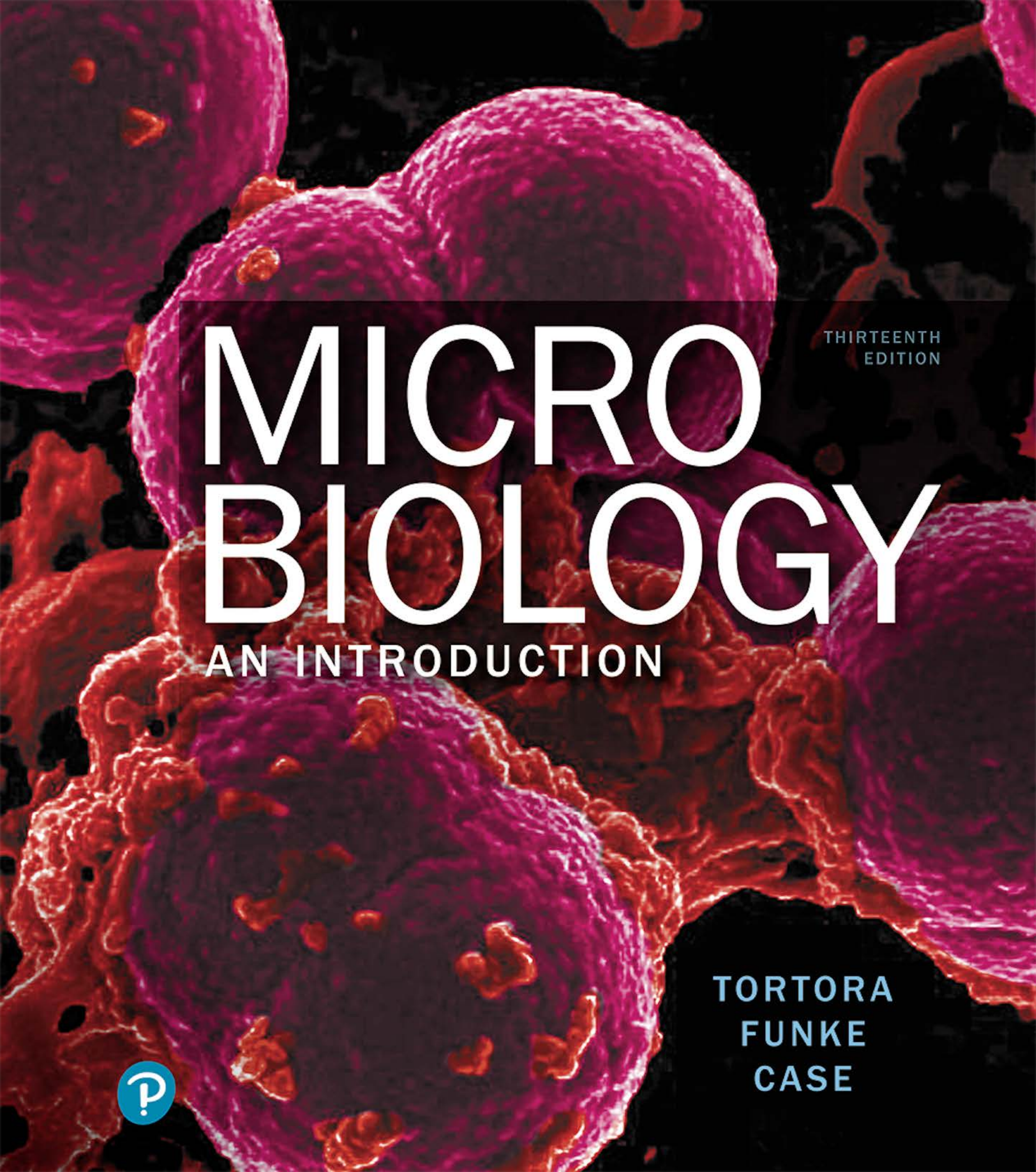


THIRTEENTH EDITION

MICROBIOLOGY

AN INTRODUCTION

TORTORA
FUNKE
CASE

Brief Contents

PART ONE Fundamentals of Microbiology

PART TWO A Survey of the Microbial World

PART THREE Interaction between Microbe and Host

PART FOUR Microorganisms and Human Disease

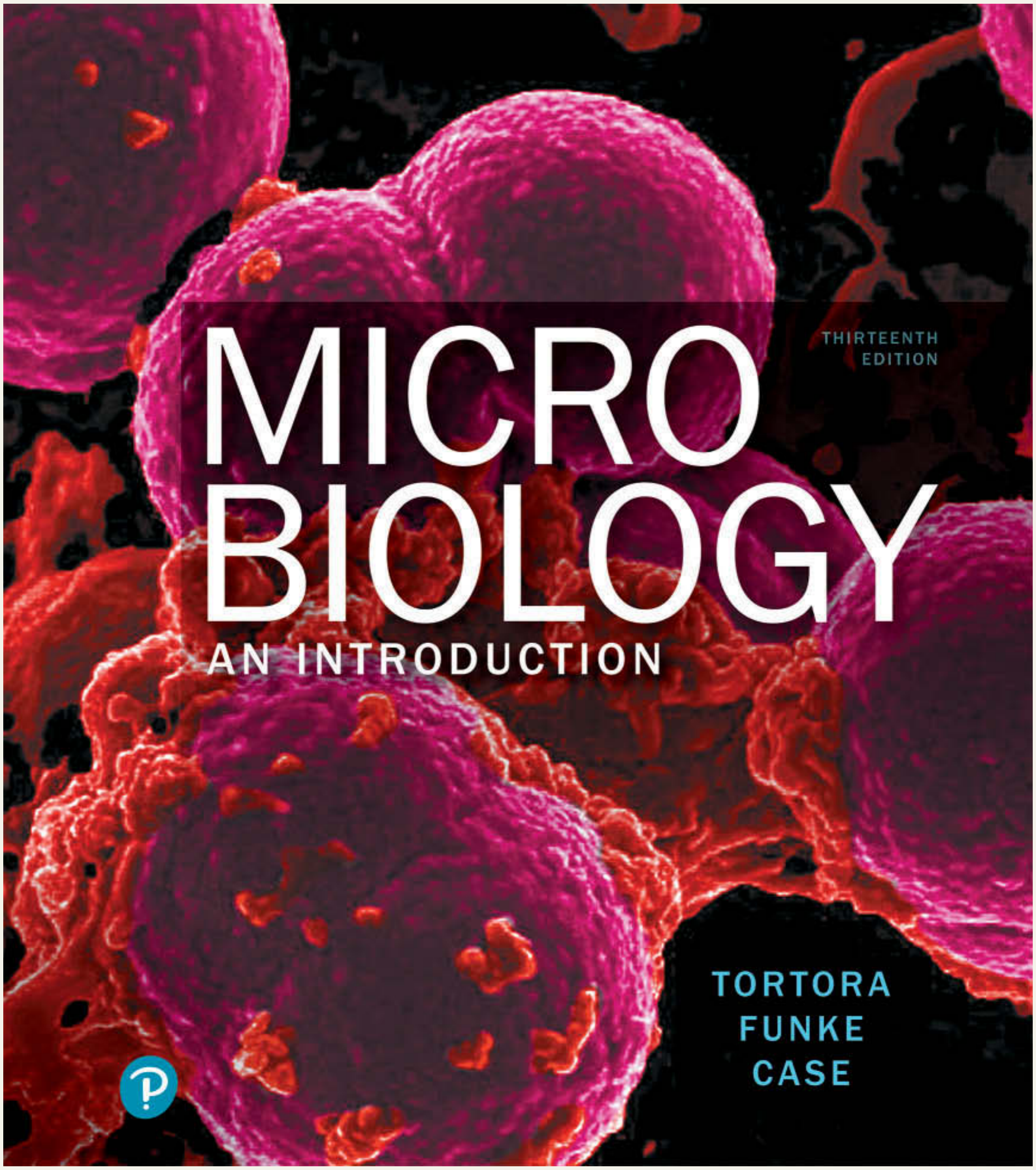
PART FIVE Environmental and Applied Microbiology

AMERICAN SOCIETY FOR MICROBIOLOGY — All chapter content is tagged to ASM Curriculum Guidelines for Undergraduate Microbiology

Exploring the Microbiome

Cutting Edge Microbiology Research for *Today's* Learners

The 13th Edition of Tortora, Funke, and Case's ***Microbiology: An Introduction*** brings a 21st-century lens to this trusted market-leading introductory textbook. New and updated features, such as **Exploring the Microbiome** boxes and **Big Picture** spreads, emphasize how our understanding of microbiology is constantly expanding. New **In the Clinic Video Tutors** in **Mastering™ Microbiology** illustrate how students can apply their learning to their future careers. Mastering Microbiology also includes new Ready-to-Go Teaching Modules that guide you through the most effective teaching tools available.



Do your students struggle to make connections between course

NEW! Exploring the Microbiome boxes illustrate how research in microbiology is revolutionizing our understanding of health and disease. These boxes highlight the possibilities in this exciting field and present insights into some of the newly identified ways that microbes influence human health. In addition, they provide examples of how research in this field is done—building on existing information, designing fair testing, drawing conclusions, and raising new questions.

EXPLORING THE MICROBIOME **Do Artificial Sweeteners (and the Intestinal Microbiota That Love Them) Promote Diabetes?**

For years, beverages made with artificial sweeteners were embraced by diabetics and weight watchers because, unlike sugar, artificial sweeteners don't impact blood glucose levels and don't provide calories. However, recent research indicates artificial sweeteners may actually increase the risk of nondiabetics developing the disease. One study published in 2009 by the American Diabetes Association found that daily consumption of diet soda was associated with a 67% greater relative risk of developing type 2 diabetes.

