins**, which are composed mostly of carbon, hydrogen, oxygen, nitrogen, and sulfur. Proteins perform many functions in cells, including the following:

- *Structure.* Proteins are structural components found in cell walls, in membranes, and within cells themselves. Proteins are also the primary structural material of hair, nails, the outer cells of skin, muscle, and flagella and cilia (the last two act to move microorganisms through their environment).
- *Enzymatic catalysis.* Catalysts are chemicals that enhance the speed or likelihood of a chemical reaction. Protein catalysts in cells are called *enzymes*.
- *Regulation.* Some proteins regulate cell function by stimulating or hindering either the action of other proteins or the expression of genes. Hormones are examples of regulatory proteins.
- *Transportation.* Certain proteins act as channels and "pumps" that move substances into or out of cells.
- *Defense and offense. Antibodies* and *complement* are examples of proteins that defend your body against pathogens.

A protein's function is dependent on its shape, which is determined by the molecular structures of its constituent parts and by the bonds within the molecule.

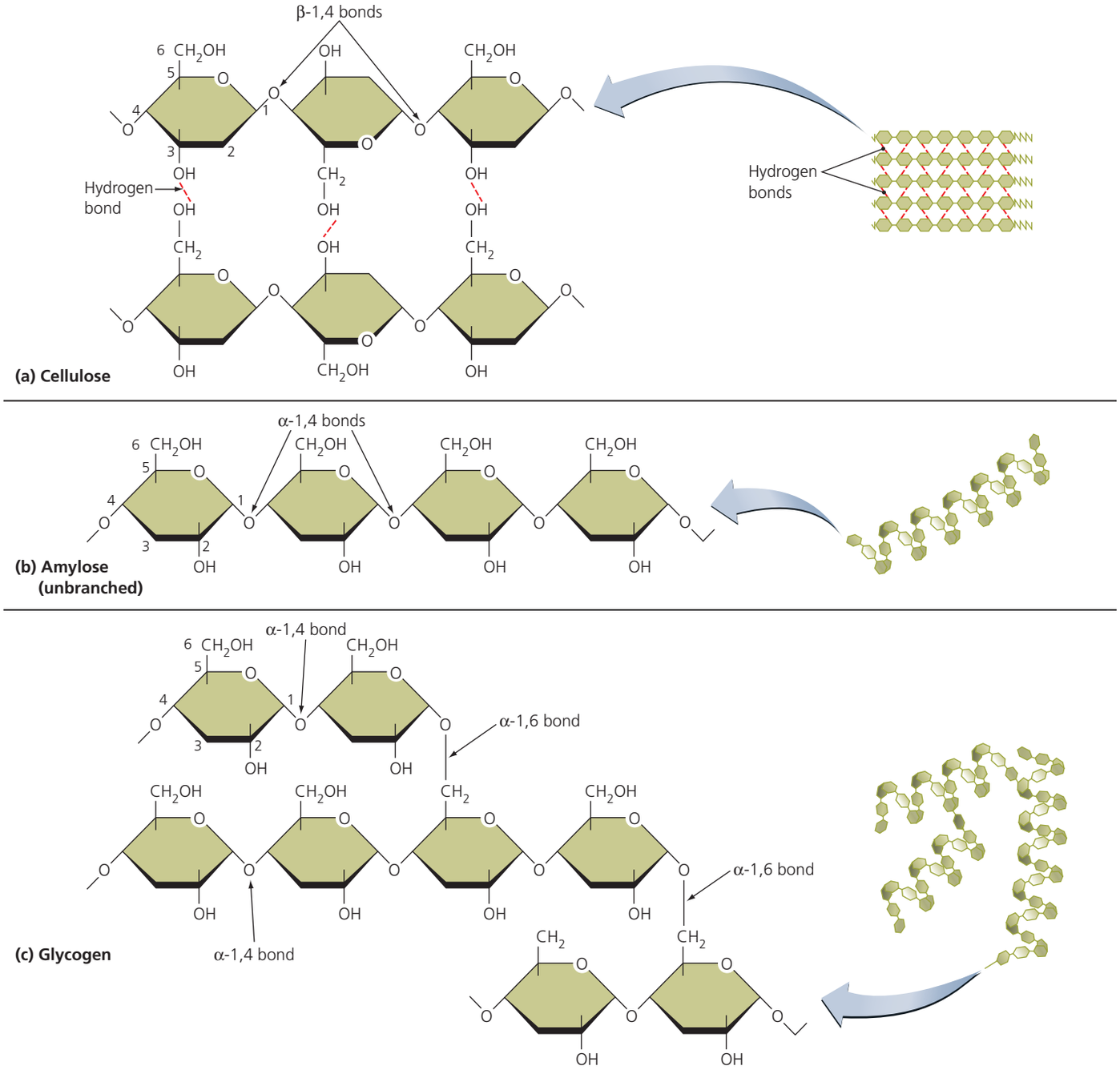
Amino Acids

Proteins are polymers composed of monomers called **amino acids.** Amino acids contain a basic amino group (—NH_2), a hydrogen atom, and an acidic carboxyl group (—COOH). All attach to the same carbon atom, which is known as the α-carbon **(FIGURE 2.21)**. A fourth bond attaches the α-carbon to a side group (—R) that varies among different amino acids. The side group may be a single hydrogen atom, various chains, or various complex ring structures. Hundreds of amino acids are possible, but most organisms use only 21 amino acids in synthesizing proteins.[18] The different side groups affect the way amino acids interact with one another within a given protein as well as how a protein interacts with other molecules. A change in an amino acid's side group may seriously interfere with a protein's normal function.

Because amino acids contain both an acidic carboxyl group and a basic amino group, they have both positive and negative charges and are easily soluble in water. Aqueous solutions of organic molecules such as amino acids and simple sugars bend light rays passing through the solution. Molecules known as *D forms*[19] bend light rays clockwise; other molecules bend light rays counterclockwise and are known as *L forms*.[20]

Many organic molecules exist as both D and L forms that are *stereoisomers* of one another; that is, they have the same atoms and functional groups but are mirror images of each other **(FIGURE 2.22)**. Amino acids in proteins are almost always L forms—except for glycine, which does not have a stereoisomer. Interestingly, organisms almost always use D sugars in metabolism and polysaccharides.

[18]While 20 amino acids are commonly listed, the genes of almost all organisms code for a 21st amino acid—selenocysteine.
[19]From Latin *dexter*, meaning "on the right."
[20]From Latin *laevus*, meaning "on the left."



▲ **FIGURE 2.20 Polysaccharides.** All three polysaccharides shown here are composed solely of glucose but differ in the configuration of the glucose monomers and the amount of branching. **(a)** Cellulose, the major structural material in plants, is unbranched and contains only β-1,4 bonds. **(b)** Amylose is an unbranched plant starch with only α-1,4 bonds. **(c)** Glycogen, a highly branched storage molecule in animals, is composed of glucose monomers linked by α-1,4 or α-1,6 bonds.

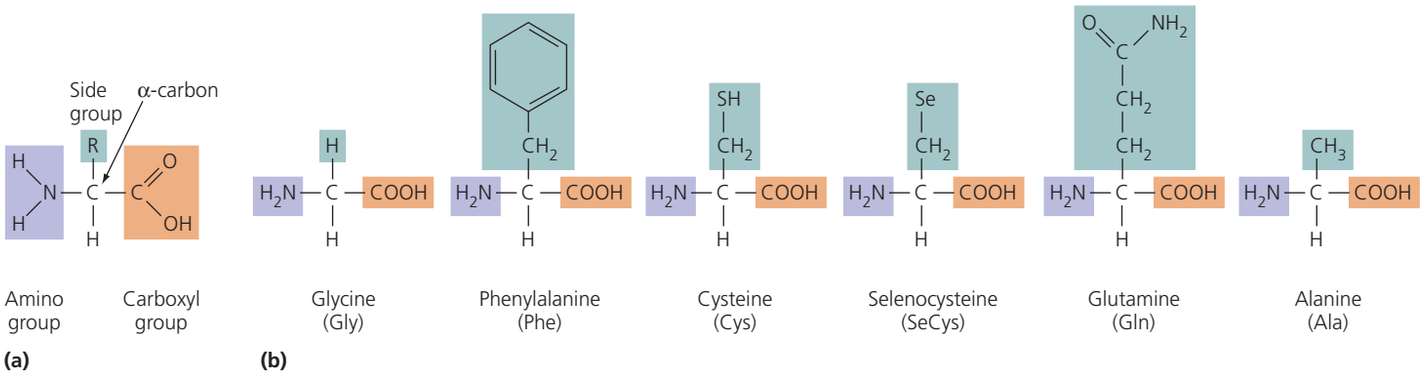
Rare stereoisomers—D amino acids and L sugars—do exist in some bacterial cell walls and in some antibiotics.

Peptide Bonds

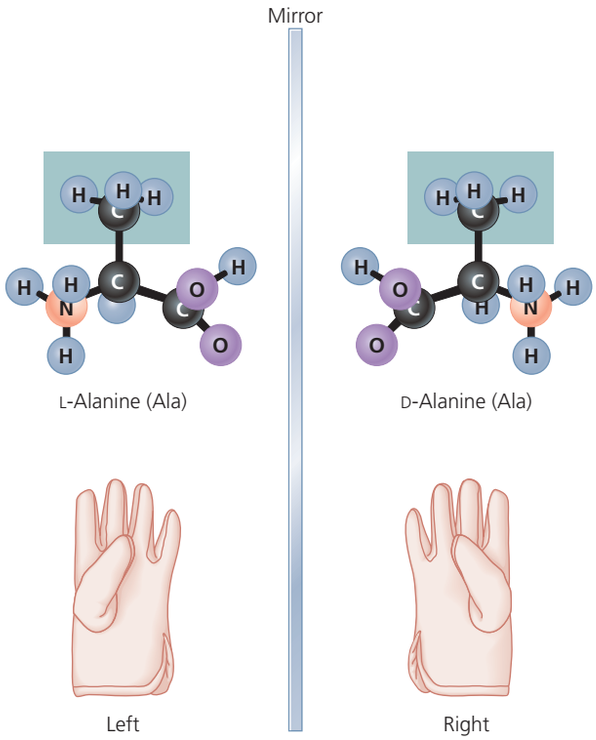
Cells link amino acids together in chains that somewhat resemble beads on a necklace. By a dehydration synthesis reaction, a covalent bond is formed between the carbon of the carboxyl group of one amino acid and the nitrogen of the amino group of the next amino acid in the chain **(FIGURE 2.23)**. Cells follow the organism's genetic instructions to link amino acids together in precise sequences. (Chapter 7 examines this process in more detail.)

