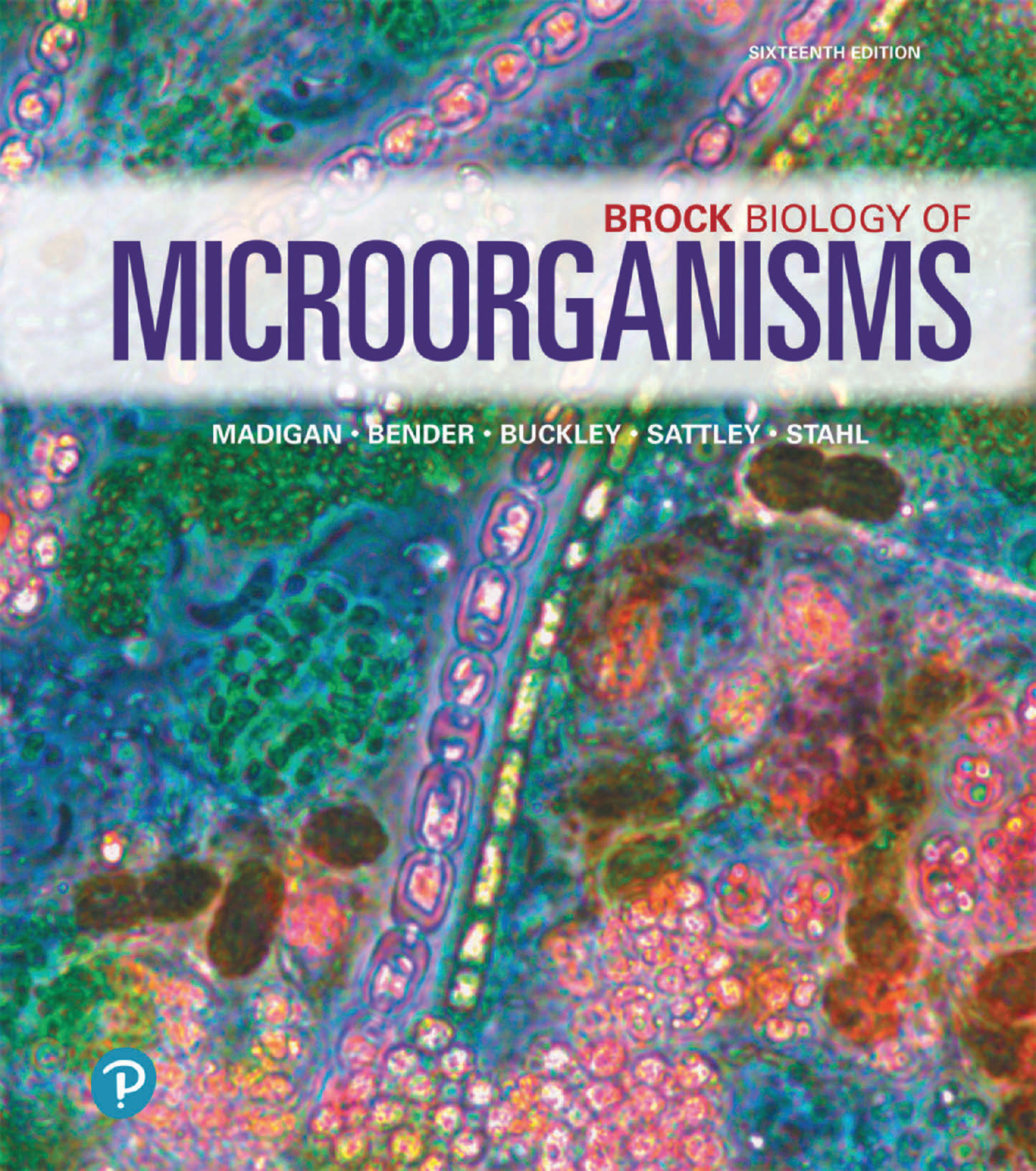
SIXTEENTH EDITION
BROCK BIOLOGY OF
MICROORGANISMS
MADIGAN • BENDER • BUCKLEY • SATTLEY • STAHL

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 major part of a chapter give students a big picture view of the content to come before they dive in and immerse themselves in the details.

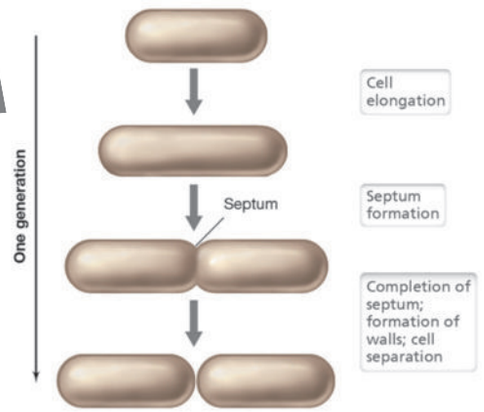

Figure 4.8 Binary fission in a rod-shaped bacterium. Cell numbers (and all components of the cells) double every generation.

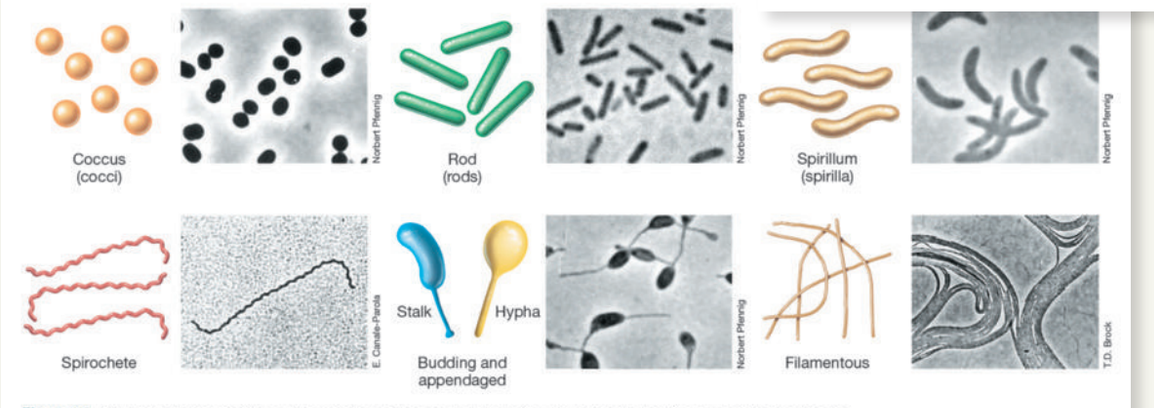

Figure 1.8 Cell morphologies. Beside each drawing is a phase-contrast photomicrograph of cells showing that morphology. Coccus (cell diameter in photomicrograph, 1.5 μm); rod (1 μm); spirillum (1 μm); spirochete (0.25 μm); budding (1.2 μm); filamentous (0.8 μm). All photomicrographs are of species of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

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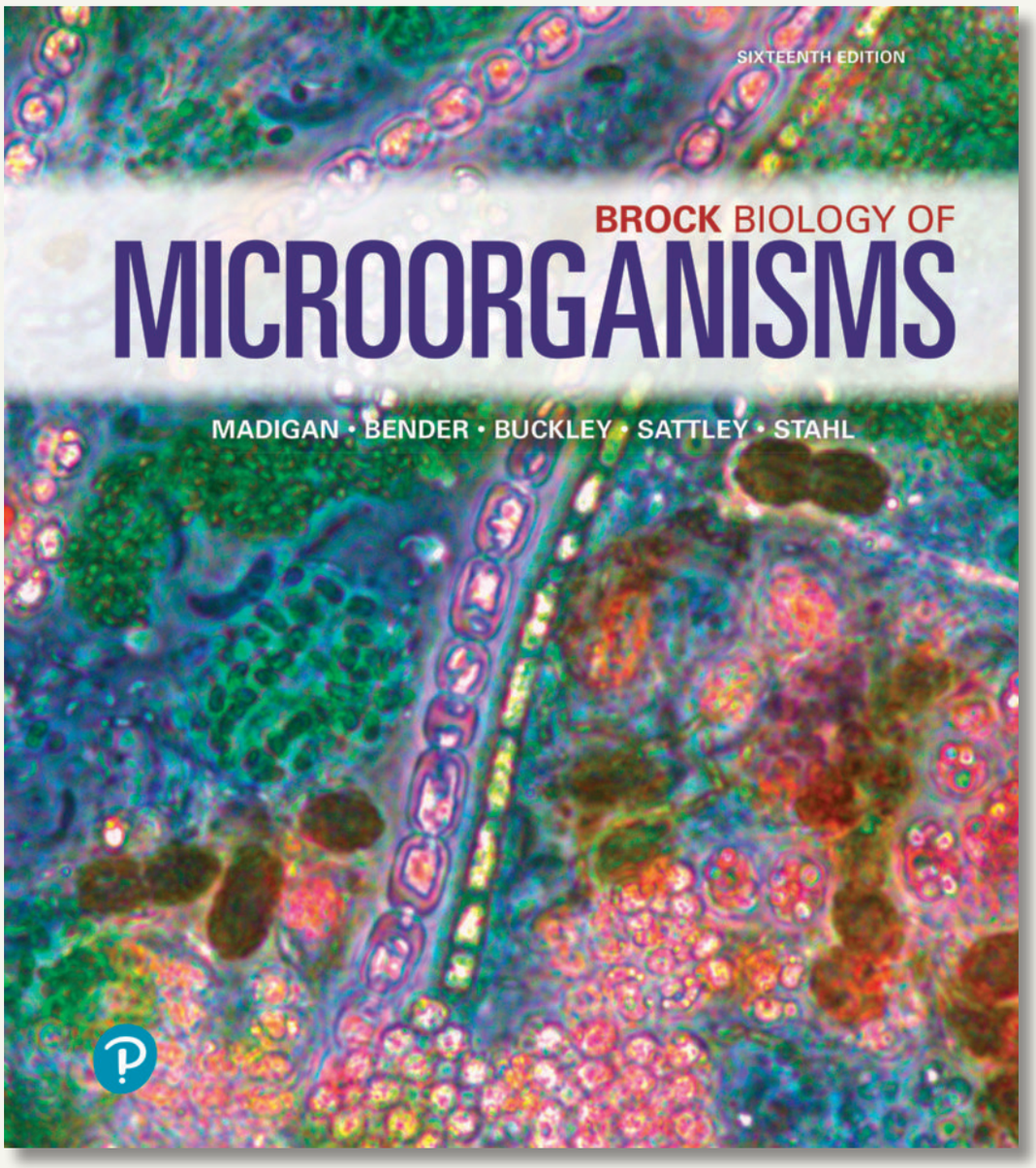
Brief Contents

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

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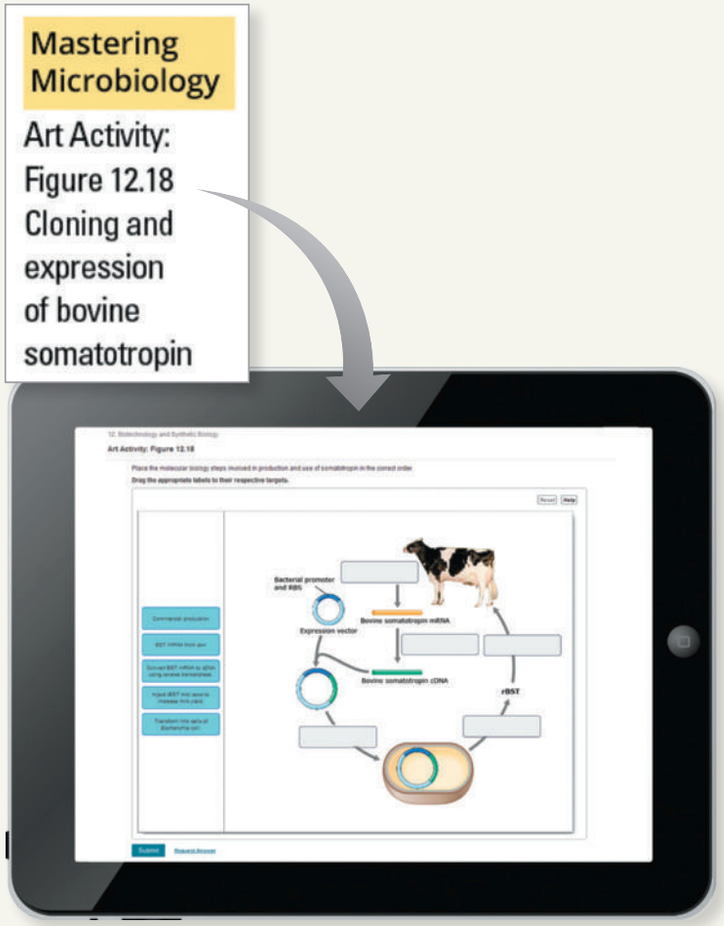
Concepts in Microbiology

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.



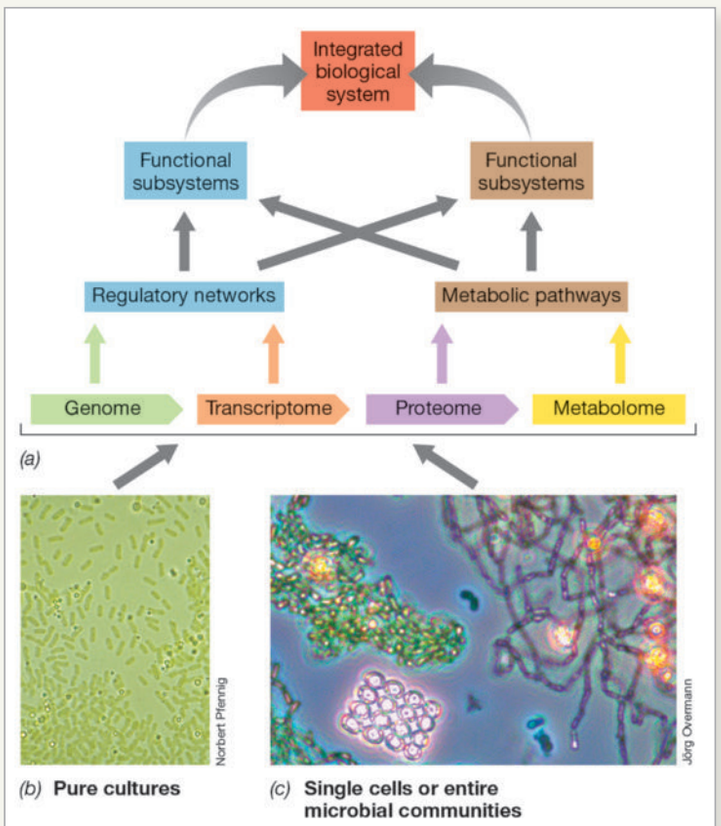


Figure 10.29 The components of systems biology. *(a)* The results of various "omics" analyses are combined and successively integrated into higher-level views of the entire biology of a pure culture, such as *(b)* that of the green sulfur bacterium *Chlorobium*; or of a mixed microbial community, such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

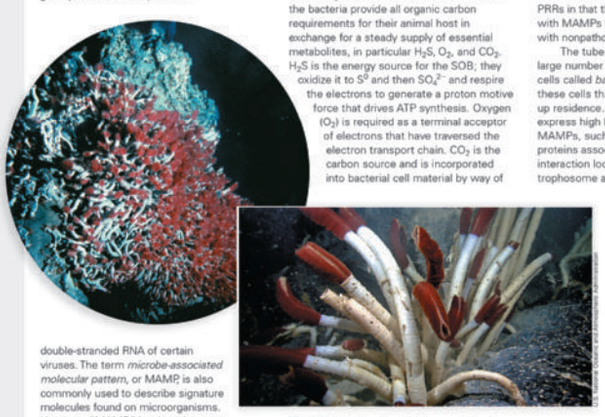


Figure 1 Hydrothermal vent tube worms harboring endosymbiotic sulfur-oxidizing bacteria. Top: A "black smoker" hydrothermal vent community containing several tube worms that obtain organic carbon from sulfur-oxidizing chemolithotrophic bacteria (SOB) living within them. Bottom: A close-up view of tube 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.