Undigestible by humans, artificial sweeteners provide zero calories to us when we consume them. But they are a great source of nutrients for *Bacteroides* bacteria living in the colon. As *Bacterioides* break down the sweeteners and increase in numbers, other types of microbiota simultaneously decline. Among these are *Lactobacillus* bacteria. Studies indicate that high *Lactobacillus* levels in the intestine are associated with decreased blood sugar levels. The exact mechanism remains unclear, but it is hypothesized that decreases in the population of *Lactobacillus* bacteria lead to higher blood glucose levels, thereby forcing the body to produce more insulin to control the rising blood glucose. Prolonged high insulin levels may lead to insulin resistance, a condition where the body stops responding correctly to the hormone. Insulin resistance is the hallmark sign of type 2 diabetes.

Recent and current research are exploring whether ingesting probiotics with *Lactobacillus acidophilus* and *Bifidobacterium animalis* may be a useful treatment for type 2 diabetes. Initial studies were promising, showing that these species might lower blood glucose levels. If proven effective, one day bacteria could be key weapons in preventing a deadly disease.

Lactobacillus acidophilus.

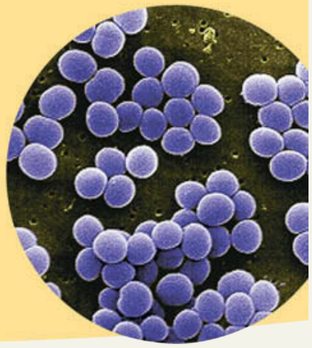
EXPLORING THE MICROBIOME **Antimicrobial Soaps: Doing More Harm Than Good?**

Staphylococcus aureus is a normal member of the human microbiome, found on the skin and in the nose. *S. aureus* is also a significant cause of healthcare-associated infections in patients. The bacterium can switch from benign member of the skin community to a disease-causing pathogen if it gains entry to the body through a wound.

Since most hospital-acquired *S. aureus* infections are endogenous—that is, caused by bacteria that have colonized in or on the body before someone became a patient—hospitals have long used a disinfectant called triclosan in clinical soaps and skin lotions to prevent staphylococcal infections. Over the years, triclosan was also added to many household products, such as dishwashing detergent, toothpastes, and body washes. However, using these antimicrobial products daily seems to be a case of "too much of a good thing."

Triclosan enters the blood and is excreted in urine. Therefore, triclosan can be found in many areas of the body, including the nasal mucosa, of people who use it. The nose is the primary habitat of *S. aureus*. In an example of unintended consequences, presence of triclosan in blood is also associated with nasal colonization of the *S. aureus*. *S. aureus* is more likely to bind to host-cell-membrane proteins in the presence of triclosan. Moreover, constant exposure to triclosan selects for triclosan-resistant mutants over generations of bacterial growth. Triclosan-resistant bacteria avoid death by removing the chemical from their cells using transporter proteins. These transporters can also remove some antibiotics from the bacterial cells. Morever, methicillin-resistant *S. aureus* (MRSA) is more resistant to triclosan than methicillin-sensitive staphylococci.

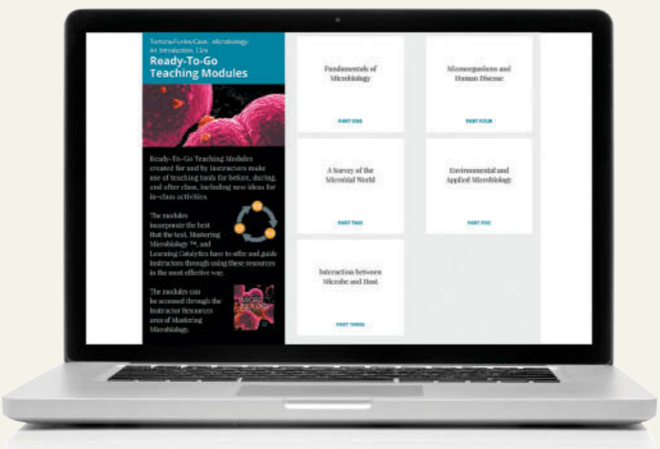
Starting in late 2016, the Federal Drug Association banned triclosan from over-the-counter consumer washing products. The American Medical Association recommends using plain soap and water and proper handwashing techniques instead—these products and techniques remove microbes without the harmful unintended consequences associated with widespread triclosan use.



Staphylococcus aureus.

content and their future careers?

New! In the Clinic Video Tutors bring to life the scenarios in the chapter-opening In the Clinic features. Concepts related to infection control, principles of disease, and antimicrobial therapies are integrated throughout the chapters, providing a platform for instructors to introduce clinically relevant topics throughout the term. Each Video Tutor has a series of assessments assignable in Mastering Microbiology that are tied to learning outcomes.

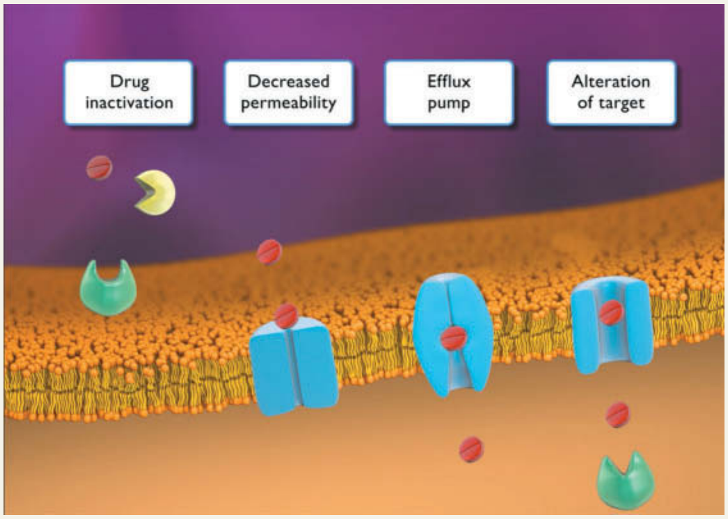


NEW! Ready-to-Go Teaching Modules in the Instructor Resources of Mastering Microbiology help instructors efficiently make use of the available teaching tools for the toughest topics in microbiology. Pre-class assignments, in-class activities, and post-class assessments are provided for ease of use.

Within the Ready-to-Go Teaching Modules, **Adopt a Microbe** modules enable instructors to select specific pathogens for additional focus throughout the text.

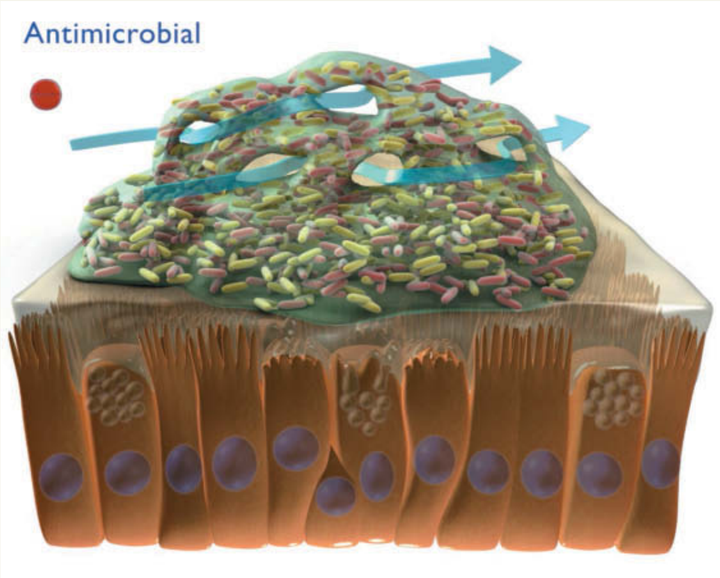
Do your students need help understanding the toughest

Interactive Microbiology is a dynamic suite of interactive tutorials and animations that teach key microbiology concepts. Students actively engage with each topic and learn from manipulating variables, predicting outcomes, and answering assessment questions that test their understanding of basic concepts and their ability to integrate and build on these concepts. These are available in Mastering Microbiology.



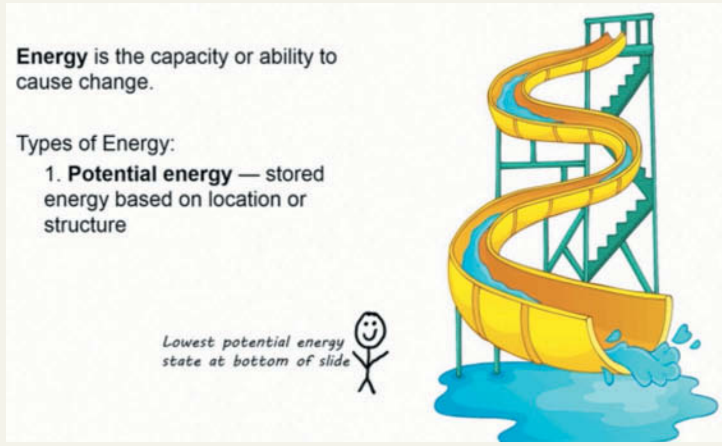
NEW! Even more Interactive Microbiology modules are available for Fall 2018. Additional titles include:

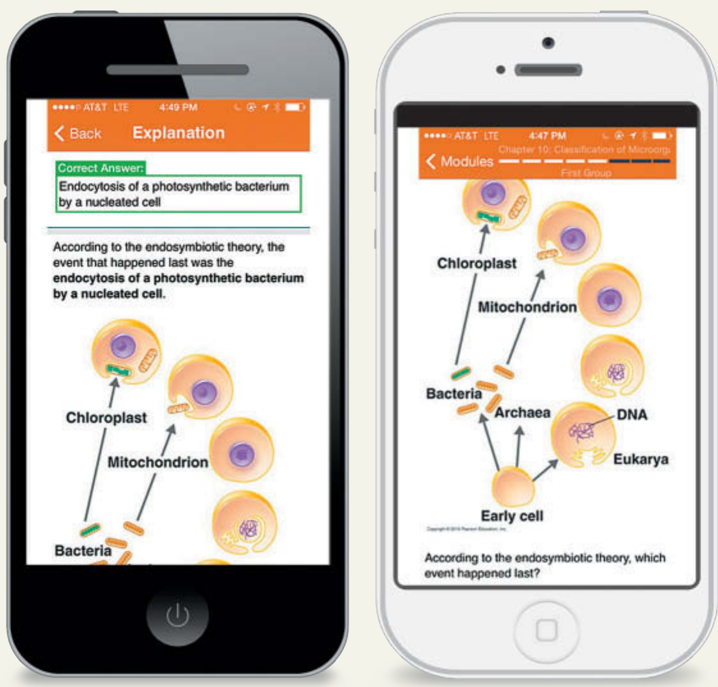
- Antimicrobial Resistance: Mechanisms
- Antimicrobial Resistance: Selection
- Aerobic Respiration in Prokaryotes
- The Human Microbiome



concepts in microbiology?