Scientists refer to covalent bonds between amino acids by a special name: **peptide**[21] **bonds.** A molecule composed of two

[21]From *peptone*, the name given to short chains of amino acids resulting from the partial digestion of protein.



▲ FIGURE 2.21 Amino acids. (a) The basic structure of an amino acid. The central α-carbon is attached to an amino group, a hydrogen atom, a carboxyl group, and a side group (—R group) that varies among amino acids. **(b)** Some selected amino acids, with their side groups highlighted. Note that each amino acid has a distinctive abbreviation.



▲ FIGURE 2.22 Stereoisomers, molecules that are mirror images of one another. When dissolved in water, D isomers bend light clockwise, and L forms bend light counterclockwise. Just as a right-handed glove does not fit a left hand, so a D stereoisomer cannot be substituted for an L stereoisomer in metabolic reactions.

amino acids linked together by a single peptide bond is called a *dipeptide;* longer chains of amino acids are called *polypeptides*.

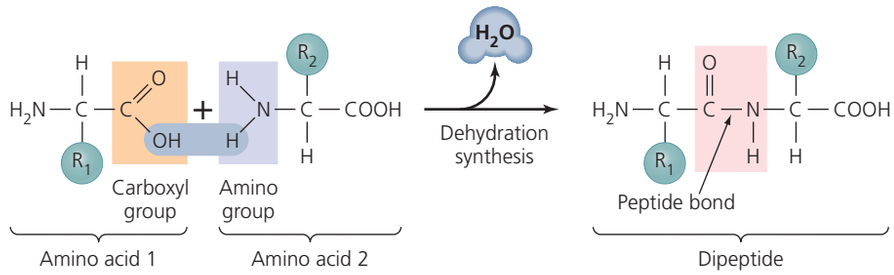
Protein Structure

Proteins are unbranched polypeptides composed of hundreds to thousands of amino acids linked together in specific patterns as determined by genes. The structure of a protein molecule is directly related to its function; therefore, understanding protein structure is critical to understanding certain specific chemical reactions, the action of antibiotics, and specific defenses against pathogens. Every protein has at least three levels of structure, and some proteins have four levels.

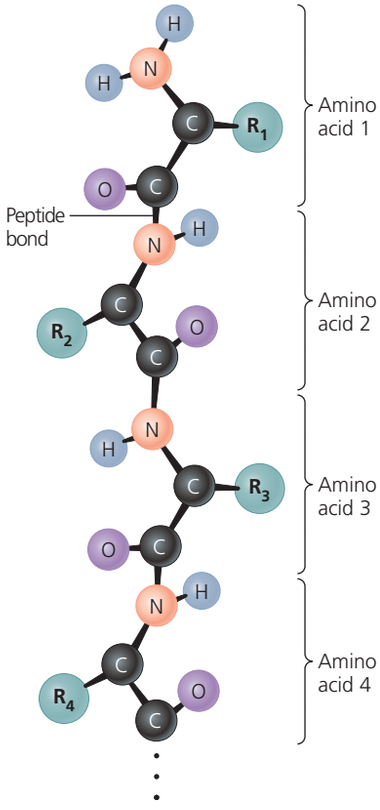
- *Primary structure.* The primary structure of a protein is its sequence of amino acids **(FIGURE 2.24a)**. Cells use many different types of amino acids in proteins, though not every protein contains all types. The primary structures of proteins vary widely in length and amino acid sequence.

  A change in a single amino acid in the sequence can drastically affect a protein's overall structure and function, though this is not always the case. For instance, a change in a particular amino acid in the primary structure of a sheep brain protein, called cellular prion (prē´on) protein, may result in a disease called *scrapie*. The altered protein has spread into cows, causing *mad cow disease,* and spread from cows into humans, causing *variant Creutzfeldt-Jakob* (kroytsfelt-yah-kŭp) *disease*.[22]
- *Secondary structure.* Ionic bonds, hydrogen bonds, and hydrophobic and hydrophilic characteristics cause many polypeptide chains to fold into either coils called α-*helices* or accordion-like structures called β-*pleated sheets* **(FIGURE 2.24b)**. Proteins are typically composed of both α-helices and β-pleated sheets linked by short sequences of amino acids that do not show such secondary structure. Because of its primary structure, the protein that causes variant Creutzfeldt-Jakob disease has β-pleated sheets in locations where the normal protein has α-helices (see Chapter 13, Figure 13.22).
- *Tertiary structure.* Polypeptides further fold into complex three-dimensional shapes that are not repetitive like α-helices and β-pleated sheets **(FIGURE 2.24c)** but are uniquely designed to accomplish the function of the

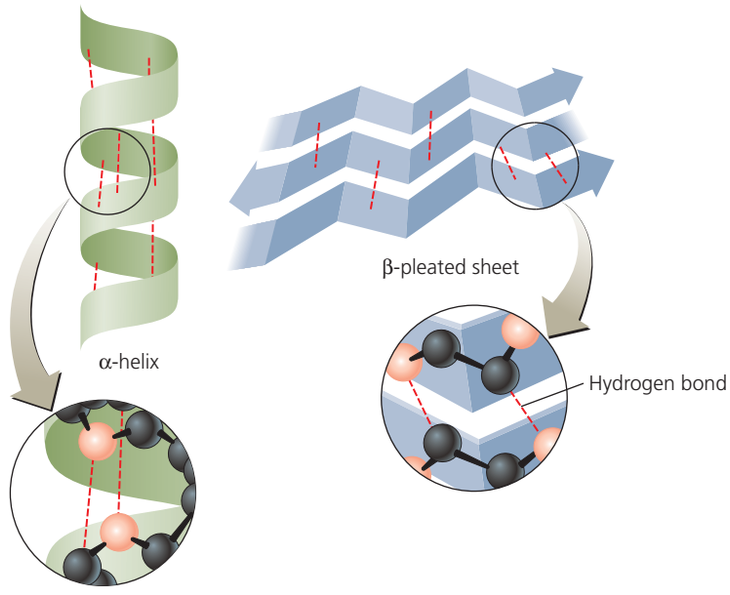
[22]Named for the two German neurobiologists who first described the disease.



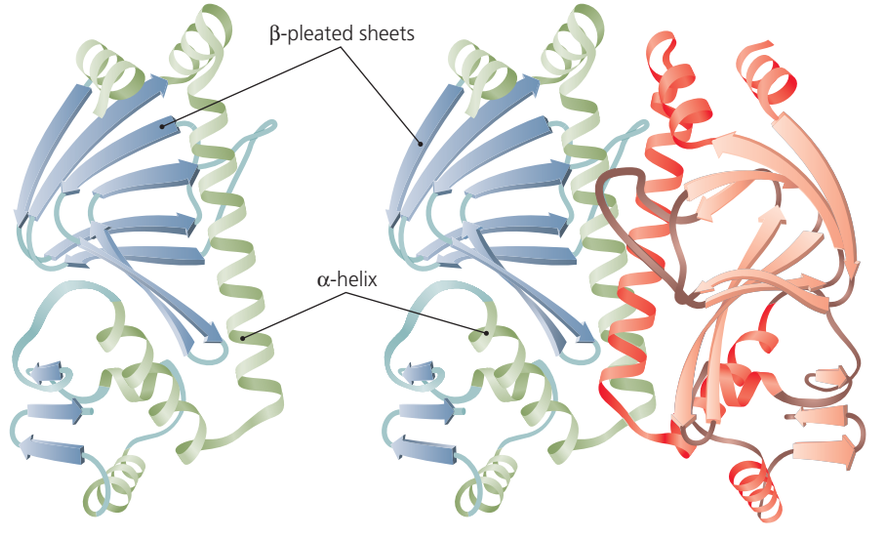
◀ FIGURE 2.23 The linkage of amino acids by peptide bonds via a dehydration reaction. In this reaction, removing a hydroxyl group from amino acid 1 and a hydrogen atom from amino acid 2 produces a dipeptide—which is two amino acids linked by a single peptide bond—and a molecule of water.



(a) Primary structure



(b) Secondary structure



(c) Tertiary structure

(d) Quaternary structure: Two or more polypeptides act together as a single protein.

▲ FIGURE 2.24 Levels of protein structure. **(a)** A protein's primary structure is the sequence of amino acids in a polypeptide. **(b)** Secondary structure arises as a result of interactions, such as hydrogen bonding, between regions of the polypeptide. Secondary structure takes two basic shapes: α-helices and β-pleated sheets. **(c)** The more complex tertiary structure is a three-dimensional shape defined by further hydrogen bonding as well as disulfide bridges between neighboring cysteine amino acid molecules. **(d)** Those proteins that are composed of more than one polypeptide chain have a quaternary structure.

protein. Scientists are only beginning to understand the interactions that determine tertiary structure, but it is clear that covalent bonds between —R groups of amino acids, hydrogen bonds, ionic bonds, and other molecular interactions are important. For instance, nonpolar (hydrophobic) side chains fold into the interior of molecules, away from the presence of water.

Some proteins form strong covalent bonds between sulfur atoms of cysteine amino acids that are brought into proximity by the folding of the polypeptide. These *disulfide bridges* are critical in maintaining tertiary structure of many proteins.

- *Quaternary structure.* Some proteins are composed of two or more polypeptide chains linked together by disulfide bridges or other bonds. The overall shape of such a protein may be fibrous (threadlike) or more globular **(FIGURE 2.24d)**.