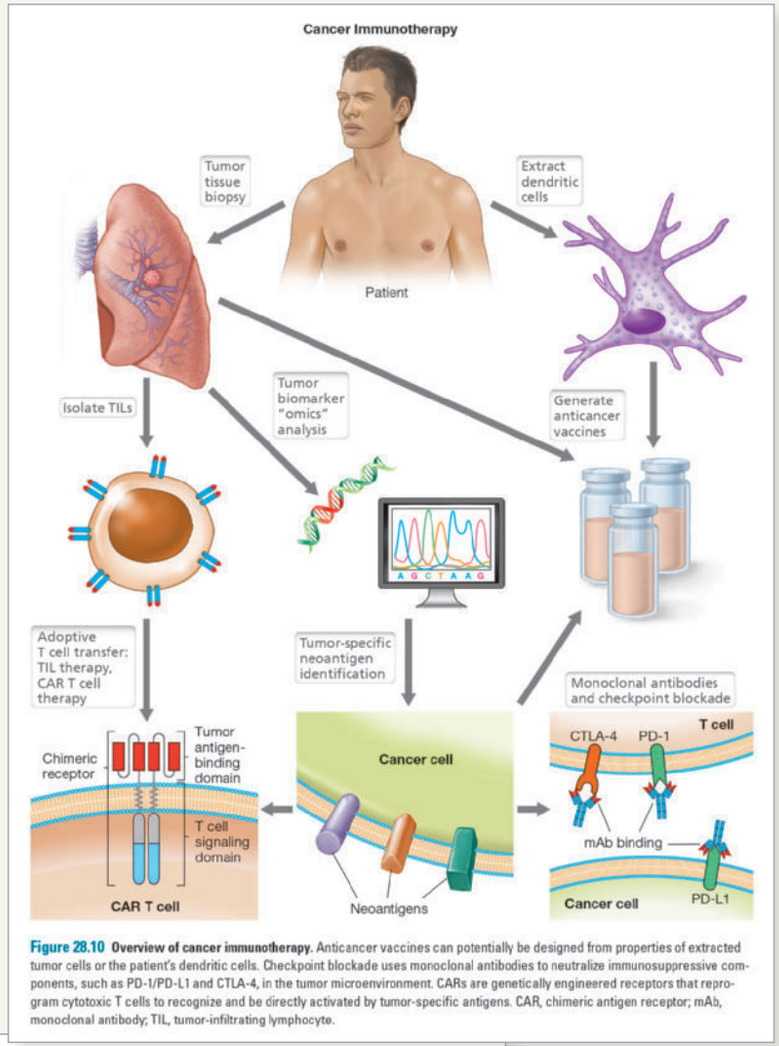


Figure 28.10 Overview of cancer immunotherapy. Anticancer vaccines can potentially be designed from properties of extracted tumor cells or the patient's dendritic cells. Checkpoint blockade uses monoclonal antibodies to neutralize immunosuppressive components, such as PD-1/PD-L1 and CTLA-4, in the tumor 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.

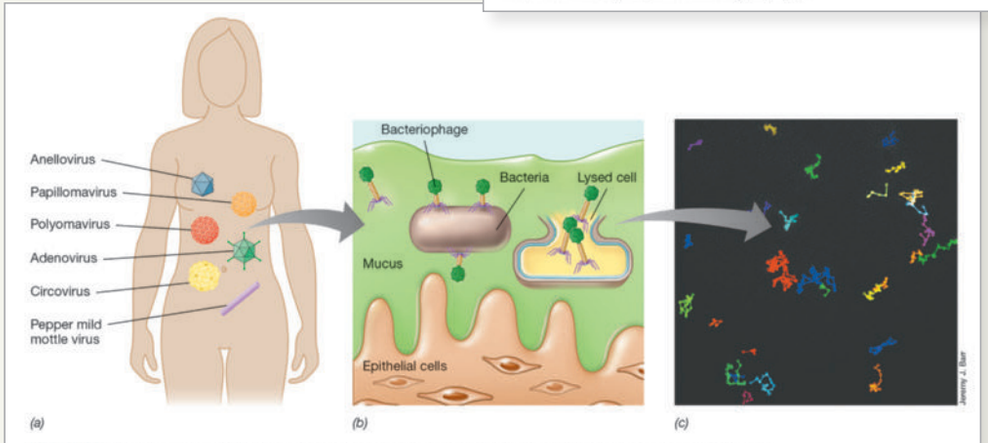
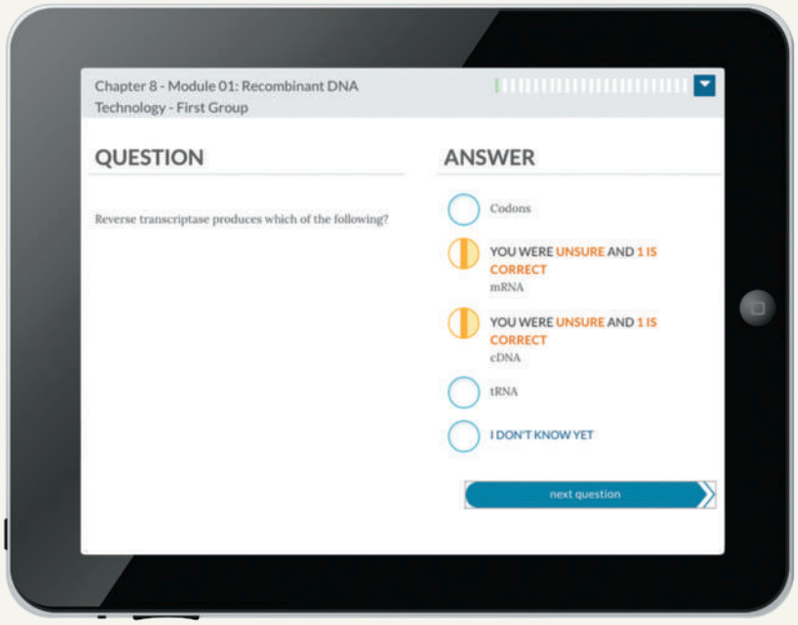


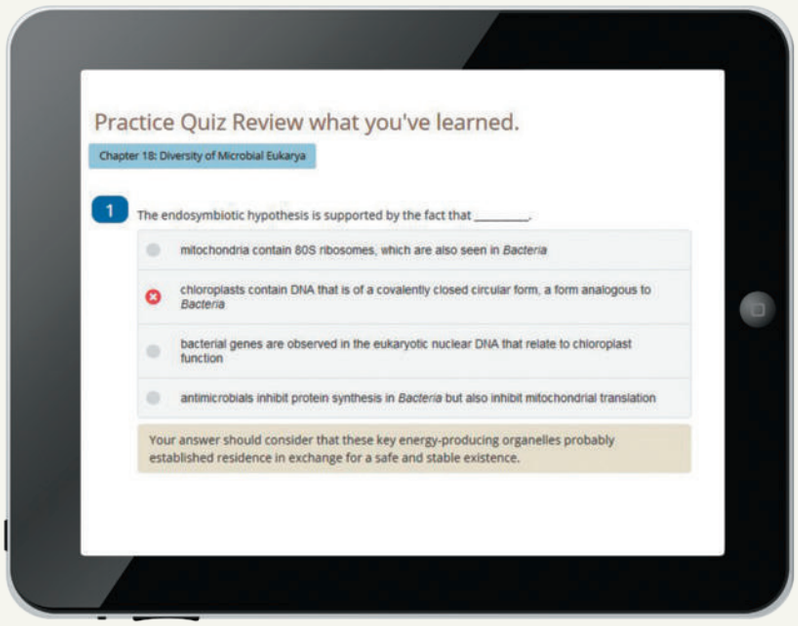
Figure 24.18 The human virome. *(a)* Common viruses of eukaryotes found in the virome of a healthy human. *(b)* Bacteriophages within the mucosa of the human respiratory and gastrointestinal tracts protect epithelial cells from the invasion of bacterial pathogens. *(c)* Movement of T4 bacteriophages 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

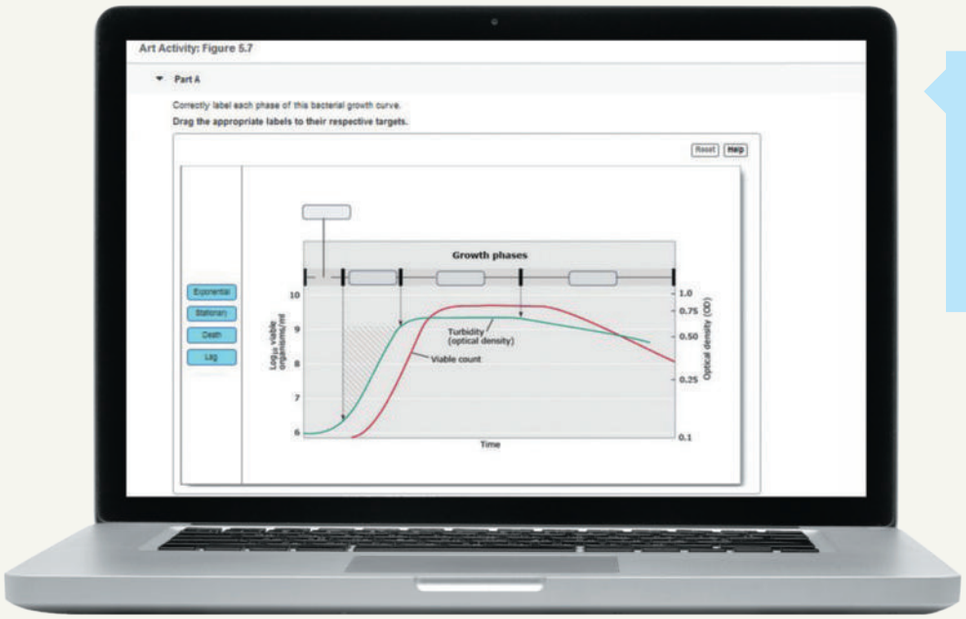


NEW! Dynamic Study Modules help students study course topics by adapting to their performance in real time. Students build the confidence they need to deepen their understanding, participate meaningfully, and perform better — in and out of class. Available on smartphones, tablets, and computers.



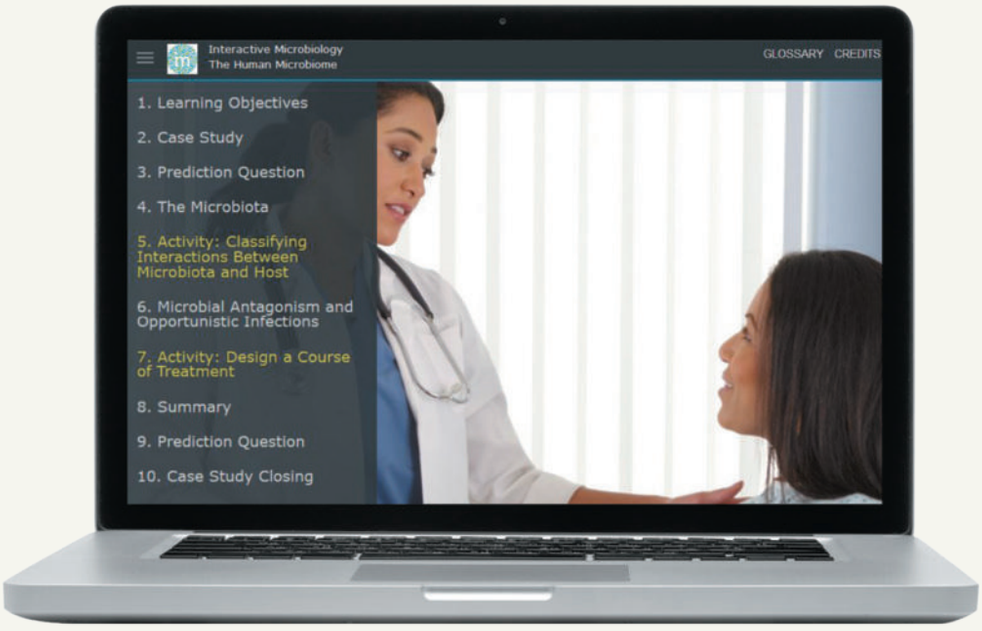
Mastering is so much more than homework. The **Pearson Study Area** allows students to access multiple study tools in one place. They don't need to search Google to find study tools that align with their course materials. Students have access to practice quizzes, videos and animations, vocabulary tools,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

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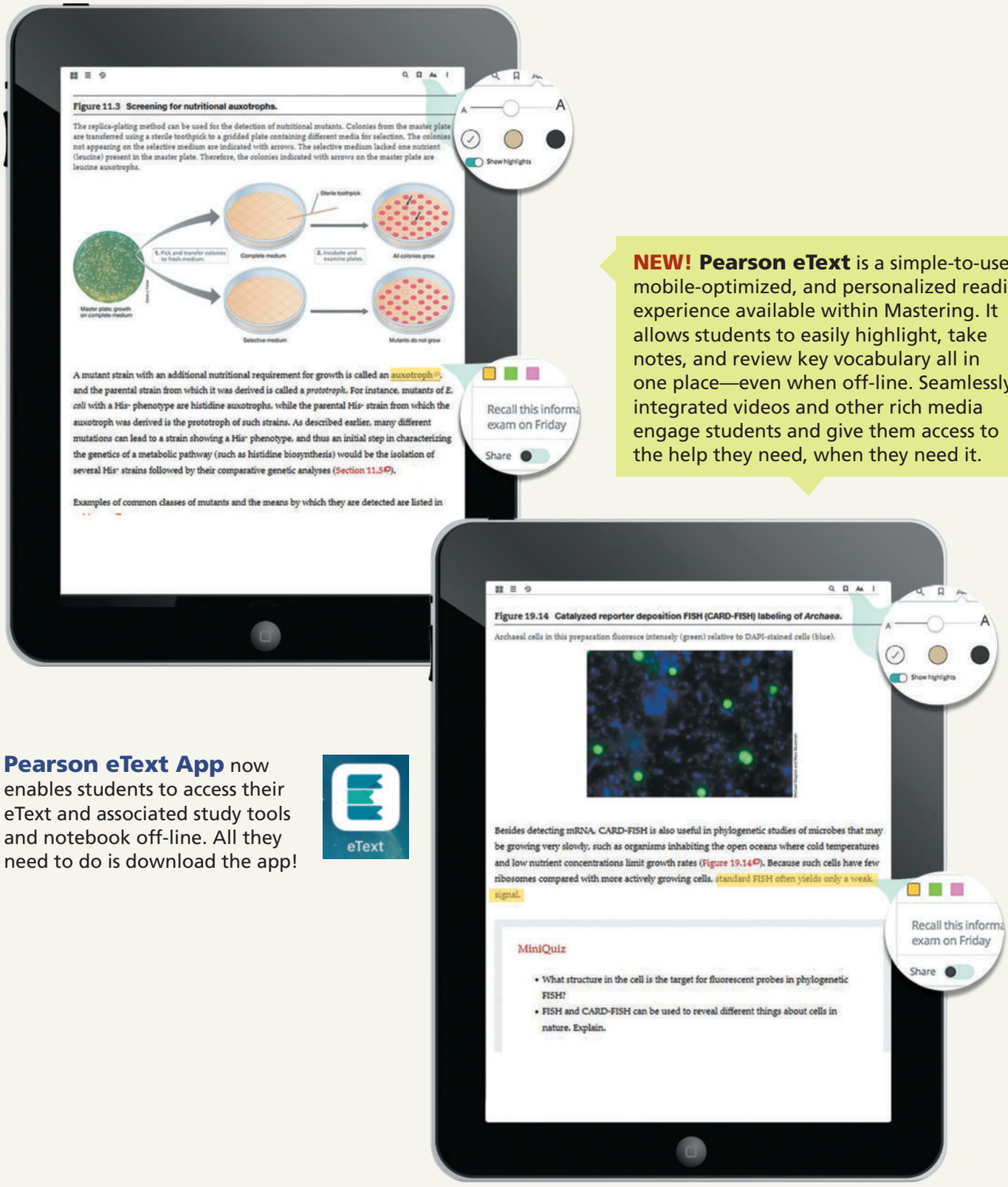

NEW! Pearson eText is a simple-to-use, mobile-optimized, and personalized reading experience available within Mastering. It allows students to easily highlight, take notes, and review key vocabulary all in one place—even when off-line. Seamlessly integrated videos and other rich media engage students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

BROCK BIOLOGY OF MICROORGANISMS

SIXTEENTH EDITION

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Southern Illinois University Carbondale

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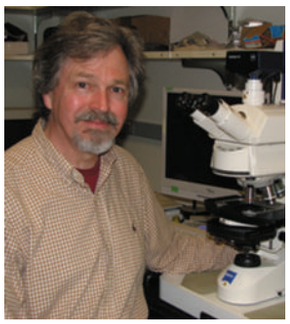
About the Authors

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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ASM Recommended Curriculum Guidelines for Undergraduate Microbiology

The American Society for Microbiology (ASM) endorses a concept-based curriculum for undergraduate microbiology, emphasizing skills and concepts that have lasting importance beyond the classroom and laboratory. The ASM (in its *Curriculum Guidelines for Understanding Microbiology Education*) recommends deep understanding of 27 key concepts, 4 scientific thinking competencies, and 7 key skills. These guidelines follow scientific literacy reports and recommendations from the American Association for the Advancement of Science and the Howard Hughes Medical Institute by encouraging an active learning, student-based course. Consider these guiding statements as you progress through this book and master principles, problem solving, and laboratory skills in microbiology.

