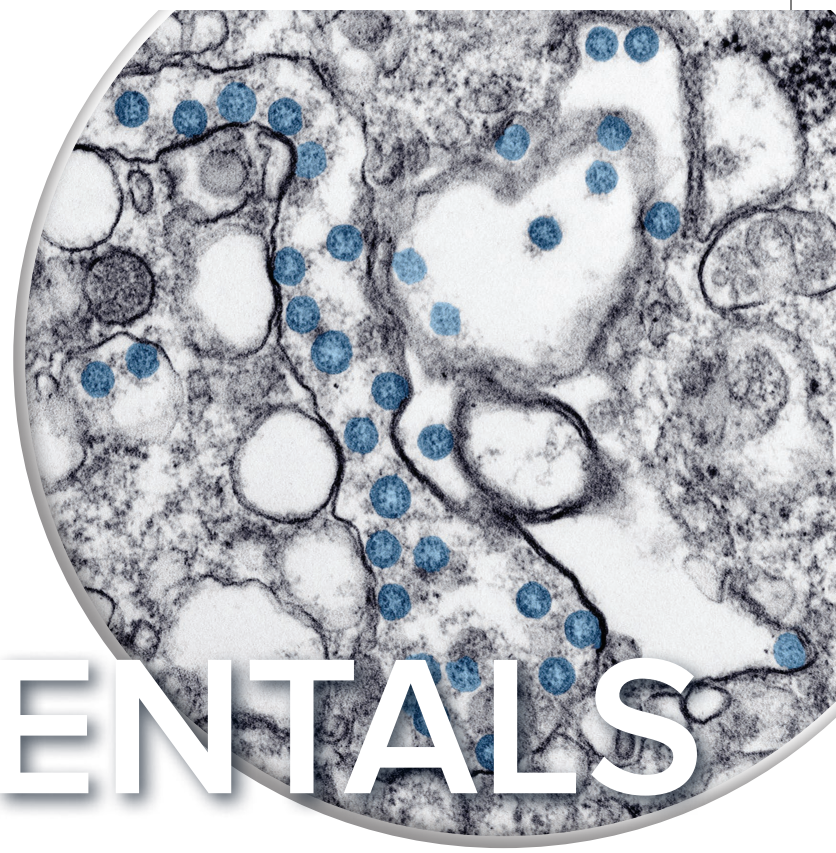
Fourth Edition

Microbiology FUNDAMENTALS

A Clinical Approach



CDC/ Hannah A Bullock; Azaibi Tamin

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Brief Contents

Contributions by Ronald M. Atlas, University of Louisville

About the Authors

©Kelly Cowan

Marjorie Kelly Cowan, PhD, started teaching microbiology at Miami University in 1993. Her specialty is teaching microbiology for pre-nursing/allied health students at the university's Middletown campus, a regional open-admissions campus. She started life as a dental hygienist. She then went on to attain her PhD at the University of Louisville, and later worked at the University of Maryland's Center of Marine Biotechnology and the University of Groningen in The Netherlands. Kelly has published (with her students) 24 research articles stemming from her work on bacterial adhesion mechanisms and plant-derived antimicrobial compounds. But her first love is teaching—both doing it and studying how to do it better. She is past chair of the Undergraduate Education Committee of the American Society for Microbiology (ASM). Her current research focuses on the student achievement gap associated with economic disparities, as well as literacy in the science classroom. In her spare time, Kelly hikes, reads, and still tries to (s)mother her three grown kids.

©Heidi Smith

Heidi Smith, MS, leads the microbiology department at Front Range Community College in Fort Collins, Colorado. Collaboration with other faculty across the nation, the development and implementation of new digital learning tools, and her focus on student learning outcomes have revolutionized Heidi's face-to-face and online teaching approaches and student performance in her classes. The use of digital technology has given Heidi the ability to teach courses driven by real-time student data and with a focus on active learning and critical thinking activities.

Heidi is an active member of the American Society for Microbiology and participated as a task force member for the development of their Curriculum Guidelines for Undergraduate Microbiology Education. At FRCC, Heidi directs a federal grant program designed to increase student success in transfer and completion of STEM degrees at the local university as well as facilitate undergraduate research opportunities for underrepresented students.

Off campus, Heidi spends as much time as she can enjoying the beautiful Colorado outdoors with her husband and four children.

©Tia Brayman

Jennifer Lusk, BSN, RN, CCRN, is a registered nurse at a large academic children's hospital in Denver, Colorado. She has practiced in pediatric intensive care for 10 years in large inner-city pediatric hospitals. Jennifer has spent her nursing career caring for critically ill children as a bedside nurse, charge nurse, and Continuous Renal Replacement Therapy (CRRT) specialist. She is the CRRT Clinical Program Coordinator, providing oversight and program development for the critical care dialysis therapy. She enjoys her diverse clinical role, which involves educating nurses and physicians, mentoring, researching, writing policies, and quality improvement work. In her time away from work, Jennifer enjoys spending time outdoors with her husband, son, and dog, especially hiking and exploring national parks.

Preface

Students:

Welcome! I am so glad you are here. I am very excited for you to try this book. I wrote it after years of frustration, teaching from books that didn't focus on the right things that my students needed. My students (and, I think, you) need a solid but not overwhelming introduction to microbiology and infectious diseases. I asked myself: What are the major concepts I want my students to remember five years from now? And then I worked backward from there, making sure everything pointed to the big picture. And of course, the COVID-19 pandemic has made it clear how important this subject matter is to all of us.

While this book has enough detail to give you context, there is not so much detail that you will lose sight of the major principles. Biological processes are described right next to the illustrations that illustrate them. The format is easier to read than most books because there is only one column of text on a page and wider margins. The margins gave me space to add interesting illustrations and clinical content. A working nurse, Jennifer Lusk, brings her experience to life on the pages and shows you how this information will matter to you when you are working as a health care provider. We have interesting and up-to-the-moment Case Files, Medical Moments, Microbiome selections, and NCLEX® questions in every chapter. COVID-19 content is woven in from beginning to end. My coauthor, Heidi Smith, writes all of the online content specifically for this book. I don't think you'll find a better online set of learning tools anywhere.

I really wanted this to be a different kind of book. I use it in my own classes and my students love it! Well, maybe they have to say that, but I hope you truly do enjoy it and find it to be a refreshing kind of science book.

—Kelly Cowan

C Squared Studios/Photodisc/Getty Images

I dedicate this book to every front-line health care worker. During the COVID-19 pandemic your heroism has become obvious to all.–Kelly

I dedicate this book to the newest addition to our family, Kume, and all of the other diligent students who one day want to help people prevent and heal from disease.–Heidi

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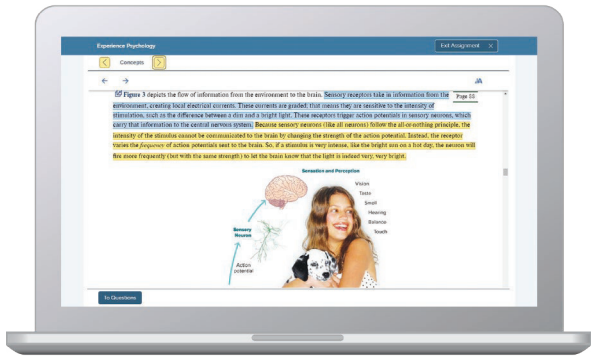

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"I really liked this app—it made it easy to study when you don't have your text-book in front of you."

- Jordan Cunningham, Eastern Washington University

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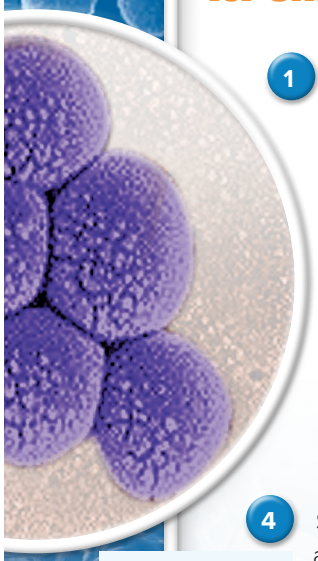
UNIQUE INTERACTIVE QUESTION TYPES

Unique Interactive Question Types in Connect, Tagged to ASM's Curriculum Guidelines for Undergraduate Microbiology



Centers for Disease Control/Janice Carr

1. **Case Study:** Case studies come to life in a learning activity that is interactive, self-grading, and assessable. The integration of the cases with videos and animations adds depth to the content, and the use of integrated questions forces students to stop, think, and evaluate their understanding. Pre- and post-testing allow instructors and students to assess their overall comprehension of the activity.
2. **Concept Maps:** Concept maps allow students to manipulate terms in a hands-on manner in order to assess their understanding of chapter-wide topics. Students become actively engaged and are given immediate feedback, enhancing their understanding of important concepts within each chapter.
3. **What's the Diagnosis:** Specifically designed for the disease chapters of the text, this is an integrated learning experience designed to assess the student's ability to utilize information learned in the preceding chapters to successfully culture, identify, and treat a disease-causing microbe in a simulated patient scenario. This question type is true experiential learning and allows the students to think critically through a real-life clinical situation.
4. **SmartGrid Questions:** SmartGrid questions replace the traditional end-of-chapter questions, and all of these questions are available for assignment in Connect. These questions were carefully constructed to assess chapter material as it relates to all six concepts outlined in the American Society of Microbiology curriculum guidelines plus the competency of "Scientific Thinking." The questions are cross-referenced with Bloom's taxonomy of learning level. Seven concepts × three increasing Bloom's levels = a robust assessment tool of 21 questions.
5. **Animations:** Animation quizzes pair our high-quality animations with questions designed to probe student understanding of the illustrated concepts.
6. **Animation Learning Modules:** Animations, videos, audio, and text all combine to help students understand complex processes. These tutorials take a stand-alone, static animation and turn it into an interactive learning experience for your students and include real-time remediation. Key topics have an Animated Learning Module assignable through Connect.
7. **Labeling:** Using the high-quality art from the textbook, check your students' visual understanding as they practice interpreting figures and learning structures and relationships.
8. **Classification:** Ask students to organize concepts or structures into categories by placing them in the correct "bucket."
9. **Sequencing:** Challenge students to place the steps of a complex process in the correct order.
10. **Composition:** Fill in the blanks to practice vocabulary, and then reorder the sentences to form a logical paragraph (these exercises may qualify as "writing across the curriculum" activities).

