GLOBAL EDITION

BROCK BIOLOGY OF MICROORGANISMS

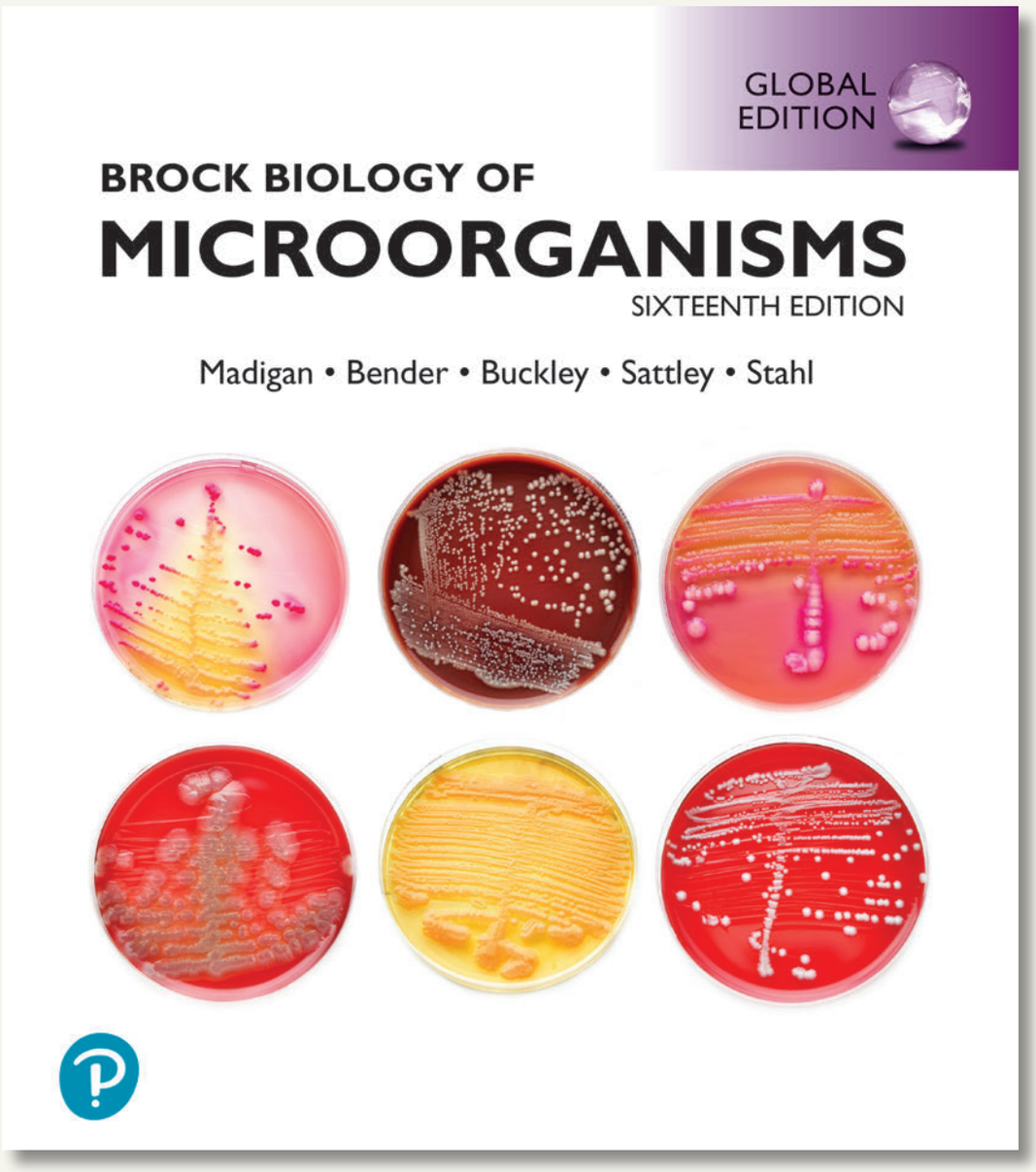
SIXTEENTH EDITION

Madigan • Bender • Buckley • Sattley • Stahl

Brief Contents

Authoritative. Accurate. Accessible.

Brock Biology of Microorganisms **is the leading microbiology text for majors, setting the standard for impeccable scholarship, accuracy, a visually stunning art program, and the use of cutting-edge research to illustrate basic concepts.**



Pearson

Making Connections Across

UPDATED! Each chapter is carefully cross-referenced to connect students with related material found earlier (◀) or later (▶) in the book.

I • Bacterial Cell Division

Prokaryotic cell division is preceded by chromosome replication and the synthesis of new cell wall material in a way that defines cell shape. Cell division is orchestrated in a carefully controlled fashion by protein complexes whose activities can be visualized by powerful light microscopic techniques.

Most cells divide by binary fission (◀ Section 4.6 and Figure 4.8), and this process occurs in a defined series of steps such that each daughter cell obtains a copy of the genome. During the division cycle, the cell must also produce new peptidoglycan and cytoskeleton elements to prevent bursting from osmotic forces. This cytoskeleton gives the cell its distinct morphology (◀ Figure 1.8). To successfully orchestrate all of these events, various regulatory cascades are put into play. In this first part of the chapter we focus on the molecular mechanisms employed by two well-studied gram-negative bacteria, *Escherichia coli* and *Caulobacter crescentus*, and introduce advanced microscopic techniques that have revealed the major molecular events that underlie cell division and cell morphology.

NEW! Key Concept statements at the start of each key topic of a chapter give students a big-picture view of the content to come before they dive in and immerse themselves in the details.

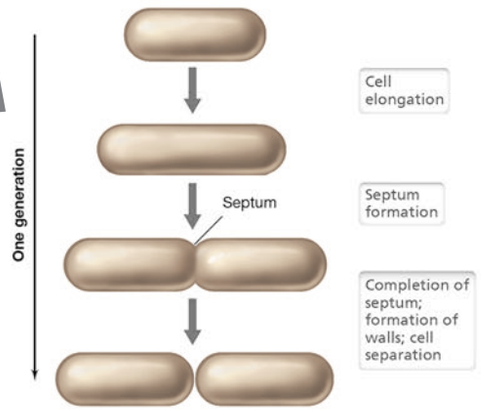


Figure 4.8 Binary fission in a rod-shaped bacterium. Cell numbers (and all components of the cells) double every generation.

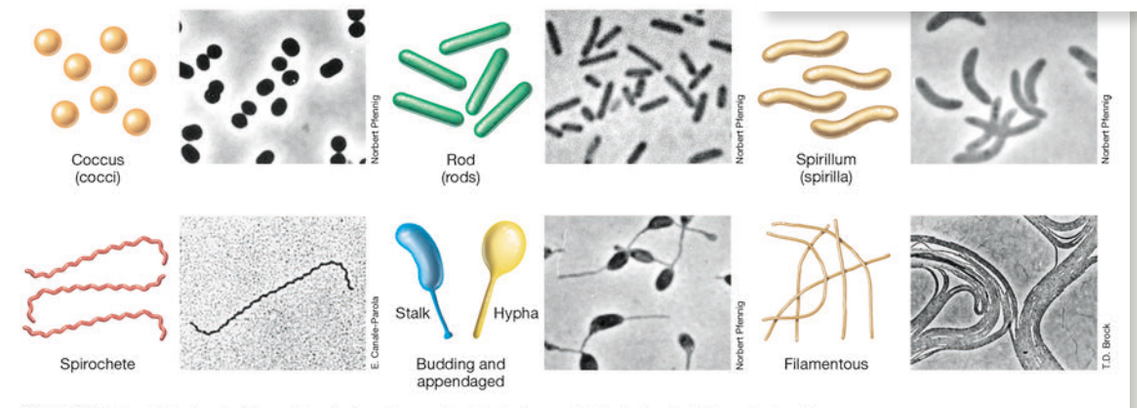
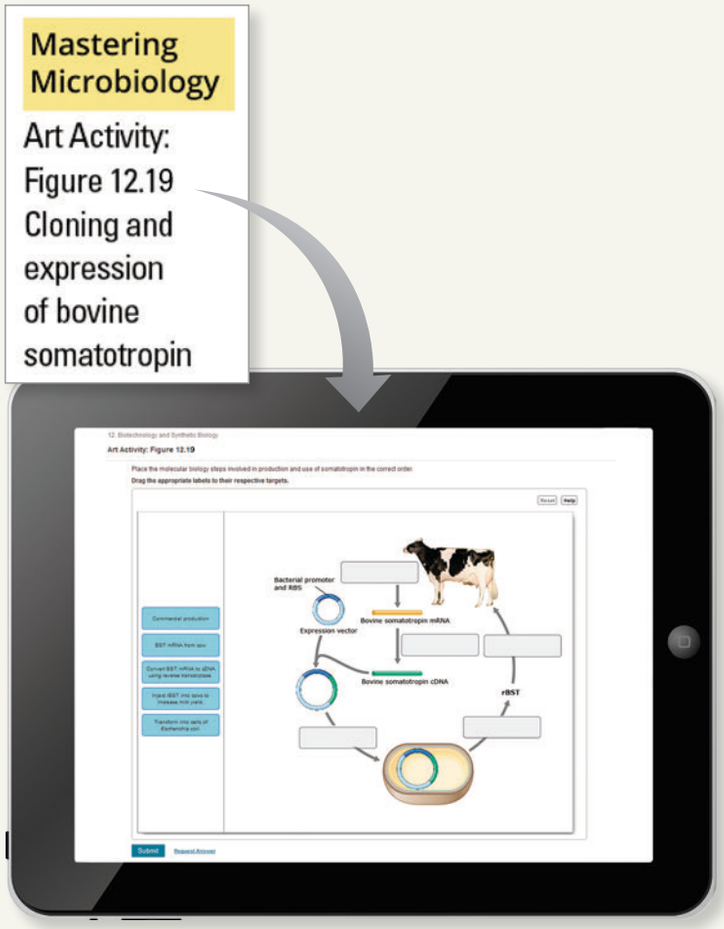