ASM Guideline Concepts and Statements

Evolution: Chapters 1, 9, 10–14, 20, 30

- Cells, organelles (e.g., mitochondria and chloroplasts), and all major metabolic pathways evolved from early prokaryotic cells.
- Mutations and horizontal gene transfer, with the immense variety of microenvironments, have selected for a huge diversity of microorganisms.
- Traditional concept of species is not readily applicable to microbes due to asexual reproduction and the frequent occurrence of horizontal gene transfer.
- Evolutionary relatedness of organisms is best reflected in phylogenetic trees.
- Human impact on the environment influences the evolution of microorganisms (e.g., emerging diseases and the selection of antibiotic resistance).

Cell Structure and Function: Chapters 1, 2, 5, 8, 11, 18

- Structure and function of microorganisms have been revealed by the use of microscopy (including bright-field, phase contrast, fluorescence, super-resolution, and electron).
- Bacteria have unique cell structures that can be targets for antibiotics, immunity, and phage infection.
- *Bacteria* and *Archaea* have specialized structures (e.g., flagella, endospores, and pili) that often confer critical capabilities.
- While microscopic eukaryotes (for example, fungi, protozoa, and algae) carry out some of the same processes as bacteria, many of the cellular properties are fundamentally different.
- Replication cycles of viruses (lytic and lysogenic) differ among viruses and are determined by their unique genomes.

Metabolic Pathways: Chapters 1, 3, 4, 7, 8, 12, 14

- *Bacteria and Archaea* exhibit extensive, and often unique, metabolic diversity (e.g., nitrogen fixation, methane production, anoxygenic photosynthesis).
- Interactions of microorganisms among themselves and with their environment are determined by their metabolic abilities (e.g., quorum sensing, oxygen consumption, nitrogen transformations).
- Survival and growth of any microorganism in a given environment depends on its metabolic characteristics.
- Growth of microorganisms can be controlled by physical, chemical, mechanical, or biological means.

Information Flow and Genetics: Chapters 1, 5–13

- Genetic variations can impact microbial functions (e.g., in biofilm formation, pathogenicity, and drug resistance).
- Although the central dogma is universal in all cells, the processes of replication, transcription, and translation differ in *Bacteria*, *Archaea*, and eukaryotes.
- Regulation of gene expression is influenced by external and internal molecular cues and/or signals.
- Synthesis of viral genetic material and proteins is dependent on host cells.
- Cell genomes can be manipulated to alter cell function.

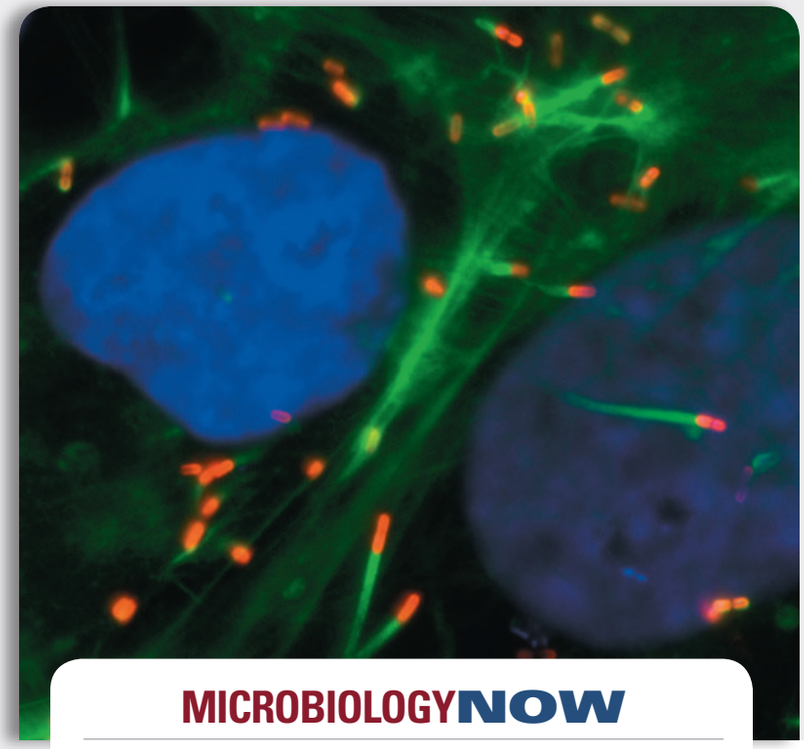
Microbial Systems: Chapters 1, 15–34

- Microorganisms are ubiquitous and live in diverse and dynamic ecosystems.
- Many bacteria in nature live in biofilm communities.
- Microorganisms and their environment interact with and modify each other.
- Microorganisms, cellular and viral, can interact with both human and nonhuman hosts in beneficial, neutral, or detrimental ways.

Impact of Microorganisms: Chapters 1, 6–8, 12, 19–34

- Microbes are essential for life as we know it and the processes that support life (e.g., in biogeochemical cycles and plant and/or animal microbiota).
- Microorganisms provide essential models that give us fundamental knowledge about life processes.
- Humans utilize and harness microorganisms and their products.
- Because the true diversity of microbial life is largely unknown, its effects and potential benefits have not been fully explored.

1 The Microbial World



MICROBIOLOGY**NOW**

Microbiology in Motion

The microbial world is strange and fierce. It is teeming with life, ancient, diverse, and constantly changing. Microorganisms are Earth's life support system, and from our first breath they influence nearly every moment of our lives. Microbes are in our water and our food, and we carry them on us and in us. Indeed, microbes abound in any natural environment that will support life, including many environments too hostile for higher life forms.

While the microbial world is invisible, we can explore it through the science of microbiology. Microbiology evolves at a breathtaking pace. Even the microscope continues to evolve, providing an ever more detailed picture of the microbial world. The image above was made with a fluorescence microscope that uses lasers, guided by a computer, to map the three-dimensional structure of cells. The image shows neighboring human cells with their nuclei stained blue and actin filaments stained green. These cells are infected with the foodborne bacterial pathogen *Listeria monocytogenes*, stained red.

Listeria are soil organisms that sometimes find their way into our food. In soils they infect other microbes such as amoebae. Our cells are similar in many ways to those of microscopic organisms, and so *Listeria* finds itself well adapted to live within us. This bacterium has the unique ability to hijack cellular systems, causing actin to polymerize and propel the cell like a rocket within the host cytoplasm. The force of this propulsion causes *Listeria* to penetrate adjacent cells (image, lower left), spreading the infection. *Listeria* can also invade host vacuoles (not shown), where it hides and survives. This persistent state can prolong infection and promote resistance to antibiotic therapy. Research on *Listeria* has provided new insights on the biology of this pathogen and an ever-changing view of a microbial world in motion.

Source: Kortebi, M., et al. 2017. *Listeria monocytogenes* switches from dissemination to persistence by adopting a vacuolar lifestyle in epithelial cells. *PLoS Pathog. 13*: e1006734.

This chapter launches our journey into the microbial world. Here we will begin to discover what the science of microbiology is all about and what microorganisms are, what they do, and how they can be studied. We also place microbiology in historical context, as a process of scientific discovery driven by simple (yet powerful) experiments and insightful minds.

I • Exploring the Microbial World

The microbial world consists of microscopic organisms that have defined structures, unique evolutionary histories, and are of enormous importance to the biosphere.

1.1 Microorganisms, Tiny Titans of the Earth

Microorganisms (also called *microbes*) are life forms too small to be seen by the unaided human eye. These microscopic organisms are diverse in form and function, and they inhabit every environment on Earth that supports life. Many microbes are undifferentiated single-celled organisms, but some can form complex structures, and some are even multicellular. Microorganisms typically live in complex **microbial communities** (Figure 1.1), and their activities are regulated by interactions with each other, with their environments, and with other organisms. The science of microbiology is all about microorganisms, who they are, how they work, and what they do.

Microorganisms were teeming on the land and in the seas for billions of years before the appearance of plants and animals, and their diversity is staggering. Microorganisms represent a major fraction of Earth's biomass, and their activities are essential to sustaining life. Indeed, the very oxygen (O_2) we breathe is the result of microbial activities. Plants and animals are immersed in a world of microbes, and their evolution and survival are heavily influenced by microbial activities, by microbial symbioses, and by *pathogens*—those microbes that cause disease. Microorganisms are woven into the fabric of human life as well (Figure 1.2), from infectious diseases, to the food we eat, the water we drink, the fertility of our soils, the health of our animals, and even the fuel we put in automobiles. Microbiology is the study of the dominant form of life on Earth, and the effect that microbes have on our planet and all of the living things that call it home.

Microbiologists have many tools for studying microorganisms. Microbiology was born of the microscope, and microscopy is foundational to microbiology. Microbiologists have developed an array of methods for visualizing microorganisms, and these microscopic techniques are essential to microbiology. The cultivation of microorganisms is also foundational to microbiology. A microbial **culture** is a collection of cells that have been grown in or on a nutrient medium. A **medium** (plural, media) is a liquid or solid nutrient mixture that contains all of the nutrients required for a microorganism to grow. In microbiology, we use the word **growth** to refer to the increase in cell number as a result of cell division. A single microbial cell placed on a solid nutrient medium can grow and divide into millions or even billions of cells that form a visible **colony** (Figure 1.3). The formation of visible colonies makes it easier to see and grow microorganisms. Comprehension of the microbial basis of disease and microbial biochemical diversity has relied on the ability to grow microorganisms in the laboratory.

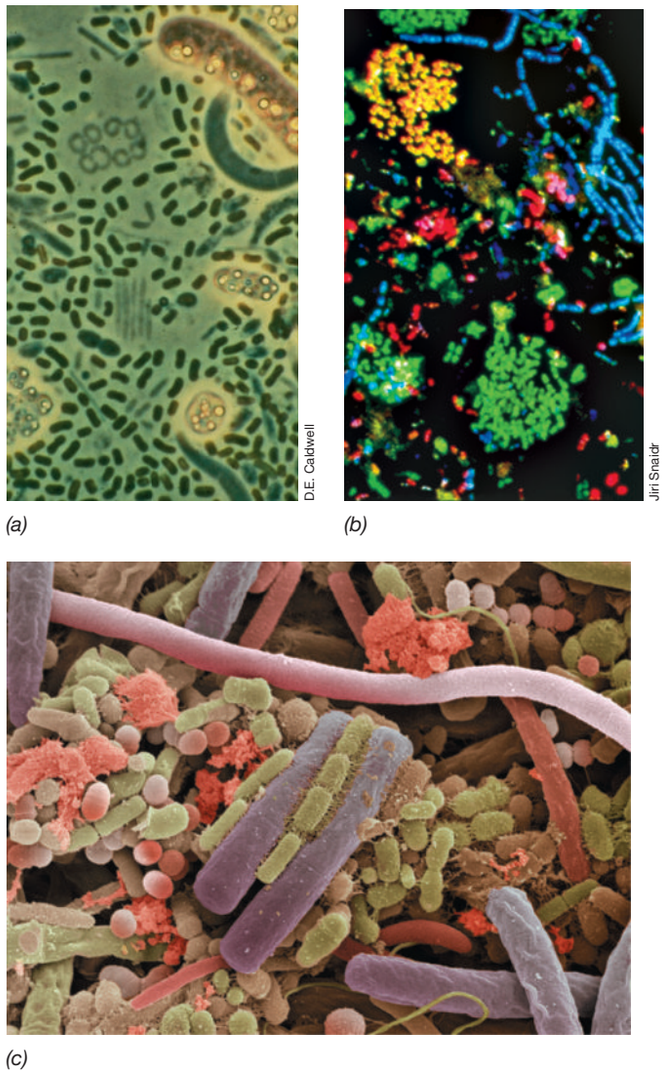


Figure 1.1 Microbial communities. *(a)* A bacterial community that developed in the depths of a small Michigan lake, including cells of various phototrophic bacteria. The bacteria were visualized using phase-contrast microscopy. *(b)* A bacterial community in a sewage sludge sample. The sample was stained with a series of dyes, each of which stained a specific bacterial group. From *Journal of Bacteriology 178*: 3496–3500, Fig. 2b. © 1996 American Society for Microbiology. *(c)* Colorized scanning electron micrograph of a microbial community scraped from a human tongue.

The ability to grow microorganisms rapidly under controlled conditions makes them highly useful for experiments that probe the fundamental processes of life. Most discoveries relating to the molecular and biochemical basis of life have been made using microorganisms. The study of molecules and their interactions is essential to defining the workings of microbial cells, and the tools of molecular biology and biochemistry are foundational to microbiology. Molecular biology has also provided a variety of tools to study microorganisms without need for their cultivation in the laboratory. These molecular tools have greatly expanded our knowledge of microbial ecology and diversity. Finally, the tools of genomics and molecular genetics are also cornerstones of modern

Figure 1.2 Microbial applications. Microorganisms have major impacts on the world in which we live. In the chapters that follow we will learn how microorganisms impact our health, the foods we eat, the water we drink, and even the air we breathe. We will learn how microbes can be used to produce valuable products and the many ways in which microorganisms touch our lives.

microbiology and allow microbiologists to study the genetic basis of life, how genes evolve, and how they regulate the activities of cells.

In the next section, we explore the basic elements of microbial cell structure and summarize the major physiological activities that take place in all cells, regardless of their structure.

Check Your Understanding

- In what ways are microorganisms important to humans?
- Why are microbial cells useful for understanding the basis of life?
- What is a microbial colony and how is one formed?

1.2 Structure and Activities of Microbial Cells

Microbial cells are living compartments that interact with their environment and with other cells in dynamic ways. We purposely exclude viruses in most of this discussion because although they resemble cells in many ways, viruses are not cells but instead a special category of microorganism. We consider the structure, diversity, and activities of viruses in Section 1.4 and in Chapters 5 and 11.

Elements of Microbial Structure

All cells have much in common and contain many of the same components (Figure 1.4). All cells have a permeability barrier called the **cytoplasmic membrane** that separates the inside of the cell, the **cytoplasm**, from the outside. The cytoplasm is an aqueous mixture of **macromolecules** (for example proteins, lipids, nucleic acids, and polysaccharides), small organic molecules (mostly the precursors of macromolecules), various inorganic ions, and ribosomes. All cells also contain **ribosomes**, which are the structures responsible for protein synthesis. Some cells have a **cell wall** that lends structural strength to a cell. The cell wall is a relatively permeable structure located outside the cytoplasmic membrane and is a much stronger layer than the membrane itself. Cell walls are typically found in plant cells and most microorganisms but are not found in animal cells.

There are two fundamental cell types that differ categorically in cellular organization: those having **prokaryotic** cell structure, and those having **eukaryotic** cell structure (Figure 1.4). Cells having eukaryotic cell structure are found in a group of organisms called the *Eukarya*. This group includes plants and animals as well as diverse microbial eukaryotes such as algae, protozoa, and fungi. Eukaryotic cells contain an assortment of membrane-enclosed cytoplasmic structures called **organelles** (Figure 1.4*b*). These include, most prominently, the DNA-containing nucleus but also mitochondria and chloroplasts, organelles that specialize in supplying the cell with energy, and various other organelles.