MicroBoosters are a suite of brief video tutorials that cover key concepts some students may need to review or relearn. Titles include Study Skills, Math, Scientific Terminology, Basic Chemistry, Cell Biology, and Basic Biology.





Dynamic Study Modules help students acquire, retain, and recall information faster and more efficiently than ever before. The flashcard-style modules are available as a self-study tool or can be assigned by the instructor.

NEW! Instructors can now remove questions from **Dynamic Study Modules** to better fit their course.

Do your students have trouble organizing and synthesizing

Big Picture spreads integrate text and illustrations to help students gain a broad, "big picture" understanding of important course topics.

Each Big Picture spread includes an overview that **breaks down important concepts** into manageable steps and gives students a clear learning framework for related chapters. Each spread includes Key Concepts that **help students make the connection** between the presented topic and previously learned microbiology principles. Each spread is paired with a coaching activity and assessment questions in Mastering Microbiology.

BIG PICTURE

Bioterrorism

Biological agents were first tapped by armies, and now by terrorists. Today, technology and ease of travel increase the potential damage.

History of Bioweapons

Biological weapons (bioweapons)—pathogens intentionally used for hostile purposes—are not new. The "ideal" bioweapon is one that disseminates by aerosol, spreads efficiently from human to human, causes debilitating disease, and has no readily available treatment.

The earliest recorded use of a bioweapon occurred in 1346 during the Siege of Kaffa, in what is now known as Feodosia, Ukraine. There the Tartar army catapulted their own dead soldiers' plague-ridden bodies over city walls to infect opposing troops. Survivors from that attack went on to introduce the "Black Death" to the rest of Europe, sparking the plague pandemic of 1348–1350.

In the eighteenth century, blankets contaminated with smallpox were intentionally introduced into Native American populations by the British during the French and Indian War. And during the Sino-Japanese War (1937–1945), Japanese planes dropped canisters of fleas carrying *Yersinia pestis* bacteria, the causative agent of plague, on China. In 1975, *Bacillus anthracis* endospores were accidentally released from a bioweapon production facility in Sverdlovsk.

A citadel in Ukraine, location of the first known biowarfare attack in history.

Selected Diseases Identified as Potential Bioweapons	
Bacterial	**Viral**
Anthrax (*Bacillus anthracis*)	Nonbacterial meningitis (Arenaviruses)
Psittacosis (*Chlamydophila psittaci*)	*Hantavirus* disease
Botulism (*Clostridium botulinum* toxin)	Hemorrhagic fevers (Ebola, Marburg, Lassa)
Tularemia (*Francisella tularensis*)	Monkeypox
Cholera (*Vibrio cholerae*)	Nipah virus infection
Plague (*Yersinia pestis*)	Smallpox

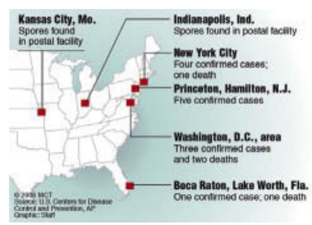
Biological Weapons Banned in the Twentieth Century

The Geneva Conventions are internationally agreed upon standards for conducting war. Written in the 1920s, they prohibited deploying bioweapons—but did not specify that possessing or creating them was illegal. As such, most powerful nations in the twentieth century continued to create bioweapons, and the growing stockpiles posed an ever-growing threat. In 1975, the Biological Weapons Convention banned both possession and development of biological weapons. The majority of the world's nations ratified the treaty, which stipulated that any existing bioweapons be destroyed and related research halted.

***(Clockwise from top left): Bacillus anthracis, Ebolavirus, and Vibrio cholerae* are just a few microbes identified as potential bioterrorism agents.**

Emergence of Bioterrorism

Unfortunately, the history of biowarfare doesn't end with the ratification of the Biological Weapons Convention. Since then, the main actors engaging in biowarfare have not been nations but rather radical groups and individuals. One of the most publicized bioterrorism incidents occurred in 2001, when five people died from, and many more were infected with, anthrax that an army researcher sent through the mail in letters.



Map showing location of 2001 bioterrorism anthrax attacks.

visual information?

Play MicroFlix 3D Animation
@MasteringMicrobiology

Public Health Authorities Try to Meet the Threat of Bioterrorism

One of the problems with bioweapons is that they contain living organisms, so their impact is difficult to control or even predict. However, public health authorities have created some protocols to deal with potential bioterrorism incidents.

Biological hazard symbol.

New Technologies and Techniques to Identify Bioweapons

Monitoring public health, and reporting incidence of diseases of note, is the first step in any bioterrorism defense plan. The faster a potential incident is uncovered, the greater the chance for containment. Rapid tests are being investigated to detect genetic changes in hosts due to bioweapons even before symptoms develop. Early-warning systems, such as DNA chips or recombinant cells that fluoresce in the presence of a bioweapon, are also being developed.

Pro Strips Rapid Screening System, developed by ADVNT Biotechnologies LLC, is the first advanced multi-agent biowarfare detection kit that tests for anthrax, ricin toxin, botulinum toxin, plague, and SEB (staphylococcal enterotoxin B).

Vaccination: A Key Defense

When the use of biological agents is considered a possibility, military personnel and first -responders (health care personnel and others) are vaccinated—if a vaccine for the suspected agent exists. New vaccines are being developed, and existing vaccines are being stockpiled for use where needed.

The current plan to protect civilians in the event of an attack with a microbe is illustrated by the smallpox preparedness plan. This killer disease has been eradicated from the population, but unfortunately, a cache of the virus remains preserved in research facilities, meaning that it might one day be weaponized. It's not practical to vaccinate all people against the disease. Instead, the U.S. government's strategy following a confirmed smallpox outbreak includes "ring containment and voluntary vaccination." A "ring" of vaccinated/protected individuals is built around the bioterrorism infection case and their contacts to prevent further transmission.

Examining mail for *B. anthracis*.

KEY CONCEPTS

- Vaccination is critical to preventing spread of infectious diseases, especially those that can be weaponized. **(See Chapter 18, "Principles and Effects of Vaccinations," pages 500–501.)**
- Many organisms that could be used for weapons require BSL-3 facilities. **(See Chapter 6, "Special Culture Techniques," pages 161–162.)**
- Tracking pathogen genomics provides information on its source. **(See Chapter 9, "Forensic Microbiology," pages 258–260.)**

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Three Big Picture spreads focus on **important fundamental topics in microbiology:**

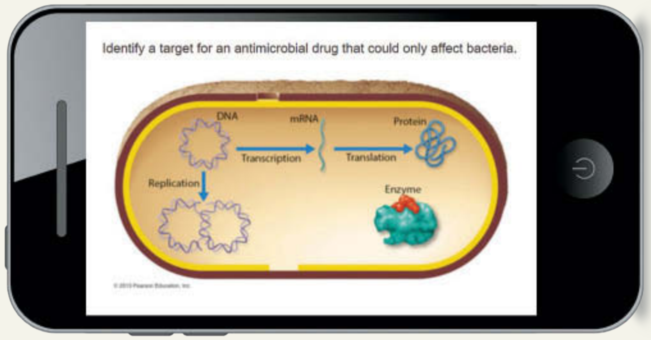
- Metabolism
- Genetics
- Immunity

Eight Big Picture spreads focus on **diseases and related public health issues that present complex real-world challenges:**

- Vaccine-Preventable Diseases
- The Hygiene Hypothesis
- Neglected Tropical Diseases
- Vertical Transmission: Mother to Child
- Climate Change and Disease
- Bioterrorism
- Cholera After Natural Disasters
- STI Home Test Kits

Additional Instructor and Student Resources

Learning Catalytics is a "bring your own device" (laptop, smartphone, or tablet) student engagement, assessment, and classroom intelligence system. With **Learning Catalytics**, instructors can assess students in real time using open-ended tasks to probe student understanding. Mastering Microbiology users may select from Pearson's library of questions designed especially for use with **Learning Catalytics**.



Instructor Resource Materials for *Microbiology: An Introduction*

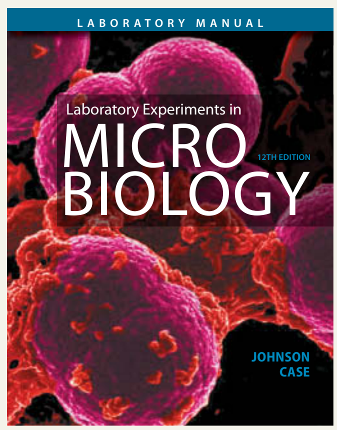
The Instructor Resource Materials organize all instructor media resources by chapter into one convenient and easy-to-use package containing:

- All figures, photos, and tables from the textbook in both labeled and unlabeled formats
- TestGen Test Bank
- MicroFlix animations
- Instructor's Guide

A wealth of additional classroom resources can be downloaded from the Instructor Resources area of Mastering Microbiology.

Laboratory Experiments in Microbiology, 12th Edition by Johnson/Case

0-134-60520-9 / 978-0-134-60520-3



Engaging, comprehensive and customizable, ***Laboratory Experiments in Microbiology*** is the perfect companion lab manual for ***Microbiology: An Introduction***, 13th Edition.