Figure 1.8 Cell morphologies. Beside each drawing is a phase-contrast photomicrograph of cells showing that morphology. Coccus (cell diameter in photomicrograph, 1.5 μm); rod (1 μm); spirillum (1 μm); spirochete (0.25 μm); budding (1.2 μm); filamentous (0.8 μm). All photomicrographs are of species of *Bacteria*. Not all of these morphologies are known among the *Archaea*, but cocci, rods, and spirilla are common.

Concepts in Microbiology

NEW! Marginal annotations highlight some of the best material available for instructors to assign in Mastering Microbiology, guiding students along their journey with insightful materials that support and strengthen the learning experience.



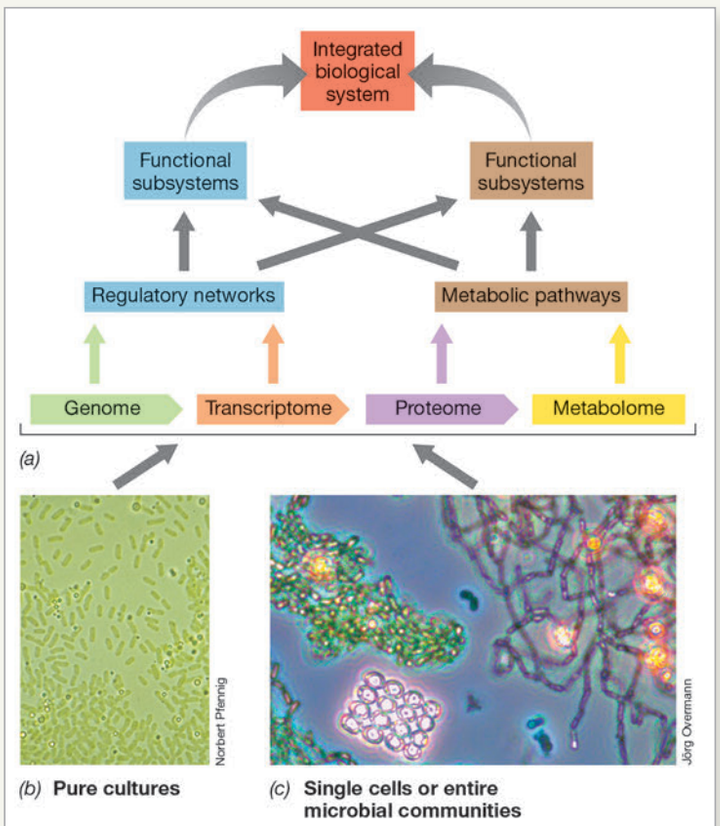


Figure 10.29 The components of systems biology. *(a)* The results of various "omics" analyses are combined and successively integrated into higher-level views of the entire biology of a pure culture, such as *(b)* that of the green sulfur bacterium *Chlorobium*; or of a mixed microbial community, such as *(c)* that of phototrophic sulfur bacteria obtained from a lake; or of a single cell isolated from a microbial community (see Figure 10.30).

Genomics, and the various "omics" it has spawned, is woven into every chapter of the text, providing students with concrete examples of how powerful tools have allowed microbiologists to probe deeper and farther into the microbial world than ever before.

Cutting-Edge Content

MICROBIOLOGYNOW

When Antibiotics Fail, Bacteriophage Therapy to the Rescue

Acquiring an antibiotic-resistant infection or "superbug" is one of medicine's biggest nightmares. What can medical practitioners do to treat the patient? Besides drugs, viruses known as bacteriophages have been recruited to specifically target and kill bacteria.

Despite microbiologists' tinkering with using bacteriophages as antimicrobials for decades, their actual application in medicine has been minimal. However, the emergence of antibiotic resistance has led to renewed focus on using these tiny microbes as therapeutic agents. The photo above shows Ella Balasa (right side of photo), a microbiologist who has cystic fibrosis. Cystic fibrosis is a genetic disease that results in a buildup of thick mucus in the lungs. This mucus allows bacteria to flourish in the lungs, which results in infections and subsequent lung damage that can be fatal. Ella had been treated numerous times with strong antibiotics specific for a respiratory infection caused by the bacterial pathogen *Pseudomonas aeruginosa*, but the microbial cells had become unresponsive to the drugs. At the time of this photo, the recurrent infection had decreased her lung function to the point where she required constant supplemental oxygen.

As an alternative treatment route, Dr. Benjamin Chan (on the left) took mucus from Ella's lungs infected with *P. aeruginosa* and isolated a bacteriophage that specifically killed the pathogen (see zones of clearing on Petri plate). This bacteriophage was propagated and then poured into a device so that Ella could inhale the therapy. The result of her treatment? Amazingly, the bacteriophage therapy along with a mixture of antibiotics resulted in the infection clearing a few weeks later!

While bacteriophage therapy is l
specificity and the ability of the path
become resistant to viral infection, t
success stories illustrate the future
therapy when all other options fail.

Source: Kortright, K.E., B.K. Chan, J.
Phage therapy: A renewed approach
bacteria. *Cell Host Microbe* 25(2): 21

NEW! Thirty-four Microbiology Now chapter opening vignettes were composed for this edition, each designed to introduce a chapter's theme through a recent discovery in the field of microbiology. These exciting accounts will draw students into the chapter and show how the chapter content connects with real-world problems.

NEW! Several new Explore the Microbial World features provide fascinating stories that highlight how important chapter concepts have evolved from research in the microbial world.

Explore the Microbial World

Pattern Recognition Receptors of Hydrothermal Vent Tube Worms Facilitate Endosymbiosis

Invertebrates and plants lack adaptive immunity but have a well-developed innate immune response to a wide variety of pathogens. As discussed in Section 26.6, virtually all multicellular organisms respond to pathogen invasion by recognizing signature molecules found on pathogen surfaces. These molecules contain conserved, repetitive structures called pathogen-associated molecular patterns (PAMPs) that include molecules such as the lipopolysaccharide (LPS) and flagellin of gram-negative bacteria, the peptidoglycan of gram-positive bacteria, and the double-stranded RNA of certain viruses. The term *microbe-associated molecular pattern*, or MAMP, is also commonly used to describe signature molecules found on microorganisms. However, "MAMP" is a broader term than "PAMP" because it includes components found on microorganisms that are not pathogenic.

Unlike PAMPs, which are exploited specifically for innate defense against pathogens, MAMPs found on nonpathogenic bacteria can serve an entirely different purpose—that of facilitating, through host pattern recognition receptors (PRRs), a mutualistic partnership rather than a confrontation between a host and the bacteria that colonize it. As we learned in Chapter 23, a wide variety of plants and animals maintain symbiotic relationships with microorganisms. There we discussed the association of tube worms that develop near hydrothermal vents in the deep sea with autotrophic, sulfur-oxidizing bacteria (SOB) that inhabit their *trophosome*, a spongy internal organ that comprises most of the volume of the 1- to 2-m-long worms (Figure 1). These SOB form an endosymbiosis with the worms in which the bacteria provide all organic carbon requirements for their animal host in exchange for a steady supply of essential metabolites, in particular H_2S, O_2, and CO_2. H_2S is the energy source for the SOB; they oxidize it to S^0 and then SO_4^{2-} and respire the electrons to generate a proton motive force that drives ATP synthesis. Oxygen (O_2) is required as a terminal acceptor of electrons that have traversed the electron transport chain. CO_2 is the carbon source and is incorporated into bacterial cell material by way of the Calvin cycle, the major means of autotrophy in chemolithotrophic bacteria.

This fascinating association raises the question of how it is established. Specifically, how does the tube worm populate its trophosome with SOB to the exclusion of other, potentially pathogenic, bacteria? The answer appears to be closely linked to MAMPs associated with the endosymbiotic SOB. Although host PRRs are typically used to recognize and eliminate pathogens, the study of tube worms and other animals that harbor endosymbiotic microbes shows a broader functionality for PRRs in that they can also interact beneficially with MAMPs to selectively populate a host with nonpathogenic symbionts.