All McGraw Hill Connect content is tagged to Learning Outcomes for each chapter as well as topic, section, Bloom's Level, ASM topic, and ASM Curriculum Guidelines to assist you in customizing assignments and in reporting on your students' performance against these points. This will enhance your ability to assess student learning in your courses by allowing you to align your learning activities to peer-reviewed standards from an international organization.

NCLEX®

NCLEX® Prep Questions: Sample questions are available in Connect to assign to students, and there are questions throughout the book as well.

Source: CDC/Janice Haney Carr (*S. aureus* and *Legionella*); Source: CDC/Dr. Erskine Palmer & Byron Skinner (Rotavirus); Source: CDC/Dr. Stan Erlandsen (*Giardia* cyst); ©Science Photo Library/ Getty Images (white blood cells); ©Steve Gschmeissner/ Science Source (fallopian tube surface); NIAID, NIH/Rocky Mountain Laboratories (*Salmonella typhimurium*)

ADDITIONAL RESOURCES

McGraw Hill Create is a self-service website that allows you to create custom course materials using McGraw Hill's comprehensive, cross-disciplinary content and digital products.

Writing Assignment

Available within McGraw Hill Connect® and McGraw Hill Connect® Master, the Writing Assignment tool delivers a learning experience to help students improve their written communication skills and conceptual understanding. As an instructor you can assign, monitor, grade, and provide feedback on writing more efficiently and effectively.

Tegrity in Connect is a tool that makes class time available 24/7 by automatically capturing every lecture. With a simple one-click start-and-stop process, you capture all computer screens and corresponding audio in a format that is easy to search, frame by frame. Students can replay any part of any class with easy-to-use, browser-based viewing on a PC, Mac, or other mobile device.

Educators know that the more students can see, hear, and experience class resources, the better they learn. Tegrity's unique search feature helps students efficiently find what they need, when they need it, across an entire semester of class recordings. Help turn your students' study time into learning moments immediately supported by your lecture.

LearnSmart® Prep is designed to get students ready for a forthcoming course by quickly and effectively addressing prerequisite knowledge gaps that may cause problems down the road. This question bank highlights a series of questions, including Fundamentals of Science, Fundamentals of Math and Statistics, Fundamental Skills for the Scientific Laboratory, and Student Success, to give students a refresher on the skills needed to enter and be successful in their course! LearnSmart Prep maintains a continuously adapting learning path individualized for each student, and tailors content to focus on what the student needs to master in order to have a successful start in the new class.

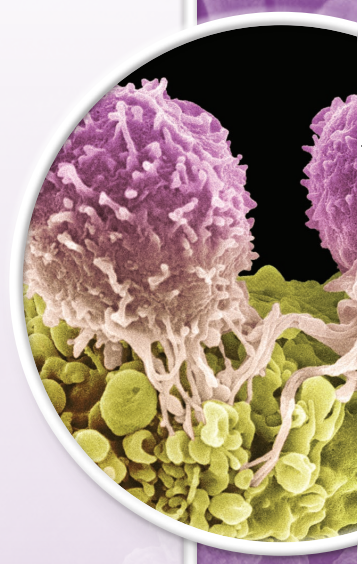
Remote Proctoring & Browser-Locking Capabilities

New remote proctoring and browser-locking capabilities, hosted by Proctorio within Connect, provide control of the assessment environment by enabling security options and verifying the identity of the student.

Seamlessly integrated within Connect, these services allow instructors to control students' assessment experience by restricting browser activity, recording students' activity, and verifying students are doing their own work.

Instant and detailed reporting gives instructors an at-a-glance view of potential academic integrity concerns, thereby avoiding personal bias and supporting evidence-based claims.

Steve Gschmeissner/ Getty Images

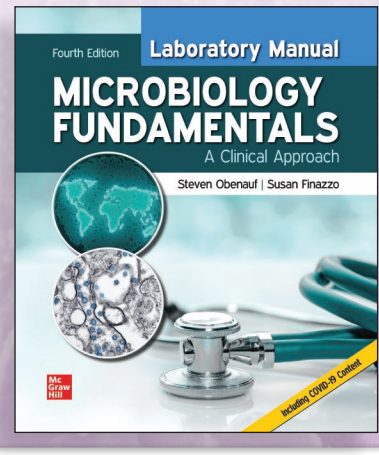


Steve Gschmeissner/ Science Source

Microbiology Fundamentals Laboratory Manual, Fourth Edition

Steven Obenauf, Broward College
Susan Finazzo, Perimeter College, Georgia State University

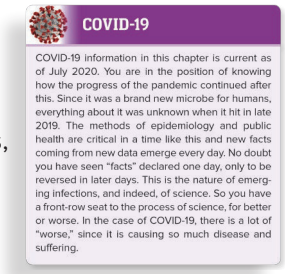
Written specifically for pre-nursing and allied health microbiology students, this manual features brief, visual exercises with a clinical emphasis.



CLINICAL

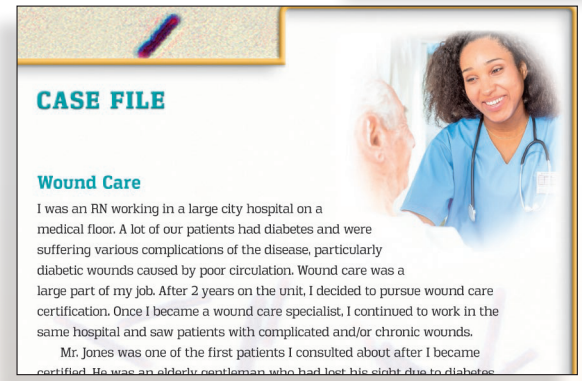
Clinical applications help students see the relevance of microbiology.

COVID-19 Content Throughout the text, small COVID-19 boxes appear in the margins next to content that can be connected to the pandemic virus. Since COVID is immediately relevant to students, it helps to pique their interest and imbues many fundamental concepts with a real life application.



Case File Each chapter begins with a case written from the perspective of a former microbiology student who is working in health care now.

These high-interest introductions provide a specific example of how the chapter content is relevant to real life and future health care careers.



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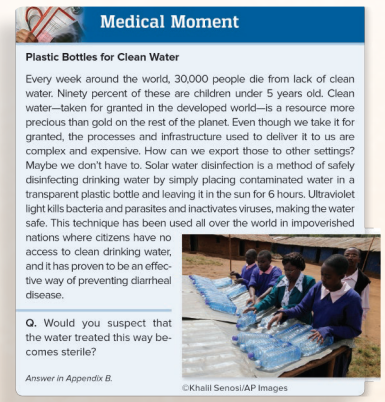
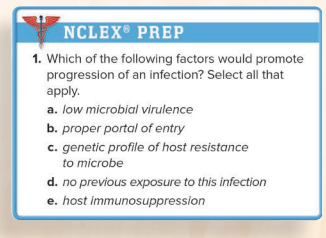
SmartGrid: From Knowledge to Critical Thinking

SmartGrid

In place of traditional end-of-chapter questions, Kelly Cowan has created a grid made up of three columns and seven rows, for a total of 21 questions. The rows contain the six major curricular guidelines (and the competency of *scientific thinking*) from the American Society for Microbiology. The columns represent increasing levels of Bloom's taxonomy of learning. Each question is carefully constructed of material from the chapter that meets both the ASM guideline and the Bloom's level indicated. Instructors can assign a row (to emphasize a curriculum guideline) or a column (asking a variety of questions at a particular Bloom's level). The questions in column 3 (Bloom's level 5 and 6) can easily be used for group problem solving and other higher-order learning activities.

Medical Moment These boxes give students a more detailed clinical application of a nearby concept in the chapter. Each Medical Moment ends with a question. Answers appear in Appendix B.

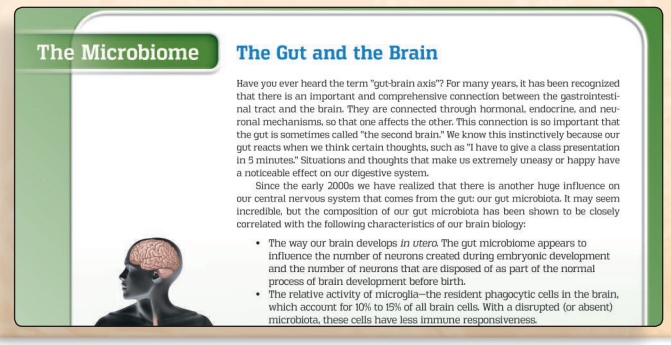




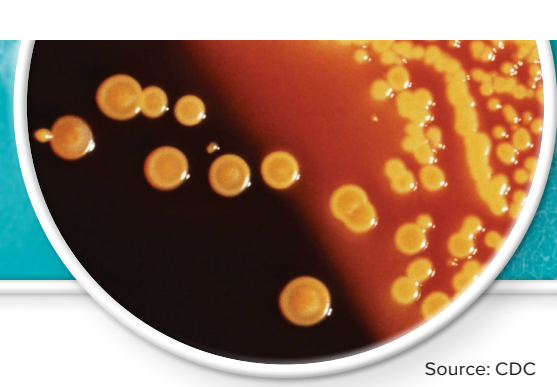
NCLEX® Prep Questions Found throughout the chapter, these multiple-choice questions are application-oriented and designed to help students learn the microbiology information they will eventually need to pass the NCLEX® examination. Students will begin learning to think critically, apply information, and, over time, prep themselves for the examination.