Organisms may further modify proteins by combining them with other organic or inorganic molecules. For instance, *glycoproteins* are proteins covalently bound with carbohydrates, *lipoproteins* are proteins bonded with lipids, *nucleoproteins* are proteins bonded with nucleic acids.

Because protein shape determines protein function, anything that severely interrupts shape also disrupts function. As we have seen, amino acid substitution can alter shape and function. Additionally, physical and chemical factors, such as heat, changes in pH, and salt concentration, can interfere with hydrogen and ionic bonding between parts within a protein. This in turn can disrupt the three-dimensional structure. This process is called **denaturation.** Denaturation can be temporary (if the denatured protein is able to return to its original shape again) or permanent.

Nucleotides and Nucleic Acids

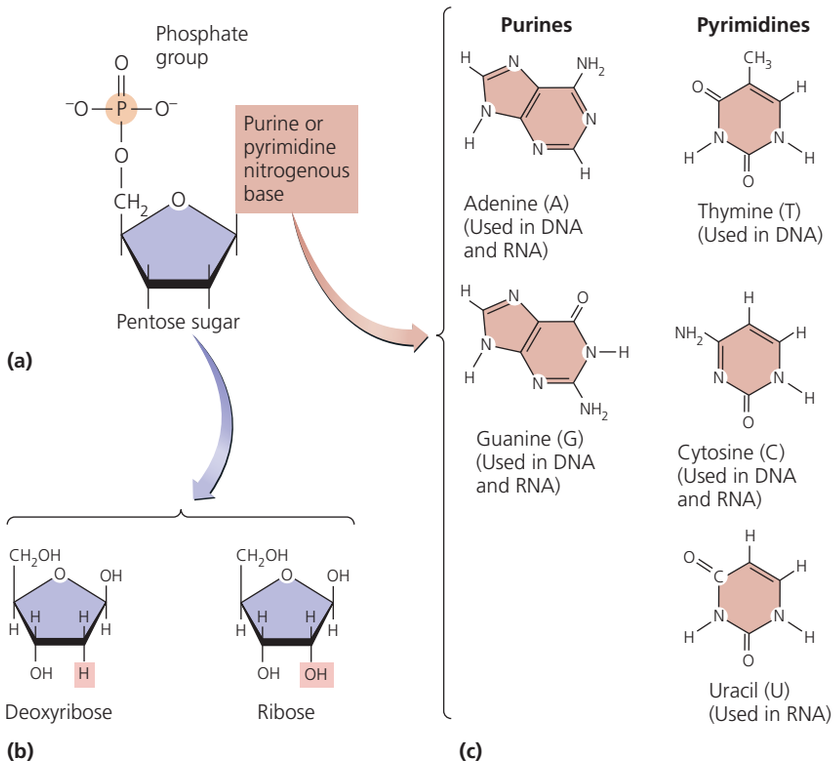
LEARNING OUTCOMES

2.26 Describe the basic structure of a nucleotide.
2.27 Compare and contrast DNA and RNA.
2.28 Contrast the structures of ATP, ADP, and AMP.

The nucleic acids **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)** are the vital genetic material of cells and viruses. Moreover, RNA, acting as an enzyme, binds amino acids together to form polypeptides. Both DNA and RNA are unbranched macromolecular polymers that differ primarily in the structures of their monomers, which we discuss next.

Nucleotides and Nucleosides

Each monomer of nucleic acids is a **nucleotide** and consists of three parts **(FIGURE 2.25a)**: (1) phosphate (PO_4^{3-}); (2) a pentose sugar, either deoxyribose or ribose **(FIGURE 2.25b)**; and (3) one of five cyclic (ring-shaped) nitrogenous bases: **adenine (A), guanine (G), cytosine (C), thymine (T),** or **uracil (U)** **(FIGURE 2.25c)**. Adenine and guanine are double-ringed molecules of a class called *purines*, whereas cytosine, thymine, and uracil have single rings and are *pyrimidines*. DNA contains A, G, C, and T bases, whereas RNA contains A, G, C, and U bases. As their names suggest, DNA nucleotides contain deoxyribose, and RNA nucleotides contain ribose. The similarly named **nucleosides** are nucleotides lacking phosphate; that is, a nucleoside is one of the nitrogenous bases attached only to a sugar.



◀ FIGURE 2.25 Nucleotides. (a) The basic structure of nucleotides, each of which is composed of a phosphate, a pentose sugar, and a nitrogenous base. **(b)** The pentose sugars deoxyribose, which is found in deoxyribonucleic acid (DNA), and ribose, which is found in ribonucleic acid (RNA). **(c)** The nitrogenous bases, which are either the double-ringed purines adenine or guanine, or the single-ringed pyrimidines thymine, cytosine, or uracil. *How does a nucleoside differ from a nucleotide?*

VIDEO TUTOR

Figure 2.25 *A nucleoside is composed only of a nitrogenous base and a sugar, whereas a nucleotide has a base, sugar, and phosphate.*

Each nucleotide or nucleoside is also named for the base it contains. Thus, a nucleotide made with ribose, uracil, and phosphate is a uracil RNA nucleotide, which is also called a uracil *ribonucleotide*. Likewise, a nucleoside composed of adenine and deoxyribose is an adenine DNA nucleoside (or adenine *deoxyribonucleoside*).

To explore the structure and function of nucleotides more fully, scan this QR code with your smart phone or tablet.

Nucleic Acid Structure

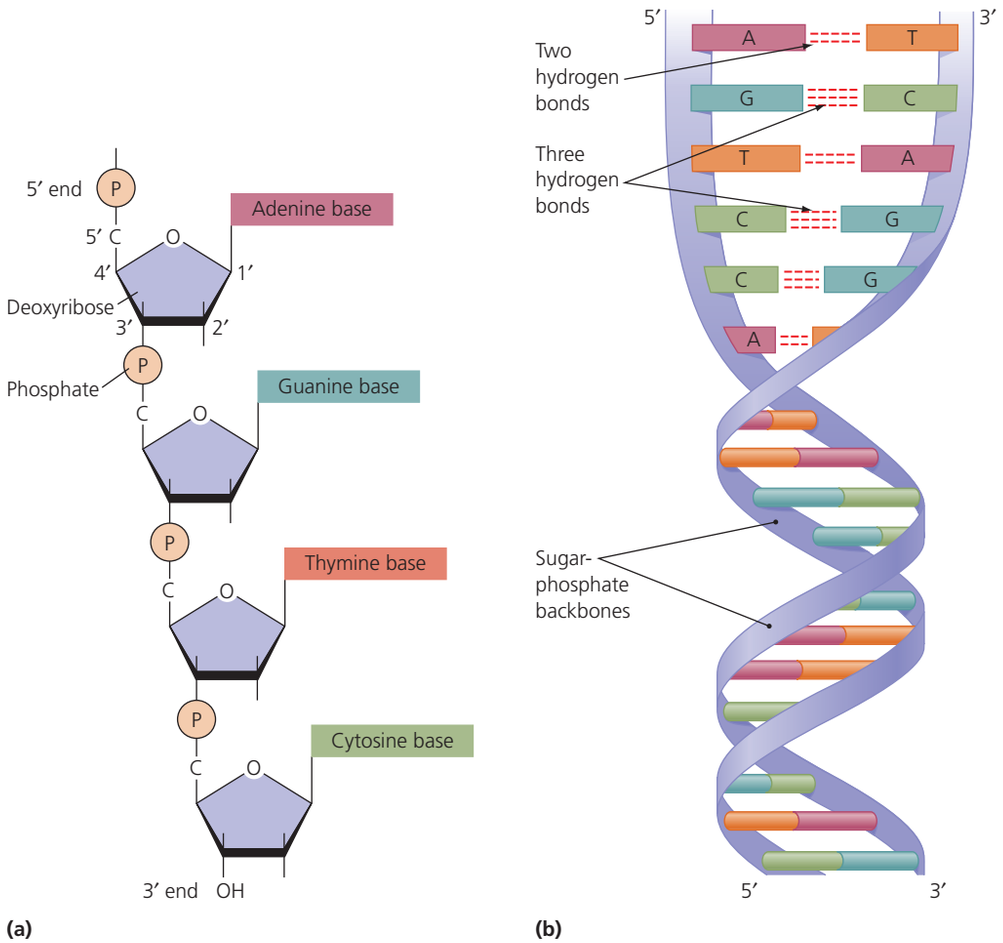
Nucleic acids, like polysaccharides and proteins, are polymers. They are composed of nucleotides linked by covalent bonds between the phosphate of one nucleotide and the sugar of the next. Polymerization results in a linear spine composed of alternating sugars and phosphates, with bases extending from it rather like the teeth of a comb **(FIGURE 2.26a)**. The two ends of a chain of nucleotides are different. At one end, called the 5′ end[23] (five prime end), carbon 5′ of the sugar is attached to a phosphate group. At the other end (the 3′ end), carbon 3′ of the sugar is attached to a hydroxyl group.

[23]Carbon atoms in organic molecules are commonly identified by numbers. In a nucleotide, carbon atoms 1, 2, 3, and so on belong to the base, and carbon atoms 1′, 2′, 3′, and so on belong to the sugar.

The atoms of the bases in nucleotides are arranged in such a manner that hydrogen bonds readily form between specific bases of two adjacent nucleic acid chains. Three hydrogen bonds form between an adjacent pair composed of cytosine (C) and guanine (G), whereas two hydrogen bonds form between an adjacent pair composed of adenine (A) and thymine (T) in DNA **(FIGURE 2.26b)** or between an adjacent pair composed of adenine (A) and uracil (U) in RNA. Hydrogen bonds do not readily form between other combinations of nucleotide bases; for example, adenine does not readily pair with cytosine, guanine, or another adenine nucleotide.

In cells, DNA molecules are double stranded. Most DNA viruses (viruses that use DNA as a genome) also use double-stranded DNA, though some single-stranded DNA viruses are known. The two strands of double-stranded DNA are complementary to one another; that is, the specificity of nucleotide base pairing ensures that opposite strands are composed of complementary nucleotides. For instance, if one strand has the sequence AATGCT, then its complement has TTACGA.