Mastering Microbiology
Art Activity: Figure 1.3 Common elements of prokaryotic/eukaryotic cells

Prokaryotic cell structure is found within two different groups of organisms we know as *Bacteria* and *Archaea*. Prokaryotic cells have few internal structures, they lack a nucleus, and they typically lack organelles (Figure 1.4*a*). *Bacteria* and *Archaea* appeared long before the evolution of eukaryotes (Section 1.5). While all *Archaea* and

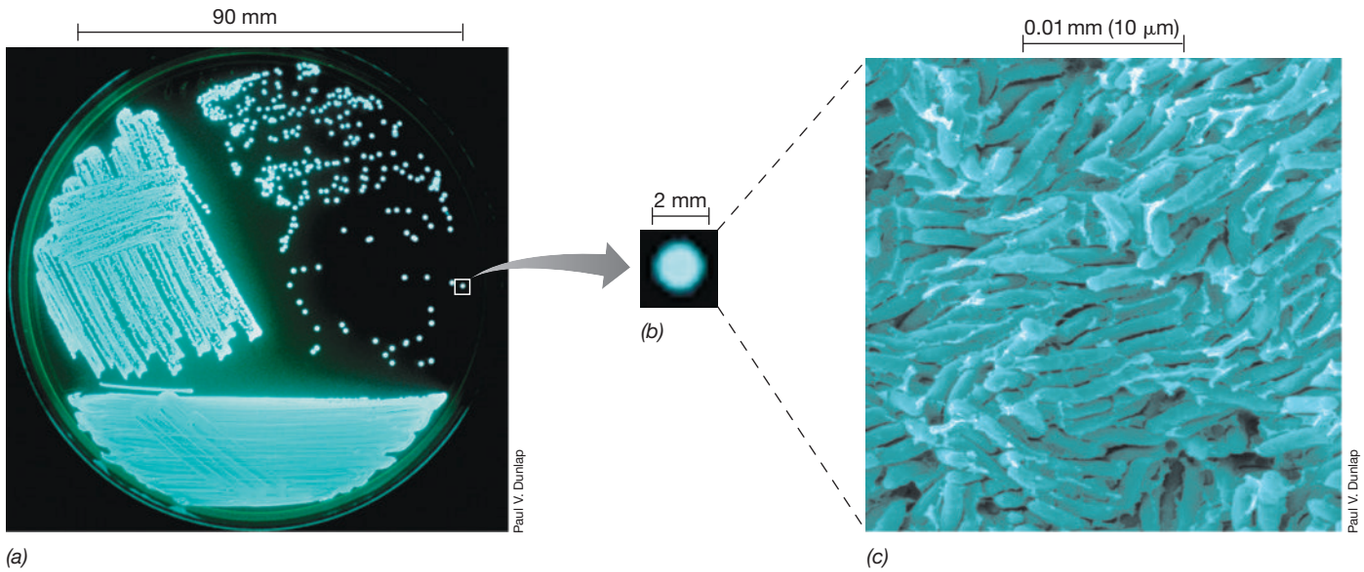


Figure 1.3 Microbial cells. *(a)* Bioluminescent (light-emitting) colonies of the bacterium *Photobacterium* grown in laboratory culture on a Petri plate. *(b)* A single colony can contain more than 10 million (10^7) individual cells. *(c)* Colorized scanning electron micrograph of cells of *Photobacterium*.

Bacteria have prokaryotic cell structure, these two groups diverged very early in the history of life and as a result many of their molecular and genetic characteristics differ at a fundamental level. Indeed, we will see later that in many ways *Archaea* and *Eukarya* are more similar to each other than either is to *Bacteria*.

Genes, Genomes, Nucleus, and Nucleoid

In addition to a cytoplasmic membrane and ribosomes, all cells also possess a DNA **genome**. The genome is the full set of genes in a cell. A gene is a segment of DNA that encodes a protein or an RNA molecule. The genome is the living blueprint of an organism; the characteristics, activities, and very survival of a cell are governed by its genome.

The genomes of prokaryotic cells and eukaryotic cells are organized into structures called **chromosomes**. In eukaryotic cells, DNA is present as several linear molecules (each one formed into its own chromosome) within the membrane-enclosed **nucleus**. By contrast, the genomes of *Bacteria* and *Archaea* are typically closed circular chromosomes (though some prokaryotic cells have linear chromosomes). The chromosome aggregates within the prokaryotic cell to form the **nucleoid**, a mass that is visible in the electron microscope (Figure 1.4*a*) but which is *not* enclosed by a membrane. Most prokaryotic cells have only a single chromosome, but many also contain one or more small circles of DNA distinct from that of the chromosome, called **plasmids** (Figure 1.4*a*). Plasmids typically contain genes that are not essential but often confer some special property on the cell (such as a unique metabolism, or antibiotic resistance). The genomes of *Bacteria* and *Archaea* are typically small and compact, and most contain between 500 and 10,000 genes encoded by 0.5 to 10 million base pairs of DNA. Eukaryotic cells typically have much larger and much less streamlined genomes than prokaryotic cells. A human cell, for example, contains approximately 3 billion base pairs, which encode about 20,000–25,000 genes.

Mastering Microbiology
Art Activity: Figure 1.4 Basic properties of microbial cells

Activities of Microbial Cells

To be competitive in nature, a microorganism must survive and reproduce. **Figure 1.5** considers structure and some of the activities that are performed by cells to drive survival and reproduction. All cells show some form of **metabolism** through which nutrients are acquired from the environment and transformed into new cellular materials and waste products. During these transformations, energy is used to support synthesis of new structures. Production of these new structures culminates in the division of the cell to form two cells. Microbial growth results from successive rounds of cell division.

Genes contain information that is used by the cell to perform the work of metabolism. Genes are decoded to form proteins that regulate cellular processes. **Enzymes**, those proteins that have catalytic activity, carry out reactions that supply energy and perform biosynthesis within the cell. Enzymes and other proteins are synthesized during *gene expression* in the sequential processes of transcription and translation. **Transcription** is the process by which the information encoded in DNA sequences is copied into an RNA molecule, and **translation** is the process whereby the information in an RNA molecule is used by a ribosome to synthesize a protein (Chapter 6). Gene expression and enzyme activity in a microbial cell are coordinated and highly regulated to ensure that the cell remains optimally tuned to its surroundings. Ultimately, microbial growth requires replication of the genome through the process of **DNA replication**, followed by cell division. All cells carry out the processes of transcription, translation, and DNA replication.

Microorganisms have the ability to sense and respond to changes in their local environment. Many microbial cells are capable of **motility**, typically by self-propulsion (Figure 1.5). Motility allows cells to relocate in response to environmental conditions. Some microbial cells undergo **differentiation**, which may result

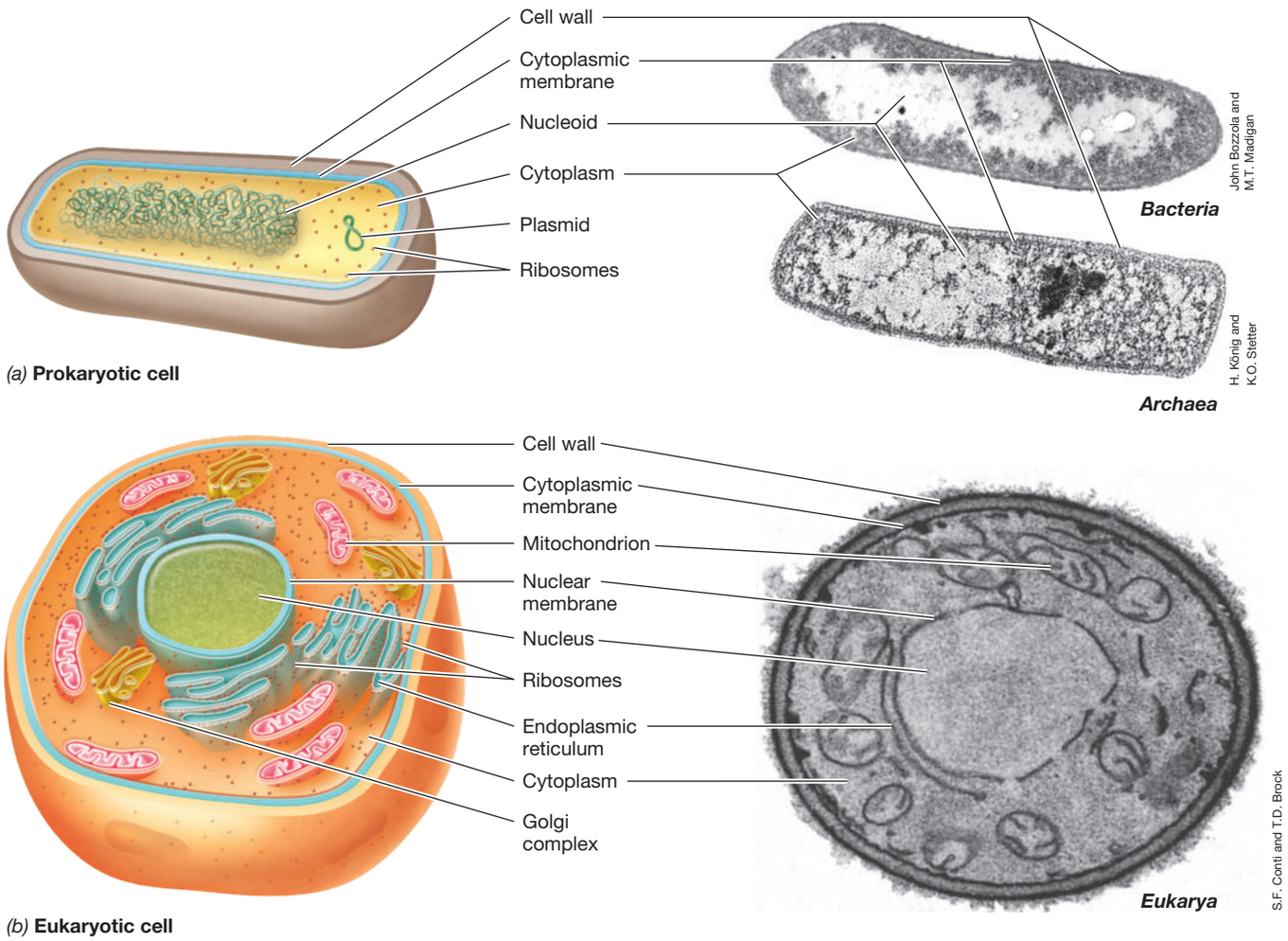


Figure 1.4 **Microbial cell structure.** *(a)* (Left) Diagram of a prokaryotic cell. (Right) Electron micrograph of *Heliobacterium modesticaldum* (*Bacteria*, cell is about 1 μm in diameter) and *Thermoproteus neutrophilus* (*Archaea*, cell is about 0.5 μm in diameter). *(b)* (Left) Diagram of a eukaryotic cell. (Right) Electron micrograph of a cell of *Saccharomyces cerevisiae* (*Eukarya*, cell is about 8 μm in diameter). In terms of relative scale, the bacterial cell in *a* is about the same size as the mitochondria of *Saccharomyces* in *b*.

in the formation of modified cells specialized for growth, dispersal, or survival. Cells respond to chemical signals in their environment, including those produced by other cells of either the same or different species, and these signals often trigger new cellular activities. Microbial cells thus exhibit **intercellular communication**; that is, they are "aware" of their neighbors and can respond accordingly. Many prokaryotic cells can also exchange genes with neighboring cells, regardless of their species, in the process of **horizontal gene transfer**.

Evolution (Figure 1.5) results when genes in a population of cells change in sequence and frequency over time, leading to descent with modification. The evolution of microorganisms can be very rapid relative to the evolution of plants and animals. For example, the indiscriminate use of antibiotics in human and veterinary medicine has selected for the proliferation of antibiotic resistance in pathogenic bacteria. The rapid pace of microbial evolution can be attributed in part to the ability of microorganisms to grow very quickly and to acquire new genes though the process of horizontal gene transfer. Not all of the processes depicted in Figure 1.5 occur in all cells. Metabolism, growth, and evolution, however, are universal and will be major areas of emphasis throughout this text.

We now move on to consider the diversity of cell shapes and sizes found in the microbial world.

Check Your Understanding

- What structures are universal to all type of cells?
- What processes are universal to all types of cells?
- What structures can be used to distinguish between prokaryotic cells and eukaryotic cells?

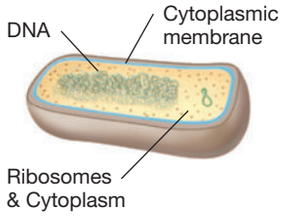
1.3 Cell Size and Morphology

Microscopic examination of microorganisms immediately reveals their **morphology**, which is defined by cell size and shape. A variety of cell shapes pervade the microbial world, and although microscopic by their very nature, microbial cells come in a variety of sizes.

Properties of *all* cells:

Structure

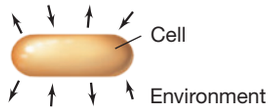
All cells have a cytoplasmic membrane, cytoplasm, a genome made of DNA, and ribosomes.



Metabolism

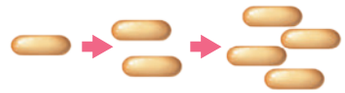
All cells use information encoded in DNA to make RNA and protein. All cells take up nutrients, transform them, conserve energy, and expel wastes.

1. **Catabolism** (transforming molecules to produce energy and building blocks)
2. **Anabolism** (synthesizing macromolecules)



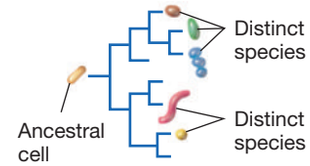
Growth

Information from DNA is converted into proteins, which do work. Proteins are used to convert nutrients from the environment into new cells.



Evolution

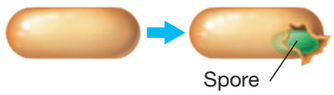
Chance mutations in DNA cause new cells to have new properties, thereby promoting evolution. Phylogenetic trees built from DNA sequences capture evolutionary relationships between species.



Properties of *some* cells:

Differentiation

Some cells can form new cell structures such as a spore.

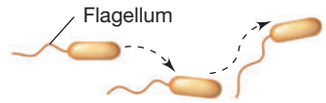


Communication

Cells interact with each other by chemical messengers.

Motility

Some cells are capable of self-propulsion.



Horizontal gene transfer

Cells can exchange genes by several mechanisms.

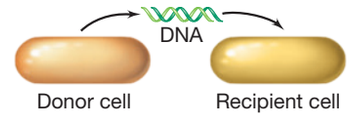


Figure 1.5 The properties of microbial cells. While cells are tremendously diverse in form and function, certain properties are shared by all cells.

Cell shape can be useful for distinguishing different microbial cells and often has ecological significance. Moreover, the very small size of most microbial cells has a profound effect on their ecology and dictates many aspects of their biology. We begin by considering cell size and then consider cell shape.

The Small World

A micrometer (μm or micron) is one-millionth of a meter in length. The unaided human eye has difficulty resolving objects that are less than 100 μm in diameter, but this is the scale of the microbial world. Most prokaryotic cells are small, ranging between 0.5 and 10 μm in length, but prokaryotic cells can vary widely in size. For example, the smallest prokaryotic cells are about 0.2 μm in diameter and the largest can be more than 600 μm long (**Table 1.1**). In contrast, most eukaryotic cells are larger on average than prokaryotic cells, being between 5 and 100 μm in length, but eukaryotic cells can vary widely in size too. For example, the smallest eukaryotic microorganism known is about 0.8 μm in diameter and the largest eukaryotic cells can be many centimeters in length (Section 1.4).

Cell size is influenced fundamentally by cell structure. Eukaryotic cells, owing to their complex intracellular structure and organelles (Figure 1.4), can actively transport molecules and macromolecules within the cytoplasm. Prokaryotic cells, in contrast, rely on diffusion for transport through the cytoplasm and this limits their size. While diffusion is very fast at small distances, the rate of diffusion increases as the square of the distance traveled. Hence, the metabolic rate in a prokaryotic cell varies inversely with the square of its size. This relationship means that, as cell size increases, it becomes advantageous to have cellular structures that facilitate transport and compartmentalize cellular activities as seen in eukaryotic cells. In contrast, since diffusion is rapid at small spatial scales, high metabolic rates can be maintained in small prokaryotic cells without a need for complex cellular structures.