Additional questions are available in Connect for homework and assessment.

The Microbiome Each chapter ends with a reading about a microbiome discovery or story that is relevant to that chapter.



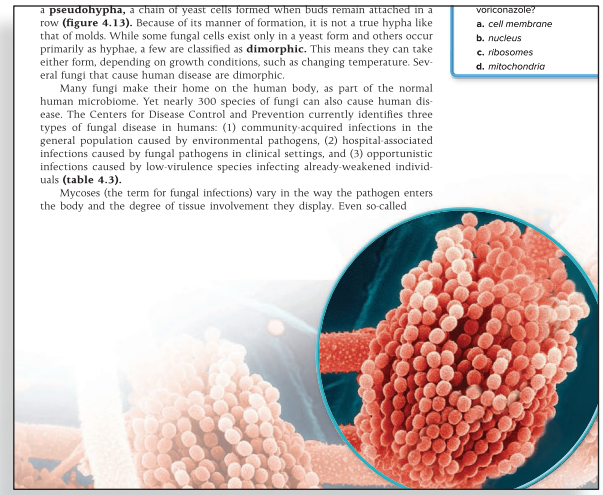
VISUAL



Source: CDC

Visually appealing layouts and vivid art closely linked to narrative for easier comprehension.

Engaging, Accurate, and Educational Art Single column of text is easier to read and leaves space for eye-catching art to keep students engaged.



a **pseudohypha,** a chain of yeast cells formed when buds remain attached in a row **(figure 4.13).** Because of its manner of formation, it is not a true hypha like that of molds. While some fungal cells exist only in a yeast form and others occur primarily as hyphae, a few are classified as **dimorphic.** This means they can take either form, depending on growth conditions, such as changing temperature. Several fungi that cause human disease are dimorphic.

Many fungi make their home on the human body, as part of the normal human microbiome. Yet nearly 300 species of fungi can also cause human disease. The Centers for Disease Control and Prevention currently identifies three types of fungal disease in humans: (1) community-acquired infections in the general population caused by environmental pathogens, (2) hospital-associated infections caused by fungal pathogens in clinical settings, and (3) opportunistic infections caused by low-virulence species infecting already-weakened individuals **(table 4.3).**

Mycoses (the term for fungal infections) vary in the way the pathogen enters the body and the degree of tissue involvement they display. Even so-called

voriconazole?
a. *cell membrane*
b. *nucleus*
c. *ribosomes*
d. *mitochondria*

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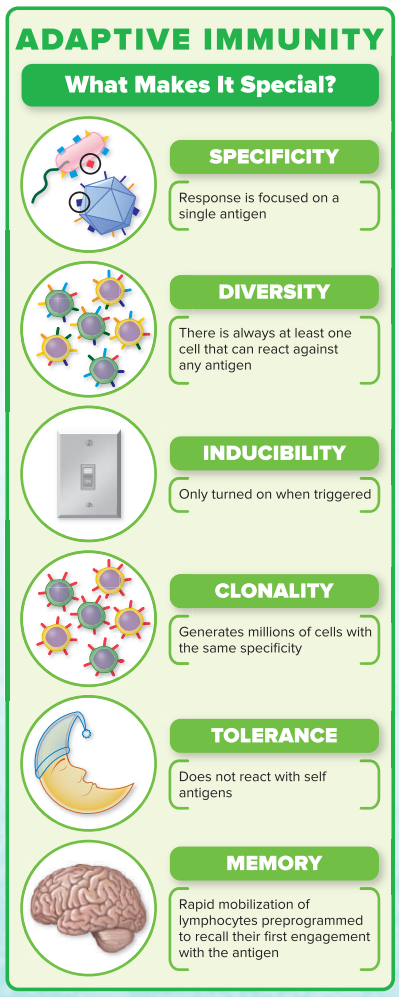
Infographics New infographic-style visual summaries that students can relate to.



Visual Tables The most important points explaining a concept are distilled into table format and paired with the relevant art.

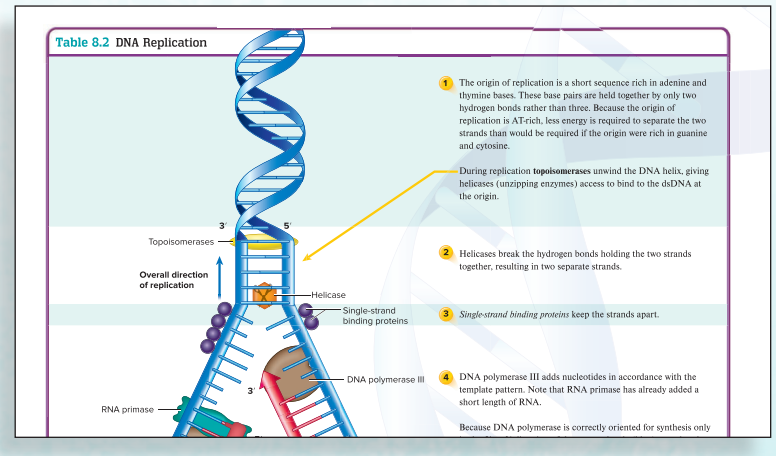


Table 8.2 DNA Replication

1 The origin of replication is a short sequence rich in adenine and thymine bases. These base pairs are held together by only two hydrogen bonds rather than three. Because the origin of replication is AT-rich, less energy is required to separate the two strands than would be required if the origin were rich in guanine and cytosine.

During replication **topoisomerases** unwind the DNA helix, giving helicases (unzipping enzymes) access to bind to the dsDNA at the origin.

2 Helicases break the hydrogen bonds holding the two strands together, resulting in two separate strands.

3 *Single-strand binding proteins* keep the strands apart.

4 DNA polymerase III adds nucleotides in accordance with the template pattern. Note that RNA primase has already added a short length of RNA.

Because DNA polymerase is correctly oriented for synthesis only

Topoisomerases
Overall direction of replication
Helicase
Single-strand binding proteins
DNA polymerase III
RNA primase
3′
5′

Process Figures Complex processes are broken into easy-to-follow steps. Numbered steps help students walk through the figure.

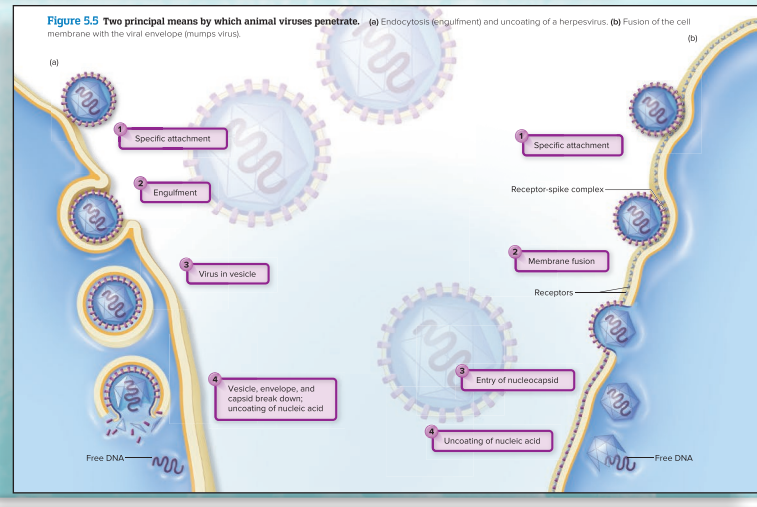


Figure 5.5 **Two principal means by which animal viruses penetrate.** **(a)** Endocytosis (engulfment) and uncoating of a herpesvirus. **(b)** Fusion of the cell membrane with the viral envelope (mumps virus).

BRIEF

Streamlined coverage of core concepts helps students retain the information they will need for advanced courses.

Martin Oeggerli/ Science Source

Chemistry topics required for understanding microbiology are combined with the foundational content found in chapter 1.

Basic genetics and genetic engineering are synthesized into one chapter covering the concepts that are key to microbiology students.

A chapter in microbiology textbooks that is often not used in health-related classes becomes relevant because it presents the 21st-century idea of "One Health"—that the environment and animals influence human health and infections. This is extremely relevant to the COVID-19 pandemic.

Brief Contents

Contributions by Ronald M. Atlas, University of Louisville

Duplication Eliminated Detail is incorporated into figures so students can learn in context with the art. This allows a more concise narrative flow while still retaining core information.

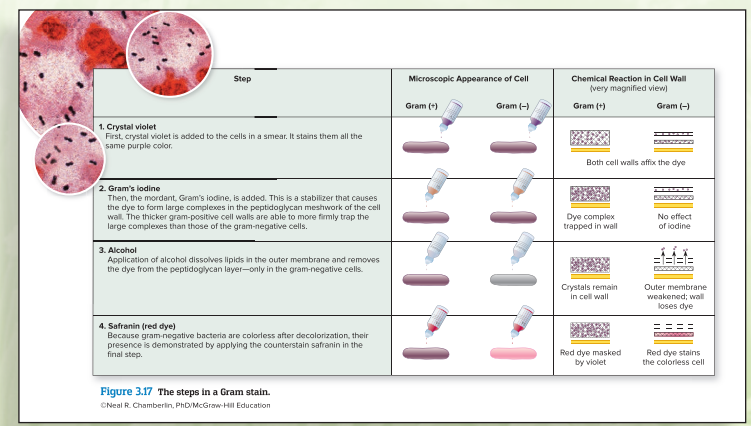


Figure 3.17 The steps in a Gram stain.

Changes to the Fourth Edition

Significant Changes

COVID-19 content (in addition to being featured in the respiratory disease chapter and the One Health chapter) is included throughout the text, in small COVID-19 boxes. Since this is immediately relevant to students, it helps to pique their interest and embed many different concepts in a real life scenario.