The tube worm trophosome contains a large number of specialized host immune cells called *bacteriocytes*, and it is within these cells that the bacterial symbionts take up residence. The tube-worm bacteriocytes express high levels of PRRs that recognize MAMPs, such as specific cell surface lipoproteins associated with SOB. This positive interaction locates the bacteria to the trophosome and, with a steady supply of simple nutrients from the hydrothermal vent system delivered by blood circulating in the worm, stimulates colonization and growth of the symbionts in their animal host.

As this example illustrates, in addition to providing a rapid response to pathogen challenge, innate immune mechanisms—specifically, the interaction of PRRs with MAMPs—may also serve the primary role in governing host–symbiont interactions and the establishment of endosymbiotic relationships. Given the critical role innate immune mechanisms play in maintaining the animal–bacterial symbiosis within the tube-worm trophosome, it is likely that similar tightly choreographed molecular mechanisms constitute a host–microbe "dialogue" that helps to maintain balanced communities of beneficial microbiota in virtually all animals, including humans.

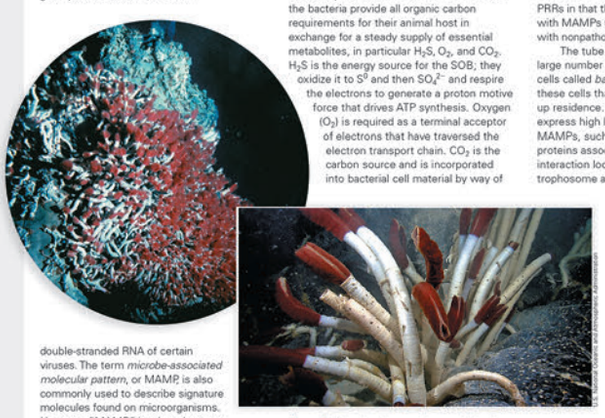


Figure 1 Hydrothermal vent tube worms harboring endosymbiotic sulfur-oxidizing bacteria. Top: A "black smoker" hydrothermal vent community containing several tube worms that obtain organic carbon from sulfur-oxidizing chemolithotrophic bacteria (SOB) living within them. Bottom: A close-up view of tube worms; each worm is 1–2 m long. The red area on the top of each worm, called the plume, is where O_2 and H_2S are taken in to be fed to the worm's SOB endosymbionts residing in the trophosome.

NEW! A section on immunotherapy highlights exciting advancements in the use of genetic engineering and molecular immunology to treat cancer.

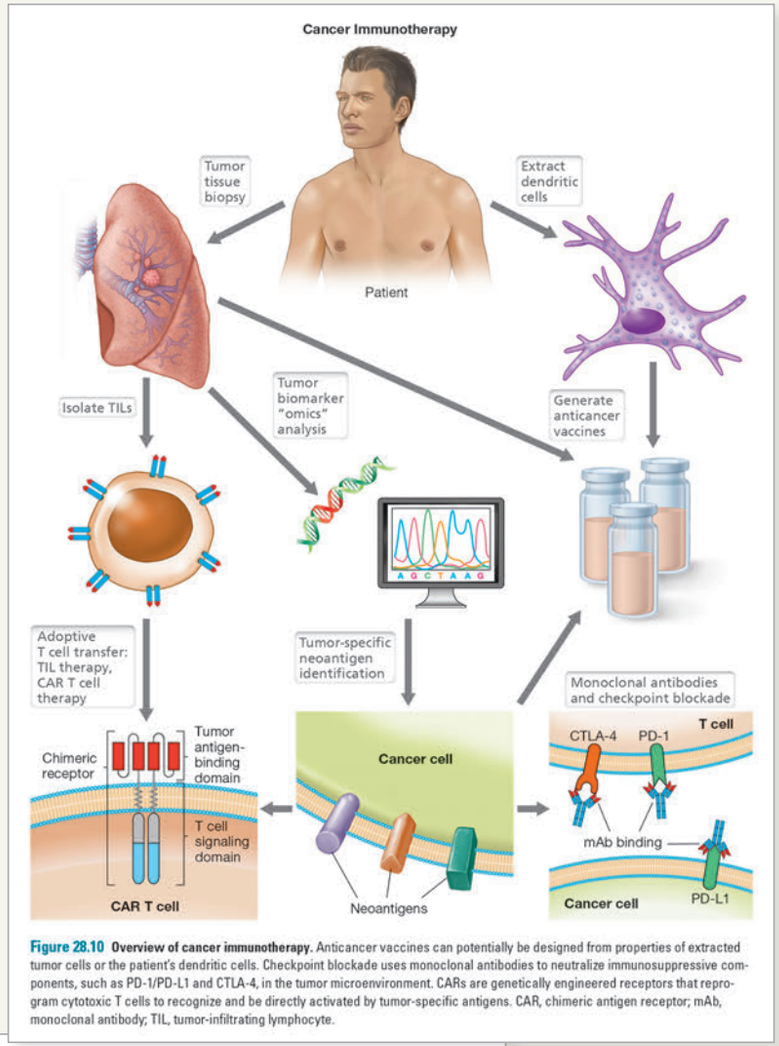


Figure 28.10 Overview of cancer immunotherapy. Anticancer vaccines can potentially be designed from properties of extracted tumor cells or the patient's dendritic cells. Checkpoint blockade uses monoclonal antibodies to neutralize immunosuppressive components, such as PD-1/PD-L1 and CTLA-4, in the tumor microenvironment. CARs are genetically engineered receptors that reprogram cytotoxic T cells to recognize and be directly activated by tumor-specific antigens. CAR, chimeric antigen receptor; mAb, monoclonal antibody; TIL, tumor-infiltrating lymphocyte.

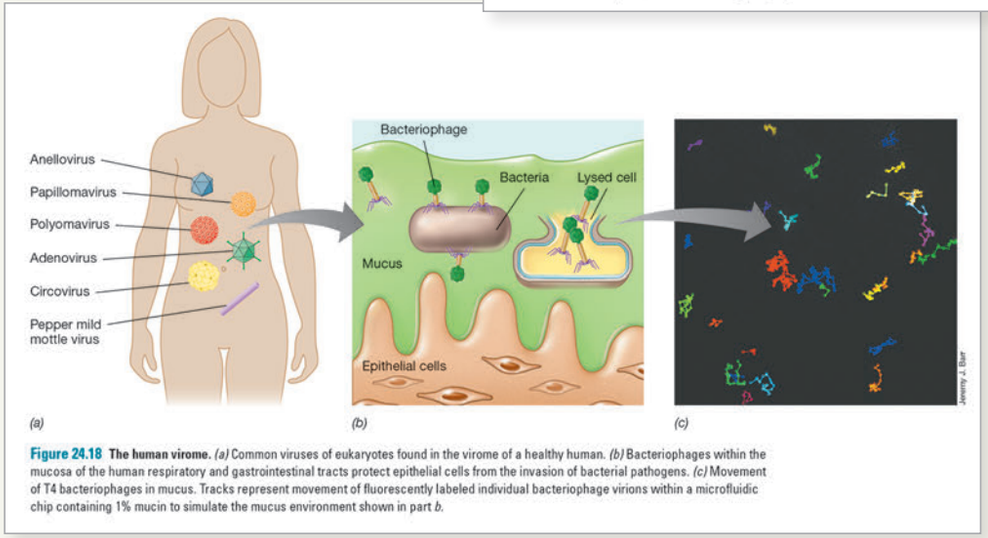
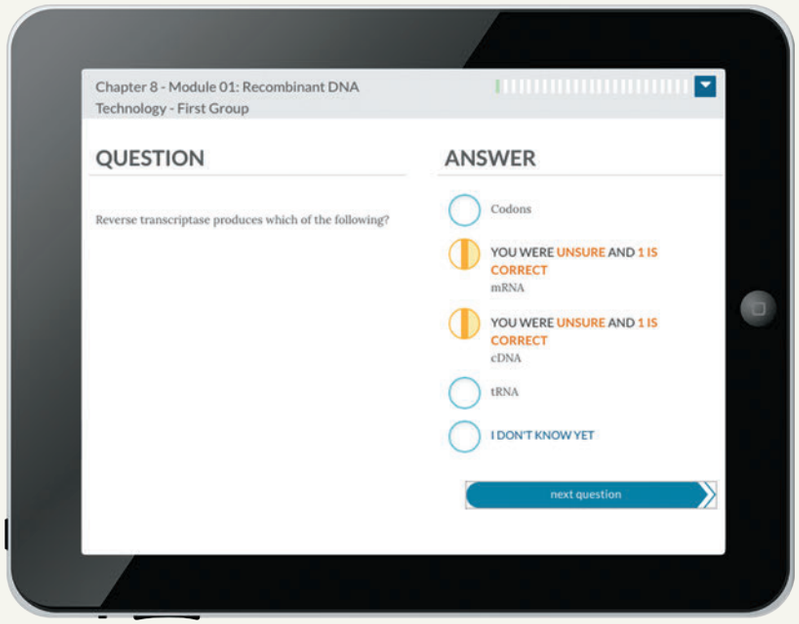