MICROBIOLOGY

AN INTRODUCTION

THIRTEENTH EDITION

Gerard J. Tortora
BERGEN COMMUNITY COLLEGE

Berdell R. Funke
NORTH DAKOTA STATE UNIVERSITY

Christine L. Case
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Above all, Jerry is devoted to his students and their aspirations. In recognition of this commitment, MACUB presented Jerry with the organization's 1992 President's Memorial Award. In 1995, he was selected as one of the finest faculty scholars of Bergen Community College and was named Distinguished Faculty Scholar. In 1996, he received a National Institute for Staff and Organizational Development (NISOD) excellence award from the University of Texas and was selected to represent Bergen Community College in a campaign to increase awareness of the contributions of community colleges to higher education.

Jerry is the author of several best-selling science textbooks and laboratory manuals, a calling that often requires an additional 40 hours per week beyond his full-time teaching responsibilities. Nevertheless, he still makes time for four or five weekly aerobic workouts. He also enjoys attending opera performances at the Metropolitan Opera House, Broadway plays, and concerts. He spends his quiet time at his beach home on the New Jersey Shore.

To all my children, the most important gift I have: Lynne, Gerard Jr., Kenneth, Anthony, and Drew, whose love and support have been such an important part of my personal life and professional career.

Berdell R. Funke Bert Funke received his Ph.D., M.S., and B.S. in microbiology from Kansas State University. He has spent his professional years as a professor of microbiology at North Dakota State University. He taught introductory microbiology, including laboratory sections, general microbiology, food microbiology, soil microbiology, clinical parasitology, and pathogenic microbiology. As a research scientist in the Experiment Station at North Dakota State, he has published numerous papers in soil microbiology and food microbiology.

Christine L. Case Chris Case is a professor of microbiology at Skyline College in San Bruno, California, where she has taught for the past 46 years. She received her Ed.D. in curriculum and instruction from Nova Southeastern University and her M.A. in microbiology from San Francisco State University. She was Director for the Society for Industrial Microbiology and is an active member of the ASM. She received the ASM and California Hayward outstanding educator awards. Chris received the SACNAS Distinguished Community College Mentor Award for her commitment to her students, several of whom have presented at undergraduate research conferences and won awards. In addition to teaching, Chris contributes regularly to the professional literature, develops innovative educational methodologies, and maintains a personal and professional commitment to conservation and the importance of science in society. Chris is also an avid photographer, and many of her photographs appear in this book.

I owe my deepest gratitude to Don Biederman and our three children, Daniel, Jonathan, and Andrea, for their unconditional love and unwavering support.

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Derek Weber Derek Weber is a professor of biology and microbiology at Raritan Valley Community College in Somerville, New Jersey. He received his B.S. in chemistry from Moravian College and his Ph.D. in biomolecular chemistry from the University of Wisconsin–Madison. His current scholarly work focuses on the use of instructional technology in a flipped classroom to create a more active and engaging learning environment. Derek has received multiple awards for these efforts, including the Award for Innovative Excellence in Teaching, Learning and Technology at the International Teaching and Learning Conference. As part of his commitment to foster learning communities, Derek shares his work at state and national conferences and is a regular attendee at the annual American Society for Microbiology Conference for Undergraduate Educators (ASMCUE). He has previously authored MicroBooster Video Tutorials, available in MasteringMicrobiology, which remediate students on basic concepts in biology and chemistry as they apply to microbiology. Derek acknowledges the support of his patient wife, Lara, and his children, Andrew, James, and Lilly.

Preface

Since the publication of the first edition nearly 30 years ago, well over 1 million students have used *Microbiology: An Introduction* at colleges and universities around the world, making it the leading microbiology textbook for non-majors. The thirteenth edition continues to be a comprehensive beginning text, assuming no previous study of biology or chemistry. The text is appropriate for students in a wide variety of programs, including the allied health sciences, biological sciences, environmental science, animal science, forestry, agriculture, nutrition science, and the liberal arts.

The thirteenth edition has retained the features that have made this book so popular:

- **An appropriate balance between microbiological fundamentals and applications, and between medical applications and other applied areas of microbiology.** Basic microbiological principles are given greater emphasis, and health-related applications are featured.
- **Straightforward presentation of complex topics**. Each section of the text is written with the student in mind.
- **Clear, accurate, and pedagogically effective illustrations and photos.** Step-by-step diagrams that closely coordinate with narrative descriptions aid student comprehension of concepts.
- **Flexible organization.** We have organized the book in what we think is a useful fashion while recognizing that the material might be effectively presented in other sequences. For instructors who wish to use a different order, we have made each chapter as independent as possible and have included numerous cross-references. The Instructor's Guide provides detailed guidelines for organizing the material in several other ways.
- **Clear presentation of data regarding disease incidence.** Graphs and other disease statistics include the most current data available.
- **Big Picture core topic features.** These two-page spreads focus on the most challenging topics for students to master: metabolism (Chapter 5), genetics (Chapter 8), and immunology (Chapter 16). Each spread breaks down these important concepts into manageable steps and gives students a clear learning framework for the related chapters. Each refers the student to a related MicroFlix video accessible through MasteringMicrobiology.
- **Big Picture disease features.** These two-page spreads appear within each chapter in Part Four, Microorganisms and Human Disease (Chapters 21–26), as well as Chapters 18 (Practical Applications of Immunology) and 19 (Disorders of the Immune System). Each spread focuses on one significant public health aspect of microbiology.
- **ASM guidelines.** The American Society for Microbiology has released six underlying concepts and 27 related topics to provide a framework for key microbiological topics deemed to be of lasting importance beyond the classroom. The thirteenth edition explains the themes and competencies at the beginning of the book and incorporates callouts when chapter content matches one of these 27 topics. Doing so addresses two key challenges: it helps students and instructors focus on the enduring principles of the course, and it provides another pedagogical tool for instructors to assess students' understanding and encourage critical thinking.
- **Cutting-edge media integration.** MasteringMicrobiology (www.masteringmicrobiology.com) provides unprecedented, cutting-edge assessment resources for instructors as well as self-study tools for students. Big Picture Coaching Activities are paired with the book's Core Topics and Clinical Features. Interactive Microbiology is a dynamic suite of interactive tutorials and animations that teach key concepts in microbiology; and MicroBoosters are brief video tutorials that cover key concepts that some students may need to review or relearn.

New to the Thirteenth Edition

The thirteenth edition focuses on big-picture concepts and themes in microbiology, encouraging students to visualize and synthesize more difficult topics such as microbial metabolism, immunology, and microbial genetics.

The thirteenth edition meets all students at their respective levels of skill and understanding while addressing the biggest challenges that instructors face. Updates to the thirteenth edition enhance the book's consistent pedagogy and clear explanations. Some of the highlights follow.

- **Exploring the Microbiome.** Each chapter has a new box featuring an aspect of microbiome study related to the chapter. Most feature the human microbiome. The boxes are designed to show the importance of microorganisms in health, their importance to life on Earth, and how research on the microbiome is being done.
- **In the Clinic videos accompanying each chapter opener.** In the Clinic scenarios that appear at the start of every chapter include critical-thinking questions that encourage students to think as health care professionals would in various clinical scenarios and spark student interest in the forthcoming chapter content. For the thirteenth edition, videos have been produced for the In the Clinic features for Chapters 1 through 20 and are accessible through MasteringMicrobiology.

- **New Big Picture disease features.** New Big Picture features include Vaccine-Preventable Diseases (Chapter 18), Vertical Transmission: Mother to Child (Chapter 22), and Bioterrorism (Chapter 24).
- **Reworked immunology coverage in Chapters 17, 18, and 19.** New art and more straightforward discussions make this challenging and critical material easier for students to understand and retain.

Chapter-by-Chapter Revisions

Data in text, tables, and figures have been updated. Other key changes to each chapter are summarized below.

Chapter 1

- The resurgence in microbiology is highlighted in sections on the Second and Third Golden Ages of Microbiology.
- The Emerging Infectious Diseases section has been updated.
- A discussion of normal microbiota and the human microbiome has been added.

Chapter 2

- A discussion of the relationship between starch and normal microbiota has been added.

Chapter 3

- Coverage of super-resolution light microscopy has been added.

Chapter 4

- The description of the Gram stain method of action has been revised.
- Archaella are now covered.

Chapter 5

- The potential for probiotic therapy using lactic acid bacteria is introduced.
- Reoxidation of NADH in fermentation is now shown in Figure 5.18.

Chapter 6

- Discussion has been added regarding the influence of carrying capacity on the stationary phase of microbial growth.
- Discussion of quorum sensing in biofilms is included.
- The plate-streaking figure is revised.

Chapter 7

- A new section on plant essential oils has been added.

Chapter 8

- The discussion of operons, induction, and repression has been revised.
- Riboswitches are defined.
- A new box about tracking Zika virus is included.

Chapter 9

- Discussion of gene editing using CRISPR technology has been added.

Chapter 10

- Rapid identification using mass spectrophotometry is included.

Chapter 11

- The genus *Prochlorococcus* is now included.
- The phylum Tenericutes has been added.

Chapter 12

- The classification of algae and protozoa is updated.

Chapter 13

- Baltimore classification is included.
- Virusoids are defined.

Chapter 14

- Discussions of herd immunity and the control of healthcare-associated infections are expanded.
- Clinical trials are defined.
- Congenital transmission of infection is included.
- Discussion of the emerging HAI pathogen *Elizabethkingia* is now included.
- Epidemiological data have been updated.

Chapter 15

- Genotoxin information is updated.

Chapter 16

- The discussion of the role of normal microbiota in innate immunity is expanded.
- A table of chemical mediators of inflammation is included.

Chapter 17

- A new table listing cytokines and their functions has been added.
- Cells involved in cell-mediated immunity are summarized in a table.

Chapter 18

- Vaccine-preventable diseases are discussed in a new Big Picture.
- Coverage of recombinant vector vaccines has been added.