New chapter summaries The chapter summaries have been converted into succinct, visual infographics, a format students are accustomed to and that provides the high points in a format that is reproduced chapter after chapter.

Short author commentaries Several figures in each chapter are accompanied by a word bubble from the authors, emphasizing key parts of the figure or interesting aspects.

Chapter Highlights

Chapter 1 New infographic about the types of microorganisms we will study in the book. Added section on the cautions we should take about research on the microbiome: that it *is* big but many results are still preliminary.

Chapter 3 I describe my own recent experience with *C. diff*. Throughout the book, the genus *Clostridium* has been updated to *Clostridioides* in the case of *C. diff*.

Chapter 4 Emphasis on the rise of fungal infections in immunocompromised persons. "The progress of these infections in immunosuppressed people was vividly described: They'll just rot you down quick as a flash," said one of the authors."

Chapter 5 New infographic explaining cytopathic effects.

Chapter 6 Made illustrations of levels of oxygen growth clearer. Clarified the illustration of serial dilution counting of growth.

Chapter 7 The commentaries on the (often difficult) figures are particularly helpful in this chapter.

Chapter 8 A comment on the flow-of-genetic-information figure, emphasizing how the knowledge of the regulatory RNAs is new, and how science works. Same type of commentary about mutations. More epigenetic discussion. A commentary about the similarity between binary fission and PCR processes. Discussion of using DNA for information storage.

Chapter 10 New discussion about how the microbiome affects efficacy of antimicrobial drugs. FDA ban of antimicrobials in agriculture.

Chapter 11 New sites of the microbiome: placenta, etc. Changes in epidemiology of hospital-acquired infections (HAIs). Important information about the emergence of *Candida auris*.

Chapter 12 Comment bubble points out the discovery of lymphatic system in brain. Made figures of phagocytosis and of interferon much clearer, with commentary bubble on the latter.

Chapter 13 More explanation on the figure of genetic rearrangements for antibody diversity.

Chapter 14 Added the newly appreciated influence of T cells on allergies.

Chapter 15 Explanation of the NAAT (nucleic acid amplification techniques) and how they relate to the techniques we have already described. The new practice of PCR'ing tissue samples.

Chapter 16 Measles epidemics due to lack of vaccinations. *Malassezia* association with pancreatic cancer.

Chapter 17 Demoted Zika virus disease from a Highlight disease; latest data about acute flaccid myelitis. Highlighted the Global Polio Eradication Initiative. Updated the arbovirus epidemiology.

Chapter 18 Did some clarification of the size of insects involved in various diseases. Ebola updates.

Chapter 19 COVID-19 featured as a highlight disease. Added *Candida auris* otitis media; expanded and updated discussion of influenza vaccines; new epidemiology of whooping cough; use of gene amplification and antibiotic susceptibility testing for tuberculosis; new section on novel coronaviruses.

Chapter 20 Thirty-state *Campylobacter* outbreak from handling puppies; rise of antibiotic resistance in *Helicobacter;* new infographic about foodborne disease outbreaks.

Chapter 21 A commentary that helps students understand data reported as "per 100,000 people."

Chapter 22 Critical information and graphics describing how the COVID-19 pandemic illustrates the principles of One Health. Added discussion of the emergence of *Candida auris* and the influence of climate change; the creep northward of mosquito and tick-borne diseases; hepatitis A epidemic in the United States; wildfires in California and Australia; longer duration of mosquito-borne disease season.

Acknowledgments

I am always most grateful to the students in my classes. They teach me every darned day how to do a better job helping them understand these concepts that are familiar to me but new to them. All the instructors who reviewed the manuscript were also great allies. I thank them for lending me some of their microbiological excellence. Heidi Smith improves everything she touches, especially this book. Jennifer Lusk added very meaningful medical insights and clinical content. My handlers at McGraw Hill make the wheels go around. They include Lauren Vondra, Tami Hodge, Jessica Portz, David Hash, Tammy Juran, Laura Fuller, and Lori Hancock. Darlene Schueller, my day-to-day editor, is a wonderful human being and taskmaster, in that order. In short, I'm just a lucky girl surrounded by talented people.

—Kelly Cowan

I, too, am thankful for the many students that enter my classroom every year. My work is greatly inspired by their questions, their ideas, and their unique way of looking at complex things. I am filled with gratitude to Kelly Cowan for her willingness to partner with me; I constantly learn from her about better ways to reach all students. I appreciate the entire microbiology team at McGraw Hill who truly believes in producing materials that lead to student success.

—Heidi Smith

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We are very pleased to have been able to incorporate real student data points and input, derived from thousands of our SmartBook users, to help guide our revision. SmartBook heat maps provided a quick visual snapshot of usage of portions of the text and the relative difficulty students experienced in mastering the content. With these data, we were able to hone not only our text content but also the SmartBook questions.

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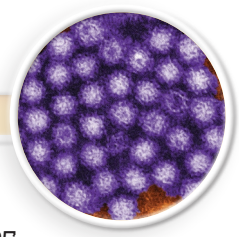

CHAPTER 5

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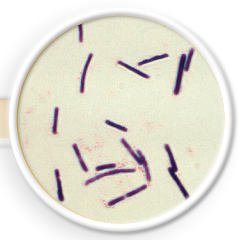

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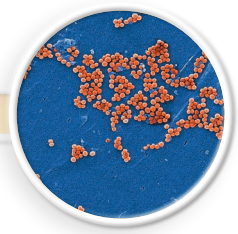

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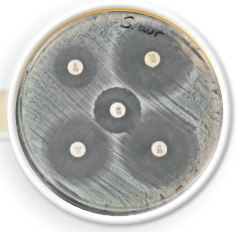

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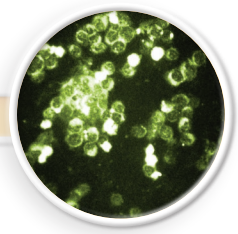

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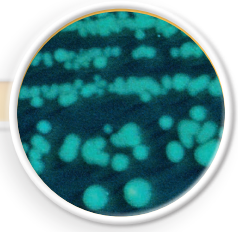

Centers for Disease Control and Prevention

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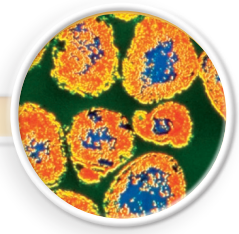

Moredun Animal Health Ltd/Science Source

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Bob Riha, Jr./Archive Photos/ Getty Images

CHAPTER 22

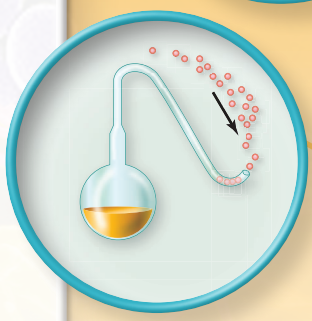
One Health: The Interconnected Health of the Environment, Humans, and Other Animals Contributions by Ronald M. Atlas, University of Louisville 686

1 Introduction to Microbes and Their Building Blocks

IN THIS CHAPTER...

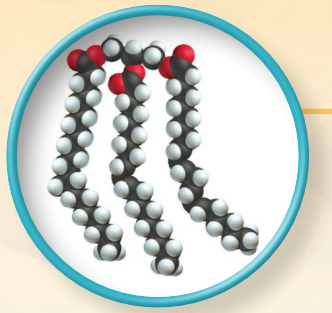
1.1 Microbes: Tiny but Mighty

1. List the various types of microorganisms that can colonize humans.
2. Describe the role and impact of microbes on the earth.
3. Explain the theory of evolution and why it is called a theory.
4. Explain the ways that humans manipulate organisms for their own uses.
5. Summarize the relative burden of human disease caused by microbes.
6. Differentiate among bacteria, archaea, and eukaryotic microorganisms.
7. Identify two acellular infectious agents that are studied in microbiology.
8. Compare and contrast the relative sizes of the different microbes.



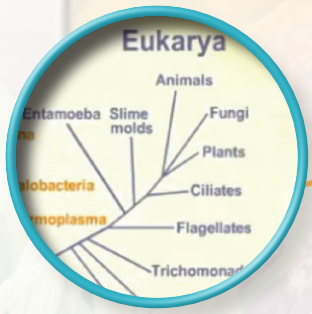
1.2 Microbes in History

9. Make a time line of the development of microbiology from the 1600s to today.
10. List some recent microbiology discoveries of great impact.
11. Identify the important features of the scientific method.



1.3 Macromolecules: Superstructures of Life

12. Name the four main families of biochemicals.
13. Provide examples of cell components made from each of the families of biochemicals.
14. Differentiate among primary, secondary, tertiary, and quaternary levels of protein structure.
15. List the three components of a nucleotide.
16. Name the nitrogen bases of DNA and RNA.
17. List the three components of ATP.
18. Recall three characteristics common to all cells.



1.4 Naming, Classifying, and Identifying Microorganisms

19. Differentiate among the terms *nomenclature*, *taxonomy*, and *classification*.
20. Create a mnemonic device for remembering the taxonomic categories.
21. Correctly write the binomial name for a microorganism.
22. Draw a diagram of the three major domains.
23. Explain the difference between traditional and molecular approaches to taxonomy.

CASE FILE

The Subject Is You!

At the beginning of every chapter in this book, a different health care worker will tell you a story about something "microbiological" that happened to him or her in the line of duty. For this first chapter, though, I am claiming "dibs" as author and am going to introduce myself to you by telling you about the first day of class in my course.