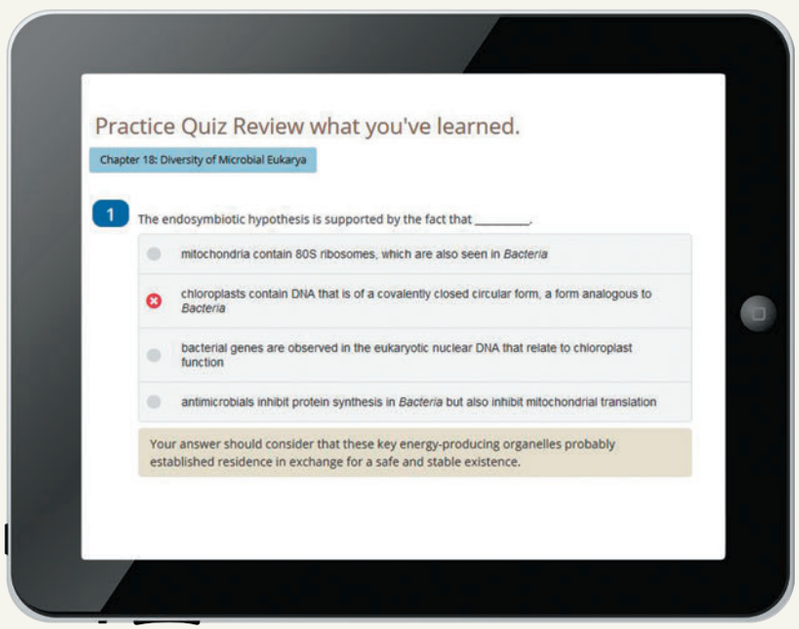
Figure 24.18 The human virome. *(a)* Common viruses of eukaryotes found in the virome of a healthy human. *(b)* Bacteriophages within the mucosa of the human respiratory and gastrointestinal tracts protect epithelial cells from the invasion of bacterial pathogens. *(c)* Movement of T4 bacteriophages in mucus. Tracks represent movement of fluorescently labeled individual bacteriophage virions within a microfluidic chip containing 1% mucin to simulate the mucus environment shown in part *b*.

NEW! The chapter on the human microbiome now includes a new section on the human virome, describing how metagenomics is aiding the discovery and isolation of many new viruses. Extensive coverage is provided of the impact of early life events on the development of the newborn gut microbiome and of recent successes in probiotic therapy for preventing newborn intestinal diseases.

Empower Each Learner

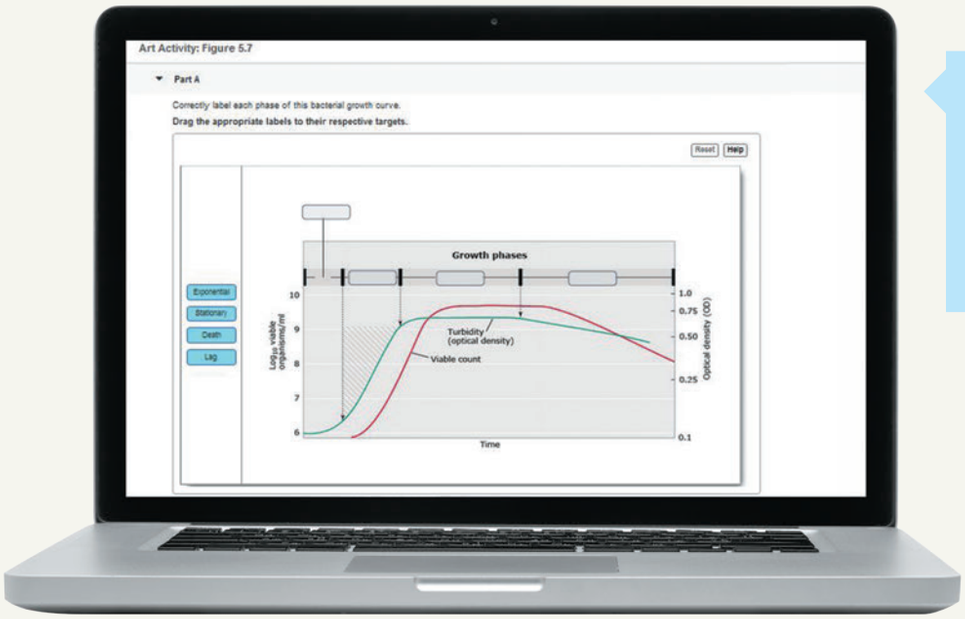


NEW! Dynamic Study Modules help students study course topics by adapting to their performance in real time. Students build the confidence they need to deepen their understanding, participate meaningfully, and perform better—in and out of class. Available on smartphones, tablets, and computers.



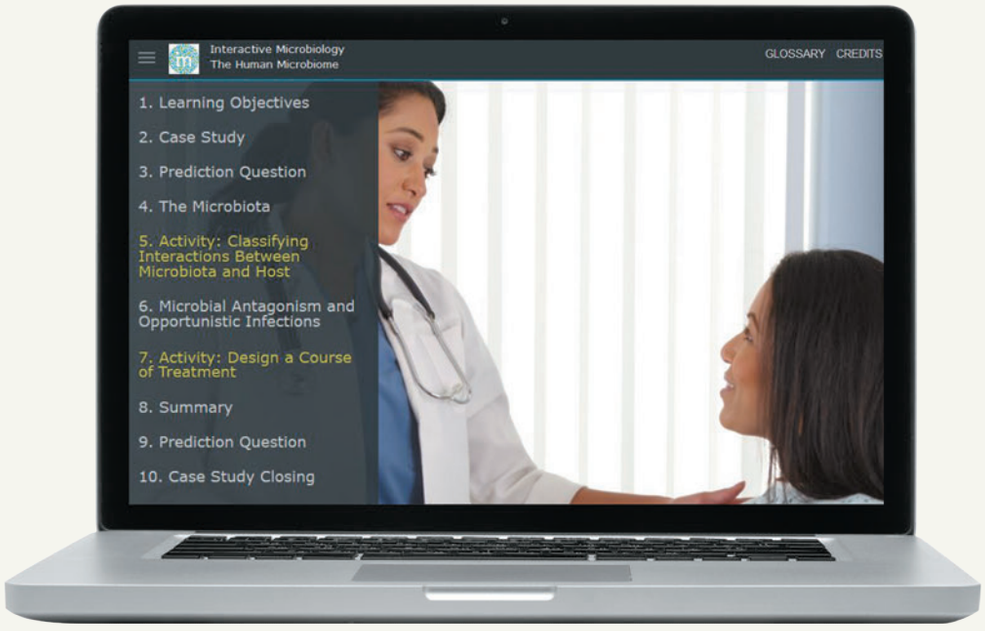
Mastering is so much more than homework. The **Pearson Study Area** allows students to access multiple study tools in one place. They don't need to search Google to find study tools that align with their course materials. Students have access to practice quizzes, videos and animations, vocabulary tools, and more.