It is possible, though unusual, for prokaryotic cells to be visible to the human eye; the largest are more than 600 μm (0.6 mm) long. To achieve this size, these bacteria must have traits that allow them to overcome diffusional limitation. The bacterium *Epulopiscium fishelsoni* (**Figure 1.6*a***; Figure 1.9), which is found in the gut of the surgeonfish, can be more than 75 μm wide and 600 μm long (Table 1.1). One of the traits that allows this bacterium to get so large is that it can have more than 10,000 copies of its genome distributed throughout its cytoplasm, thereby preventing diffusional limitation between the genome and any region of the cytoplasm. Cells of the largest known bacterium, the sulfur-oxidizing chemolithotroph *Thiomargarita* (Figure 1.6*b*, Table 1.1), are even larger than those of *Epulopiscium*, about 750 μm in diameter. *Thiomargarita* achieves this enormous size by having a large vacuole that fills the center of the cell. Hence, the cytoplasm of *Thiomargarita* occurs as a thin layer squeezed between the cytoplasmic membrane and this central vacuole. In this way, the cytoplasm is never more than 1 μm from the membrane. In addition, *Thiomargarita*, like *Epulopiscium*, also has many copies of its genome, which are distributed throughout its cytoplasm.

TABLE 1.1 Cell size and volume of some cells of *Bacteria*, from the largest to the smallest

Organism	Characteristics	Morphology	Size[a] (μm^3)	Cell volume (μm^3)	Volumes compared to *E. coli*
Thiomargarita namibiensis	Sulfur chemolithotroph	Cocci in chains	750	200,000,000	100,000,000×
Epulopiscium fishelsoni[a]	Chemoorganotroph	Rods with tapered ends	80 × 600	3,000,000	1,500,000×
Beggiatoa species[a]	Sulfur chemolithotroph	Filaments	50 × 160	1,000,000	500,000×
Achromatium oxaliferum	Sulfur chemolithotroph	Cocci	35 × 95	80,000	40,000×
Lyngbya majuscula	Cyanobacterium	Filaments	8 × 80	40,000	20,000×
Thiovulum majus	Sulfur chemolithotroph	Cocci	18	3,000	1,500×
Staphylothermus marinus[a]	Hyperthermophile	Cocci in irregular clusters	15	1,800	900×
Magnetobacterium bavaricum	Magnetotactic bacterium	Rods	2 × 10	30	15×
Escherichia coli	Chemoorganotroph	Rods	1 × 2	2	1×
Pelagibacter ubique[a]	Marine chemoorganotroph	Rods	0.2 × 0.5	0.014	0.007×
Ultra-small bacteria[a]	Uncultured, from groundwater	Variable	<0.2	0.009	0.0045×
Mycoplasma pneumoniae	Pathogenic bacterium	Pleomorphic[b]	0.2	0.005	0.0025×

[a]Where only one number is given, this is the diameter of spherical cells. The values given are for the largest cell size observed in each species. For example, for *T. namibiensis*, an average cell is only about 200 μm in diameter. But on occasion, giant cells of 750 μm are observed. Likewise, an average cell of *S. marinus* is about 1 μm in diameter. The species of *Beggiatoa* here is unclear, and *E. fishelsoni*, *M. bavaricum*, and *P. ubique* are not formally recognized names in taxonomy. For more on ultra-small bacteria, see Explore the Microbial World "Tiny Cells."

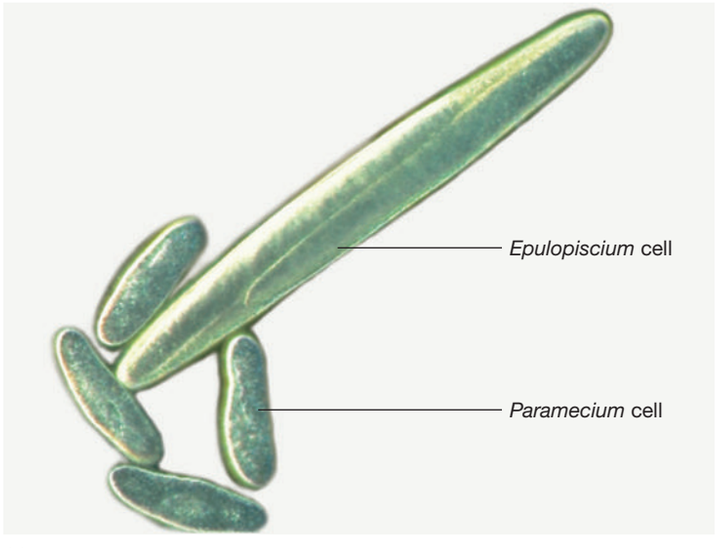
[b]*Mycoplasma* is a bacterium that lacks a cell wall and can thus take on many shapes (*pleomorphic* means "many shapes").

Source: Data obtained from Schulz, H.N., and B.B. Jørgensen. 2001. *Annu. Rev. Microbiol. 55*: 105–137, and Luef, B., et al. 2015. *Nat. Commun.* doi:10.1038/ncomms7372.

At the opposite end of the spectrum from these large prokaryotic cells are very small prokaryotic cells. Exactly how small a cell can be is not precisely known. However, cells 0.2 μm in diameter exist (see Explore the Microbial World, "Tiny Cells"), and the lower limit is probably only a bit smaller than this. Ultimately, the lower limit to cell size is likely a function of the amount of space needed to house the essential biochemical components—proteins, nucleic acids, ribosomes and so on (Section 1.2)—that all cells need to survive and reproduce.

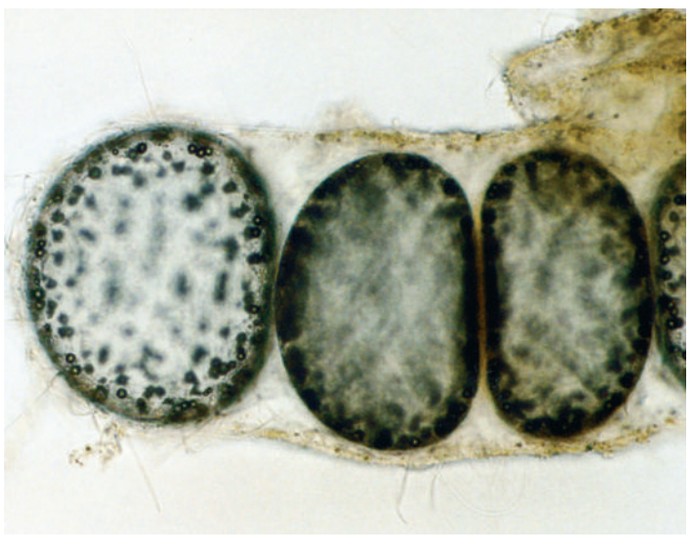
Surface-to-Volume Ratios, Growth Rates, and Evolution

For a cell, there are advantages to being small. Small cells have more surface area relative to cell volume and thus have a higher *surface-to-volume ratio* than larger cells. To understand this principle, consider a spherical cell. The volume of a sphere is a function of the cube of its radius ($V = \frac{4}{3}\pi r^3$), whereas its surface area is a function of the square of the radius ($S = 4\pi r^2$). Therefore, the S/V ratio of a coccus is $3/r$ (**Figure 1.7**). As cell size *increases*, its S/V ratio *decreases*.



Esther R. Angert, Harvard University

(a)



Heide Schulz-Vogt

(b)

Figure 1.6 Two very large *Bacteria*. *(a) Epulopiscium fishelsoni.* The rod-shaped cell is about 600 μm (0.6 mm) long and 75 μm wide and is shown with four cells of the protist *Paramecium* (a microbial eukaryote), each of which is about 150 μm long. *(b) Thiomargarita namibiensis*, a large sulfur chemolithotroph and currently the largest known of all prokaryotic cells. Cell widths vary from 400 to 750 μm.

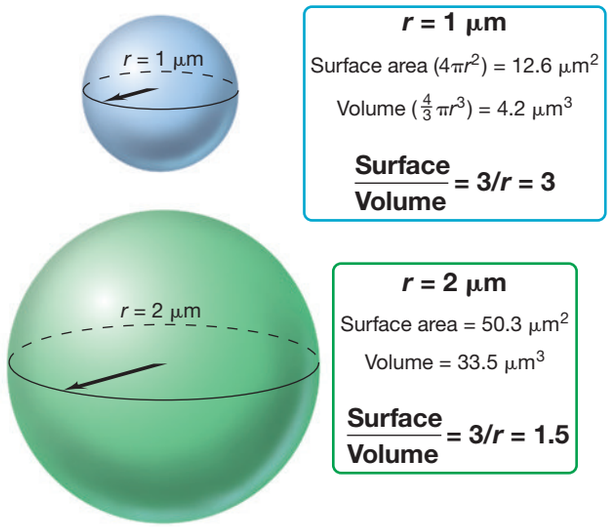


Figure 1.7 Surface area and volume relationships in cells. As a cell increases in size, its *S*/*V* ratio decreases.

To illustrate this, consider the *S*/*V* ratio for some of the cells of different sizes listed in Table 1.1: *Pelagibacter ubique*, 22; *Escherichia coli*, 4.5; and *E. fishelsoni* (Figure 1.6*a*), 0.05. The *S*/*V* of a rod-shaped organism can be estimated as if it were a cylinder; hence, the *S*/*V* of the cell will *decrease* as its radius *increases*.

The *S*/*V* ratio of a cell controls many of its properties, including how fast it grows (its *growth rate*) and shape. Cellular growth rate depends in part on the rate at which cells exchange nutrients and waste products with their environment. As cell size decreases, the *S*/*V* ratio of the cell increases, and this means that small cells can exchange nutrients and wastes more rapidly (per unit cell volume) than can large cells. As a result, free-living cells that are smaller tend to be more efficient than those that are larger, and any given mass of nutrients will support the synthesis of more small cells than large cells. We will see that cell morphology is also often predicated on the effect of cell shape on *S*/*V* ratio. For example, cell shapes that increase the overall membrane area of the cell, such as those having long thin appendages or invaginations, allow bacteria to increase their *S*/*V* ratio for a given mass of cytoplasm. We will see that prokaryotic cell morphology is remarkably diverse and different cell shapes can convey different benefits upon the cell.

Major Morphologies of Prokaryotic Cells

Common morphologies of prokaryotic cells are shown in **Figure 1.8**. A cell that is spherical or ovoid in morphology is called a *coccus* (plural, cocci). A cylindrically shaped cell is called a *rod* or a *bacillus* (plural, bacilli). A spiral-shaped cell is called a *spirillum* (plural, spirilla). A cell that is slightly curved and comma-shaped is called a *vibrio*. A *spirochete* is a special kind of organism (▶ Section 15.17) that has a spiral shape but which differs from spirilla because the cells of spirochetes are flexible, whereas cells of spirilla are rigid. Some bacteria are irregular in shape. Appendages, such as stalks and hyphae, are used by some cells for attachment or to increase surface area. In addition, asymmetrical cell division such as budding can result in irregular and asymmetrical cell shapes.

Cell division has a major impact on morphology because cells that remain attached to each other can form distinctive shapes. For instance, some cocci occur in pairs (diplococci), some form long chains (streptococci), others occur in three-dimensional cubes (tetrads or sarcinae), and still others occur in grapelike clusters (staphylococci). Filamentous bacteria are long, thin, rod-shaped bacteria that divide terminally and then form long filaments composed of many cells attached end to end.

The cell morphologies described here are representative but certainly not exhaustive; many variations of these morphologies are known. For example, there can be fat rods, thin rods, short rods, and long rods, rods that occur as single cells, as pairs of cells, or rods that

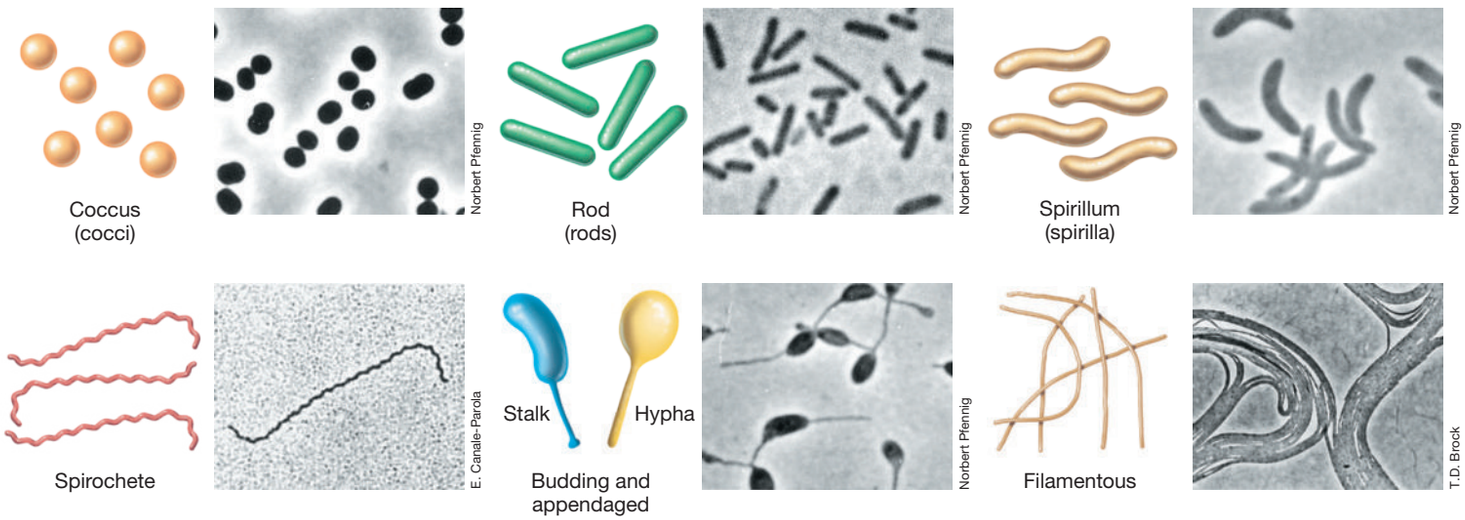


Figure 1.8 Cell morphologies. Beside each drawing is a phase-contrast photomicrograph of cells showing that morphology. Coccus (cell diameter in photomicrograph, 1.5 μm); rod (1 μm); spirillum (1 μm); spirochete (0.25 μm); budding (1.2 μm); filamentous (0.8 μm). All photomicrographs are of species of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

Tiny Cells

Viruses are very small microbes and range in diameter from as small as 20 nm to almost 750 nm. Although no cells exist that are as small as most viruses, the recent discovery of ultra-small bacterial cells[1,2] has pushed the lower limits of cell size to what microbiologists feel must be very close to the minimal value. And, because microbiologists today can deduce amazing amounts of information about cells in nature without culturing them, the lack of laboratory cultures of these tiny cells has been only a minor impediment to understanding their biology in detail.

Microbiologists collected groundwater, which travels through Earth's deep subsurface, from a Colorado (USA) aquifer (**Figure 1**) and passed it through a membrane filter whose pores were only 0.2 μm in diameter. The liquid that passed through the filter was then subjected to microbiological analyses. Surprisingly, since filters with 0.2-μm pores have been used for decades to remove bacterial cells from solutions to generate "sterile solutions," prokaryotic cells were present in the groundwater filtrate. In fact, a diverse array of *Bacteria* were present in the filtrate, revealing that the groundwater was inhabited by a microbial community of tiny cells[1] that microbiologists have come to call ultramicrobacteria.

Figure 1 **Sampling the anoxic groundwater aquifer that parallels the Colorado River near Rifle, Colorado.**

Electron cryotomography, a microscopic technique in which a specimen is examined at extremely cold temperatures without fixation (chemical treatment that can alter a cell's morphology, see Section 1.10), showed the groundwater ultramicrobacteria to consist primarily of oval-shaped cells about 0.2 μm in diameter (**Figure 2**). The volume of these cells was calculated to be about 1/200 that of a cell of the bacterium *Escherichia coli* (see Table 1.1) such that more than 200 of the small cells could fit into one *E. coli* cell! Each of the tiny cells contained about 50 ribosomes, which is also about 1/100 of the number present in a slowly growing (100-min generation time) cell of *E. coli*. The very small size of the groundwater ultramicrobacteria gives them an enormous surface-to-volume ratio, and it is hypothesized that this advantage benefits them in extracting resources from their nutrient-deficient habitat.

Despite the fact that the tiny groundwater bacteria have yet to be cultured in the laboratory, much is already known about them because their small genomes—less than 1 megabase (Mb) in size—were obtained and analyzed.[2] From a phylogenetic perspective, the different species detected were distantly related to major phyla of *Bacteria* known from environmental analyses of diverse environments but which have thus far defied laboratory culture. Further analyses showed that genes encoding the enzymes for several core metabolic pathways widely distributed among microorganisms were absent from the genomes of the groundwater ultramicrobacteria. This suggests a metabolically minimalist lifestyle for these tiny cells and a survival strategy of cross-feeding essential nutrients with neighboring species in their microbial community.