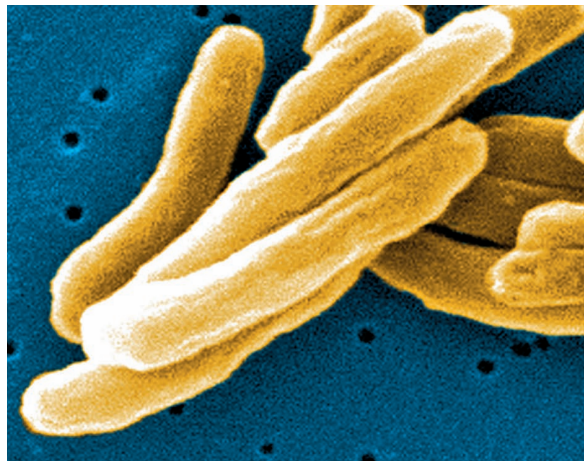
Long ago I noticed that students have a lot of anxiety about their microbiology course. I know that starts you out with one strike against you because attitudes are powerful determinants of our success. So on the first day of class I often spend some time talking with students about how much they already know about microbiology.

Sometimes I start with "How many of you have taken your kids for vaccinations?" since in the classes I teach very many students are parents. Right away students will tell me why they or friends they know have not vaccinated their children, and I can tell them there's a sophisticated microbiological concept they are referencing, even if they aren't naming it: *herd immunity*, discussed in chapter 11 of this book.

Of course, nowadays, everyone has some type of experience with COVID-19, and the virus that causes it, SARS-CoV-2. The whole world has undergone a crash course in infection, and in epidemiology. This course will help you sort out all of the information that has been pouring out about COVID-19.

- Think about how many times you have taken antibiotics in the past few years. What is special about antibiotics that they are only given to treat infections?
- What is the most unusual infection you have ever encountered among family or friends or patients you have cared for?

Case File Wrap-Up appears at the end of the chapter.



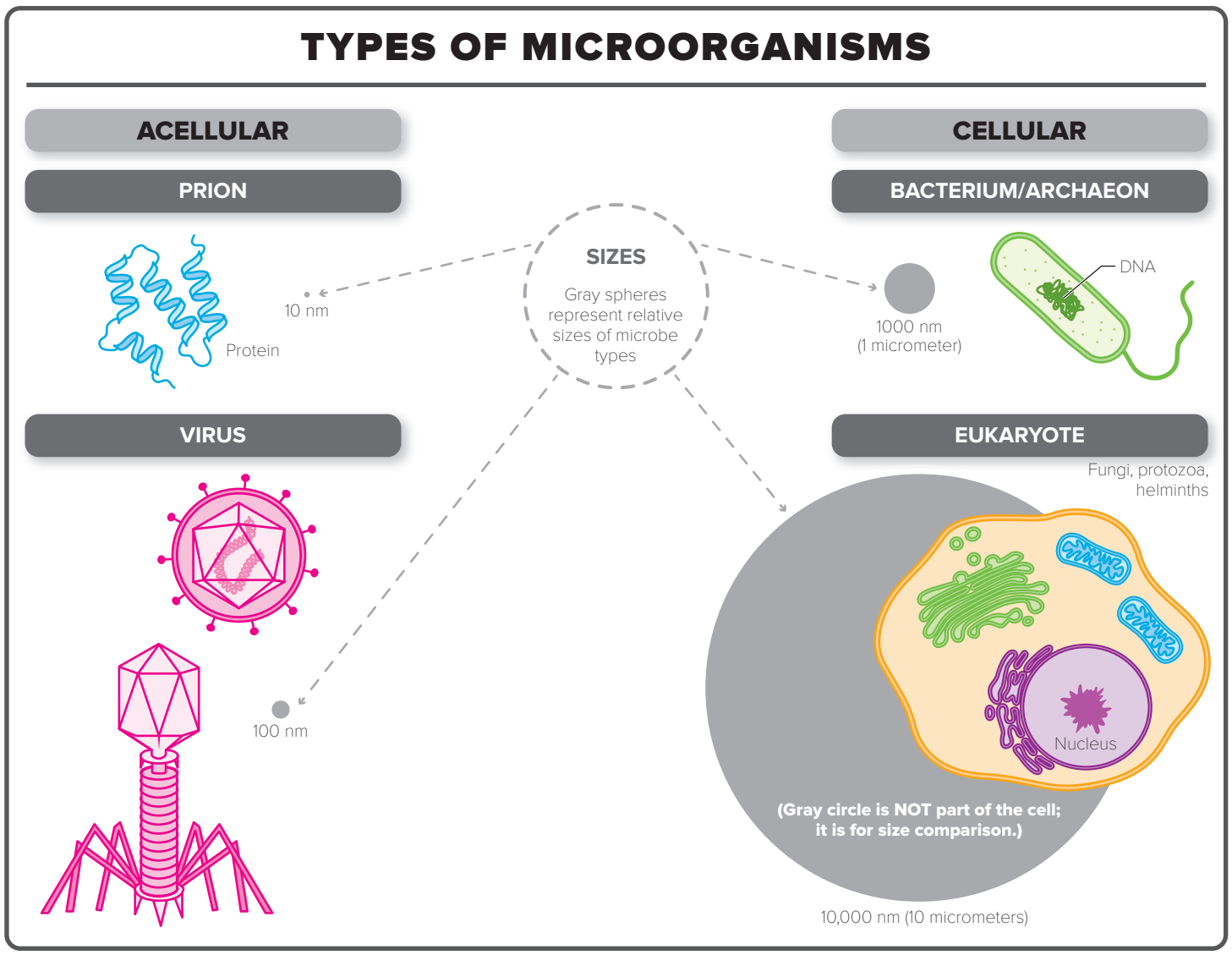
Mycobacterium tuberculosis bacteria
Source: CDC/Janice Carr

1.1 Microbes: Tiny but Mighty

Microbiology is a specialized area of biology that deals with living things ordinarily too small to be seen without magnification. Such **microscopic** organisms are collectively referred to as **microorganisms** (my″-kroh-or′-gun-izms), **microbes,** or several other terms depending on the kind of microbe or the purpose. There are several major groups of microorganisms that we'll be studying. They can be either cellular or noncellular. The cellular microorganisms we will study are **bacteria, archaea, fungi, and protozoa.** Another cellular organism that causes human infections is not technically a microorganism. **Helminths** are multicellular animals whose mature form is visible to the naked eye. Acellular microorganisms causing human disease are the **viruses** and **prions. Table 1.1** gives you a first glimpse at these microorganisms. There is another very important group of organisms called algae. They are critical to the health of the biosphere but do not directly infect humans, so we will not consider them in this book. Each of the other seven groups contains members that colonize humans, so we will focus on them.

The nature of microorganisms makes them both very easy and very difficult to study–easy because they reproduce so rapidly and we can quickly grow large populations in the laboratory, and difficult because we usually can't see them directly. We rely on a variety of indirect means of analyzing them in addition to using microscopes.

Table 1.1 The Types of Microorganisms We Will Study in this Book



Microbes and the Planet

For billions of years, microbes have extensively shaped the development of the earth's habitats and the evolution of other life forms. It is understandable that scientists searching for life on other planets first look for signs of microorganisms.

Single-celled organisms appeared on this planet about 3.8 billion years ago according to the fossil record. One of these organisms–referred to as LCA, or the Last Common Ancestor–eventually led to the appearance of two newer single cell types, called bacteria and archaea. A little bit later this single-celled ancestor gave rise to **eukaryotic** (yoo-kar′-ee-ot-ic) cells. The type of cell known as LCA no longer exists. Only its "offspring"–bacteria, archaea, and eukaryotes–remain. *Eu-kary* means "true nucleus," and these were the only cells containing a nucleus. Bacteria and archaea have no true nucleus. For that reason, they have traditionally been called **prokaryotes** (pro-kar′-ee-otes), meaning "prenucleus." But researchers are suggesting we no longer use the term *prokaryote* to lump them together because archaea and bacteria are so distinct genetically. Some scientists have started calling them **akaryotes,** meaning "no nucleus." If you consider the seven types of microorganisms we will be dealing with in this book, you will recognize bacteria and archaea as each having their own domain. The protozoa, fungi, and helminths are all in the domain Eukarya. Viruses and prions do not appear on the tree of life because they are not cells, and not considered living. That sounds strange, but we will delve into that in the virus chapter, which comes later.

Figure 1.1 depicts the resulting tree of life–a diagram of all organisms on the planet. There are two important things to note about this figure. First, all of biologic life falls into these three categories, known as domains. Most of the organisms you are familiar with (animals, plants, etc.) are in one category, Eukarya. Second, these three domains all emerged from a single common cell type (the "stem" at the bottom).

Bacteria and archaea are predominantly single-celled organisms. Many eukaryotic organisms are also single-celled, but the eukaryotic cell type also developed into highly complex multicellular organisms such as worms and humans. In terms of numbers, eukaryotic cells are a small minority compared to the bacteria and archaea, but their larger size (and our own status as eukaryotes!) makes us perceive them as dominant to–and more important than–bacteria and archaea.

Important Note to Students!