Chapter 19

- The discussion of autoimmune diseases has been updated.
- The discussion of HIV/AIDS has been updated.
- The Big Picture box has been revised to expand discussion of dysbiosis-linked disorders.

Chapter 20

- Tables have been reorganized.
- Coverage regarding the mechanisms of action of antimicrobial drugs has been updated.
- In the Clinical Focus box, data on antibiotics in animal feed have been updated.

Chapter 21

- All data are updated.
- The Big Picture on Neglected Tropical Diseases has been revised to include river blindness.

Chapter 22

- All data are updated.
- Coverage of Zika virus disease has been added.
- Discussion of Bell's palsy has been added.
- A new Big Picture covering vertical transmission of congenital infections has been added.

Chapter 23

- All data are updated.
- The new species of *Borrelia* are included.
- Maps showing local transmission of vector-borne diseases have been updated.

Chapter 24

- All data, laboratory tests, and drug treatments have been updated.
- The emerging pathogen *Enterovirus* D68 is included.
- A new Big Picture covering bioterrorism has been added.

Chapter 25

- All data, laboratory tests, and drug treatments are updated.
- *Salmonella* nomenclature has been revised to reflect CDC usage.
- Images of protozoan oocysts and helminth eggs have been added to illustrate laboratory identification.

Chapter 26

- All data, laboratory tests, and drug treatments have been updated.
- STIs that do not affect the genitourinary system are cross-referenced to the organ system affected.
- Discussion of ocular syphilis is now included.

Chapter 27

- The concept of the Earth microbiome is introduced.
- Discussion of hydrothermal vent communities has been added.
- The discussions of bioremediation of oil and wastewater have been updated.

Chapter 28

- The discussion of industrial fermentation has been updated.
- The definition of *biotechnology* is included.
- A discussion of the iChip has been added.
- A table listing fermented foods has been added.
- Discussion of microbial fuels cells is now included.

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Gerard J. Tortora *Berdell R. Funke* *Christine Case*

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ASM Recommended Curriculum Guidelines for Undergraduate Microbiology

The American Society for Microbiology (ASM) endorses a concept-based curriculum for introductory microbiology, emphasizing skills and concepts that remain important long after students exit the course. The ASM *Curriculum Guidelines for Undergraduate Microbiology Education* provide a framework for key microbiological topics and agree with scientific literacy reports from the American Association for the Advancement of Science and Howard Hughes Medical Institute. This textbook references part one of curriculum guidelines throughout chapters. When a discussion touches on one of the concepts, readers will see the ASM icon, along with a summary of the relevant statement.

ASM:

ASM Guideline Concepts and Statements

Evolution

- 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.
- Human impact on the environment influences the evolution of microorganisms (e.g., emerging diseases and the selection of antibiotic resistance).
- The traditional concept of species is not readily applicable to microbes due to asexual reproduction and the frequent occurrence of horizontal gene transfer.
- The evolutionary relatedness of organisms is best reflected in phylogenetic trees.

Cell Structure and Function

- The structure and function of microorganisms have been revealed by the use of microscopy (including brightfield, phase contrast, fluorescent, 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.
- The replication cycles of viruses (lytic and lysogenic) differ among viruses and are determined by their unique structures and genomes.

Metabolic Pathways

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

Information Flow and Genetics

- 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.
- The regulation of gene expression is influenced by external and internal molecular cues and/or signals.
- The synthesis of viral genetic material and proteins is dependent on host cells.
- Cell genomes can be manipulated to alter cell function.

Microbial Systems

- Microorganisms are ubiquitous and live in diverse and dynamic ecosystems.
- Most 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

- 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.

The Microbial World and You 1

The overall theme of this textbook is the relationship between microbes—very small organisms that usually require a microscope to be seen—and our lives. We've all heard of epidemics of infectious diseases such as plague or smallpox that wiped out populations. However, there are many positive examples of human-microbe interactions. For example, we use microbial fermentation to ensure safe food supplies, and the human microbiome, a group of microbes that lives in and on our bodies, helps keep us healthy. We begin this chapter by discussing how organisms are named and classified and then follow with a short history of microbiology. Next, we discuss the incredible diversity of microorganisms and their ecological importance, noting how they recycle chemical elements such as carbon and nitrogen among the soil, organisms, and the atmosphere. We also examine how microbes are used to treat sewage, clean pollutants, control pests, and produce foods, chemicals, and drugs. Finally, we will discuss microbes as the cause of diseases such as Zika virus disease, avian (bird) flu, Ebola virus disease, and diarrhea, and we examine the growing public health problem of antibiotic-resistant bacteria.

ASM: Microorganisms provide essential models that give us fundamental knowledge about life processes.

Shown in the photograph are *Staphylococcus aureus* (STAF-i-lō-kok'kus OR-ē-us) bacteria on human nasal epithelial cells. These bacteria generally live harmlessly on skin or inside the nose. Misuse of antibiotics, however, allows the survival of bacteria with antibiotic-resistance genes, such as methicillin-resistant *S. aureus* (MRSA). As illustrated in the Clinical Case, an infection caused by these bacteria is resistant to antibiotic treatment.

◄ ***Staphylococcus aureus*** **bacteria on skin cell culture.**

In the Clinic

As the nurse practitioner in a rural hospital, you are reviewing a microscope slide of a skin scraping from a 12-year-old girl. The slide shows branched, intertwined nucleated hyphae. The girl has dry, scaly, itchy patches on her arms. **What is causing her skin problem?**

Hint: Read about types of microorganisms (pages 4–6).

Play In the Clinic Video @ MasteringMicrobiology

Microbes in Our Lives

LEARNING OBJECTIVES

1-1 List several ways in which microbes affect our lives.

1-2 Define *microbiome*, *normal microbiota*, and *transient microbiota*.

For many people, the words *germ* and *microbe* bring to mind a group of tiny creatures that do not quite fit into any of the categories in that old question, "Is it animal, vegetable, or mineral?" *Germ* actually comes from the Latin word *germen*, meaning to spout from, or germinate. Think of wheat germ, the plant embryo from which the plant grows. It was first used in relation to microbes in the nineteenth century to explain the rapidly growing cells that caused disease. **Microbes**, also called **microorganisms**, are minute living things that individually are usually too small to be seen with the unaided eye. The group includes bacteria, fungi (yeasts and molds), protozoa, and microscopic algae. It also includes viruses, those noncellular entities sometimes regarded as straddling the border between life and nonlife (Chapters 11, 12, and 13, respectively).

We tend to associate these small organisms only with infections and inconveniences such as spoiled food. However, the majority of microorganisms actually help maintain the balance of life in our environment. Marine and freshwater microorganisms form the basis of the food chain in oceans, lakes, and rivers. Soil microbes break down wastes and incorporate nitrogen gas from the air into organic compounds, thereby recycling chemical elements among soil, water, living organisms, and air. Certain microbes play important roles in *photosynthesis*, a food- and oxygen-generating process that is critical to life on Earth.

Microorganisms also have many commercial applications. They are used in the synthesis of such chemical products as vitamins, organic acids, enzymes, alcohols, and many drugs. For example, microbes are used to produce acetone and butanol, and the vitamins B_2 (riboflavin) and B_{12} (cobalamin) are made biochemically. The process by which microbes produce acetone and butanol was discovered in 1914 by Chaim Weizmann, a Russian-born chemist working in England. With the outbreak of World War I in August of that year, the production of acetone became very important for making cordite (a smokeless form of gunpowder used in munitions). Weizmann's discovery played a significant role in determining the outcome of the war.

The food industry also uses microbes in producing, for example, vinegar, sauerkraut, pickles, soy sauce, cheese, yogurt, bread, and alcoholic beverages. In addition, enzymes from microbes can now be manipulated to cause the microbes to produce substances they normally don't synthesize, including cellulose, human insulin, and proteins for vaccines.

The Microbiome

An adult human is composed of about 30 trillion body cells and harbors another 40 trillion bacterial cells. Microbes that live stably in and on the human body are called the human **microbiome**, or **microbiota**. Humans and many other animals depend on these microbes to maintain good health. Bacteria in our intestines, including *E. coli*, aid digestion (see Exploring the Microbiome on page 3) and even synthesize some vitamins that our bodies require, including B vitamins for metabolism and vitamin K for blood clotting. They also prevent growth of **pathogenic** (disease-causing) species that might otherwise take up residence, and they seem to have a role in training our immune system to know which foreign invaders to attack and which to leave alone. (See Chapter 14 for more details on relationships between normal microbiota and the host.)

Even before birth, our bodies begin to be populated with bacteria. As newborns, we acquire viruses, fungi, and bacteria (**Figure 1.1**). For example, *E. coli* and other bacteria acquired from foods take residence in the large intestine. Many factors influence where and whether a microbe can indefinitely colonize the body as benign **normal microbiota** or be only a fleeting member of its community (known as **transient microbiota**). Microbes can colonize only those body sites that can supply the appropriate nutrients. Temperature, pH, and the presence or absence of chemical compounds are some factors that influence what types of microbes can flourish.

To determine the makeup of typical microbiota of various areas of the body, and to understand the relationship between changes in the microbiome and human diseases, is the goal of the **Human Microbiome Project**, which began in 2007. Likewise, the **National Microbiome Initiative (NMI)** launched in 2016 to expand our understanding of the role microbes play in different ecosystems, including soil, plants, aquatic environments, and the human body. Throughout the book, look for

Figure 1.1 Several types of bacteria found as part of the normal microbiota in an infant's intestine.

Q How do we benefit from the production of vitamin K by microbes?

EXPLORING THE MICROBIOME How Does Your Microbiome Grow?

The specific traits of microbes that reside in human intestines can vary greatly—even within the same microbial species. Take *Bacteroides*, a bacterium commonly found in gastrointestinal tracts of humans worldwide. The strain residing in Japanese people has specialized enzymes that break down nori, the red algae used as the wrap component of sushi. These enzymes are absent from *Bacteroides* found in the gastrointestinal tracts of North Americans.