A strategy of obtaining nutrients from other organisms is one widely used in the microbial world. As we will see later in this book, many disease-causing (pathogenic or parasitic) bacteria have very small genomes that are missing many key genes otherwise necessary for a free-living lifestyle. However, the pathogenic or parasitic way of life of these microbes lets them "get away" with a minimal genomic complement because any essential molecules they are unable to biosynthesize are supplied by the host.

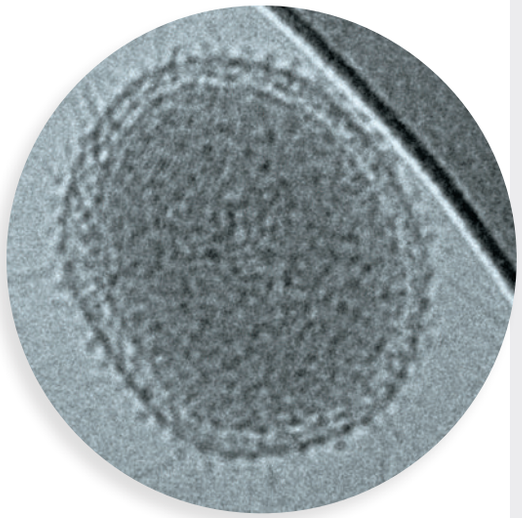


Figure 2 **A tiny bacterial cell from anoxic groundwater that passed through a filter with 0.2-μm pores.** The cell is not quite 0.2 μm in diameter.

Although we do not yet know exactly how small a microbial cell can be, microbiologists are closing in on this number from environmental analyses such as the Colorado groundwater study. From the same samples that yielded ultra-small *Bacteria* in this study, ultra-small *Archaea* were also detected and found to contain small and highly reduced genomes.[2]

It is thus likely that a large diversity of very small prokaryotic cells occurs in nature, and from the continued study of these tiny cells, more precise values for both the lower limits to cell size and the minimal genomic requirements for life should emerge. Moreover, theoretical considerations of cell size have shown that DNA and proteins dominate the volume of very small cells and that the theoretical lower limit to cell size agrees closely with the smallest bacteria observed in nature thus far.[3]

[1]Luef, B., et al. 2015. *Nat. Commun.* doi:10.1038/ncomms7372.
[2]Castelle, C.J., et al. 2015. *Curr. Biol. 25:* 1–12.
[3]Kempes, C.P., et al. 2016. *ISME J. 10:* 2145–2157.

form into filaments. As we will see, there are even square bacteria, hexagon-shaped bacteria, and star-shaped bacteria! Cell morphologies thus form a continuum, with some shapes, such as rods and cocci, being very common, whereas others, such as spiral, budding, and filamentous shapes, are less common.

Check Your Understanding

- What properties of the cell change as it gets smaller?
- Why is it that eukaryotic cells are typically larger than prokaryotic cells?
- What traits have allowed the bacteria *Epulopiscium* and *Thiomargarita* to have such large cells?

1.4 An Introduction to Microbial Life

As we have seen, microorganisms vary dramatically in size, shape, and structure. In this section we will learn more about different evolutionary (phylogenetic) lineages of cells. All cells fall into one of three major groups: *Bacteria*, *Archaea*, or *Eukarya*. These three major cell lineages are called **domains**, and all known cellular organisms belong to one of these three domains. In addition, while much of our focus in this chapter is on cellular forms of life, not all microbes form cells. In this section, we will also consider viruses, which are a group of microorganisms that lack a cellular structure. All known microorganisms can be classified into one of these four groups.

Bacteria

Bacteria have a prokaryotic cell structure (Figure 1.4*a*). *Bacteria* are often thought of as undifferentiated single cells with a length that ranges from 0.5 to 10 μm. While bacteria that fit this description are common, the *Bacteria* are actually tremendously diverse in appearance, size, and function (**Figure 1.9**). Although most bacteria are unicellular, some bacteria can differentiate to form multiple cell types and others are even multicellular (for example, *Magnetoglobus*, Figure 1.9).

Among the *Bacteria*, 30 major phylogenetic lineages (called *phyla*) have at least one species that has been grown in culture, though many more phyla exist which remain largely uncharacterized. Some of these phyla contain thousands of described species while others contain only a few. More than 90% of cultivated bacteria belong to one of only four phyla: *Actinobacteria*, *Firmicutes*, *Proteobacteria*, and *Bacteroidetes*. The analyses of environmental DNA sequences provide evidence for the existence of at least 80 bacterial phyla (Section 1.15).

Archaea

Like *Bacteria*, *Archaea* also have a prokaryotic cell structure (Figure 1.4*a*). The domain *Archaea* consists of five described phyla: *Euryarchaeota*, *Crenarchaeota*, *Thaumarchaeota*, *Nanoarchaeota*, and *Korarchaeota*. *Archaea* have historically been associated with extreme environments; the first isolates came from hot, salty, or acidic sites. But not all *Archaea* are extremophiles. *Archaea* are indeed common in

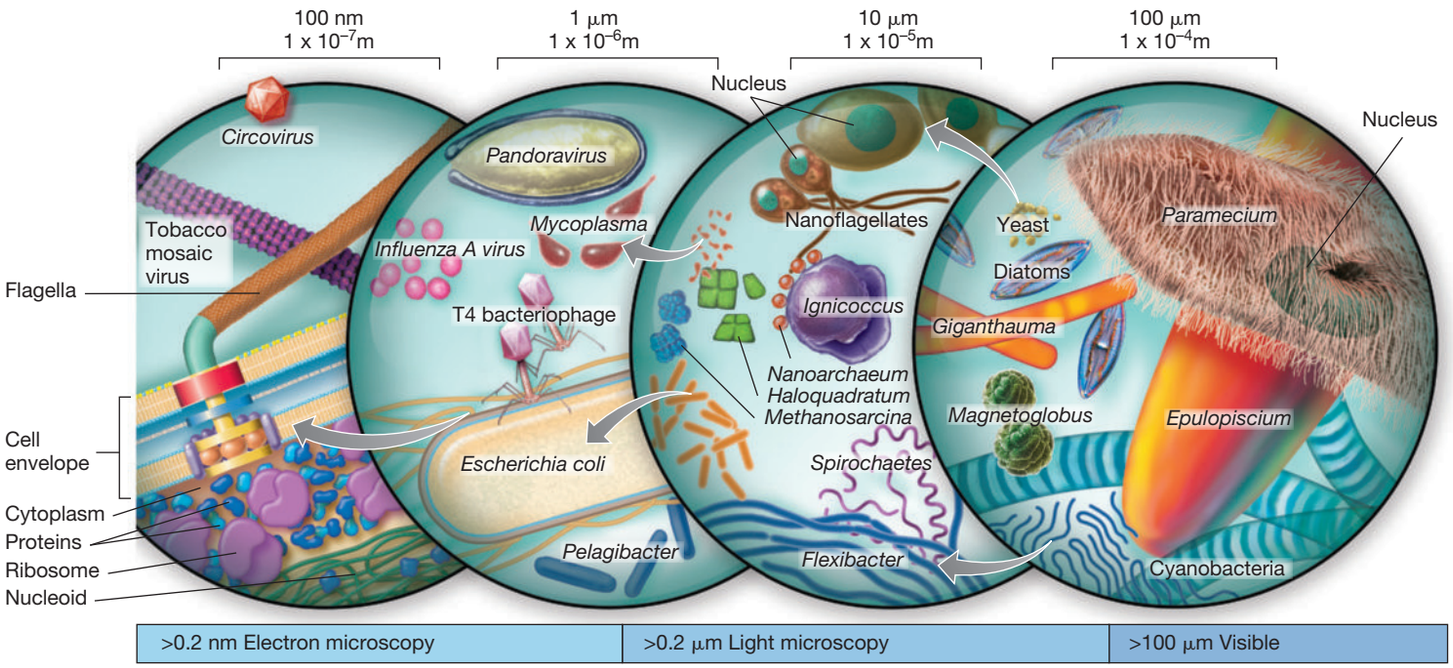


Figure 1.9 Microorganisms vary greatly in size and shape. The smallest known microbe is the circovirus (20 nm) and the largest shown here is the bacterium *Epulopiscium* (700 μm), which represents a 35,000-fold difference in length! Certain protozoa can be even larger than *Epulopiscium* (>2 mm long) and are visible to the unaided eye. Included in the figure are *Eukarya*: *Paramecium* (300 μm × 85 μm), diatoms (*Navicula*, 50 μm × 12 μm), yeast (*Saccharomyces*, 5 μm), and nanoflagellates (*Cafeteria*, 2 μm); *Bacteria*: *Epulopiscium* (700 μm × 80 μm), cyanobacteria (*Oscillatoria*, 10-μm-diameter multicellular filaments), *Magnetoglobus* (multicellular aggregate, 20 μm diameter), *Spirochaetes* (2–10 μm × 0.25 μm), *Flexibacter* (5–100 μm × 0.5 μm filaments), *Escherichia coli* (2 μm × 0.5 μm), *Pelagibacter* (0.4 μm × 0.15 μm), and *Mycoplasma* (0.2 μm); *Archaea*: *Giganthauma* (10-μm-diameter multicellular filament), *Ignicoccus* (6 μm), *Nanoarchaeum* (0.4 μm), *Haloquadratum* (2 μm), *Methanosarcina* (2 μm per cell in packet); and viruses: *Pandoravirus* (1 μm × 0.4 μm), T4 bacteriophage (200 nm × 90 nm), *Influenza A virus* (100 nm), *Tobacco mosaic virus* (300 nm × 20 nm), *Circovirus* (20 nm).

the most extreme environments that support life, such as those associated with volcanic systems, and species of *Archaea* hold many of the records that define the chemical and physical limits of life as we know them. However, in addition to these, *Archaea* are found widely in nature in nonextreme environments. For example, methane-producing *Archaea* (methanogens) are common in wetlands and in the guts of animals (including humans) and have a major impact on the greenhouse gas composition of our atmosphere. In addition, species of *Thaumarchaeota* inhabit soils and oceans worldwide and are important contributors to the global nitrogen cycle.

Archaea are also notable in that this domain lacks any known disease-causing (pathogenic or parasitic) species of plants or animals. Most described species of *Archaea* fall within the phyla *Crenarchaeota* and *Euryarchaeota* while only a handful of species have been described for the *Nanoarchaeota*, *Korarchaeota*, and *Thaumarchaeota*. Analysis of environmental DNA sequences indicate more than 12 archaeal phyla likely exist. We discuss *Archaea* in detail in Chapter 17.

Eukarya

Plants, animals, and fungi are the most well-known groups of *Eukarya*. These groups are phylogenetically relatively young compared with *Bacteria* and *Archaea*, originating during an evolutionary burst called the *Cambrian explosion*, which began about 600 million years ago. The first eukaryotes, however, were unicellular microbes. Microbial eukaryotes, which include diverse algae and protozoa, may have first appeared as early as 2 billion years ago, well before the origin of plants, animals, and fungi (Section 1.5). The major lineages of *Eukarya* are traditionally called *kingdoms* instead of phyla. There are at least six kingdoms of *Eukarya*, and this diverse domain contains microorganisms as well as the plants and animals.

Microbial eukaryotes vary dramatically in size, shape, and physiology (Figure 1.9). Among the smallest are the nanoflagellates, which are microbial predators that can be as small as 2 μm long. In addition, *Ostreococcus*, a genus of green algae that contains species whose cells are only 0.8 μm in diameter, are smaller than many bacteria. The largest single-celled organisms are eukaryotes, but they are hardly microbial. Xenophyophores are amoeba-like, single-celled organisms that live exclusively in the deep oceans and can be up to 10 *centimeters* in length. In addition, plasmodial slime molds consisting of a single cytoplasmic compartment can be up to 30 cm in diameter. In Chapter 18 we consider microbial eukaryotes in detail.

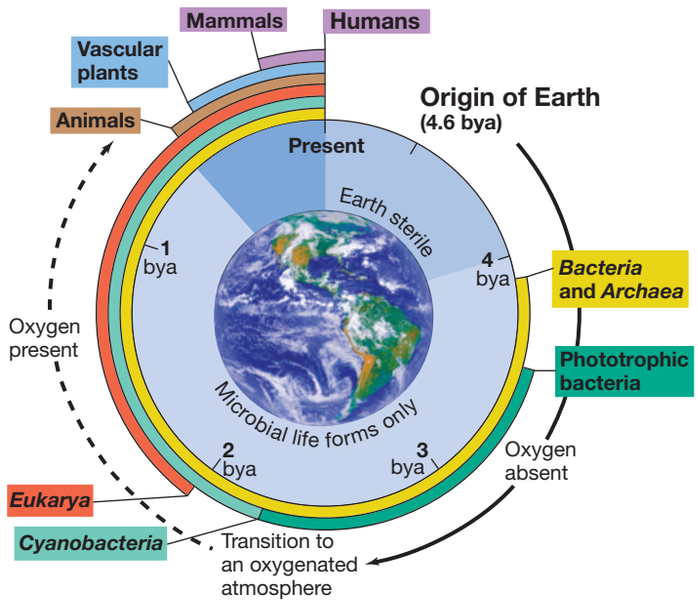
Viruses

Viruses are not found on the tree of life, and for a variety of reasons, it can be argued that they are not truly alive. Although viruses can replicate—a hallmark of cells—viruses are obligate parasites that can only replicate within the cytoplasm of a host cell. Viruses are not cells, and they lack the cytoplasmic membrane, cytoplasm, and ribosomes found in all forms of cellular life. Viruses do not carry out metabolic processes; instead, they take over the metabolic systems of infected cells and turn them into vessels for producing more viruses. Unlike cells, which all have genomes composed of double-stranded DNA, viruses have genomes composed of DNA *or* RNA that can be either double- or single-stranded. Viral genomes are often quite small, with the smallest having only three genes. The small size of most viral genomes means that no genes are conserved among all viruses, or between all viruses and all cells.

Although they are not cells, viruses are as diverse as the cells they infect, and different viruses are known to infect cells from all three domains of life. Viruses are often classified on the basis of their structure, genome composition, and host specificity. Viruses that infect bacteria are called *bacteriophages* (or *phages*, for short). Bacteriophages have been used as model systems to explore many aspects of viral biology. While most viruses are considerably smaller than bacterial cells (Figure 1.9), there are also unusually large viruses such as the Pandoraviruses, which can be more than 1 micrometer long and have a genome that contains as many as 2500 genes, larger than that of many bacteria! We will learn much more about viruses in Chapters 5 and 11.

Check Your Understanding

- How are viruses different from *Bacteria*, *Archaea*, and *Eukarya*?
- What four bacterial phyla contain the largest number of well-characterized species?
- What phylum of *Archaea* is common worldwide in soils and in the oceans?



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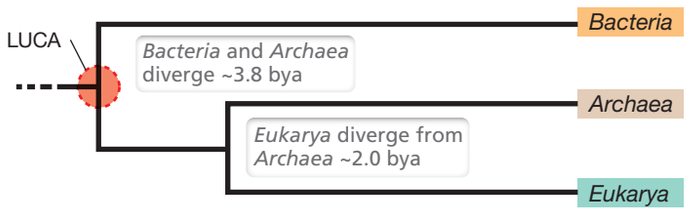

(b)

Figure 1.10 A summary of life on Earth through time and origin of the cellular domains. *(a)* At its origin, Earth was sterile and anoxic. Cellular life, in the form of *Bacteria* and *Archaea*, was present on Earth by 3.8 billion years ago (bya). The evolution of phototrophic bacteria called *Cyanobacteria* caused Earth's atmosphere to become oxygenated over time. While the first evidence for oxygen in Earth's atmosphere appears 2.4 bya, current levels of atmospheric O_2 were not achieved until 500–800 million years ago. *(b)* The three domains of cellular organisms are *Bacteria*, *Archaea*, and *Eukarya*. *Bacteria* and *Archaea* appeared first and *Eukarya* evolved later, diverging from the *Archaea*. LUCA, last universal common ancestor.

1.5 Microorganisms and the Biosphere

Microbes are the oldest form of life on Earth, and they have evolved to perform critical functions that sustain the biosphere. In this section we will learn how microbes have changed our planet and how they continue to do so.