The two strands are also *antiparallel;* that is, they run in opposite directions. One strand runs from the 3′ end to the 5′ end, whereas its complement runs in the opposite direction, from its 5′ end to its 3′ end. Though hydrogen bonds are relatively weak bonds, thousands of them exist at normal temperatures, forming a stable, double-stranded DNA molecule that looks much like a ladder: the two deoxyribose-phosphate chains



◀ FIGURE 2.26 General nucleic acid structure. (a) Nucleotides are polymerized to form chains in which the nitrogenous bases extend from a sugar-phosphate backbone like the teeth of a comb. **(b)** Specific pairs of nitrogenous bases form hydrogen bonds between adjacent nucleotide chains to form the familiar DNA double helix. *How can you determine that the molecule in (a) is DNA and not RNA?*

Figure 2.26 *It is DNA because its nucleotides have deoxyribose sugar and because some of them have thymine bases (not uracil, as in RNA).*

are the side rails, and base pairs form the rungs. Hydrogen bonding also twists the phosphate-deoxyribose backbones into a helix. Thus, typical DNA is a double helix.

Nucleic Acid Function

DNA is the genetic material of all organisms and of DNA viruses; it carries instructions for the synthesis of RNA molecules and proteins. By controlling the synthesis of enzymes and regulatory proteins, DNA controls the synthesis of all other molecules in an organism. Genetic instructions are carried in the sequence of nucleotides that make up the nucleic acid. Even though only four kinds of bases are found in DNA (A, T, G, and C), they can be sequenced in distinctive patterns that create genetic diversity and code for an infinite number of proteins, just as an alphabet of only four letters could spell a very large number of words. Cells replicate their DNA molecules and pass copies to their descendants, ensuring that each has the instructions necessary for life.

Several kinds of ribonucleic acids, such as messenger RNA, transfer RNA, and ribosomal RNA, play roles in the formation of proteins, including catalyzing the synthesis of proteins. RNA molecules also function in place of DNA as the genome of RNA viruses.

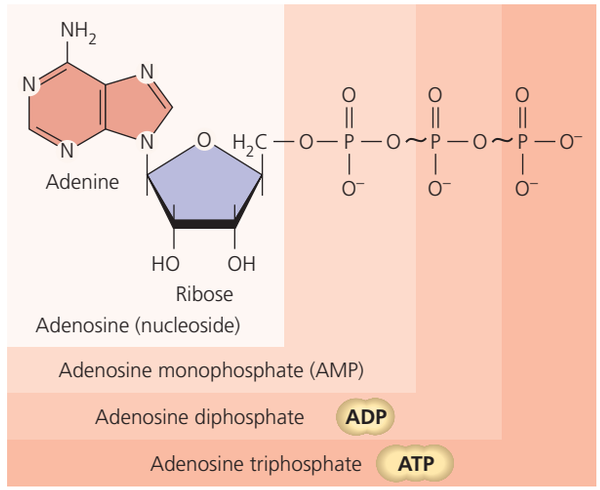
TABLE 2.5 compares and contrasts RNA and DNA. (We examine the synthesis and function of DNA and RNA in detail in Chapter 7.)

ATP (Adenosine Triphosphate)

Phosphate in nucleotides and other molecules is a highly reactive functional group and can form covalent bonds with other phosphate groups to make diphosphate and triphosphate molecules. Such molecules made from ribose nucleotides are important in many metabolic reactions. The names of these molecules indicate the nucleotide base and the number of phosphate groups they contain. Thus, cells make adenosine monophosphate (AMP) from the nitrogenous base adenine, ribose sugar, and one phosphate group; adenosine diphosphate (ADP), which has two phosphate groups; and **adenosine triphosphate** (ă-den´ō-sēn trī-fos´fāt) or **ATP,** which has three phosphate groups **(FIGURE 2.27)**.

ATP is the principal, short-term, recyclable energy supply for cells. When the phosphate bonds of ATP are broken, a significant amount of energy is released; in fact, more energy is released from phosphate bonds than is released from most other covalent bonds. For this reason, the phosphate-phosphate bonds of ATP are known as *high-energy bonds*, and to show these specialized bonds, ATP can be symbolized as

$$A\text{–}\textcircled{P}\sim\textcircled{P}\sim\textcircled{P}$$



▲ **FIGURE 2.27 ATP.** Adenosine triphosphate (ATP), the main short-term, recyclable energy supply for cells. Energy is stored in high-energy bonds between the phosphate groups. *What is the relationship between AMP and adenine ribonucleotide?*

Figure 2.27 *AMP and adenine ribonucleotide are two names for the same thing.*

Energy is released when ATP is converted to ADP and when phosphate is removed from ADP to form AMP, though the latter reaction is not as common in cells. Energy released from the phosphate bonds of ATP is used for important life-sustaining activities, such as synthesis reactions, locomotion, and transportation of substances into and out of cells.

Cells also use ATP as a structural molecule in the formation of *coenzymes*. Coenzymes such as *flavin adenine dinucleotide*, *nicotinamide nucleotide*, and *coenzyme A* function in many metabolic reactions (as discussed in Chapter 5).

A cell's supply of ATP is limited; therefore, an important part of cellular metabolism is to replenish ATP stores. (Chapter 5 discusses the important ATP-generating reactions.)

TELL ME WHY

Why do the cell membranes of microbes living in Arctic water likely contain more unsaturated fatty acids than do membranes of microbes living in hot springs?

TABLE 2.5 Comparison of Nucleic Acids

Characteristic	DNA	RNA
Sugar	Deoxyribose	Ribose
Purine nucleotides	A and G	A and G
Pyrimidine nucleotides	T and C	U and C
Number of strands	Double stranded in cells and in most DNA viruses; single stranded in parvoviruses	Single stranded in cells and in most RNA viruses; double stranded in reoviruses
Function	Genetic material of all cells and DNA viruses	Protein synthesis in all cells; genetic material of RNA viruses

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CHAPTER SUMMARY

Atoms (pp. 57–59)

1. **Matter** is anything that takes up space and has mass. Its smallest chemical units, **atoms**, contain negatively charged **electrons** orbiting a nucleus composed of uncharged **neutrons** and positively charged **protons.**
2. An **element** is matter composed of a single type of atom.
3. The number of protons in the nucleus of an atom is its **atomic number.** The sum of the masses of its protons, neutrons, and electrons is an atom's **atomic mass**, which is estimated by adding the number of neutrons and protons (because electrons have little mass).
4. **Isotopes** are atoms of an element that differ only in the numbers of neutrons they contain.

Chemical Bonds (pp. 60–64)

1. The region of space occupied by electrons is an electron shell. The number of electrons in the outermost shell, or **valence** shell, of an atom determines the atom's reactivity. Most valence shells hold a maximum of eight electrons. Sharing or transferring valence electrons to fill a valence shell results in **chemical bonds.**
2. A chemical bond results when two atoms share a pair of electrons. The **electronegativities** of each of the atoms, which is the strength of their attraction for electrons, determines whether the bond between them will be a **nonpolar covalent bond** (equal sharing of electrons), a **polar covalent bond** (unequal sharing of electrons), or an **ionic bond** (giving up of electrons from one atom to another).
3. A **molecule** that contains atoms of more than one element is a **compound. Organic compounds** are those that contain carbon and hydrogen atoms.
4. An **anion** is an atom with an extra electron and thus a negative charge. A **cation** has lost an electron and thus has a positive charge. Ionic bonding between the two types of ions makes **salt.** When salts dissolve in water, their ions are called **electrolytes.**
5. **Hydrogen bonds** are relatively weak but important chemical bonds. They hold molecules in specific shapes and confer unique properties to water molecules.

Chemical Reactions (pp. 64–65)

1. **Chemical reactions** result from the making or breaking of chemical bonds in a process in which **reactants** are changed into **products.** Biochemistry involves chemical reactions of life.
2. **Synthesis reactions** form larger, more complex molecules. In **dehydration synthesis,** a molecule of water is removed from the reactants as the larger molecule is formed. **Endothermic reactions** require energy. **Anabolism** is the sum of all synthesis reactions in an organism.
3. **Decomposition reactions** break larger molecules into smaller molecules and are **exothermic** because they release energy. **Hydrolysis** is a decomposition reaction that uses water as one of the reactants. The sum of all decomposition reactions in an organism is called **catabolism.**
4. **Exchange reactions** involve exchanging atoms between reactants.
5. **Metabolism** is the sum of all anabolic, catabolic, and exchange chemical reactions in an organism.

Water, Acids, Bases, and Salts (pp. 65–68)

1. **Inorganic chemicals** typically lack carbon.
2. Water is a vital inorganic compound because of its properties as a solvent, its liquidity, its great capacity to absorb heat, and its participation in chemical reactions.
3. **Acids** release hydrogen ions. **Bases** release hydroxyl anions. The relative strength of each is assessed on a logarithmic **pH scale,** which measures the hydrogen ion concentration in a substance.
4. **Buffers** are substances that prevent drastic changes in pH.

Organic Macromolecules (pp. 68–80)

1. Certain groups of atoms in common arrangements, called **functional groups,** are found in organic macromolecules. **Monomers** are simple subunits that can be covalently linked to form chainlike **polymers.**
2. **Lipids**, which include fats, phospholipids, waxes, and steroids, are **hydrophobic** (insoluble in water) macromolecules.
3. **Fat** (triglyceride) molecules are formed from a glycerol and three chainlike fatty acids. **Saturated fatty acids** contain more hydrogen in their structural formulas than **unsaturated fatty acids,** which contain double bonds between some carbon atoms. If several double bonds exist in the fatty acids of a molecule of fat, it is a polyunsaturated fat.
4. **Phospholipids** contain two fatty acid chains and a phosphate functional group. The phospholipid head is **hydrophilic,** whereas the fatty acid portion of the molecule is hydrophobic.
5. **Waxes** contain a long-chain fatty acid covalently linked to a long-chain alcohol. Waxes, which are water insoluble, are components of cell walls and are sometimes used as energy storage molecules.