How did the Japanese *Bacteroides* acquire the ability to digest algae? It's thought the skill hails from *Zobellia galactanivorans*, a marine bacterium that lives on this alga. Not surprisingly, *Zobellia* readily breaks down the alga's main carbohydrate with enzymes. Since people living in Japan consumed algae regularly, *Zobellia* routinely met up with *Bacteroides* that lived in the human intestine. Bacteria can swap genes with other species—a process called *horizontal gene transfer*—and at some point, *Zobellia* must have given *Bacteroides* the genes to produce algae-digesting enzymes. (For more on horizontal gene transfer, see Chapter 8).

In an island nation where algae are an important diet component, the ability to extract more nutrition from algal carbohydrates would give an intestinal microbe a competitive advantage over others that couldn't use it as a food source. Over time, this *Bacteroides* strain became the dominant one found within the gastrointestinal tracts of people living in Japan.

You may be wondering whether North American sushi eaters can expect their own *Bacteroides* to shift to the algae-eating variety, too. Researchers say this is unlikely. Traditional Japanese food included raw algae, which allowed for living *Zobellia* to reach the large intestine. By contrast, the algae used in foods today is usually roasted or dried; these processes kill any bacteria that may be present on the surface.

***Porphyra*, an alga commonly used in sushi.**

stories related to the human microbiome, highlighted in the Exploring the Microbiome feature boxes.

Our realization that some microbes are not only harmless to humans, but also are actually essential, represents a large shift from the traditional view that the only good microbe was a dead one. In fact, only a minority of microorganisms are pathogenic to humans. Although anyone planning to enter a health care profession needs to know how to prevent the transmission and spread of pathogenic microbes, it's also important to know that pathogens are just one aspect of our full relationship with microbes.

Today we understand that microorganisms are found almost everywhere. Yet not long ago, before the invention of the microscope, microbes were unknown to scientists. Next we'll look at the major groups of microbes and how they are named and classified. After that, we'll examine a few historic milestones in microbiology that have changed our lives.

CHECK YOUR UNDERSTANDING

- **1-1*** Describe some of the destructive and beneficial actions of microbes.
- **1-2** What percentage of all the cells in the human body are bacterial cells?

* The numbers preceding Check Your Understanding questions refer to the corresponding Learning Objectives.

CLINICAL CASE A Simple Spider Bite?

Andrea is a normally healthy 22-year-old college student who lives at home with her mother and younger sister, a high school gymnast. She is trying to work on a paper for her psychology class but is having a hard time because a red, swollen sore on her right wrist is making typing difficult. "Why won't this spider bite heal?" she wonders. "It's been there for days!" She makes an appointment with her doctor so she can show him the painful lesion. Although Andrea does not have a fever, she does have an elevated white blood cell count that indicates a bacterial infection. Andrea's doctor suspects that this isn't a spider bite at all, but a staph infection. He prescribes a β-lactam antibiotic, cephalosporin. Learn more about the development of Andrea's illness on the following pages.

What is staph? Read on to find out.

3 16 18 19

Naming and Classifying Microorganisms

LEARNING OBJECTIVES

1-3 Recognize the system of scientific nomenclature that uses two names: a genus and a specific epithet.

1-4 Differentiate the major characteristics of each group of microorganisms.

1-5 List the three domains.

Nomenclature

The system of nomenclature (naming) for organisms in use today was established in 1735 by Carolus Linnaeus. Scientific names are latinized because Latin was the language traditionally used by scholars. Scientific nomenclature assigns each organism two names—the **genus** (plural: **genera**) is the first name and is always capitalized; the **specific epithet** (**species** name) follows and is not capitalized. The organism is referred to by both the genus and the specific epithet, and both names are underlined or italicized. By custom, after a scientific name has been mentioned once, it can be abbreviated with the initial of the genus followed by the specific epithet.

Scientific names can, among other things, describe an organism, honor a researcher, or identify the habitat of a species. For example, consider *Staphylococcus aureus*, a bacterium commonly found on human skin. *Staphylo-* describes the clustered arrangement of the cells; *-coccus* indicates that they are shaped like spheres. The specific epithet, *aureus*, is Latin for golden, the color of many colonies of this bacterium. The genus of the bacterium *Escherichia coli* (esh'er-IK-ē-ah KŌ-lī, or KŌ-lē) is named for a physician, Theodor Escherich, whereas its specific epithet, *coli*, reminds us that *E. coli* live in the colon, or large intestine. Table 1.1 contains more examples.

CHECK YOUR UNDERSTANDING

✓ **1-3** Distinguish a genus from a specific epithet.

Types of Microorganisms

In health care, it is very important to know the different types of microorganisms in order to treat infections. For example, antibiotics can be used to treat bacterial infections but have no effect on viruses or other microbes. Here is an overview of the main types of microorganisms. (The classification and identification of microorganisms are discussed in Chapter 10.)

Bacteria

Bacteria (singular: **bacterium**) are relatively simple, single-celled (unicellular) organisms. Because their genetic material is not enclosed in a special nuclear membrane, bacterial cells are called **prokaryotes** (prō-KAR-e-ōts), from Greek words meaning prenucleus. Prokaryotes include both bacteria and archaea.

Bacterial cells generally appear in one of several shapes. *Bacillus* (bah-SIL-lus) (rodlike), illustrated in Figure 1.2a, *coccus* (KOK-kus) (spherical or ovoid), and *spiral* (corkscrew or curved) are among the most common shapes, but some bacteria are star-shaped or square (see Figures 4.1 through 4.5, pages 74–75). Individual bacteria may form pairs, chains, clusters, or other groupings; such formations are usually characteristic of a particular genus or species of bacteria.

Bacteria are enclosed in cell walls that are largely composed of a carbohydrate and protein complex called *peptidoglycan*.

TABLE 1.1 Making Scientific Names Familiar

Use the word roots guide to find out what the name means. The name will not seem so strange if you translate it. When you encounter a new name, practice saying it out loud (guidelines for pronunciation are given in Appendix D). The exact pronunciation is not as important as the familiarity you will gain.

Following are some examples of microbial names you may encounter in the popular press as well as in the lab.

	Pronunciation	Source of Genus Name	Source of Specific Epithet
Salmonella enterica (bacterium)	sal'mō-NEL-lah en-TER-i-kah	Honors public health microbiologist Daniel Salmon	Found in the intestines (*entero-*)
Streptococcus pyogenes (bacterium)	strep'tō-KOK-kus pī-AH-jen-ēz	Appearance of cells in chains (*strepto-*)	Forms pus (*pyo-*)
Saccharomyces cerevisiae (yeast)	sak'kar-ō-MĪ-sēz se-ri-VIS-ē-ī	Fungus (*-myces*) that uses sugar (*saccharo-*)	Makes beer (*cerevisia*)
Penicillium chrysogenum (fungus)	pen'i-SIL-lē-um krī-SO-jen-um	Tuftlike or paintbrush (*penicill-*) appearance microscopically	Produces a yellow (*chryso-*) pigment
Trypanosoma cruzi (protozoan)	tri'pa-nō-SŌ-mah KROOZ-ē	Corkscrew- (*trypano-*, borer; *soma-*, body)	Honors epidemiologist Oswaldo Cruz

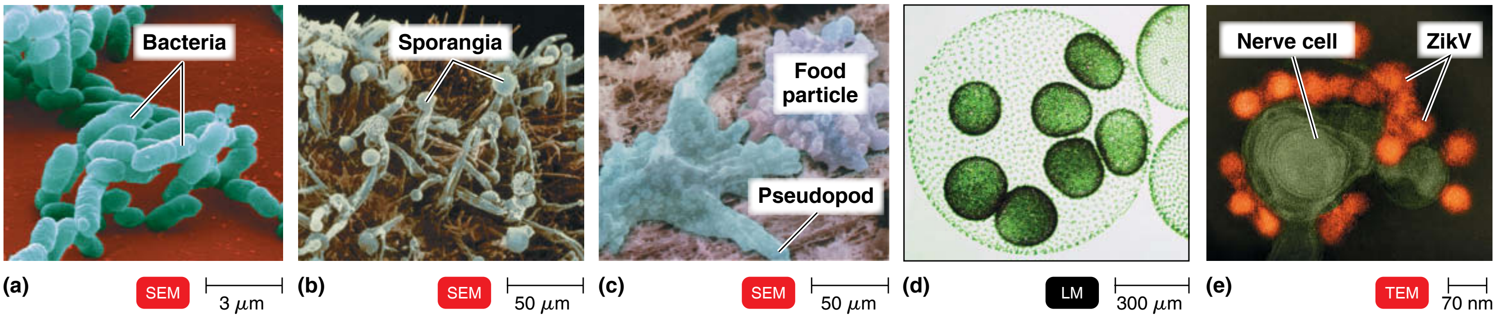


Figure 1.2 Types of microorganisms. **(a)** The rod-shaped bacterium *Haemophilus influenzae*, one of the bacterial causes of pneumonia. **(b)** *Mucor*, a common bread mold, is a type of fungus. When released from sporangia, spores that land on a favorable surface germinate into a network of hyphae (filaments) that absorb nutrients. **(c)** An ameba, a type of protozoan, approaching a food particle. **(d)** The pond alga *Volvox*. **(e)** Zika virus (ZikV). *NOTE:* Throughout the book, a red icon under a micrograph indicates that the micrograph has been artificially colored. SEM (scanning electron microscope) and LM (light microscope) are discussed in detail in Chapter 3.

Q How are bacteria, archaea, fungi, protozoa, algae, and viruses distinguished on the basis of structure?

(By contrast, cellulose is the main substance of plant and algal cell walls.) Bacteria generally reproduce by dividing into two equal cells; this process is called *binary fission*. For nutrition, most bacteria use organic chemicals, which in nature can be derived from either dead or living organisms. Some bacteria can manufacture their own food by photosynthesis, and some can derive nutrition from inorganic substances. Many bacteria can "swim" by using moving appendages called *flagella*. (For a complete discussion of bacteria, see Chapter 11.)