A Brief History of Life on Earth

Earth is about 4.6 billion years old, and microbial cells first appeared between 3.8 and 4.3 billion years ago (**Figure 1.10**). During the first 2 billion years of Earth's existence, its atmosphere was anoxic (O_2 was absent), and only nitrogen (N_2), carbon dioxide (CO_2), and a few other gases were present. Only microorganisms capable of anaerobic metabolism (that is, metabolisms that do not require O_2) could survive under these conditions.

The evolution of phototrophic microorganisms—organisms that harvest energy from sunlight—occurred within 1 billion years of the formation of Earth (Figure 1.10*a*). The first phototrophs were anoxygenic (non-oxygen-producing), such as the purple sulfur bacteria and green sulfur bacteria we know today (**Figure 1.11**). *Cyanobacteria*—oxygen-producing (oxygenic) phototrophs (Figure 1.11*f*)—evolved nearly a billion years later (Figure 1.10*a*) and began the slow process of oxygenating Earth's atmosphere. These early phototrophs lived in structures called *microbial mats*, which are still found on Earth today (Figure 1.11*a–c*). After the oxygenation of Earth's atmosphere, multicellular life forms eventually evolved, culminating in the plants and animals we know today. But plants and animals have only existed for about half a billion years. The timeline of life on Earth (Figure 1.10*a*) shows that *80% of life's history was exclusively microbial*, and thus in many ways, Earth can be considered a microbial planet.

As evolutionary events unfolded, three major lineages of microbial cells—the *Bacteria*, the *Archaea*, and the *Eukarya* (Figure 1.10*b*)—were distinguished. All cellular organisms share certain characteristics (Figure 1.5) and as a result, certain genes are found in all cells. For example, approximately 60 genes are universally present in cells of all three domains. Examination of these genes reveals that all three domains have descended from a common ancestor, the *last universal common ancestor* (LUCA, Figure 1.10*b*). Over enormous periods of time, microorganisms derived from these three domains have evolved to fill every habitable environment on Earth.

Microbial Abundance and Activity in the Biosphere

Microorganisms are present everywhere on Earth that will support life. They constitute a major fraction of global biomass and are key reservoirs of nutrients essential for life. There are an estimated 2×10^{30} microbial cells on Earth. To put this number in context, the universe in all its vast extent is estimated to contain merely 7×10^{22} stars. The total amount of carbon present in all microbial cells is a significant fraction of Earth's biomass (**Figure 1.12**). Moreover, the total amount of nitrogen and phosphorus (essential nutrients for life) within microbial cells is almost four times that in all plant and animal cells combined. Microbes also represent a major fraction of the total DNA in the biosphere (about 31%), and their genetic diversity far exceeds that of plants and animals.

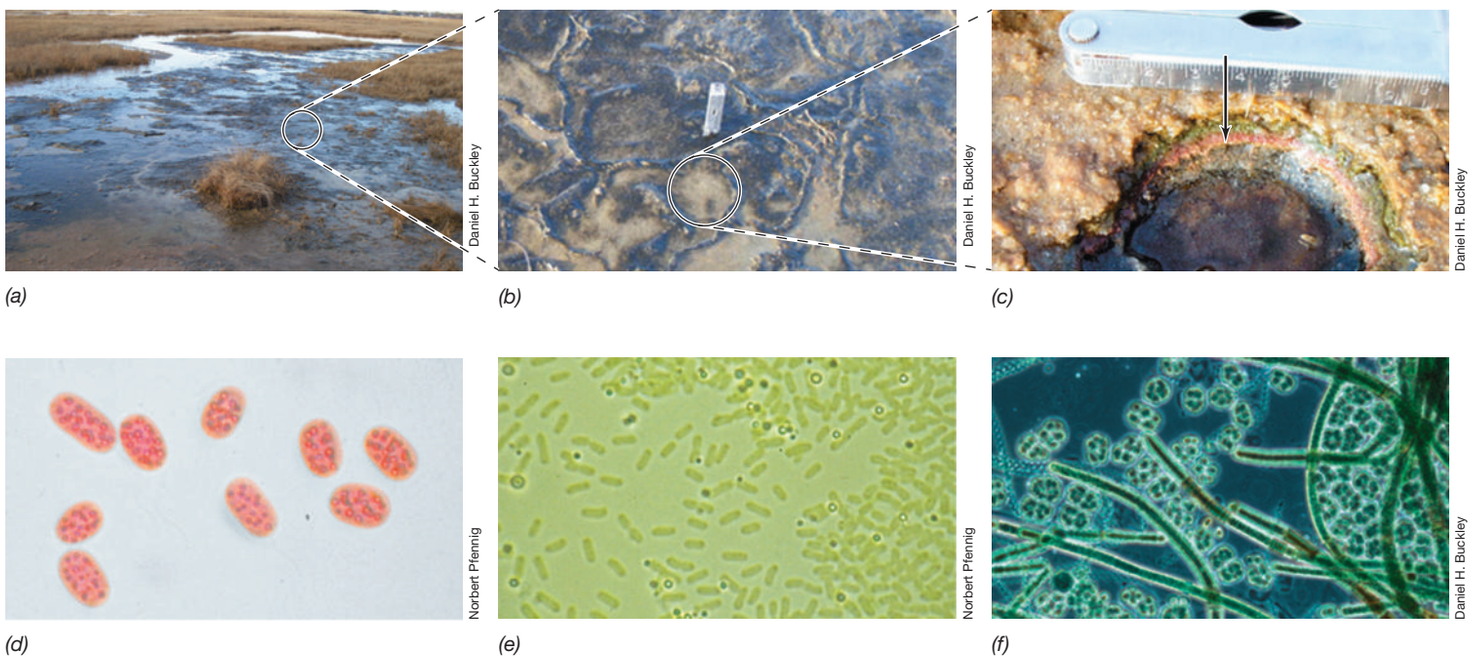

Figure 1.11 Phototrophic microorganisms. The earliest phototrophs lived in microbial mats. *(a)* Microbial mats in the Great Sippewissett Marsh, a salt marsh in Massachusetts, USA. *(b)* Mats develop a cohesive structure that forms at the sediment surface. *(c)* A slice through the mat shows colored layers that form due to the presence of photopigments. Cyanobacteria form the green layer nearest the surface, purple sulfur bacteria form the purple and yellow layers below, and green sulfur bacteria form the bottommost green layer. The scale on the knife is in cm. *(d)* Purple sulfur bacteria, *(e)* green sulfur bacteria, and *(f)* cyanobacteria imaged by bright-field and phase-contrast microscopy. Purple and green sulfur bacteria are anoxygenic phototrophs that appeared on Earth long before oxygenic phototrophs (that is, *Cyanobacteria*) evolved (see Figure 1.10*a*).

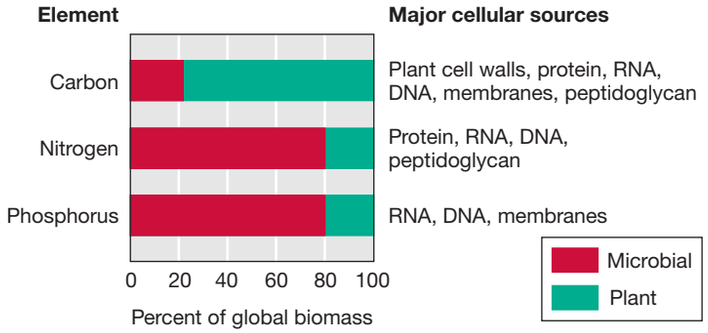

Figure 1.12 Contribution of microbial cells to global biomass. Microorganisms comprise a significant fraction of the carbon (C) and a majority of the nitrogen (N) and phosphorus (P) in the biomass of all organisms on Earth. C, N, and P are the macronutrients required in the greatest quantity by living organisms. Animal biomass is a minor fraction (<0.1%) of total global biomass and is not shown.

Microbes are even abundant in habitats that are much too harsh for other forms of life, such as volcanic hot springs, glaciers and ice-covered regions, high-salt environments, extremely acidic or alkaline habitats, and deep in the sea or deep in the earth at extremely high pressure. Such microorganisms are called **extremophiles** and their properties define the physiochemical limits to life as we know it (Table 1.2). We will revisit many of these organisms in later chapters and discover the special structural and biochemical properties that allow them to thrive under extreme conditions.

All ecosystems are influenced to one extent or another by microbial activities. The metabolic activities of microorganisms can change the habitats in which they live, both chemically and physically, and these changes can affect other organisms. For example, excess nutrients added to a habitat can cause aerobic (O_2-consuming) microorganisms to grow rapidly and consume O_2, rendering the habitat anoxic (O_2-free). Many human activities release nutrients into the coastal oceans, thereby stimulating excessive microbial growth, which can cause enormous anoxic zones in these waters. These "dead zones" cause massive mortality of fish and shellfish in coastal oceans worldwide, because most aquatic animals require O_2 and die if it is not available. Only by understanding microorganisms and microbiology can we predict and minimize the effects of human activity on the biosphere that sustains us.

Though diverse habitats are influenced strongly by microorganisms, their contributions are easy to overlook because of their small sizes. Within the human body, for example, more microbial cells can be present than human cells, and more than 200 microbial genes are present for every human gene. These microbes provide benefits and services that are essential to human health. In later chapters, we will return to a consideration of the ways in which microorganisms affect animals, plants, and the entire global ecosystem. This is the science of **microbial ecology**, perhaps the most exciting subdiscipline of microbiology today. We will see that microbes are important to myriad issues of global importance to humans including climate change, agricultural productivity, and even energy policy.

We focus now on the effects of microbes on humans and human activities.

Check Your Understanding

- How old is Earth and when did cells first appear on Earth?
- Name the three domains of life. Which of these contain eukaryotic life forms?
- Why were cyanobacteria so important in the evolution of life on Earth?

1.6 The Impact of Microorganisms on Human Society

Microbiologists have made great strides in discovering how microorganisms function, and application of this knowledge has greatly advanced human health and welfare. Besides understanding microorganisms as agents of disease, microbiology has made great

TABLE 1.2 Classes and examples of extremophiles[a]

Extreme	Descriptive term	Genus, species	Domain	Habitat	Minimum	Optimum	Maximum
Temperature							
High	Hyperthermophile	*Methanopyrus kandleri*	*Archaea*	Undersea hydrothermal vents	90°C	106°C	122°C[b]
Low	Psychrophile	*Psychromonas ingrahamii*	*Bacteria*	Sea ice	−12°C[c]	5°C	10°C
pH							
Low	Acidophile	*Picrophilus oshimae*	*Archaea*	Acidic hot springs	−0.06	0.7[d]	4
High	Alkaliphile	*Natronobacterium gregoryi*	*Archaea*	Soda lakes	8.5	10[e]	12
Pressure	Barophile (piezophile)	*Moritella yayanosii*	*Bacteria*	Deep ocean sediments	500 atm	700 atm[f]	>1000 atm
Salt (NaCl)	Halophile	*Halobacterium salinarum*	*Archaea*	Salterns	15%	25%	32% (saturation)

[a]The organisms listed are the current "record holders" for growth in laboratory culture at the extreme condition listed.
[b]Anaerobe showing growth at 122°C only under several atmospheres of pressure.
[c]The permafrost bacterium *Planococcus halocryophilus* can grow at −15°C and metabolize at −25°C. However, the organism grows optimally at 25°C and grows up to 37°C and thus is not a true psychrophile.
[d]*P. oshimae* is also a thermophile, growing optimally at 60°C.
[e]*N. gregoryi* is also an extreme halophile, growing optimally at 20% NaCl.
[f]*M. yayanosii* is also a psychrophile, growing optimally near 4°C.

advances in understanding the important roles microorganisms play in food and agriculture, and microbiologists have exploited microbial activities to produce valuable human products, generate energy, and clean up the environment.

Microorganisms as Agents of Disease

The statistics summarized in **Figure 1.13** show how microbiologists and clinical medicine have combined to conquer infectious diseases in the past 120 years. At the beginning of the twentieth century, more than half of all humans died from infectious diseases caused by bacterial and viral **pathogens**. Today, however, infectious diseases are largely preventable due to advances in our understanding of microbiology. Microbiology has fueled advances in medicine such as vaccination and antibiotic therapy, advances in engineering such as water and wastewater treatment, advances in food safety such as pasteurization, and a better understanding of how microorganisms are transmitted. Infectious diseases now cause fewer than 5% of all deaths in countries where these interventions, made possible by microbiology, are readily available. However, while infectious diseases are preventable, the World Health Organization has documented that they still account for more than a third of all deaths in countries where microbial interventions are less available, such as those having low-income economies. As we will see later in this chapter, the development of microbiology as a science can be traced to pioneering studies of infectious disease.

While pathogens and infectious disease remain a major threat to humanity, and combating these harmful organisms remains a major focus of microbiology, most microorganisms are not harmful to humans. In fact, most microorganisms are beneficial, and in many cases are even essential to human welfare and the functioning of the planet. We turn our attention to these microorganisms and microbial activities now.

Microorganisms, Agriculture, and Human Nutrition

Agriculture benefits from nutrient cycling performed by microorganisms, in particular, the cycling of nitrogen, sulfur, and carbon compounds. For example, legumes are a diverse family of plants that include major crop species such as soybeans, peas, and lentils, among others. Legumes live in close association with bacteria that form structures called *nodules* on their roots. In the nodules, these bacteria convert atmospheric nitrogen (N_2) into ammonia (NH_3) through the process of *nitrogen fixation*. NH_3 is the major nutrient found in fertilizer and is used as a nitrogen source for plant growth (**Figure 1.14**). In this way bacteria allow legumes to make their own fertilizer, thereby reducing the need for farmers to apply fertilizers produced industrially. When plants die they are decomposed by bacteria in the soil, and this process produces the nutrients that form the basis of soil fertility. Bacteria regulate nutrient cycles (Figure 1.14), in soils and throughout the biosphere, transforming and recycling the nutrients required by plants and animals.

Also of major agricultural importance are microorganisms that inhabit the rumen of ruminant animals, such as cattle and sheep. Ruminants, like most animals, lack enzymes for breaking down the polysaccharide cellulose, the major component of plant cell walls. The digestive tract of ruminants has a large specialized chamber called the *rumen* in which cellulose is digested. The rumen contains a dense and diverse community of microorganisms that digest and ferment cellulose. Without these symbiotic microorganisms, ruminants could not digest plant matter like grass and hay, most of which consists of cellulose. Ruminants ultimately get their nutrition by metabolizing the waste products of microbial fermentation and by digesting dead microbial cells. Many domesticated and wild herbivorous mammals—including deer, bison, camels, giraffes, and goats—are also ruminants.

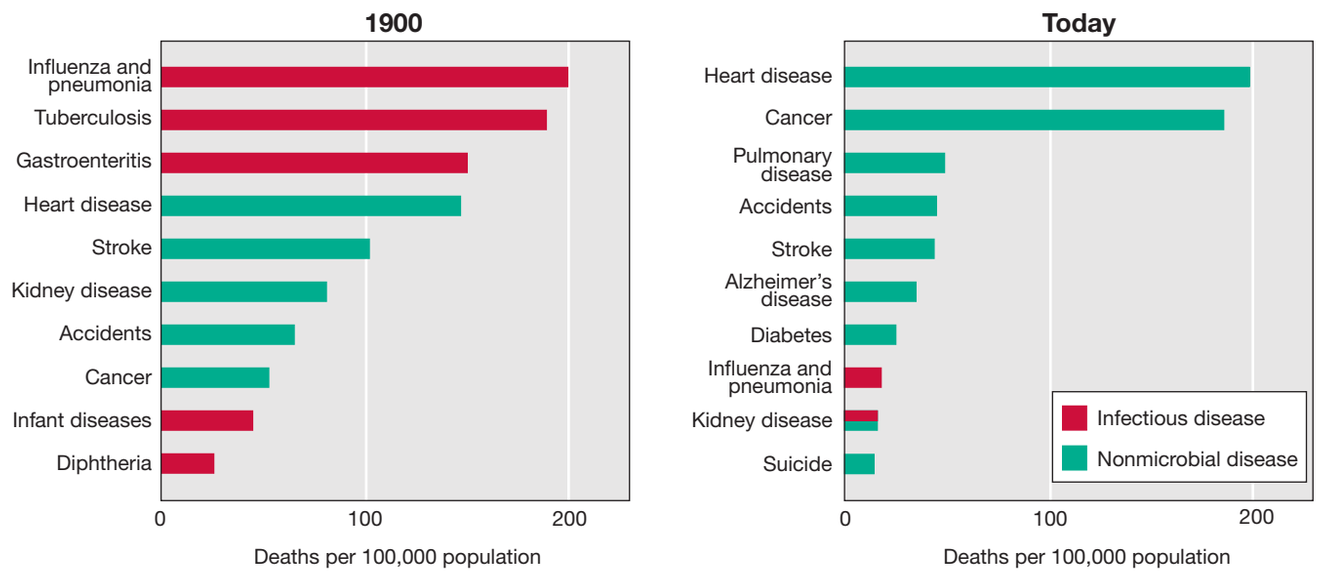

Figure 1.13 Death rates for the leading causes of death in the United States: 1900 and 2016. Infectious diseases were the leading causes of death in 1900, whereas today they account for relatively few deaths. Kidney diseases can be caused by microbial infections or systemic sources (diabetes, cancers, toxicities, metabolic diseases, etc.). Data are from the United States National Center for Health Statistics and the Centers for Disease Control and Prevention.