6. **Steroid** lipids such as cholesterol help maintain the structural integrity of membranes as temperature fluctuates.
7. **Carbohydrates** such as **monosaccharides, disaccharides,** and **polysaccharides** serve as energy sources, structural molecules, and recognition sites during intercellular interactions.
8. **Proteins** are structural components of cells, enzymatic catalysts, regulators of various activities, molecules involved in the transportation of substances, and defensive molecules. They are composed of **amino acids** linked by **peptide bonds,** and they possess primary, secondary, tertiary, and (sometimes) quaternary structures that affect their function. **Denaturation** of a protein disrupts its structure and consequently its function.
9. **Deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)** are unbranched macromolecular polymers of **nucleotides,** each composed of either deoxyribose or ribose sugar, ionized phosphate, and a nitrogenous base. Five different bases exist: **adenine, guanine, cytosine, thymine,** and **uracil.** DNA contains A, G, C, and T nucleotides. RNA uses U nucleotides instead of T nucleotides. **Nucleosides** are nucleotides lacking phosphate.

10. The structure of nucleic acids allows for genetic diversity, the correct copying of genes for their passage on to the next generation, and the accurate synthesis of proteins.
11. **Adenosine triphosphate (ATP),** which is related to adenine nucleotide, is the most important short-term energy storage molecule in cells. It is also incorporated into the structure of many coenzymes.

QUESTIONS FOR REVIEW

Answers to the Questions for Review (except Short Answer questions) begin on p. 835.

Multiple Choice

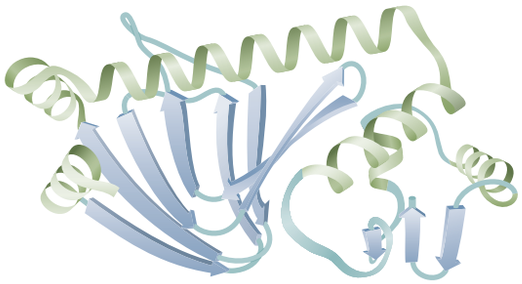
1. Which of the following bases cannot be found in DNA?
   a. adenine
   b. thymine
   c. uracil
   d. cytosine
2. The atomic mass of an atom most closely approximates the sum of the masses of all its _____.
   a. protons
   b. isotopes
   c. electrons
   d. protons and neutrons
3. Carbon-14 contains
   a. 8 electrons
   b. 8 neutrons
   c. 8 protons
   d. 14 neutrons
4. Which of the following is *not* a lipid?
   a. triglyceride
   b. steroid
   c. wax
   d. glycerol
5. Which of the following bonds is *not* directly important for the tertiary structure of proteins?
   a. disulfide bonds
   b. peptide bonds
   c. ionic bonds
   d. hydrogen bonds
6. In water, cations and anions of salts dissociate from one another and become surrounded by water molecules. In this state, the ions are also called _____.
   a. electrically negative
   b. ionically bonded
   c. electrolytes
   d. hydrogen bonds
7. Which of the following can be most accurately described as a decomposition reaction?
   a. $C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,H_2O + 6\,CO_2$
   b. glucose + ATP $\rightarrow$ glucose phosphate + ADP
   c. $6\,H_2O + 6\,CO_2 \rightarrow C_6H_{12}O_6 + 6\,O_2$
   d. A + BC $\rightarrow$ AB + C
8. Which of the following statements about a carbonated cola beverage with a pH of 2.9 is true?
   a. It has a relatively high concentration of hydrogen ions.
   b. It has a relatively low concentration of hydrogen ions.
   c. It has equal amounts of hydroxyl and hydrogen ions.
   d. Cola is a buffered solution.
9. Which of the following is *not* a polymer?
   a. protein
   b. DNA
   c. glucose
   d. cellulose
10. Peptidoglycan is made of polysaccharides and _____.
    a. glycogen
    b. peptides
    c. amino acids
    d. glucose

Fill in the Blanks

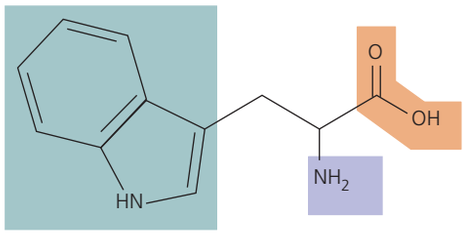
1. The outermost electron shell of an atom is known as the _____ shell.
2. The type of chemical bond between atoms with nearly equal electronegativities is called a(n) _____ bond.
3. _____, which is unbranched, is a starch storage compound in plants.
4. Common long-term storage molecules are _____, _____, _____, and _____.
5. Amino acids contain both a(n) _____ group and a(n) _____ group and have both positive and negative charges that make them easily soluble in water.
6. The reverse of dehydration synthesis is _____.
7. Anabolic reactions require energy, and are _____ in nature.
8. Lipids are a class of organic macromolecules having one common characteristic, that is, they are _____ in water.
9. The _____ scale is a measure of the concentration of hydrogen ions in a solution.
10. A nucleic acid containing the base uracil would also contain _____ sugar.

VISUALIZE IT!

1. Label a portion of the molecule below where the primary structure is visible; label two types of secondary structure; circle the tertiary structure.



2. Shown is the amino acid tryptophan. Put the letter "C" at the site of every carbon atom. Label the amino group, the carboxyl group, and the side group.



Short Answer

1. List three main types of chemical bonds, and give an example of each.
2. Name five properties of water that are vital to life.
3. What are stereoisomers? Explain the difference between D and L forms of amino acids.
4. What is the difference between atomic oxygen and molecular oxygen?
5. Explain how the polarity of water molecules makes water an excellent solvent.