with Mastering Microbiology



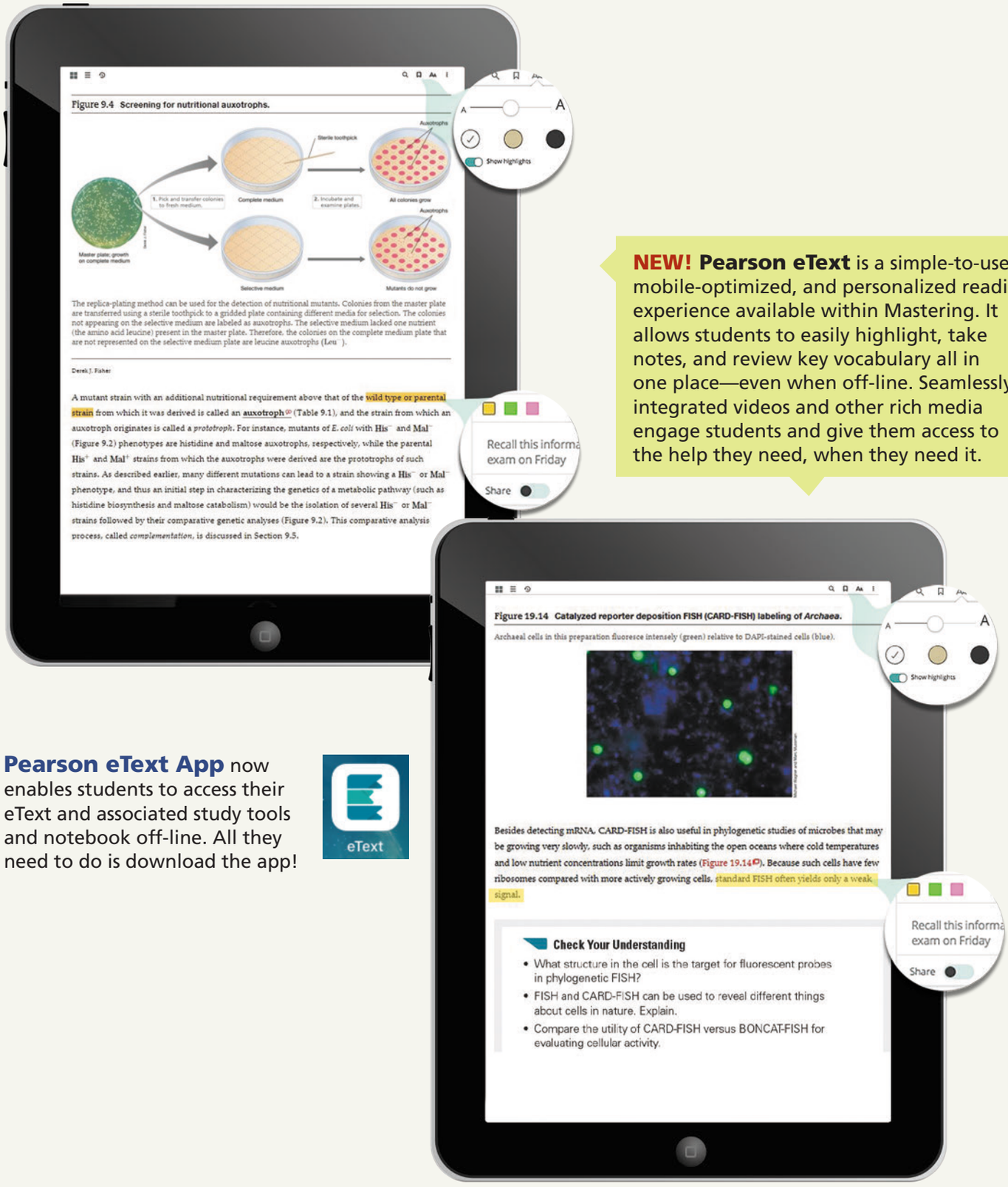
Get students engaged with content by assigning a variety of questions in Mastering Microbiology. These include:

- Reading Questions
- Art-Based Activities
- Coaching Activities and more



Interactive Microbiology is a dynamic suite of interactive tutorials and animations that teach key microbiology concepts including Operons, Biofilms and Quorum Sensing, Complement, Human Microbiota, and Antibiotic Resistance. Interactive Microbiology actively engages students with each topic, enabling them to learn from manipulating variables, predicting outcomes, and answering formative and summative assessment questions. Each tutorial presents the concept within a real healthcare scenario in order to emphasize problem solving and interest students from the beginning.

Pearson eText: A Whole New Reading Experience



NEW! Pearson eText is a simple-to-use, mobile-optimized, and personalized reading experience available within Mastering. It allows students to easily highlight, take notes, and review key vocabulary all in one place—even when off-line. Seamlessly integrated videos and other rich media engage students and give them access to the help they need, when they need it.

Pearson eText App now enables students to access their eText and associated study tools and notebook off-line. All they need to do is download the app!

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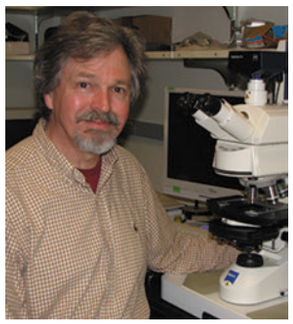
About the Authors

Michael T. Madigan received his B.S. in Biology and Education from Wisconsin State University–Stevens Point (1971) and his M.S. (1974) and Ph.D. (1976) in Bacteriology from the University of Wisconsin–Madison in the laboratory of Thomas Brock. Following a postdoc at Indiana University with Howard Gest, Mike moved to Southern Illinois University Carbondale, where he taught courses in introductory microbiology and bacterial diversity as a professor of microbiology for 33 years. In 1988 Mike was selected as the Outstanding Teacher in the College of Science and in 1993, the Outstanding Researcher. In 2001 he received the SIUC Outstanding Scholar Award and Distinguished Professor title. In 2003 Mike received the Carski Award for Distinguished Undergraduate Teaching from the American Society for Microbiology (ASM), and he is an elected Fellow of the American Academy of Microbiology (ASM) and the American Association for the Advancement of Science (AAAS). He has also been recognized by the American Red Cross as a major volunteer blood donor for the 24 gallons of blood he has donated since 1967. Mike's research is focused on phototrophic bacteria that inhabit extreme environments, and for the past 20 years his emphasis has been Antarctic microbiology. Mike has co-edited a major treatise on phototrophic bacteria and served for 10 years as chief editor of the journal *Archives of Microbiology.* He currently serves on the editorial board of the journals *Environmental Microbiology* and *Antonie van Leeuwenhoek*. Mike's other interests include forestry, swimming, reading, and caring for his dogs and horses. He lives on a small farm near a quiet lake with his wife, Nancy, three dogs (Kato, Nut, and Merlyn), and three horses (Eddie, Georgie, and Roscoe).

Kelly S. Bender received her B.S. in Biology from Southeast Missouri State University (1999) and her Ph.D. (2003) in Molecular Biology, Microbiology, and Biochemistry from Southern Illinois University Carbondale. Her dissertation research focused on the genetics of perchlorate-reducing bacteria. During her postdoctoral fellowship, Kelly worked on the genetic regulation of sulfate-reducing bacteria in the laboratory of Judy Wall at the University of Missouri–Columbia. She also completed a transatlantic biotechnology fellowship at Uppsala University in Sweden researching regulatory small RNAs in bacteria. In 2006, Kelly returned to her alma mater, Southern Illinois University Carbondale, as an Assistant Professor in the Department of Microbiology and in 2012 was tenured and promoted to Associate Professor. She has served as Chair of the SIUC Department of Microbiology since 2018. Her lab studies a range of topics including regulation in sulfate-reducing bacteria, the microbial community dynamics of sites impacted by acid mine drainage, and diversity of phototrophic heliobacteria. Kelly teaches courses in introductory microbiology and microbial diversity, has served on numerous federal grant review panels, and is an active member of the American Society for Microbiology (ASM). Her other interests include spending time with her daughter, Violet, and husband, Dick.

Daniel H. Buckley is a Professor at Cornell University in the School of Integrative Plant Science and the Department of Microbiology. He earned his B.S. in Microbiology (1994) at the University of Rochester and his Ph.D. in Microbiology (2000) at Michigan State University. His graduate research in the laboratory of Thomas M. Schmidt explored environmental factors that influence microbial diversity in soils. Dan then received a National Science Foundation Postdoctoral Fellowship to work with Pieter T. Visscher, University of Connecticut, investigating linkages between microbial diversity and biogeochemistry within microbial mats and stromatolites. Dan moved to Cornell in 2003 where he investigates the ecology and evolution of the diverse microorganisms that live in soils. He has taught both introductory and advanced courses in microbiology, microbial diversity, and microbial genomics. He received a National Science Foundation Faculty Early Career Development (CAREER) award in 2005 for excellence in integrating research and education, and served as Co-Director of the MBL Microbial Diversity summer course in Woods Hole, Massachusetts (2009–2013). He currently serves on the editorial boards of *Applied and Environmental Microbiology* and *Environmental Microbiology*. Dan lives in Ithaca, New York, with his wife, Merry, and sons, Finn and Colin.

W. Matthew Sattley received his B.A. in Biology in 1998 from Blackburn College (Illinois) and his Ph.D. (2006) in Molecular Biology, Microbiology, and Biochemistry from Southern Illinois University Carbondale. His graduate studies focused on the microbiology of sulfur cycling and other biogeochemical processes in permanently ice-covered lakes of Antarctica. In his postdoctoral research at Washington University in Saint Louis, he studied the physiology and genomics of anoxygenic phototrophic bacteria in Robert Blankenship's laboratory. Matt then accepted a faculty appointment to the Department of Biology at MidAmerica Nazarene University (Kansas), where he supervised undergraduate research and taught courses in microbiology, environmental science, and cell biology. In 2010, Matt transitioned to the Division of Natural Sciences at Indiana Wesleyan University (IWU), where he is a Professor of Biology and has served as the Director of the Hodson Research Institute, a faculty-led summer research program for undergraduate students in the Natural Sciences. Matt's research group investigates the ecology, diversity, and genomics of bacteria that inhabit extreme environments, and in 2017, he was the recipient of IWU's Outstanding Scholarship Award. Matt is a member of the American Society for Microbiology (including its Indiana Branch) and the Indiana Academy of Science. Matt lives in Marion, Indiana, with his wife, Ann, and sons, Josiah and Samuel. Outside of teaching and research, Matt enjoys playing drums, reading, motorcycling, and baseball.