Archaea

Like bacteria, **archaea** (ar-KĒ-ah) consist of prokaryotic cells, but if they have cell walls, the walls lack peptidoglycan. Archaea, often found in extreme environments, are divided into three main groups. The *methanogens* produce methane as a waste product from respiration. The *extreme halophiles* (*halo* = salt; *philic* = loving) live in extremely salty environments such as the Great Salt Lake and the Dead Sea. The *extreme thermophiles* (*therm* = heat) live in hot sulfurous water, such as hot springs at Yellowstone National Park. Archaea are not known to cause disease in humans.

Fungi

Fungi (singular: **fungus**) are **eukaryotes** (ū-KAR-ē-ōts), organisms whose cells have a distinct nucleus containing the cell's genetic material (DNA), surrounded by a special envelope called the *nuclear membrane*. Organisms in the Kingdom Fungi may be unicellular or multicellular (see Chapter 12, page 324). Large multicellular fungi, such as mushrooms, may look somewhat like plants, but unlike most plants, fungi cannot carry out photosynthesis. True fungi have cell walls composed primarily of a substance called *chitin*. The unicellular forms of fungi, *yeasts*, are oval microorganisms that are larger than bacteria. The most typical fungi are *molds* (Figure 1.2b). Molds form visible masses called *mycelia*, which are composed of long filaments (*hyphae*) that branch and intertwine. The cottony growths sometimes found on bread and fruit are mold mycelia. Fungi can reproduce sexually or asexually. They obtain nourishment by absorbing organic material from their environment—whether soil, seawater, freshwater, or an animal or plant host. Organisms called *slime molds* are actually ameba-like protozoa (see Chapter 12).

Protozoa

Protozoa (singular: **protozoan**) are unicellular eukaryotic microbes (see Chapter 12, page 341). Protozoa move by pseudopods, flagella, or cilia. Amebae (Figure 1.2c) move by using extensions of their cytoplasm called *pseudopods* (false feet). Other protozoa have long *flagella* or numerous shorter appendages for locomotion called *cilia*. Protozoa have a variety of shapes and live either as free entities or as *parasites* (organisms that derive nutrients from living hosts) that absorb or ingest organic compounds from their environment. Some protozoa, such as *Euglena* (ū-GLĒ-nah), are photosynthetic. They use light as a source of energy and carbon dioxide as their chief source of carbon to produce sugars. Protozoa can reproduce sexually or asexually.

Algae

Algae (singular: **alga**) are photosynthetic eukaryotes with a wide variety of shapes and both sexual and asexual reproductive forms (Figure 1.2d). The algae of interest to microbiologists are usually unicellular (see Chapter 12, page 337). The cell walls of many algae are composed of a carbohydrate called *cellulose*. Algae are abundant in freshwater and saltwater, in soil, and in association with plants. As photosynthesizers, algae need light, water, and carbon dioxide for food production and growth, but they do not generally require organic compounds from the environment. As a result of photosynthesis, algae produce oxygen and carbohydrates that are then utilized by other organisms, including animals. Thus, they play an important role in the balance of nature.

Viruses

Viruses (Figure 1.2e) are very different from the other microbial groups mentioned here. They are so small that most can be seen only with an electron microscope, and they are acellular (that is, they are not cells). Structurally very simple, a virus particle contains a core made of only one type of nucleic acid, either DNA or RNA. This core is surrounded by a protein coat, which is sometimes encased by a lipid membrane called an *envelope*. All living cells have RNA *and* DNA, can carry out chemical reactions, and can reproduce as self-sufficient units. Viruses can reproduce only by using the cellular machinery of other organisms. Thus, on the one hand, viruses are considered to be living only when they multiply within host cells they infect. In this sense, viruses are parasites of other forms of life. On the other hand, viruses are not considered to be living because they are inert outside living hosts. (Viruses will be discussed in detail in Chapter 13.)

Multicellular Animal Parasites

Although multicellular animal parasites are not strictly microorganisms, they are of medical importance and therefore will be discussed in this text. Animal parasites are eukaryotes. The two major groups of parasitic worms are the flatworms and the roundworms, collectively called **helminths** (see Chapter 12, page 347). During some stages of their life cycle, helminths are microscopic in size. Laboratory identification of these organisms includes many of the same techniques used for identifying microbes.

CHECK YOUR UNDERSTANDING

✓ **1-4** Which groups of microbes are prokaryotes? Which are eukaryotes?

Classification of Microorganisms

Before the existence of microbes was known, all organisms were grouped into either the animal kingdom or the plant kingdom. When microscopic organisms with characteristics of animals and plants were discovered late in the seventeenth century, a new system of classification was needed. Still, biologists couldn't agree on the criteria for classifying these new organisms until the late 1970s.

In 1978, Carl Woese devised a system of classification based on the cellular organization of organisms. It groups all organisms in three domains as follows:

1. Bacteria (cell walls contain a protein–carbohydrate complex called peptidoglycan)
2. Archaea (cell walls, if present, lack peptidoglycan)
3. Eukarya, which includes the following:
   - Protists (slime molds, protozoa, and algae)
   - Fungi (unicellular yeasts, multicellular molds, and mushrooms)
   - Plants (mosses, ferns, conifers, and flowering plants)
   - Animals (sponges, worms, insects, and vertebrates)

Classification will be discussed in more detail in Chapters 10 through 12.

CHECK YOUR UNDERSTANDING

✓ **1-5** What are the three domains?

A Brief History of Microbiology

LEARNING OBJECTIVES

1-6 Explain the importance of observations made by Hooke and van Leeuwenhoek.

1-7 Compare spontaneous generation and biogenesis.

1-8 Identify the contributions to microbiology made by Needham, Spallanzani, Virchow, and Pasteur.

1-9 Explain how Pasteur's work influenced Lister and Koch.

1-10 Identify the importance of Koch's postulates.

1-11 Identify the importance of Jenner's work.

1-12 Identify the contributions to microbiology made by Ehrlich and Fleming.

1-13 Define *bacteriology*, *mycology*, *parasitology*, *immunology*, and *virology*.

1-14 Explain the importance of microbial genetics, molecular biology, and genomics.

Bacterial ancestors were the first living cells to appear on Earth. For most of human history, people knew little about the true causes, transmission, and effective treatment of disease. Let's look now at some key developments in microbiology that have spurred the field to its current technological state.

The First Observations

In 1665, after observing a thin slice of cork through a crude microscope, Englishman Robert Hooke reported that life's smallest structural units were "little boxes," or "cells." Using his improved microscope, Hooke later saw individual cells. Hooke's discovery marked the beginning of the **cell theory**—the theory that *all living things are composed of cells.*

Though Hooke's microscope was capable of showing large cells, it lacked the resolution that would have allowed him to see microbes clearly. Dutch merchant and amateur scientist Anton van Leeuwenhoek was probably the first to observe live microorganisms through the magnifying lenses of the more than

400 microscopes he constructed. Between 1673 and 1723, he wrote about the "animalcules" he saw through his simple, single-lens microscopes. Van Leeuwenhoek made detailed drawings of organisms he found in rainwater, feces, and material scraped from teeth. These drawings have since been identified as representations of bacteria and protozoa (Figure 1.3).

CHECK YOUR UNDERSTANDING

✓ **1-6** What is the cell theory?

The Debate over Spontaneous Generation

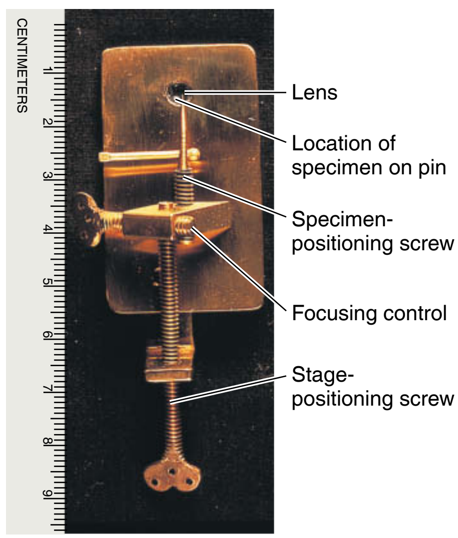
After van Leeuwenhoek discovered the previously "invisible" world of microorganisms, the scientific community became interested in the origins of these tiny living things. Until the second half of the nineteenth century, many scientists and philosophers believed that some forms of life could arise spontaneously from nonliving matter; they called this hypothetical process **spontaneous generation**. Not much more than 100 years ago, people commonly believed that toads, snakes, and mice could be born of moist soil; that flies could emerge from manure; and that maggots (which we now know are the larvae of flies) could arise from decaying corpses.

Physician Francesco Redi set out in 1668 to demonstrate that maggots did not arise spontaneously. Redi filled two jars with decaying meat. The first was left unsealed, allowing flies to lay eggs on the meat, which developed into larvae. The second jar was sealed, and because the flies could not get inside, no maggots appeared. Still, Redi's antagonists were not convinced; they claimed that fresh air was needed for spontaneous generation. So Redi set up a second experiment, in which he covered a jar with a fine net instead of sealing it. No larvae appeared in the gauze-covered jar, even though air was present.

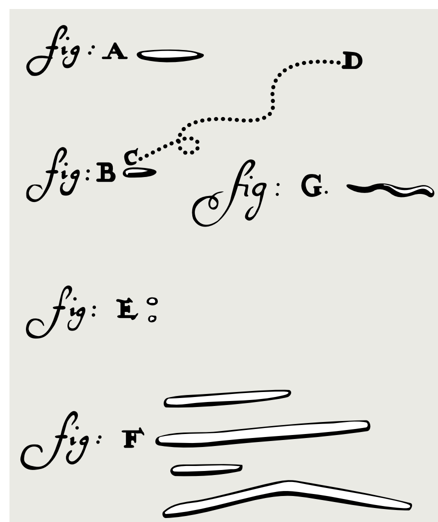
Redi's results were a serious blow to the long-held belief that large forms of life could arise from nonlife. However, many scientists still believed that small organisms, such as van Leeuwenhoek's "animalcules," were simple enough to generate from nonliving materials.