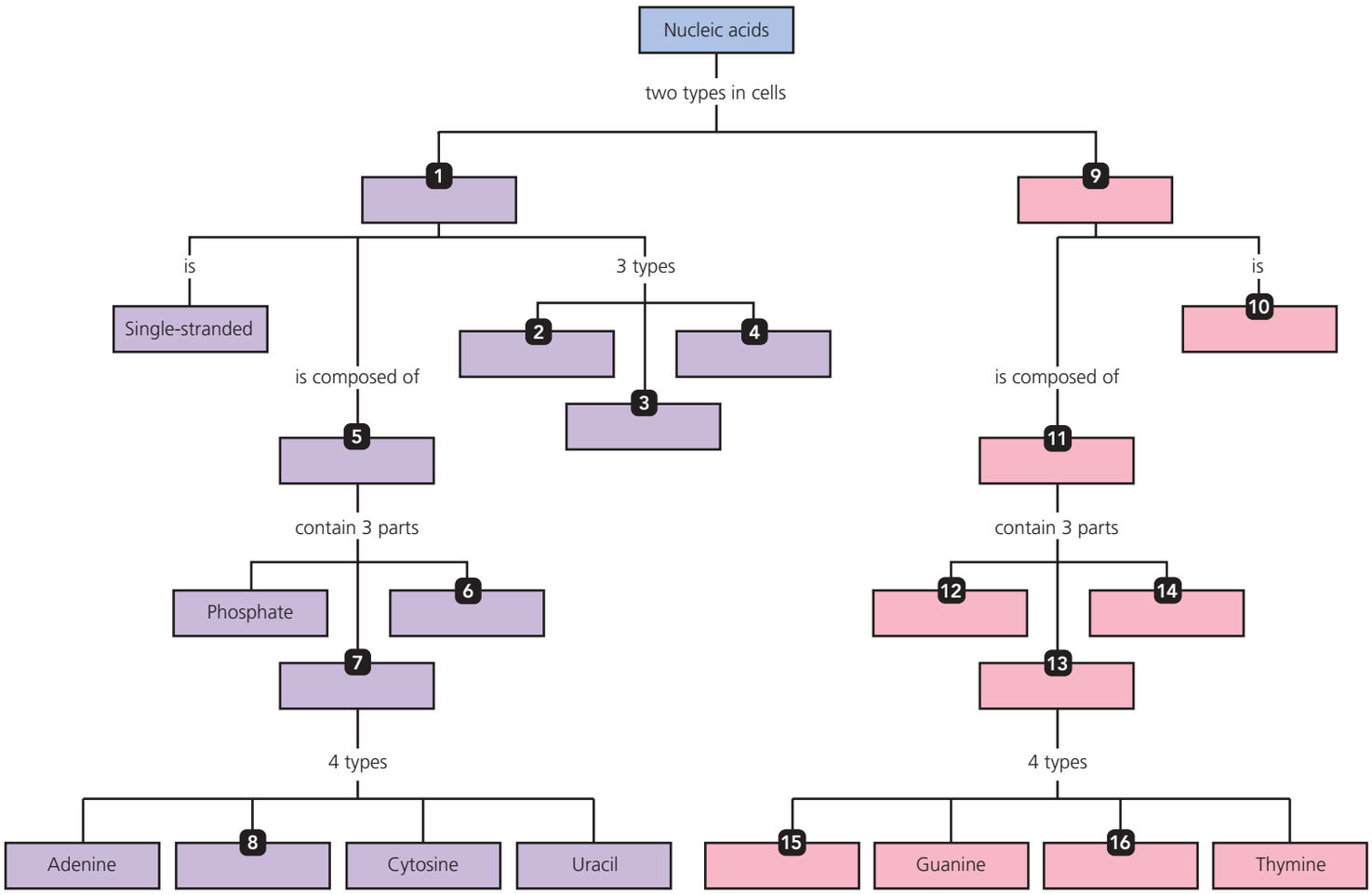
CRITICAL THINKING

1. Anthrax is caused by a bacterium, *Bacillus anthracis*, that avoids the body's defenses against disease by synthesizing an outer glycoprotein covering made from D-glutamic acid. This covering is not digestible by white blood cells that normally engulf bacteria. Why is the covering indigestible?
2. Dehydrogenation is a chemical reaction in which a saturated fat is converted to an unsaturated fat. Explain why the name for this reaction is an appropriate one.
3. Two freshmen disagree about an aspect of chemistry. The nursing major insists that H^+ is the symbol for a hydrogen ion. The physics major insists that H^+ is the symbol for a proton. How can you help them resolve their disagreement?
4. Hairdressers use hot straightening irons to straighten curly hair. Temporarily straightened hair resumes its natural shape after the first wash, whereas permanently straightened hair retains its new shape until natural hair grows again. Explain this difference based on your knowledge about proteins.
5. When amino acids are synthesized in a test tube, D and L forms occur in equal amounts. However, cells use only L forms in their proteins. Occasionally, meteorites are found to contain amino acids. Based on these facts, how could NASA scientists determine whether the amino acids recovered from space are evidence of Earth-like extraterrestrial life rather than the result of nonmetabolic processes?
6. Explain how baking soda can serve as an excellent remedy to treat acne.
7. Neon (atomic mass 10) and argon (atomic mass 18) are *inert* elements, which means that they very rarely form chemical bonds. Give the electron configuration of their atoms and explain why these elements are inert.
8. An article in the local newspaper about gangrene states that the tissue-destroying toxin, lecithinase, is an "organic compound." But many people consider "organic" chemicals to mean something is good. Explain the apparent contradiction.
9. The deadly poison hydrogen cyanide has the chemical formula H—C≡N. Describe the bonds between carbon and hydrogen and between carbon and nitrogen in terms of the number of electrons involved.
10. Which unique property of carbon makes it the "backbone" of organic molecules?
11. Explain how hydrogen bonds, which are considered to be weak ionic bonds, are essential for the stability of large DNA molecules.
12. How can a single molecule of magnesium hydroxide neutralize two molecules of hydrochloric acid?
13. We have seen that it is important that biological membranes remain flexible. Most bacteria lack sterols in their membranes and instead incorporate unsaturated phospholipids in the membranes to resist tight packing and solidification. Examine Table 2.4 on p. 71. Which fatty acid might best protect the membranes of an ice-dwelling bacterium?
14. Why is there no stereoisomer of glycine?
15. A textbook states that only five nucleotide bases are found in cells, but a laboratory worker reports that she has isolated eight different nucleotides. Explain why both are correct.

CONCEPT MAPPING

Using the following terms, fill in the following concept map that describes nucleic acids. You can also complete this and other concept maps online by going to the MasteringMicrobiology Study Area.

Adenine (2)
Cytosine (2)
Deoxyribonucleotides
Deoxyribose
DNA
Double-stranded
Guanine (2)
Messenger RNA
Nitrogenous bases (2)
Phosphate
Ribonucleotides
Ribose
RNA
Ribosomal RNA
Single-stranded
Thymine
Transfer RNA
Uracil



3

Cell Structure and Function

***Magnetospirillum magnetotacticum*, a spiral-shaped magnetobacterium, contains a clearly visible line of inclusions of magnetite, which together make a magnetosome.**

CAN A MICROBE BE A MAGNET? The answer is yes, if it is a magnetobacterium.

Magnetobacteria are microorganisms with an unusual feature: cellular structures called *magnetosomes*. Magnetosomes are stored deposits (also called inclusions) of the mineral magnetite. These deposits align magnetobacteria with the lines of the Earth's magnetic field, much like a compass. In the Southern Hemisphere, magnetobacteria exist as south-seeking varieties; in the Northern Hemisphere, they exist as north-seeking varieties.

How do these bacteria benefit from magnetosomes? Magnetobacteria prefer environments with little or no oxygen, such as those that exist below the surfaces of land and sea. The magnetosomes point toward the underground magnetic poles, helping magnetobacteria move toward regions with little oxygen.

All living things—including our bodies and the bacterial, protozoan, and fungal pathogens that attack us—are composed of living cells. If we want to understand disease and its treatment, therefore, we must first understand the life of cells. How pathogens attack our cells, how our bodies defend themselves, how current medical treatments assist our bodies in recovering—all of these activities have their basis in the biology of our, and our pathogens', cells.

In this chapter, we will examine cells and structures within cells. We will discuss similarities and differences among the three major kinds of cells—bacterial, archaeal, and eukaryotic. The differences are particularly important because they allow researchers to develop treatments that inhibit or kill pathogens without adversely affecting a patient's own cells. We will also learn about cellular structures that allow pathogens to evade the body's defenses and cause disease.

Processes of Life

LEARNING OUTCOME

3.1 Describe four major processes of living cells.

Microbiology is the study of particularly small living things. That raises a question: What does *living* mean; how do we define life? Scientists once thought that living things were composed of special organic chemicals, such as glucose and amino acids, that carried a "life force" found only in living organisms. These organic chemicals were thought to be formed only by living things and to be very different from the inorganic chemicals of nonliving things.

The idea that organic chemicals could come only from living organisms had to be abandoned in 1828, when Friedrich Wöhler (1800–1882) synthesized an organic molecule, urea, using only inorganic reactants in his laboratory. Today, we know that all living things contain both organic and inorganic chemicals and that many organic chemicals can be made from inorganic chemicals by laboratory processes. If organic chemicals can be made even in the absence of life, what is the difference between a living thing and a nonliving thing? What is life?

At first, this may seem a simple question. After all, you can usually tell when something is alive. However, defining "life" itself can prove troublesome, so biologists generally avoid setting a definition, preferring instead to describe characteristics common to all living things. Biologists agree that all living things share at least four processes of life: growth, reproduction, responsiveness, and metabolism.

- **Growth.** Living things can grow; that is, they can increase in size.
- **Reproduction.** Organisms normally have the ability to reproduce themselves. Reproduction means that they increase in number, producing more organisms organized like themselves. Reproduction may be accomplished asexually (alone) or sexually with gametes (sex cells). Note that reproduction is an increase in number, whereas growth is an increase in size. Growth and reproduction often occur simultaneously. (We consider several methods of reproduction when we examine microorganisms in detail in Chapters 11–13.)
- **Responsiveness.** All living things respond to their environment. They have the ability to change themselves in reaction to changing conditions around or within them. Many organisms also have the ability to move toward or away from environmental stimuli—a response called *taxis*.
- **Metabolism.** Metabolism can be defined as the ability of organisms to take in nutrients from outside themselves and use the nutrients in a series of controlled chemical reactions to provide the energy and structures needed to grow, reproduce, and be responsive. Metabolism is a unique process of living things; nonliving things cannot metabolize. Cells store metabolic energy in the chemical bonds of *adenosine triphosphate* (ă-den´ō-sēn trī-fos´fāt), or *ATP*. (Major processes of microbial metabolism, including the generation of ATP, are discussed in Chapters 5–7.)

TABLE 3.1 shows how these characteristics, along with cell structure, relate to various kinds of microbes.

Organisms may not exhibit these four processes at all times. For instance, in some organisms, reproduction may be postponed or curtailed by age or disease or, in humans at least, by choice. Likewise, the rate of metabolism may be reduced, as occurs in a seed, a hibernating animal, or a bacterial

TABLE 3.1 Characteristics of Life and Their Distribution in Microbes

Characteristic	Bacteria, Archaea, Eukaryotes	Viruses
Growth: increase in size	Occurs in all	Growth does not occur
Reproduction: increase in number	Occurs in all	Host cell replicates the virus
Responsiveness: ability to react to environmental stimuli	Occurs in all	Reaction to host cells seen in some viruses
Metabolism: controlled chemical reactions of organisms	Occurs in all	Viruses use host cell's metabolism
Cellular structure: membrane-bound structure capable of all of the above functions	Present in all	Viruses lack cytoplasmic membrane or cellular structure

endospore,[1] and growth often stops when an animal reaches a certain size. However, microorganisms typically grow, reproduce, respond, and metabolize as long as conditions are suitable. (Chapter 6 discusses the proper conditions for the metabolism and growth of various types of microorganisms.)

TELL ME WHY

The smallest free-living microbe—the bacterium *Mycoplasma*—is nonmotile. Why is it alive, even though it cannot move?

Prokaryotic and Eukaryotic Cells: An Overview

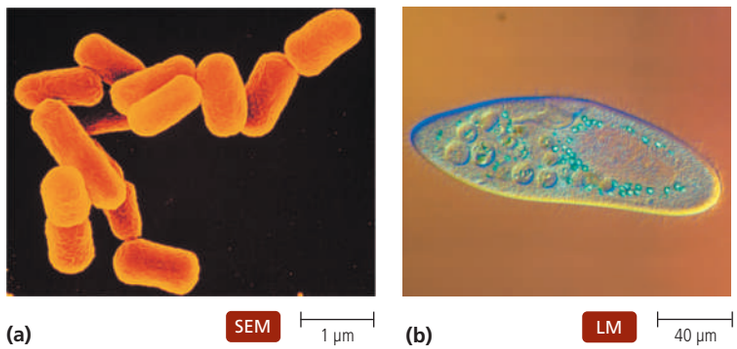
LEARNING OUTCOME

3.2 Compare and contrast prokaryotic and eukaryotic cells.

In the 1800s, two German biologists, Theodor Schwann (1810–1882) and Matthias Schleiden (1804–1881), developed the theory that all living things are composed of cells. *Cells* are living entities, surrounded by a membrane, that are capable of growing, reproducing, responding, and metabolizing. The smallest living things are single-celled microorganisms.