David A. Stahl received his B.S. degree in Microbiology from the University of Washington, Seattle, and completed graduate studies in microbial phylogeny and evolution with Carl Woese in the Department of Microbiology at the University of Illinois at Urbana–Champaign. Subsequent work as a postdoctoral fellow with Norman Pace, then at the National Jewish Hospital in Colorado, involved early applications of 16S rRNA-based sequence analysis to the study of natural microbial communities. In 1984 Dave joined the faculty at the University of Illinois with appointments in Veterinary Medicine, Microbiology, and Civil Engineering. In 1994 he moved to the Department of Civil Engineering at Northwestern University, and in 2000 returned to the University of Washington as professor in the Departments of Civil and Environmental Engineering and Microbiology. Dave is known for his work in microbial evolution, ecology, and systematics, and received the 1999 Bergey Award and the 2006 ASM Procter & Gamble Award in Applied and Environmental Microbiology. Dave is an elected fellow of the American Academy of Microbiology and a member of the National Academy of Engineering. His main research interests surround the biogeochemistry of nitrogen and sulfur and the microbial communities that sustain the associated nutrient cycles. His laboratory was the first to culture ammonia-oxidizing *Archaea,* a group believed to be the key mediators of this process in the nitrogen cycle. Dave has taught several courses in environmental microbiology, was one of the founding editors of the journal *Environmental Microbiology*, and has served on many advisory committees. Outside the lab, Dave enjoys hiking, bicycling, spending time with family, reading a good science fiction book, and—with his wife, Lin—renovating an old farmhouse on Bainbridge Island.

Dedications

Michael T. Madigan

dedicates this book to the 10^{31} (more or less) microbial cells on and within Earth that maintain our planet in a habitable state. Keep up the good work, guys.

Kelly S. Bender

dedicates this book to the memory of her grandmother, Alberta, whose biggest regret in life was not being able to attend school past the fifth grade.

Daniel H. Buckley

dedicates this book to his father, Ron, who taught me ingenuity and persistence.

W. Matthew Sattley

dedicates this book to the memory of his father, Steven, and to his mother, Patrice, for demonstrating the benefits of working hard and seeking knowledge.

David A. Stahl

dedicates this book to his wife, Lin. My love, and one that helps me keep the important things in perspective.

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Preface

Welcome to the best learning resource in microbiology education today: the visually stunning 16th Edition of *Brock Biology of Microorganisms* (*BBOM*). The 16th Edition is the most student-friendly and accessible edition yet and presents the most exciting and recent picture of the science of microbiology available today. For three generations, both students and instructors alike have praised the accuracy, authority, consistency, and teachability of *BBOM* for exploring the principles of microbiology in a readable, connected, and visually appealing way.

Both students and instructors will benefit from at least four important strengths of the 16th Edition: (1) our approach of using cutting-edge research to solidify basic concepts; (2) the seamless integration of molecular and ecological microbiology with coverage of evolution, diversity, the immune system, and infectious diseases; (3) the spectacular art program complemented with striking and compelling photos; and (4) the wide assortment of teaching and learning tools that accompany the book itself. With an extremely strong author team that employs experts in each major theme, *BBOM* 16th Edition leads the way in presenting the essential principles of microbiology that students need to master today.

What's New in the 16th Edition?

The 16th Edition guides students through the six major themes of microbiology as outlined by the American Society for Microbiology Conference on Undergraduate Education (ASMCUE): Evolution, Cell Structure and Function, Metabolic Pathways, Information Flow and Genetics, Microbial Systems, and the Impact of Microorganisms. With new and revised artwork complemented by over 60 new photos, *BBOM* 16th Edition (16e) presents microbiology as the visual science it is. Thirty-four new MicrobiologyNow chapter-opening vignettes were composed for this edition, each designed to introduce a chapter's theme through a recent discovery in the field of microbiology. These exciting accounts will naturally draw students into the chapter and show how the chapter's content connects with real-world problems. Several new Explore the Microbial World features were also developed for this edition, each designed to give students a feel for exciting special topics in microbiology and to fuel their scientific curiosity.

Genomics, and all of the various "omics" it has spawned, support content in every chapter of *BBOM* 16e, reflecting the reality of how omics has transformed all of biology, especially microbiology. The result is a robust and modern treatment of microbiology that guides students through the maze of omics with concrete examples of how these powerful tools have allowed microbiologists to probe deeper and farther into the microbial world than ever before.

To reinforce the learning experience, the 16e debuts a new pedagogical aid called Key Concepts. These brief summaries of each chapter part are written in clear and straightforward language that give students a heads-up as to what is coming in the following sections. Complementing the Key Concepts, each numbered section is summarized in the chapter review and accompanied by a review question that links concept review with concept mastery.

BBOM 16e is supported by Mastering Microbiology, Pearson's online homework, tutorial, and assessment system that assists students in pacing their learning and keeps instructors current on class performance. Mastering Microbiology includes a new feature, Dynamic Study Modules, which adapt to the student's performance in real time to help each student's study of course topics. Students build the confidence they need to deepen their understanding, participate meaningfully, and perform better in and out of class. Other highlights include chapter-specific reading quizzes, MicroLab Tutorials, MicrobiologyNow coaching activities, Clinical Case and MicroCareer coaching activities, animation quizzes, MCAT Prep questions, and many additional study and assessment tools. Collectively, the content and presentation of *BBOM* 16e, coupled with the powerful learning tools of Mastering Microbiology, create an unparalleled educational experience in microbiology.

Revision Highlights

UNIT 1 The Foundations of Microbiology

Chapter 1

- The microbial world is introduced in an exciting and novel way by weaving together core concepts in microbiology with the historical events that led to their discovery. The foundations of microbiology are revealed through introductions to microscopy, laboratory cultivation, microbial evolution, and the molecular principles that unify all life.
- Some highlights: Vibrant new images help connect students with the diverse and numerous ways in which microbiology impacts our world. Coverage of cell size and morphology is introduced here rather than in Chapter 2 in order to draw students into the microscopic world early on and introduce them to actual microbes and their properties.

Chapter 2

- In the microbial world, cellular structures are tightly linked to cell functions, and Chapter 2 offers a complete guide to the features that define and differentiate microbial cells and their functions. Updated coverage of nutrient transport here rather than in the growth chapter places this critical cellular activity firmly within the context of the cell envelope.
- Some highlights: Electron cryotomography has provided new insight into cell biology and is incorporated in new views of peptidoglycan structure, S-layers, and diversity in cell envelope organization. Vivid new illustrations developed from cutting-edge

microscopic images of the flagellum, the archaellum, and the rotating proteins that confer gliding motility provide a fresh new look at how these structures move prokaryotic cells about their environments.

Chapter 3

- This chapter remains focused on the fundamentals of metabolism and has been revised to simplify metabolic concepts and emphasize the modularity of metabolism. The chapter starts with the essential principles and then provides examples of their application while guiding the student though the major metabolic processes that define microbial life.
- Some highlights: New art provides greater clarity and realism in understanding electron transport reactions, making this process easier to understand and easier to teach. Modularity of metabolism and the importance of the proton motive force receive greater emphasis by providing simple examples of chemolithotrophy and phototrophy to reinforce the student's understanding of energy conservation as a unifying concept in biology. Updates to fermentation clarify and distinguish this process from anaerobic respiration, and an overview of autotrophy and nitrogen fixation emphasize the connectivity between anabolic and catabolic processes in the cell.

Chapter 4

- This chapter on microbial growth and its control moves up one slot from the previous edition to better prepare students for dealing with concepts in molecular biology and genetics where microbial growth plays a central role.
- Some highlights: The essentials of microbial nutrition and laboratory culture are introduced here with a segue to counting methods and quantitative aspects of microbial growth. The dynamics of microbial growth are emphasized with exciting new coverage of the biofilm mode of growth and alternatives to binary fission. The latter includes organisms that display budding division such as *Caulobacter*—the prime model for developmental studies of bacteria—and bacteria that grow by hyphal extensions characteristic of filamentous bacteria such as *Streptomyces*, a major producer of antibiotics.

Chapter 5

- This introduction to virology moves up from its position in Unit 2 in the previous edition to round out the foundations of microbiology theme of Unit 1. This move gives earlier visibility to the importance of viruses as microbes, clearly explains how they differ from cells, and lays the necessary groundwork for dealing with the genetics, genomics, and molecular biology that follows in Unit 2.
- Some highlights: Emphasis remains on the basic principles of virology including how viruses and cells can be viewed as both similar and different and how methods for replicating viruses resemble those for growing cells. Bacteriophage T4 is used as a model lytic virus, and coverage of eukaryotic viruses is expanded beyond just animal viruses to include some major viruses of plants. This highly visual chapter is embellished with over a dozen new photos of exciting, newly discovered viruses along with supporting art that underscores the fundamentals of virology.