The case for spontaneous generation of microorganisms seemed to be strengthened in 1745, when John Needham found that even after he heated chicken broth and corn broth before pouring them into covered flasks, the cooled solutions were soon teeming with microorganisms. Needham claimed that microbes developed spontaneously from the fluids. Twenty years later, Lazzaro Spallanzani suggested that microorganisms from the air probably entered Needham's solutions after they were boiled. Spallanzani showed that nutrient fluids heated *after* being sealed in a flask did not develop microbial growth. Needham responded by claiming the "vital force" necessary for spontaneous generation had been destroyed by the heat and was kept out of the flasks by the seals.

(a) Van Leeuwenhoek using his microscope



(b) Microscope replica



(c) Drawings of bacteria

Figure 1.3 Anton van Leeuwenhoek's microscopic observations. **(a)** By holding his brass microscope toward a source of light, van Leeuwenhoek was able to observe living organisms too small to be seen with the unaided eye. **(b)** The specimen was placed on the tip of the adjustable point and viewed from the other side through the tiny, nearly spherical lens. The highest magnification possible with his microscopes was about 300× (times). **(c)** Some of van Leeuwenhoek's drawings of bacteria, made in 1683. The letters represent various shapes of bacteria. C–D represents a path of motion he observed.

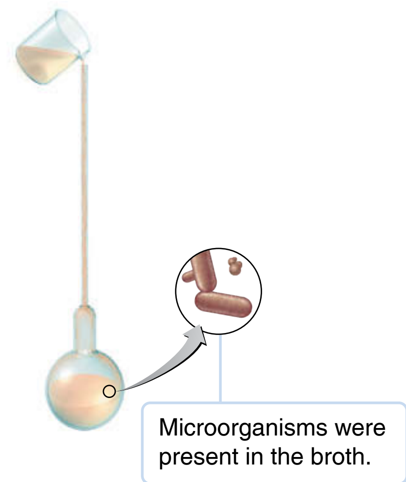
Q **Why was van Leeuwenhoek's discovery so important?**

FOUNDATION FIGURE **1.4**

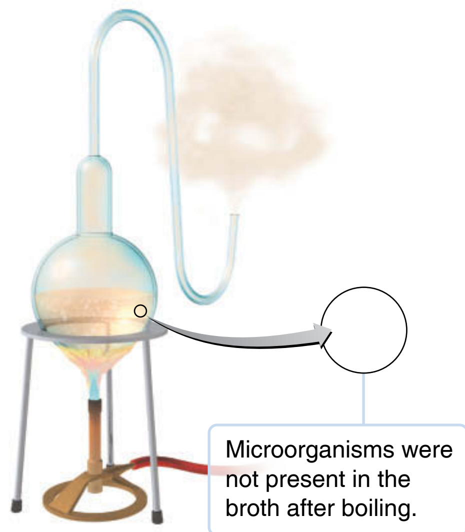
Disproving Spontaneous Generation

According to the hypothesis of spontaneous generation, life can arise spontaneously from nonliving matter, such as dead corpses and soil. Pasteur's experiment, described below, demonstrated that microbes are present in nonliving matter—air, liquids, and solids.

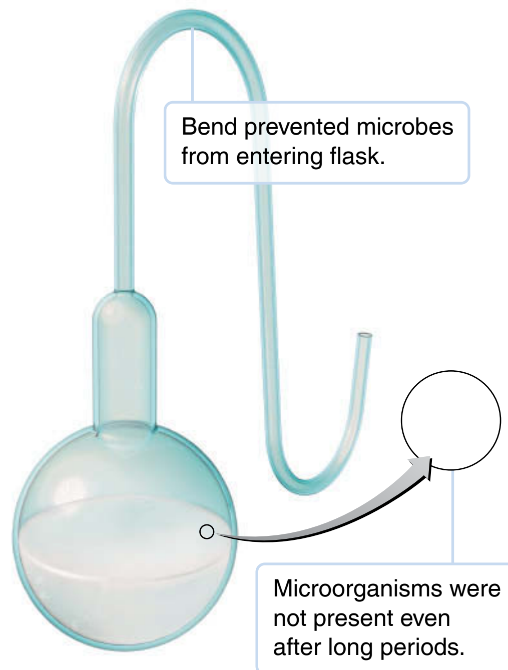
1. Pasteur first poured beef broth into a long-necked flask.



2. Next he heated the neck of the flask and bent it into an S-shape; then he boiled the broth for several minutes.



3. Microorganisms did not appear in the cooled solution, even after long periods.



Some of these original vessels are still on display at the Pasteur Institute in Paris. They have been sealed but show no sign of contamination more than 100 years later.

KEY CONCEPTS

- Pasteur demonstrated that microbes are responsible for food spoilage, leading researchers to the connection between microbes and disease.
- His experiments and observations provided the basis of aseptic techniques, which are used to prevent microbial contamination, as shown in the photo at right.

Spallanzani's observations were also criticized on the grounds that there was not enough oxygen in the sealed flasks to support microbial life.

The Theory of Biogenesis

In 1858 Rudolf Virchow challenged the case for spontaneous generation with the concept of **biogenesis**, hypothesizing that living cells arise only from preexisting living cells. Because he could offer no scientific proof, arguments about spontaneous generation continued until 1861, when the issue was finally resolved by the French scientist Louis Pasteur.

Pasteur demonstrated that microorganisms are present in the air and can contaminate sterile solutions, but that air itself does not create microbes. He filled several short-necked flasks with beef broth and then boiled their contents. Some were then left open and allowed to cool. In a few days, these flasks were found to be contaminated with microbes. The other flasks, sealed after boiling, were free of microorganisms. From these results, Pasteur reasoned that microbes in the air were the agents responsible for contaminating nonliving matter.

Pasteur next placed broth in open-ended, long-necked flasks and bent the necks into S-shaped curves (Figure 1.4). The contents of these flasks were then boiled and cooled. The broth in the flasks did not decay and showed no signs of life, even after months. Pasteur's unique design allowed air to pass into the flask, but the curved neck trapped any airborne microorganisms that might contaminate the broth. (Some of these original vessels are still on display at the Pasteur Institute in

Paris. They have been sealed but, like the flask in Figure 1.4, show no sign of contamination more than 100 years later.)

Pasteur showed that microorganisms can be present in nonliving matter—on solids, in liquids, and in the air. Furthermore, he demonstrated conclusively that microbial life can be destroyed by heat and that methods can be devised to block the access of airborne microorganisms to nutrient environments. These discoveries form the basis of **aseptic techniques**, procedures that prevent contamination by unwanted microorganisms, which are now the standard practice in laboratory and many medical procedures. Modern aseptic techniques are among the first and most important concepts that a beginning microbiologist learns.

Pasteur's work provided evidence that microorganisms cannot originate from mystical forces present in nonliving materials. Rather, any appearance of "spontaneous" life in nonliving solutions can be attributed to microorganisms that were already present in the air or in the fluids themselves. Scientists now believe that a form of spontaneous generation probably did occur on the primitive Earth when life first began, but they agree that this does not happen under today's environmental conditions.

CHECK YOUR UNDERSTANDING

- 1-7 What evidence supported spontaneous generation?
- 1-8 How was spontaneous generation disproved?

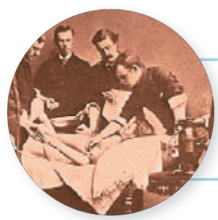
The First Golden Age of Microbiology

The period from 1857 to 1914 has been appropriately named the First Golden Age of Microbiology. Rapid advances, spearheaded mainly by Pasteur and Robert Koch, led to the establishment of microbiology. Discoveries included both the agents of many diseases and the role of immunity in preventing and curing disease. During this productive period, microbiologists studied the chemical activities of microorganisms, improved the techniques for performing microscopy and culturing microorganisms, and developed vaccines and surgical techniques. Some of the major events that occurred during the First Golden Age of Microbiology are listed in Figure 1.5.

First Golden Age of MICROBIOLOGY

1857	**Pasteur**—Fermentation
1861	**Pasteur**—Disproved spontaneous generation
1864	**Pasteur**—Pasteurization
1867	**Lister**—Aseptic surgery
1876	**Koch***—Germ theory of disease
1879	**Neisser**—*Neisseria gonorrhoeae*
1881	**Koch***—Pure cultures
	Finlay—Yellow fever
1882	**Koch***—*Mycobacterium tuberculosis*
	Hess—Agar (solid) media
1883	**Koch***—*Vibrio cholerae*
1884	**Metchnikoff***—Phagocytosis
	Gram—Gram-staining procedure
	Escherich—*Escherichia coli*
1887	**Petri**—Petri dish
1889	**Kitasato**—*Clostridium tetani*
1890	**von Bering***—Diphtheria antitoxin
	Ehrlich*—Theory of immunity
1892	**Winogradsky**—Sulfur cycle
1898	**Shiga**—*Shigella dysenteriae*
1908	**Ehrlich***—Syphilis treatment
1910	**Chagas**—*Trypanosoma cruzi*
1911	**Rous***—Tumor-causing virus (1966 Nobel Prize)

Louis Pasteur (1822–1895)
Demonstrated that life did not arise spontaneously from nonliving matter.



Joseph Lister (1827–1912)
Performed surgery under aseptic conditions using phenol. Proved that microbes caused surgical wound infections.

Robert Koch (1843–1910)
Established experimental steps for directly linking a specific microbe to a specific disease.

Figure 1.5 Milestones in the First Golden Age of Microbiology. An asterisk (*) indicates a Nobel laureate.

Q Why do you think the First Golden Age of Microbiology occurred when it did?