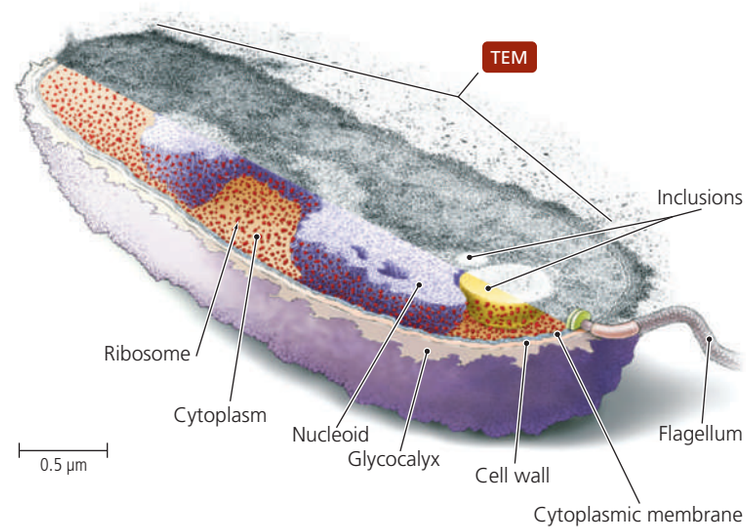
There are many different kinds of cells **(FIGURE 3.1)**. Some cells are free-living, independent organisms; others live together in colonies or form the bodies of multicellular organisms. Cells also exist in various sizes, from the smallest bacteria to bird eggs, which are the largest of cells. All cells may be described as either *prokaryotes* (prō-kar´ē-ōts) or *eukaryotes* (yū-kar´ē-ōts).

Scientists categorize organisms based on shared characteristics into groups called *taxa*. "Prokaryotic" is a characteristic of organisms in two taxa—*domain Archaea* and *domain Bacteria*—but "prokaryote" is not itself a taxon. The distinctive feature of **prokaryotes** is that they can read their DNA genetic code and simultaneously make proteins—a typical prokaryote does not have a membrane surrounding its genetic material.



▲ **FIGURE 3.1 Examples of types of cells. (a)** *Escherichia coli* bacterial cells. **(b)** *Paramecium*, a single-celled eukaryote. Note the differences in magnification.

[1]Endospores are resting stages, produced by some bacteria, that are tolerant of environmental extremes.



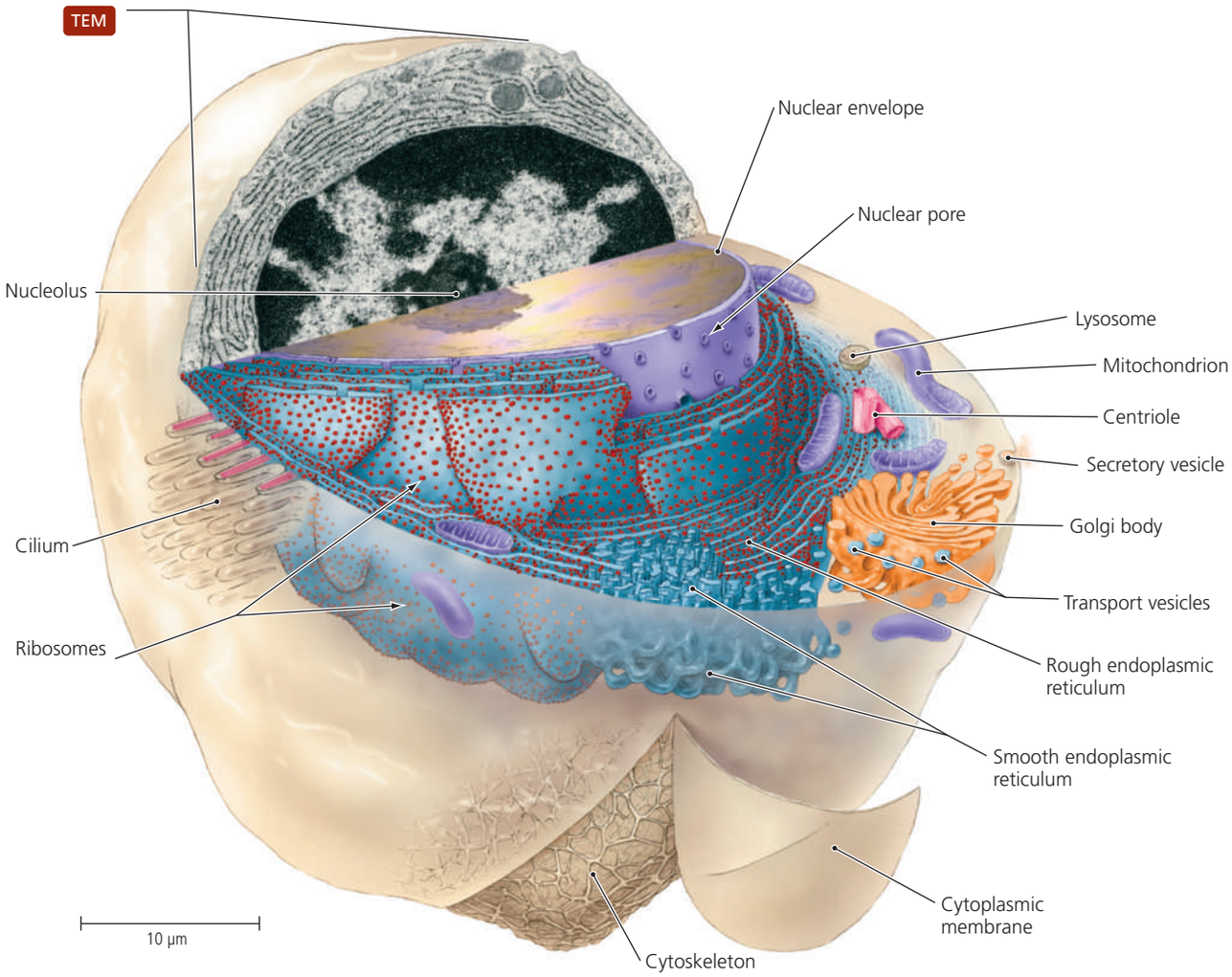
▲ **FIGURE 3.2 Typical prokaryotic cell.** Prokaryotes include archaea and bacteria. The artist has extended an electron micrograph to show three dimensions. Not all prokaryotic cells contain all these features.

In other words, a typical prokaryote does not have a nucleus **(FIGURE 3.2)**. (Researchers have discovered a few prokaryotes with internal membranes that look like nuclei, but further investigation is needed to determine what these structures are.) The word *prokaryote* comes from Greek words meaning "before nucleus." Moreover, electron microscopy has revealed that prokaryotes typically lack various types of internal structures bound with membranes that are present in eukaryotic cells.

Bacteria and archaea differ fundamentally in such ways as the type of lipids in their cytoplasmic membranes and in the chemistry of their cell walls. In many ways, archaea are more like eukaryotes than they are like bacteria. (Chapter 11 discusses archaea and bacteria in more detail.)

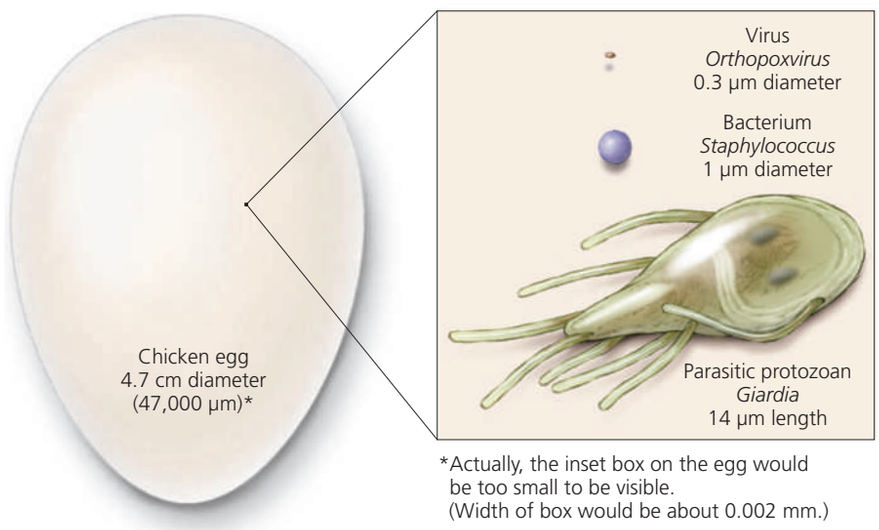
Eukaryotes have a membrane called a nuclear envelope surrounding their DNA, forming a nucleus **(FIGURE 3.3)**, which sets eukaryotes in *domain Eukarya*. Indeed, the term *eukaryote* comes from Greek words meaning "true nucleus." Besides the nuclear membrane, eukaryotes have numerous other internal membranes that compartmentalize cellular functions. These compartments are membrane-bound **organelles**—specialized structures that act like tiny organs to carry on the various functions of the cell. Organelles and their functions are discussed later in this chapter. The cells of algae, protozoa, fungi, animals, and plants are eukaryotic. Eukaryotes are usually larger and more complex than prokaryotes, which are often about 1.0 µm in diameter or smaller, as compared to 10–100 µm for eukaryotic cells **(FIGURE 3.4)**.

Although there are many kinds of cells, they all share the characteristic processes of life as previously described, as well as certain physical features. In this chapter, we will distinguish among bacterial, archaeal, and eukaryotic "versions" of physical features common to cells, including (1) external structures, (2) the cell wall, (3) the cytoplasmic membrane, and (4) the cytoplasm. We will also discuss features unique to each type.



▲ **FIGURE 3.3** **Typical eukaryotic cell.** Not all eukaryotic cells have all these features. The artist has extended the electron micrograph to show three dimensions. Note the difference in magnification between this cell and the prokaryotic cell in the previous figure. *Besides size, what major difference between prokaryotes and eukaryotes was visible to early microscopists?*

Figure 3.3 *Eukaryotic cells contain nuclei, which are visible with light microscopes, whereas prokaryotes lack nuclei.*



*Actually, the inset box on the egg would be too small to be visible. (Width of box would be about 0.002 mm.)

◀ **FIGURE 3.4** **Approximate size of various types of cells.** Birds' eggs are the largest cells. Note that *Staphylococcus*, a bacterium, is smaller than *Giardia*, a unicellular eukaryote. A smallpox virus *(Orthopoxvirus)* is shown only for comparison; viruses are not cellular.

(Chapters 11, 12, and 19–23 examine further details of prokaryotic and eukaryotic organisms, their classification, and their ability to cause disease.)

TELL ME WHY

In 1985, an Israeli scientist discovered the single-celled microbe *Epulopiscium fishelsoni*. This organism is visible with the naked eye. Why did the scientist initially think *Epulopiscium* was eukaryotic?