UNIT 2 Molecular Biology and Genetics

Chapter 6

- Moved forward two slots from its position in the previous edition to better fit as the kick-off to Unit 2, this chapter lays the necessary groundwork in molecular biology for tackling microbial genetics and genomics and the fast-moving fields of synthetic biology, molecular microbial ecology and diversity, the human microbiome, and diagnostic microbiology.
- Some highlights: Reorganized coverage of DNA supercoiling precedes new and more realistic depictions of the seminal processes of replication, transcription, and translation. New coverage of transcriptional processes in *Archaea* and their relationship to those in *Eukarya* and updated coverage of protein secretion round out this essential primer in microbe molecular biology that every student needs to master.

Chapter 7

- Because microbes must coordinate cellular processes to optimize their chances for survival and reproduction, Chapter 7 is central to Unit 2 in describing how prokaryotic cells control the seminal processes of replication, transcription, and translation. Microbial regulatory systems are highly diverse and sometimes tiered, but an appreciation for how control systems work is key to understanding metabolic diversity, pathogenesis, and synthetic biology.
- Some highlights: Reorganized and expanded coverage of gene expression in *Bacteria* and *Archaea* including activation and repression/derepression as well as chemotaxis and global controls. New coverage of two-component systems for regulating nitrogen assimilation and updated coverage of the phosphate regulon, heat shock response, and riboswitch activity exemplify the comprehensive nature of this chapter.

Chapter 8

- This chapter continues the molecular theme of Unit 2 by building on the major topics of Chapters 4, 6, and 7 in the context of the mechanisms that underlie microbial growth and differentiation. Knowledge of the molecular biology of microbial growth is central to mastering the biology of microbial populations and is keenly relevant to the topics of antibiotic efficacy, antibiotic resistance and persistence, and infectious disease microbiology in general.
- Some highlights: New high-resolution time-course images highlight the molecular processes of growth and cell shape determination. We expand coverage of biofilm formation and the signaling molecule cyclic-di-GMP in *Bacteria* and provide new coverage of biofilm formation in *Archaea*. The chapter also includes new coverage of endospore germination and phenotypic heterogeneity to encompass more topics within the evolving field of microbial growth from a molecular perspective.

Chapter 9

- This chapter rounds out Unit 2 by discussing the foundation for microbial diversity—how microbes undergo genetic change while still maintaining genomic integrity. This essential primer of microbial genetics also lays the groundwork for tackling the hot areas of

microbial omics and synthetic biology and provides the fundamental background necessary to comprehend the most recent concepts of microbial evolution that will unfold in later chapters.
- Some highlights: New and updated visual depictions of DNA exchange between microbes as well as updated coverage on natural competence and the role of pili in DNA uptake. Reorganized and new coverage of barriers to DNA transfer including CRISPR, the important bacterial and archaeal "immune system" whose applications are revolutionizing biology and clinical medicine.

UNIT 3: Genomics, Synthetic Biology, and Evolution

Chapter 10

- Because the genome is the blueprint for all biological traits, this chapter kicks off Unit 3 by discussing not only microbial genomics, but also methods to assay large pools of biological molecules. Various omics studies can be combined to provide a detailed picture of the vast range of capabilities possessed by a specific microbe or groups of microbes, which is essential to the topics of genetic engineering, synthetic biology, and microbial ecology.
- Some highlights: New and exciting coverage of functional genomics and high-throughput techniques to determine the role of individual genes. Reorganized and updated coverage of microbial genome content, proteomic applications, and systems biology highlight the ever-advancing field of omics.

Chapter 11

- This chapter continues the theme of Unit 3 by focusing on the unique genomes of viruses and the diverse mechanisms by which viral genomes are replicated. Knowledge of the molecular biology underlying viral replication is central not only to understanding how viruses infect their hosts and how they persist, but also for developing new clinical strategies for treating viral diseases of humans and other animals.
- Some highlights: New coverage of viral taxonomy precedes updated coverage of viruses that infect *Archaea*. Reorganized topics of bacteriophage genome replication and regulation of lysogeny in lambda directly link to foundational material in Chapter 5.

Chapter 12

- This high-energy chapter entitled "Biotechnology and Synthetic Biology" covers the essential tools of twenty-first-century biotechnology and describes how they have been applied to yield game-changing medical and other commercial products from the activities of genetically engineered microbes. Expanded coverage is provided of the rapidly advancing fields of synthetic biology and CRISPR genome editing—the latest revolutions to hit biology since discovery of the polymerase chain reaction (PCR). Text and art have been updated throughout.
- Some highlights: New coverage of how biobricks contribute to the construction of synthetic pathways and synthetic cells; the use of recombineering to revolutionize molecular cloning; genetically engineered delivery of human therapeutic agents; refactoring metabolic pathways; targeted microbial delivery of human drugs; and how gene drives could finally conquer malaria.

Chapter 13

- This chapter on microbial evolution was moved from the diversity unit into Unit 3 to emphasize its now closer ties to the unit theme of genomics. In addition to origin of life coverage, the chapter now focuses on how evolution affects the genome and ultimately the biology of the organism. The chapter ends with streamlined coverage of microbial systematics and the definition of a microbial species as a prelude to coverage of microbial diversity in Unit 4.
- Some highlights: New and expanded coverage of the evolution of both cells and viruses, including new art on cellular origins from hydrothermal systems and early bioenergetics; more extensive discussion of the mechanisms of microbial evolution from a genomic perspective, including genomic changes that occur during both vertical and horizontal gene transmission; broadened coverage of experimental evolution and genome dynamics.

UNIT 4 Microbial Diversity

Chapter 14

- Recent years have seen a flurry of fundamental new discoveries about how anaerobic organisms conserve energy. Chapter 14 has been updated to integrate information from new discoveries that lie at the heart of diverse metabolic pathways, including the discovery of electron bifurcation and energy-converting hydrogenases.
- Chapter 14 now includes a new introductory section that summarizes foundational principles of microbial physiology. This new section boils the diversity of the microbial world down into a few key principles that students can follow throughout the chapter. In addition, the chapter includes new art illustrating electron bifurcation, as well as electron flow in organisms such as sulfate reducers and methanogens. Old favorites throughout the chapter are also updated to account for recent discoveries in the field.

Chapter 15

- Chapter 15 has been reorganized and updated to emphasize relationships between metabolic and ecological diversity. New photos have been added to emphasize the morphological diversity of anoxygenic phototrophs and to demonstrate how microorganisms work together to modify their environments.

Chapter 16

- Chapter 16 has new coverage of difficult-to-cultivate bacteria, such as *Acidobacteria*, *Planctomycetes*, and *Fusobacteria*. The widespread application of metagenomic techniques have revealed that these *Bacteria* are of considerable importance in a range of habitats, including the human microbiome, but have only recently been obtained in laboratory culture.

Chapter 17

- Metagenomics has contributed greatly to our knowledge of archaeal diversity. Chapter 17 now exploits this and unveils the TACK, DPANN, and Asgard *Archaea*, some of which are the closest known relatives of the eukaryotes. We also update the diversity of mechanisms of methanogenesis in the archaeal domain.

Chapter 18

- Along with major updates on eukaryotic phylogeny, a new section is devoted to the haptophytes, including the globally and ecologically important coccolithophore *Emiliania huxleyi*. Coccolithophores play a major role in regulating global climate, illustrating the power that microbes exert over our biosphere.

UNIT 5 Microbial Ecology and Environmental Microbiology

Chapter 19

- The chapter begins a unit on ecology and environmental microbiology. The modern tools of the microbial ecologist are described with examples of how each has helped sculpt the science.
- Some highlights: A new method to visualize protein synthesis in single cells allows study of microbial activity in the environment. Metabolomics exploits new methods in mass spectrometry to unravel the complex metabolic interactions sustaining microbial communities. Nanosensor technologies are revealing how microbes alter the chemical landscape of three-dimensional surfaces. A new section explores multi-omics, which combines multiple state-of-the-art analytical tools to more fully characterize microbial communities.

Chapter 20

- The properties and microbial diversity of major microbial ecosystems including soils and aquatic systems are compared and contrasted in exciting ways.
- Some highlights: Expansive coverage of surface-attached microbial communities and how those communities are responding to plastic pollution of the environment. New understanding of the ecology of iron-oxidizing bacteria revealed by the isolation of new members of this biogeochemically significant group. The discovery in deep ocean sediments of novel *Archaea* that link this domain with *Eukarya*. Extensive coverage of marine viruses, their abundance and diversity, and how they alter the physiology of organisms they infect. Humans traveling to 10,000-meter depths in the oceans discover the most pressure-tolerant bacterium known.