This is your author here. I wanted to alert you right up front that you should look at the figures and read the tables in the chapters. I know that it is human nature to skip these when you see the reference in the main text (like "**figure 1.4**") and just move on with the next sentence. But in this book I made a real point to put a lot of information in the figures and tables because it is easier to digest things such as processes and categories when they are presented in a more visual format. And there are a lot of "processes" and "categories" in biology! So I opted for a bit less text, and a bit more pictures and tables. So be sure to make it a point to stop by and examine these visual features. Thanks! Kelly

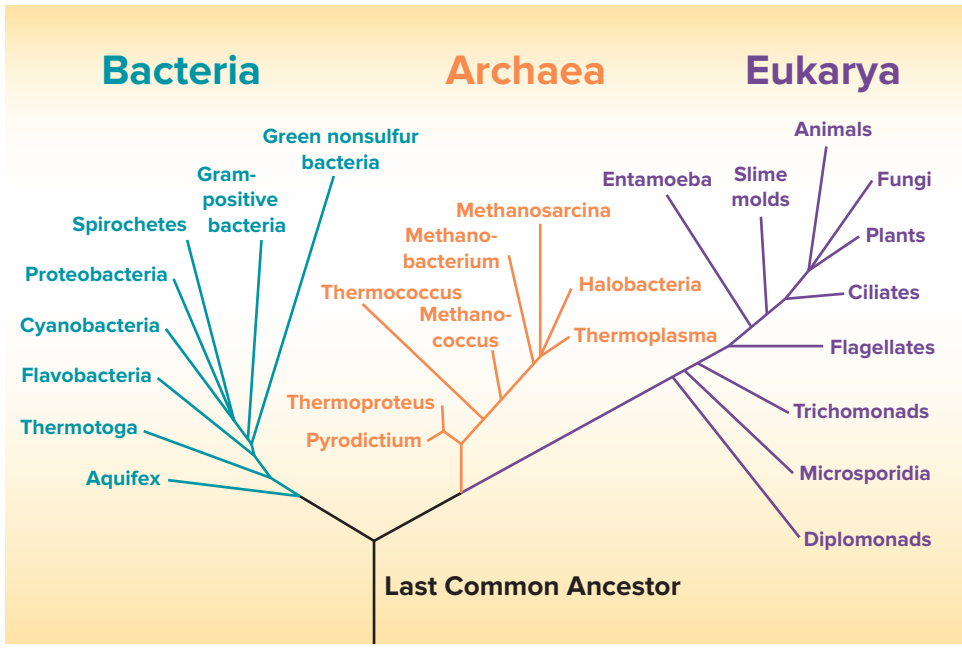


Figure 1.1 The tree of life: A phylogenetic system. A system for representing the origins of cell lines and major taxonomic groups. There are three distinct cell lines placed in superkingdoms called domains.

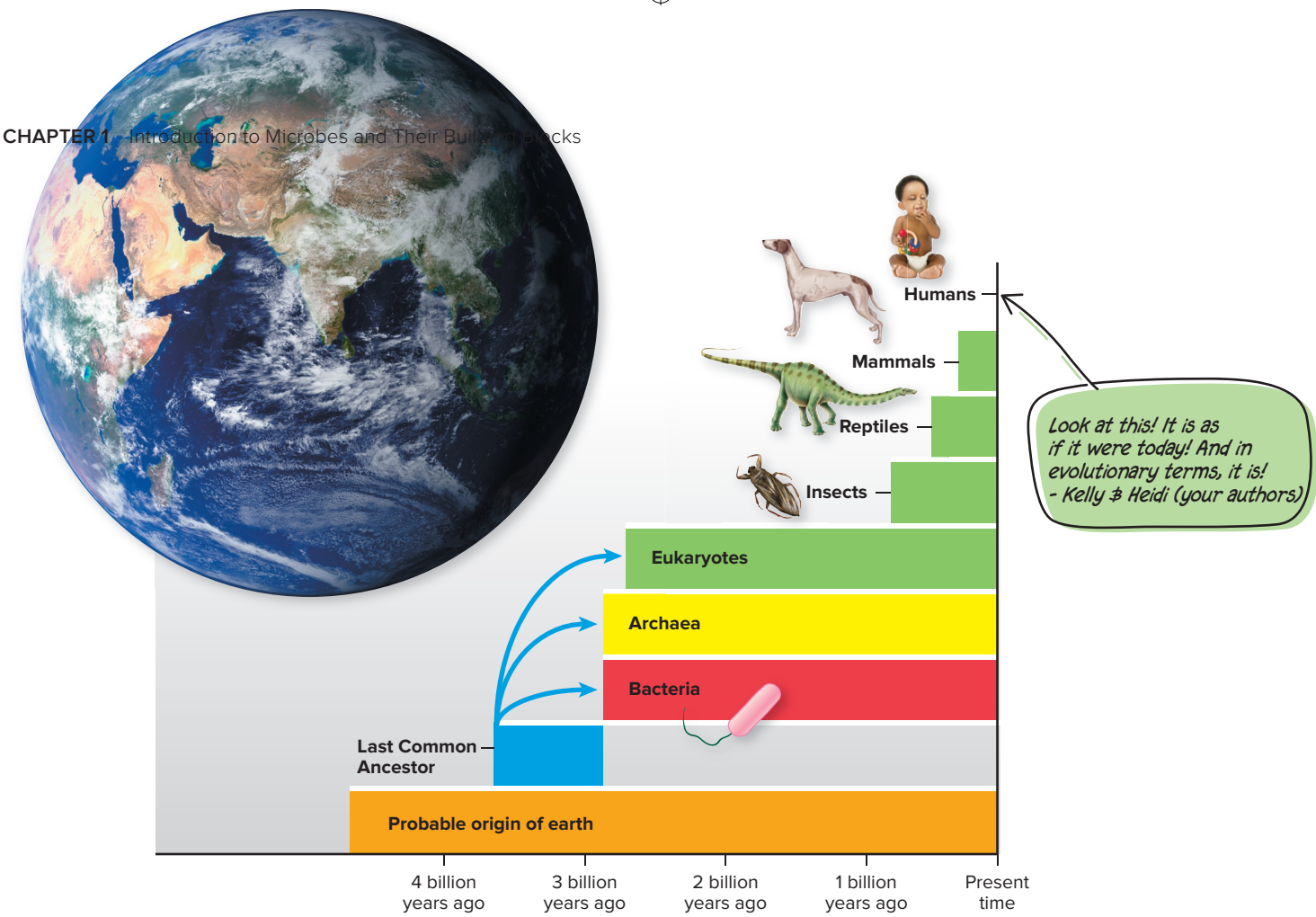


Figure 1.2 **Evolutionary time line.**
(photo): NASA/Goddard Space Flight Center

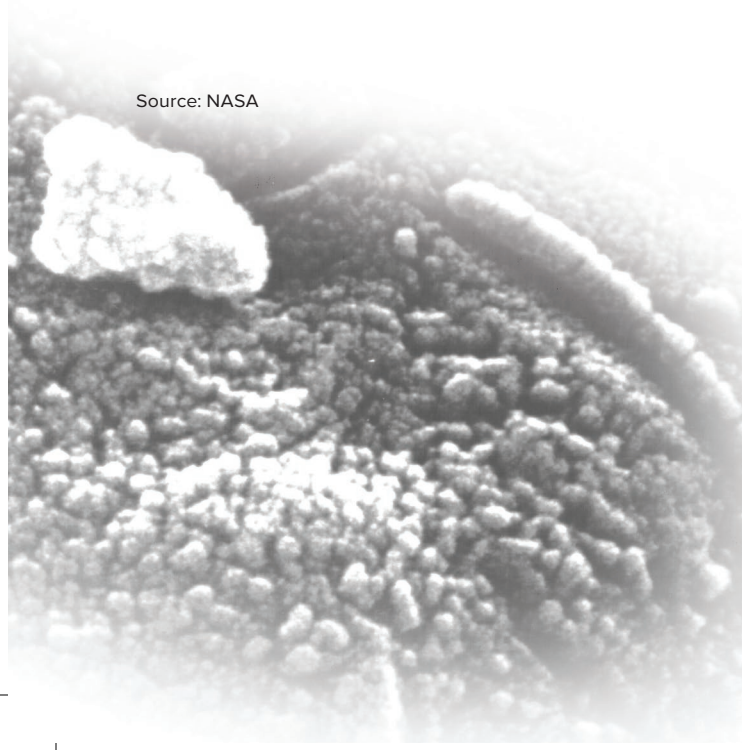

Source: NASA

Figure 1.2 depicts the time line of appearances of different types of organisms on earth. Starting on the left, you see that the ancestor cell type was here alone for quite a while before giving rise to the three domains of life. Eukaryotes came along last, and it took a very long time for single-celled eukaryotes to develop into more complex eukaryotic organisms (insects, reptiles, and mammals). On the scale pictured in the figure, humans just barely appeared in very recent earth history. Bacteria and archaea preceded even the earliest animals by more than 2 billion years. This is a good indication that humans are not likely to–nor should we try to–eliminate bacteria from our environment. They have survived and adapted to many catastrophic changes over the course of our geologic history.

Another indication of the huge influence bacteria exert is how **ubiquitous** they are. *Ubiquitous* means "found everywhere." Microbes can be found nearly everywhere, from deep in the earth's crust, to the polar ice caps and oceans, to inside the bodies of plants and animals. Being mostly invisible, the actions of microorganisms are usually not as obvious or familiar as those of larger plants and animals. They make up for their small size by their immense numbers and by living in places that many other organisms cannot survive. Above all, they play central roles in the earth's landscape that are essential to life.

When we point out that single-celled organisms have adapted to a wide range of conditions over the 3.5 billion years of their presence on this planet, we are talking about evolution. The presence of life in its present form would not be possible if the earliest life forms had not changed constantly, adapting to their environment and circumstances. Getting from the far left in figure 1.2 to the far right, where humans appeared, involved billions and billions of tiny changes, starting with the first cell that appeared about a billion years after the planet itself was formed.

You have no doubt heard this concept described as the **theory of evolution.** Let's clarify some terms. **Evolution** is the accumulation of changes that occur in

organisms as they adapt to their environments. It is documented every day in all corners of the planet, an observable phenomenon testable by science. Scientists use the term *theory* in a different way than the general public does, which often leads to great confusion. In science, a theory begins as a hypothesis, or an educated guess to explain an observation. By the time a hypothesis has been labeled a *theory* in science, it has undergone years and years of testing and not been disproved. It is taken as fact. This is much different from the common usage, as in "My theory is that he overslept and that's why he was late." The theory of evolution, like the germ theory and many other scientific theories, refers to a well-studied and well-established natural phenomenon, not just a random guess.