What discovery revealed that the microbe is really a giant bacterium?

Next, we explore characteristics of bacterial cells, beginning with external features and working into the cell.

External Structures of Bacterial Cells

Many cells have special external features that enable them to respond to other cells and their environment. In bacteria, these features include glycocalyces, flagella, fimbriae, and pili.

Glycocalyces

LEARNING OUTCOMES

3.3 Describe the composition, function, and relevance to human health of glycocalyces.
3.4 Distinguish capsules from slime layers.

Some cells have a gelatinous, sticky substance that surrounds the outside of the cell. This substance is known as a **glycocalyx** (plural: *glycocalyces*), which literally means "sweet cup." The glycocalyx may be composed of polysaccharides, polypeptides, or both. These chemicals are produced inside the cell and are extruded onto the cell's surface.

When the glycocalyx of a bacterium is composed of organized repeating units of organic chemicals firmly attached to the cell's surface, the glycocalyx is called a **capsule** (FIGURE 3.5a). In contrast, a loose, water-soluble glycocalyx is called a **slime layer** (FIGURE 3.5b).

Glycocalyces protect cells from drying (desiccation) and can also play a role in the ability of pathogens to survive and cause disease. For example, slime layers are often sticky and provide one means for bacteria to attach to surfaces as *biofilms*, which are aggregates of many bacteria living together on a surface. Oral bacteria colonize the teeth as a biofilm called dental plaque. Bacteria in a dental biofilm can produce acid and cause *dental caries* (cavities).

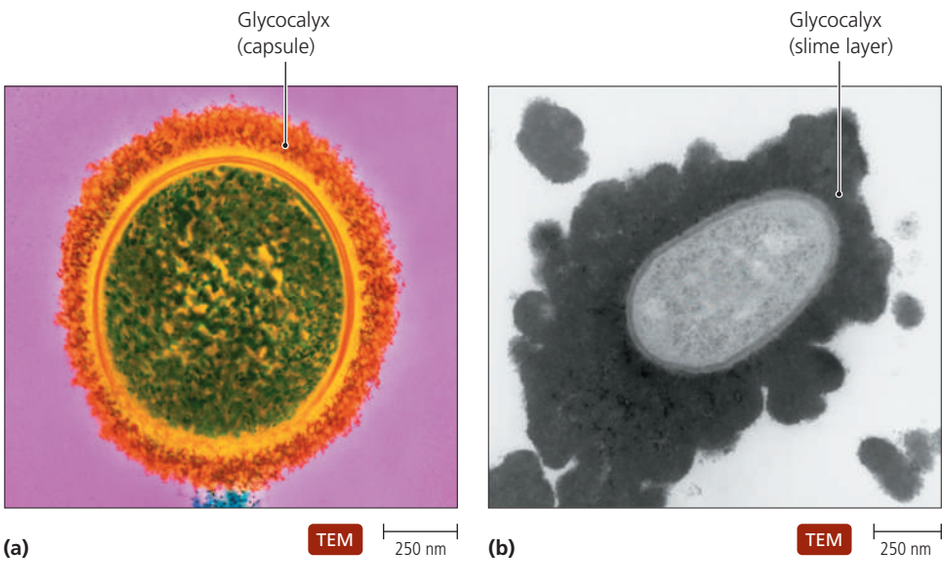
The chemicals in many bacterial capsules can be similar to chemicals normally found in the body, preventing bacteria from being recognized or devoured by defensive cells of the host. For example, the capsules of *Streptococcus pneumoniae* (strep-tō-kok´ŭs nū-mō´nē-ī) and *Klebsiella pneumoniae* (kleb-sē-el´ă nū-mō´nē-ī) enable these prokaryotes to avoid destruction by defensive cells in the respiratory tract and to cause pneumonia. Unencapsulated strains of these same bacterial species do not cause disease because the body's defensive cells destroy them.

Flagella

LEARNING OUTCOMES

3.5 Discuss the structure and function of bacterial flagella.
3.6 List and describe four bacterial flagellar arrangements.

A cell's motility may enable it to flee from a harmful environment or move toward a favorable environment, such as one where food or light is available. The most notable structures responsible for such bacterial movement are flagella. Bacterial



◀ **FIGURE 3.5 Glycocalyces. (a)** Micrograph of a single cell of the bacterium *Streptococcus* attached to a human tonsil cell (blue), showing a prominent capsule. **(b)** An unidentified skin bacterium has a slime layer surrounding the cell. *What advantage does a glycocalyx provide a cell?*

Figure 3.5 *A glycocalyx provides protection from drying and from being devoured; it may also help attach cells to one another and to surfaces in the environment.*

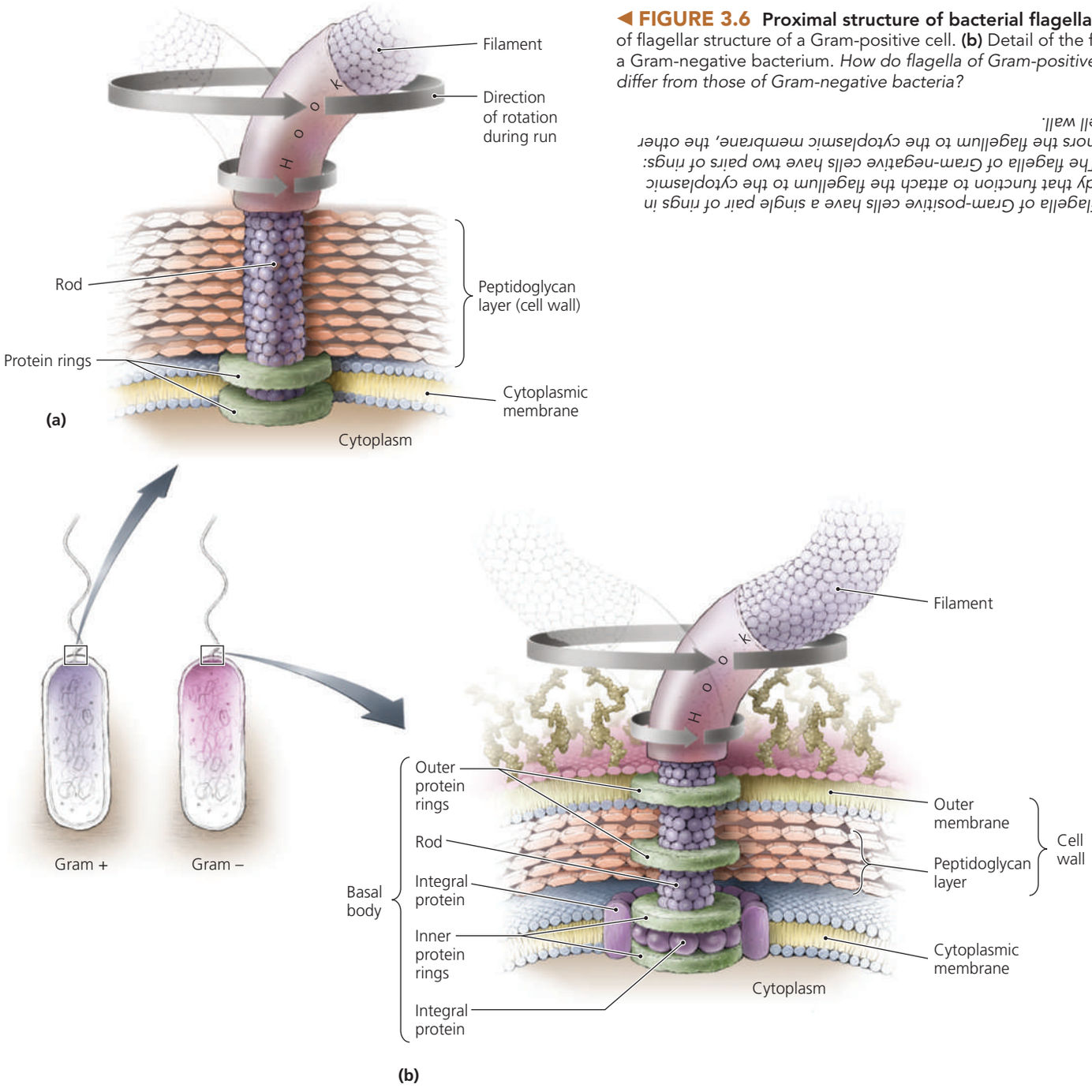
flagella (singular: *flagellum*) are long structures that extend beyond the surface of a cell and its glycocalyx and propel the cell through its environment. Not all bacteria have flagella, but for those that do, their flagella are very similar in composition, structure, and development. MM ANIMATIONS: *Motility: Overview*

Structure

Bacterial flagella are composed of three parts: a *filament*, a *hook*, and a *basal body* (FIGURE 3.6). A filament is a long hollow shaft, about 20 nm in diameter, which extends out of the cell into its environment. No membrane covers a filament.

A bacterial flagellum is composed of many identical globular molecules of a protein called *flagellin*. A flagellum lengthens by growing at its tip as the cell secretes molecules of flagellin through the hollow core of the flagellum, to be deposited in a clockwise helix at the tip of the filament. Bacterial flagella react to external wetness, inhibiting their own growth in dry habitats.

At its base, a filament inserts into a curved structure, the hook, which is composed of a different protein. The basal body, which is composed of still different proteins, anchors the filament and hook to the cell wall and cytoplasmic



◀ **FIGURE 3.6 Proximal structure of bacterial flagella. (a)** Detail of flagellar structure of a Gram-positive cell. **(b)** Detail of the flagellum of a Gram-negative bacterium. *How do flagella of Gram-positive bacteria differ from those of Gram-negative bacteria?*

Figure 3.6 *Flagella of Gram-positive cells have a single pair of rings in the basal body that function to attach the flagellum to the cytoplasmic membrane. The flagella of Gram-negative cells have two pairs of rings: one pair anchors the flagellum to the cytoplasmic membrane, the other pair to the cell wall.*