Chapter 21

- Extensive coverage of the major nutrient cycles in nature and the microbes that catalyze them are presented in a fashion that allows the cycles to be taught as individual entities or as interrelated metabolic loops.
- Some highlights: Expanded coverage of the biogeochemistry of sulfur compounds highlights the importance of volatile microbial products such as dimethyl sulfide for cloud formation. Advances in the biochemistry of extracellular electron transfer add new understanding to how the ecology and diversity of microorganisms drive the biogeochemical cycling of iron and manganese. The mystery of how methane is generated (typically a strictly anoxic process) in highly oxygenated ocean surface waters is solved by discoveries in the phosphorus cycle described in a new Explore the Microbial World.

Chapter 22

- This chapter on the built environment shows how humans create new microbial habitats through construction of buildings, supporting infrastructure, and habitat modification, and which microbes take advantage of these habitats and why.
- Some highlights: The microbial metabolism of biologically produced and manufactured chlorinated organics has been expanded, as has the basis for the bioremediation of major chemical pollutants. How microbes are responding to the mountains of plastics contaminating the environment and the discovery of novel bacteria capable of degrading plastic bottles are described. New technology that improves the efficiency of wastewater treatment using granular sludge technology is presented, and the microbial response to the excessive use of common household cleansers is considered.

Chapter 23

- A chapter devoted to nonhuman microbial symbioses describes the major microbial partners that live in symbiotic associations with other microbes, with plants, and with animals other than humans.
- Some highlights: Newly revised section on symbioses between microorganisms addresses the ecological significance of phototroph switching in lichens and how certain bacterial species use electrically conductive structures to form intimate symbiotic associations. Several updates include how insect symbionts are used to combat transmission of major viral diseases of humans and how defensive chemicals produced by symbionts protect insects from predation. Detailed coverage is given to the elaborate "cross-talk" between microbe and animal needed to establish the squid light organ.

UNIT 6 Microbe–Human Interactions and the Immune System

Chapter 24

- A chapter on the human microbiome launches the unit on microbe–human interactions and the immune system by introducing and updating advances in our understanding of the microbes that inhabit the human body and their relationship to health and disease.
- Some highlights: The discovery of ultrasmall bacteria in the mouth parasitizing other bacteria brings a new twist to the microbial ecology of the oral cavity. A new section on the human virome describes how metagenomics is driving the discovery and isolation of interesting new viruses. Extensive coverage is devoted to the impact of early-life events on the development of the newborn gut microbiome and of recent successes in probiotic therapy for preventing newborn intestinal diseases.

Chapter 25

- Beginning with this chapter, the book shifts its focus to pathogenic microorganisms, the immune system, and disease. Part I of this chapter addresses microbial adherence, colonization and invasion, and pathogenicity, including important sections on virulence and virulence attenuation. Part II highlights key enzymes and toxins produced by microbes that contribute to pathogenesis.

- Some highlights: The updated text includes expanded coverage of bacterial adhesins supported by a new, two-part figure that highlights new discoveries in staphylococcal adherence. Revised coverage of virulence attenuation includes new artwork to show how this principle can be exploited for development of effective vaccines. An updated discussion of botulinum toxins reflects new findings and clearly presents both the neurotoxic mechanism and the surprising clinical utility of these extremely potent substances.

Chapter 26

- Chapter 26 opens with an overview of the immune system and the body's first-line barriers to infection. This is followed by a brief discussion of hematopoiesis before focusing on innate immune responses to pathogen invasion. The chapter provides a natural progression into adaptive immune responses covered in Chapter 27.
- Some highlights: In addition to a new chapter opener highlighting breakthroughs that link Alzheimer's disease to microbial infection, this chapter contains heavily edited text that includes a more comprehensive discussion of leukocyte diversity and an all-new description of the role of amyloid-β protein as an innate defense in the brain. Other highlights include expanded coverage of interferons and the role of natural killer cells as the primary effectors of antibody-dependent cell-mediated cytotoxicity. Finally, a fascinating new Explore the Microbial World highlights the role of pattern recognition receptors in establishing host–microbe mutualisms using hydrothermal vent tube worms as an example.

Chapter 27

- Chapter 27 begins with an essential discussion of the principles that define adaptive immunity: specificity, immune memory, lymphocyte selection, and immune tolerance. This is followed by sections that discuss the functional mechanisms of the key cells and proteins (immunoglobulins, major histocompatibility complexes, and T cell receptors) that drive adaptive immunity.
- Some highlights: The text has been heavily edited throughout, and this has produced a clearer and more informative presentation of B and T lymphocyte selection and tolerance, including a new discussion of T-dependent versus T-independent antigens. In addition, a new section dedicated to T cell activation and anergy clearly presents the important concept of the second signal required for T cell activation.

Chapter 28

- The newly reorganized Chapters 28 and 29 have emerged from materials presented in Chapter 28 of the 15th edition. Treating immune disorders and antimicrobial therapy (Chapter 28) separately from clinical diagnostic methods (Chapter 29) has produced a more teachable format, making these topics more accessible for students and easier for the instructor to plan course assignments.
- Some highlights: The text progresses smoothly from immune disorders and deficiencies to methods used to train and hone the immune response for disease prevention and treatment. New coverage of mRNA and plant-based vaccines shares the latest innovations in vaccinology. An all-new section on immunotherapy, supported by vibrant new artwork, highlights exciting advancements in the use of genetic engineering and molecular immunology to treat cancer.

UNIT 7 Infectious Diseases

Chapter 29

- To bring better focus to the material, this chapter is now solely dedicated to the clinical microbiology laboratory and includes information on lab safety, healthcare-associated infections, and a wide array of both culture-dependent and culture-independent techniques used to diagnose infectious diseases.
- Some highlights: The chapter launches with the description of an exciting new method of diagnosing tuberculosis—humanity's most notorious scourge. The text has been edited throughout for better organization and clarity, and art modifications help clarify complex diagnostic techniques. Updated terminology includes an introduction to point-of-care diagnostics.

Chapter 30

- This chapter introduces the topics and terminology of the science of epidemiology and public health. Historical and modern examples throughout emphasize key concepts such as emerging (and reemerging) diseases, epidemics and pandemics, and the public health threat associated with the development and use of weaponized microorganisms.
- Some highlights: incorporation of the most up-to-date statistics available on disease incidence and outbreaks throughout the text and in figures and tables, as well as an all-new section supported by photos on the emergence of the important healthcare-associated pathogen *Clostridioides* (*Clostridium*) *difficile*.

Chapter 31

- This is the first of four highly visual chapters that take an ecological approach to pathogenic microorganisms by considering infectious diseases based on their modes of transmission. Bacterial and viral diseases transmitted person to person by way of airborne particles, direct contact, or sexual contact are the focus here.
- Some highlights: Statistical data regarding key emerging and reemerging diseases, including measles, pertussis, influenza, hepatitis, HIV/AIDS, gonorrhea, and syphilis have been updated to reflect the most recent data available; an all-new discussion with supporting photo of the neglected tropical disease yaws helps impart knowledge and awareness of this lingering scourge.

Chapter 32

- In this chapter we examine pathogens transmitted to humans through either an animal vector or soil-contaminated wounds or objects. Many of these diseases have high morbidity and mortality rates, and in most cases, effective vaccines are not yet available.
- Some highlights: The text and figures include the most up-to-date statistics for diseases throughout the chapter, including rabies, hantavirus, spotted fever rickettsiosis, ehrlichiosis and anaplasmosis, Lyme disease, and the major tropical hemorrhagic fevers. In addition, the text now includes updated discussions of the emergence of key tickborne diseases in the United States and coverage of new strategies against dengue fever, including description of a new vaccine and the use of the bacterial endosymbiont *Wolbachia* to control the dengue virus–infected mosquito population.

Chapter 33

- Pathogens in contaminated water or food are easily transmitted to humans, with waterborne diseases being especially common in developing countries lacking adequate water treatment facilities. This chapter highlights the most prevalent water- and foodborne diseases and emphasizes the importance of clean water and proper food preparation and preservation in preventing these physically uncomfortable and occasionally fatal illnesses.
- Some highlights: Updated statistics have been incorporated for all major water- and foodborne diseases, including *Campylobacter* infections, which have now overtaken salmonellosis as the leading cause of bacterial food infection in the United States. New discussions cover recently elucidated norovirus pathology and new food safety developments, including the use of eBeam technology and bacteriophage sprays. A new overview figure of cholera infection integrates photos with artwork to emphasize key aspects of this devastating and all too common disease.

Chapter 34

- Eukaryotic pathogens present a special challenge to medicine because, on a cellular level, they are not that different from our own cells. Thus, it can be difficult to find selective targets for chemotherapeutic drugs. Yet the microbes highlighted in this highly visual chapter cause some of the most devastating and prevalent diseases today.
- Some highlights: New color photos adorn the chapter, including two stunning fluorescent micrographs of *Entamoeba histolytica*, the causative agent of amebic dysentery. Broader coverage of distinctive features of several diseases, including cyclosporiasis, toxoplasmosis, and malaria, has been seamlessly incorporated. All statistics have been updated with the most recent surveillance data to yield a global picture of fungal and parasitic diseases.

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