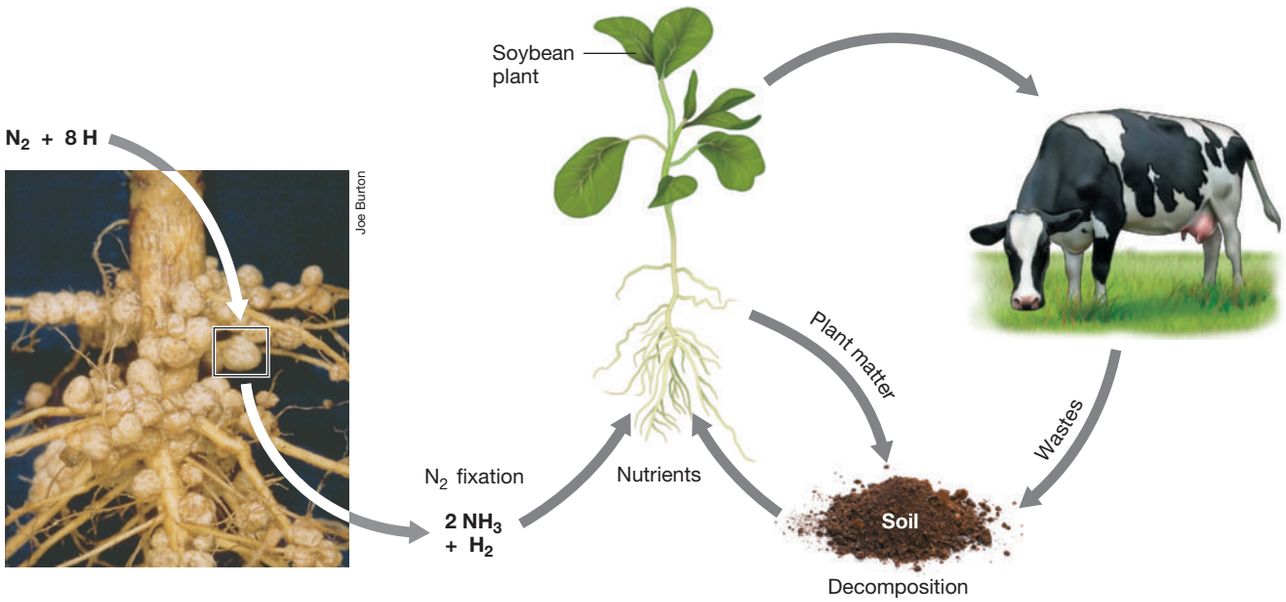

Figure 1.14 Microorganisms in modern agriculture. Root nodules on this soybean plant contain bacteria that fix atmospheric nitrogen (N_2) to form nitrogenous compounds used by the plant. Ruminant animals such as cows and sheep require rumen microbes to digest cellulose from plants. Plant matter and animal wastes are decomposed in soil to produce nutrients that are the basis of soil fertility and which are required for plant growth.

The human gastrointestinal (GI) tract lacks a rumen, but we too rely on microbial partners for our nutrition. Human enzymes lack the ability to break down complex carbohydrates (which can represent 10–30% of food energy) and so we rely on our **gut microbiome** for this purpose. The colon, or large intestine (**Figure 1.15**), follows the stomach and small intestine in the human digestive tract, and it contains about 10^{11} microbial cells per gram of colonic contents. Microbial cell numbers are low in the very acidic (pH 2) stomach (about 10^4 per gram) but increase to about 10^8 per gram near the end of the small intestine (pH 4–5) and then reach maximal numbers in the colon (pH 7) (Figure 1.15). The colon contains diverse microbial species that assist in the digestion of complex carbohydrates, and that synthesize vitamins and other nutrients essential to host nutrition. The gut microbiome develops from birth, but it can change over time with the human host. The composition of the gut microbiome has major effects on GI function and human health as we will see in Chapter 24.

Microorganisms and Food

Microbes are intimately associated with the foods we eat. Microbial growth in food can cause food spoilage and foodborne disease. The manner in which we harvest and store food (for example, canning, refrigeration, drying, salting, etc.), the ways in which we cook it, and even the spices we use, have all been fundamentally influenced by the goal of eliminating harmful organisms from our food. Microbial food safety and prevention of food spoilage is a major focus of the food industry and a major cause of economic loss every year.

While some microbes can cause foodborne disease and food spoilage, not all microorganisms in foods are harmful. Indeed, beneficial microbes have been used for thousands of years to improve food safety and to preserve foods (**Figure 1.16**). For example, cheeses, yogurt, and buttermilk are all produced by microbial fermentation of dairy products. Microbial production of lactic acid in these foods improves their shelf life and prevents the growth of foodborne pathogens. Lactic acid–producing bacteria are used to produce a variety of sour-tasting foods, including sauerkraut, kimchi, pickles, and even certain sausages. Even the production of chocolate and coffee rely on microbial fermentation. Moreover, the fermentative activities of yeast are essential for baking (by generating carbon dioxide—CO_2—to raise the dough), and for the production of alcoholic beverages (by generating alcohol). The products of microbial fermentation affect the flavor and taste of foods and can prevent spoilage as well as the growth of deleterious organisms.

Microorganisms and Industry

Microorganisms play important roles in all manner of human activity. The field of *industrial microbiology* is focused on the use of microorganisms as tools for major industries such as pharmaceuticals and brewing (**Figure 1.17**). For example, in large industrial settings, naturally occurring microorganisms are grown on a massive scale in bioreactors called *fermentors* to make large amounts of products, such as antibiotics, enzymes, alcohol, and certain other chemicals, at relatively low cost. By contrast, *biotechnology* employs genetically engineered microorganisms to synthesize products of high commercial value, such as insulin or other human proteins, usually on a small scale.

Microorganisms can also be used to produce *biofuels* (▶ Section 12.19 and Figure 12.33). For example, as previously discussed,

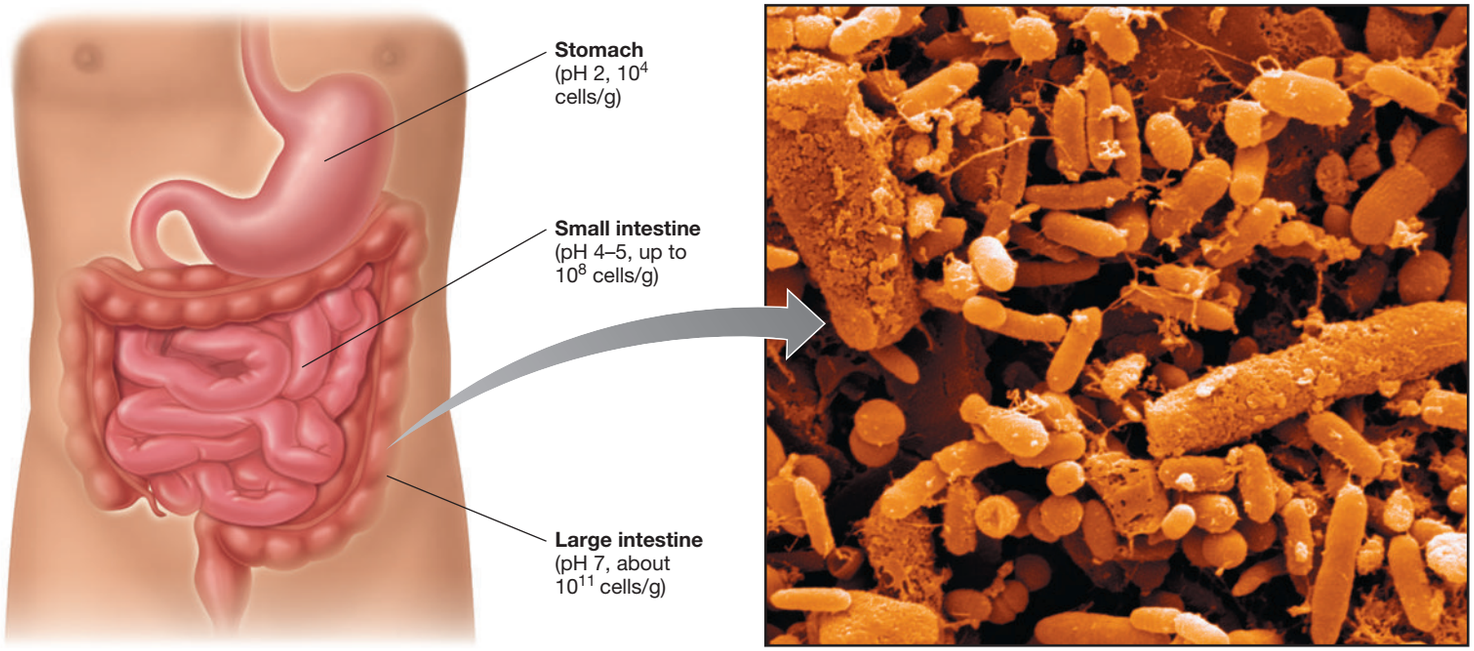

Figure 1.15 **The human gastrointestinal tract.** *(a)* Diagram of the human GI tract showing the major organs. *(b)* Scanning electron micrograph of microbial cells in the human colon (large intestine). Cell numbers in the colon can reach as high as 10^{11} per gram. As well as high *numbers* of cells, the microbial *diversity* in the colon is also quite high.

natural gas (methane, CH_4) is a product of the anaerobic metabolism of methanogenic *Archaea*. Ethyl alcohol (ethanol) is a major fuel supplement, which is produced by the microbial fermentation of glucose obtained from carbon-rich feedstocks such as sugarcane, corn, or rapidly growing grasses. Microorganisms can even convert waste materials, such as domestic refuse, animal wastes, and cellulose, into ethanol and methane. In producing these biofuels, humans are simply exploiting the metabolic features of particular microbes, but at the same time, are reducing the use of fossil fuels. As we will document in Chapter 21, CO_2 levels have been rising

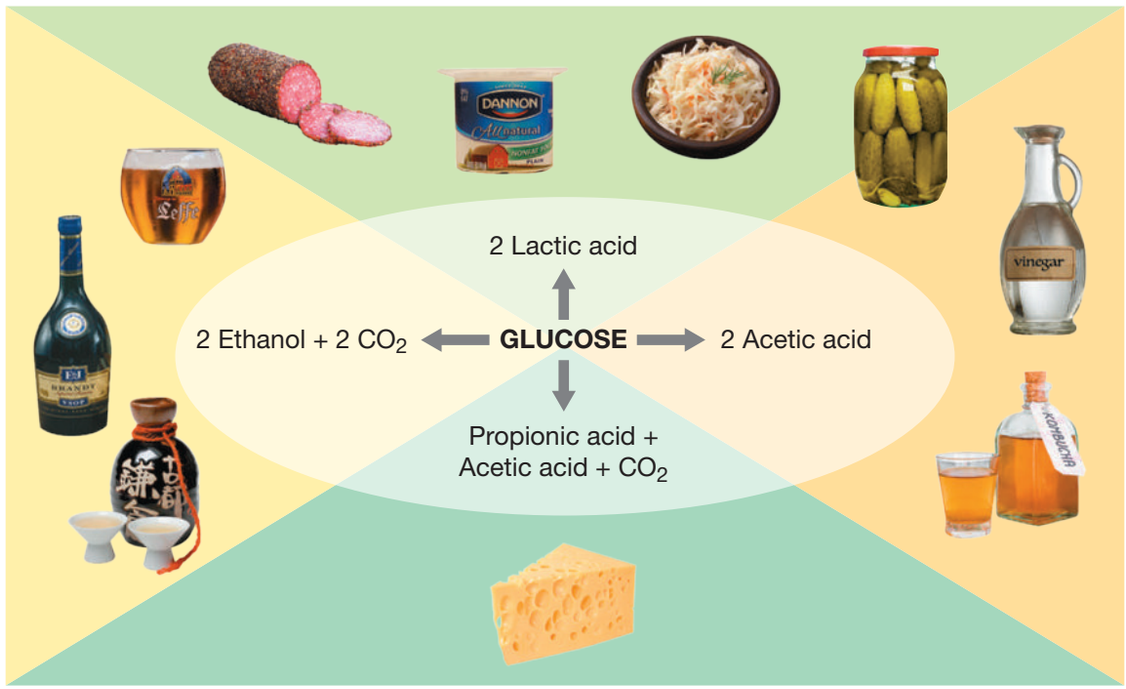

Figure 1.16 **Fermented foods.** Major fermentations in various fermented foods. It is the fermentation product (ethanol, or lactic, propionic, or acetic acids) that both preserves the food and renders in it a characteristic flavor.

Wastewater Treatment: Microbes are used to clean wastewater.

Bioremediation: Microbes are used to clean contaminated environments.

Biofilms: Microbes grow on surfaces and can foul pipes and pipelines.

Biotechnology: Microbes can be genetically modified to produce high-value products such as pharmaceuticals and enzymes.

Fermentation: Microbes are used at industrial scale to make chemicals, solvents, enzymes, and pharmaceuticals.

Biofuels: Microbes are used to convert biomass into ethanol and wastes into natural gas (methane).

Figure 1.17 Industrial microbiology. Microbes have major impacts on human industry. Microbes can be used to produce valuable products and biofuels and they can also be used to clean up our wastes. Microbial biofilms have major impacts on industry because biofilms can clog and corrode pipelines and holding tanks in factories, in ships, and in the oil industry.

rapidly on Earth in the industrial era, and the link between this "greenhouse gas" and Earth's rising temperatures is firm. Thus, as a sustainable fuel source, biofuels should help cool our planet and are one facet of the "green revolution" many countries support today.

Microorganisms are also used to clean up wastes. Wastewater treatment is essential to sanitation and human health. *Wastewater treatment* relies on microbes to treat water contaminated with human waste so that it can be reused or returned safely to the environment. Waterborne diseases such as cholera and typhoid (major killers before the blossoming of microbiology: see gastroenteritis, Figure 1.13) can proliferate in the absence of proper wastewater treatment. Microbes can also be used to clean up industrial pollution in a process called *bioremediation*. In bioremediation, microorganisms are used to transform spilled oil, solvents, pesticides, heavy metals, and other environmentally toxic pollutants into nontoxic forms. Bioremediation accelerates the cleanup process either by adding special microorganisms to a polluted environment or by adding nutrients that stimulate indigenous microorganisms to degrade the pollutants. In either case the goal is to accelerate disappearance of the pollutant.

Microbes can grow in almost any environment containing liquid water, including structures made by humans. For example, microbes often grow on submerged surfaces, forming *biofilms*. Biofilms that grow in pipes and drains can cause fouling and blockages in factory settings and pipelines, in sewers, and even in water distribution systems. In addition, biofilms that grow on ships' hulls can cause marked reductions in speed and efficiency. Biofilms can even grow in tanks that store oil and fuel, leading to spoilage of these products. We will learn that biofilms are also of great importance in medicine, as biofilms that form on implanted medical devices (▶ Section 4.9) can cause infections that are extremely difficult to treat.

As these examples show, the influence of microorganisms on humans is great and their activities are essential for the functioning of the planet. Or, as the famous French chemist and early microbiologist Louis Pasteur so aptly put it: "The role of the infinitely small in nature is infinitely large." Microscopes provide an essential portal through which microbiologists such as Pasteur gazed into the world of microbes. We therefore continue our introduction to the microbial world with an overview of microscopy.

Check Your Understanding

- How do microbes contribute to the nutrition of animals such as humans and cows?
- Describe several ways in which microorganisms are important in the food and agricultural industries.
- What is wastewater treatment and why is it important?