How Microbes Shape Our Planet

Microbes are deeply involved in the flow of energy and food through the earth's ecosystems. Most people are aware that plants carry out **photosynthesis,** which is the light-fueled conversion of carbon dioxide to organic material, accompanied by the formation of oxygen (called oxygenic photosynthesis). However, bacteria invented photosynthesis long before the first plants appeared, first as a process that did not produce oxygen (*anoxygenic photosynthesis*). This anoxygenic photosynthesis later evolved into oxygenic photosynthesis, which not only produced oxygen but also was much more efficient in extracting energy from sunlight. Hence, these ancient, single-celled microbes were responsible for changing the atmosphere of the earth from one without oxygen to one with oxygen. The production of oxygen also led to the use of oxygen for aerobic respiration and the formation of ozone, both of which set off an explosion in species diversification. Today, photosynthetic microorganisms (mainly bacteria and algae) account for more than 70% of the earth's photosynthesis, contributing the majority of the oxygen to the atmosphere **(figure 1.3).**

In the long-term scheme of things, microorganisms are the main forces that drive the structure and content of the soil, water, and atmosphere. For example:

- The temperature of the earth is regulated by gases emitted by living organisms. These gases include carbon dioxide, nitrous oxide, and methane, which create an insulation layer in the atmosphere and help retain heat. Many of these gases are produced by microbes living in the environment and the digestive tracts of animals.
- The most abundant cellular organisms in the oceans are not fish but bacteria. Think of a 2-liter soda bottle. Two liters of surface ocean water contains approximately 1,000,000,000 (1 billion) bacteria. Each of these bacteria likely harbors thousands of viruses inside of it, making viruses the most abundant inhabitants of the oceans. The bacteria and their viruses are major contributors to photosynthesis and other important processes that create our environment. (Be careful here. The first sentence in this paragraph said that bacteria are the most abundant *cellular* organisms in oceans. But viruses, which are not cellular, far outnumber them.)
- Bacteria and fungi live in complex associations with plants that assist the plants in obtaining nutrients and water and may protect them against disease. Microbes form similar interrelationships with animals, notably, in the stomach of cattle, where a rich assortment of bacteria digests the complex carbohydrates of the animals' diets and causes the animals to release large amounts of methane into the atmosphere.

Microbes and Humans

Microorganisms clearly have monumental importance to the earth's operation. Their diversity and versatility make them excellent candidates for being used by humans

Medical Moment

Medications from Microbes

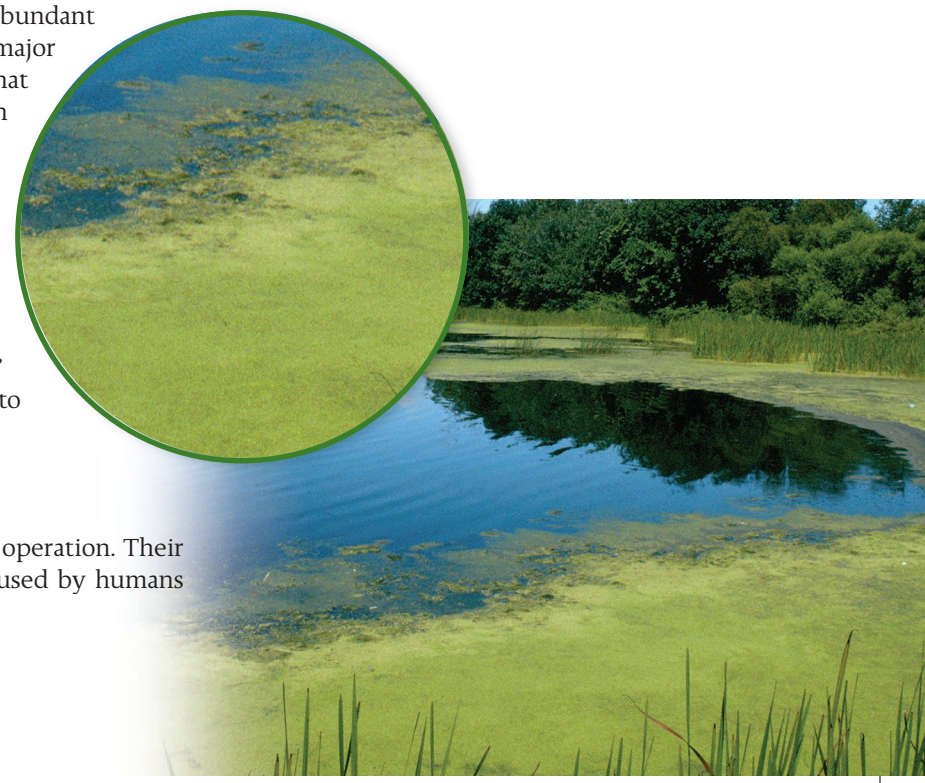
Penicillin is a worthy example of how microorganisms can be used to improve human life. Alexander Fleming, a Scottish bacteriologist, discovered penicillin quite by accident in 1928. While growing several bacterial cultures in Petri dishes, he accidentally forgot to cover them. They remained uncovered for several days. When Fleming checked the Petri dishes, he found them covered with mold. Just before Fleming went to discard the Petri dishes, he happened to notice that there were no bacteria to be seen around the mold—in other words, the mold was killing all of the bacteria in its vicinity.

Recognizing the importance of this discovery, Fleming experimented with the mold (of the genus *Penicillium*) and discovered that it effectively stopped or slowed the growth of several bacteria. The chemical that was eventually isolated from the mold—penicillin—became widely used during the Second World War and saved many soldiers' lives, in addition to cementing Fleming's reputation.

Q. Can you think of a logical reason that a microbe (the fungus) would produce a chemical that harms another microbe (the bacteria)?

Answer in Appendix B.

Figure 1.3 A rich photosynthetic community.
Summer pond with a thick mat of algae.
Jerome Wexler/Science Source



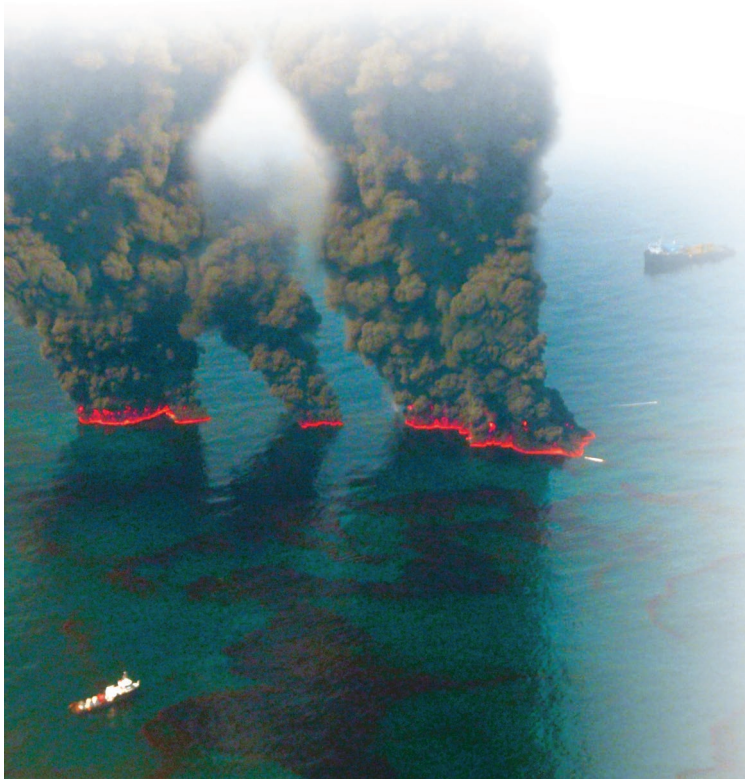


Figure 1.4 The 2011 Gulf oil spill. There is evidence that ocean bacteria metabolized ("chewed up") a lot of the spilled oil.

Chief Petty Officer John Kepsimelis/US Coast Guard

for our own needs, and for them to "use" humans for their needs, sometimes causing disease along the way. We'll look at both of these kinds of microbial interactions with humans in this section.

By accident or choice, humans have been using microorganisms for thousands of years to improve life and even to shape civilizations. Baker's and brewer's yeasts are types of single-celled fungi that cause bread to rise and ferment sugar into alcohol to make wine and beers. Other fungi are used to make special cheeses such as Roquefort or Camembert. Historical records show that households in ancient Egypt kept moldy loaves of bread to apply directly to wounds and lesions. When humans manipulate microorganisms to make products in an industrial setting, it is called **biotechnology.** For example, some specialized bacteria have unique capacities to mine precious metals or to clean up human-created contamination.

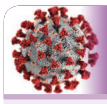
Genetic engineering is an area of biotechnology that manipulates the genetics of microbes, plants, and animals for the purpose of creating new products and genetically modified organisms (GMOs). One powerful technique for designing GMOs is called **recombinant DNA technology.** This technology makes it possible to transfer genetic material from one organism to another and to deliberately alter DNA. Bacteria and fungi were some of the first organisms to be genetically engineered. This was possible because they are single-celled organisms and they are so adaptable to changes in their genetic makeup. Recombinant DNA technology has unlimited potential in terms of medical, industrial, and agricultural uses. Microbes can be engineered to synthesize desirable products such as drugs, hormones, and enzymes. It has become popular to dislike GMOs. As with any technological advance, the capacity to create GMOs can have both positive and negative aspects. Your job is to learn about them, so that you can have an informed opinion.

Another way of tapping into the unlimited potential of microorganisms is the science of **bioremediation** (by′-oh-ree-mee-dee-ay″-shun). This term refers to the ability of microorganisms–ones already present or those introduced intentionally–to restore the stability of an ecosystem or to clean up toxic pollutants. Microbes have a surprising capacity to break down chemicals that would be harmful to other organisms **(figure 1.4).** This includes even human-made chemicals that scientists have developed and for which there are no natural counterparts.

Microbes Harming Humans

One of the most fascinating aspects of the microorganisms with which we share the earth is that, despite all of the benefits they provide, they also contribute significantly to human misery as **pathogens** (path′-oh-jenz). The vast majority of microorganisms that associate with humans cause no harm. In fact, they provide many benefits to their human hosts. Note that a diverse microbial biota living in and on humans is an important part of human well-being. However, humankind is also plagued by nearly 2,000 different microbes that can cause various types of disease. Any disease caused by a microorganism is termed an **infectious disease.** Many diseases are not caused by microorganisms, but by genetic defects, imbalances in body systems, exposure to chemicals in the environment, among others. Infectious diseases still devastate human populations worldwide, despite significant strides in understanding and treating them. The World Health Organization (WHO) estimates there are a total of 10 billion new infections across the world every year. Infectious diseases are important common causes of death in much of humankind, and they still kill a significant percentage of the U.S. population. **Table 1.2** depicts the 10 top causes of death per year (by all causes, infectious and noninfectious) in the United States and worldwide.

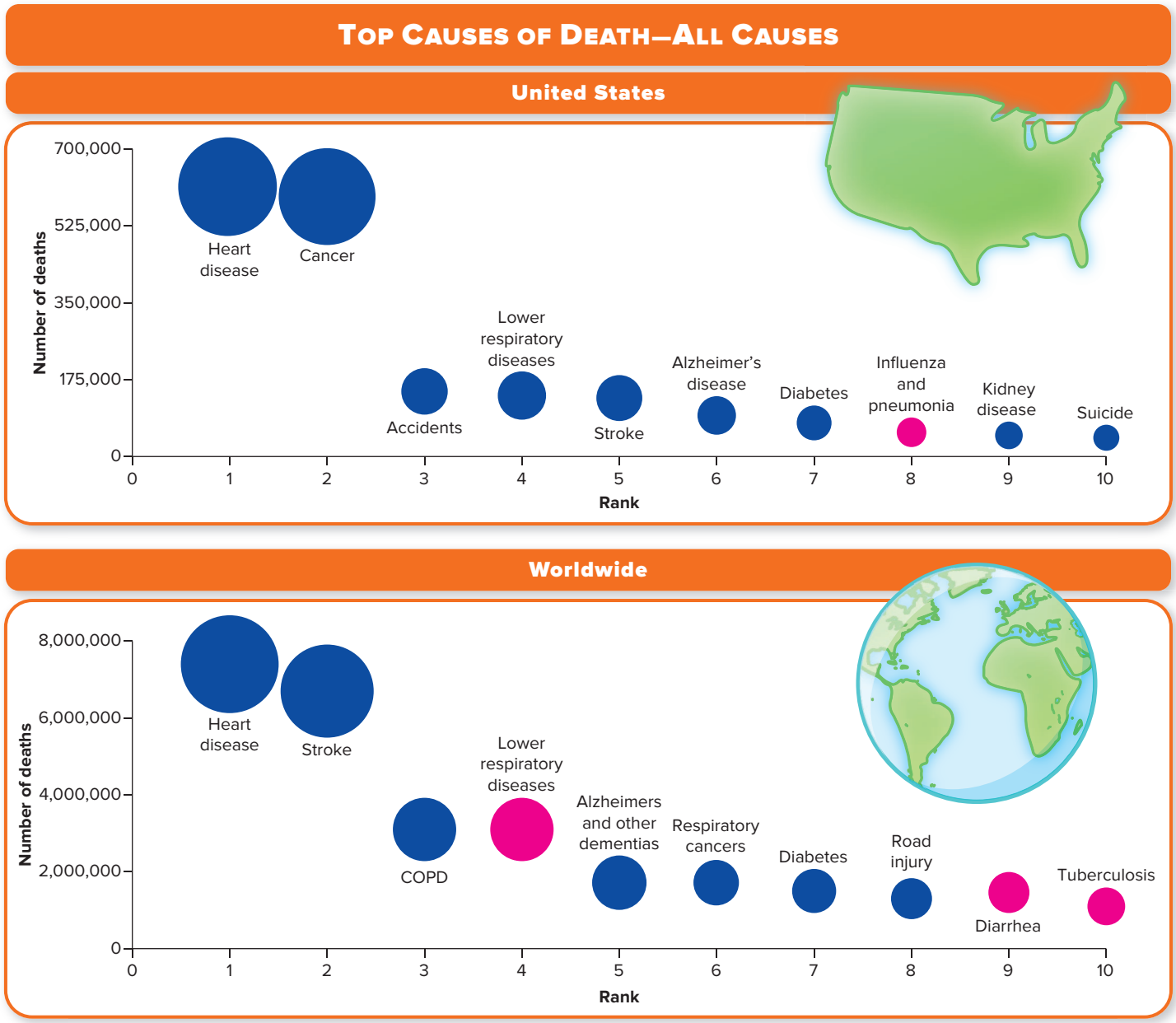
We are also witnessing an increase in the number of new (emerging) and older (reemerging) diseases. AIDS, hepatitis C, Zika virus, West Nile virus, and tuberculosis are examples. It is becoming clear that human actions in the form of deforestation, industrial farming techniques, and chemical and antibiotic usage can foster the emergence or reemergence of particular infectious diseases. These patterns will be discussed in chapter 22.



COVID-19

The top causes of death in table 1.2 do not include data for COVID-19. As of mid-2020, COVID-19 deaths would not have registered on the graph for worldwide deaths, but the numbers of deaths it caused in the United States would register in the top five.

Table 1.2 Top Causes of Death—All Causes



All data from 2016.

Sources: CDC, 2016; WHO, 2016.

One of the most eye-opening discoveries in recent years is that many diseases that used to be considered noninfectious probably do involve microbial infection. One well-known example is that of gastric ulcers, now known to be caused by a bacterium called *Helicobacter*. But there are more. Diseases as different as multiple sclerosis, obsessive compulsive disorder, coronary artery disease, and even obesity have been linked to chronic infections with microbes. It seems that the golden age of microbiological discovery, during which all of the "obvious" diseases were characterized and cures or preventions were devised for them, should more accurately be referred to as the *first*

NCLEX® PREP

1. For which of the following disease processes has microbial infection been implicated? Select all that apply.
   - **a.** *gastric ulcers*
   - **b.** *diabetes type 1*
   - **c.** *renal artery stenosis*
   - **d.** *schizophrenia*
   - **e.** *obesity*
   - **f.** *deep vein thrombosis*

golden age. We're now discovering the subtler side of microorganisms. Later in this chapter we will introduce the human microbiome–the microbes that call the human body home from birth onward. We will see that variations in the microbiome also determine a person's tendency to develop both infectious and noninfectious conditions.

Another important development in infectious disease trends is the increasing number of patients with weakened defenses, who, because of welcome medical advances, are living active lives instead of enduring long-term disability or death from their conditions. They are subject to infections by common microbes that are not pathogenic to healthy people. There is also an increase in microbes that are resistant to drugs. It appears that even with the most modern technology available to us, microbes still have the "last word," as the great French scientist Louis Pasteur observed.

What Are They Exactly?

Cellular Organization

As discussed earlier, two basic cell types appeared during evolutionary history. The bacteria and archaea, along with eukaryotic cells, differ not only in the complexity of their cell structure but also in contents and function.

In general, bacterial and archaeal cells are about 10 times smaller than eukaryotic cells, and they lack many of the eukaryotic cell structures such as **organelles.** Organelles are small, membrane-bound structures in the eukaryotic cell that perform specific functions and include the nucleus, mitochondria, and chloroplasts. Examples of bacteria, archaea, and eukaryotic microorganisms are covered in more detail in chapters 3 and 4.

All bacteria and archaea are microorganisms, but only some eukaryotes are microorganisms **(figure 1.5).** Also, of course, humans are eukaryotes. Certain small eukaryotes–such as helminths (worms), many of which can be seen with the naked eye–are also included in the study of infectious diseases because of the way they are transmitted and the way the body responds to them, though they are not microorganisms.

As stated previously, viruses are not independently living cellular organisms. Instead, they are small particles that are at a level of complexity somewhere between large molecules and cells**.** Viruses are much simpler than cells. Outside their host, they are composed of a small amount of hereditary material (either DNA or RNA but never both) wrapped up in a protein covering. Some viruses have an additional layer, a lipid membrane that is exterior to the protein part. Then we have prions, which are even simpler than viruses. They contain no nucleic acid, only protein, but act like infectious microorganisms.

1.1 LEARNING OUTCOMES—Assess Your Progress

1. List the various types of microorganisms that can colonize humans.
2. Describe the role and impact of microbes on the earth.
3. Explain the theory of evolution and why it is called a theory.
4. Explain the ways that humans manipulate organisms for their own uses.
5. Summarize the relative burden of human disease caused by microbes.
6. Differentiate among bacteria, archaea, and eukaryotic microorganisms.
7. Identify two acellular infectious agents that are studied in microbiology.
8. Compare and contrast the relative sizes of the different microbes.

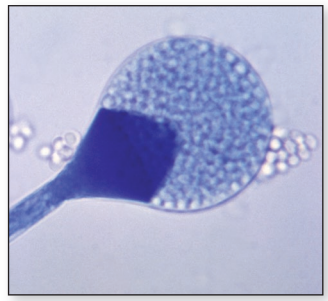
1.2 Microbes in History

If not for the extensive interest, curiosity, and devotion of thousands of microbiologists over the last 300 years, we would know little about the microscopic realm that surrounds us. Each additional insight, whether large or small, has added to our current knowledge of living things and processes. And the discoveries continue. Every day brings new surprises and insights into the microbial world. This section summarizes the prominent discoveries made in the past 300 years.

Spontaneous Generation

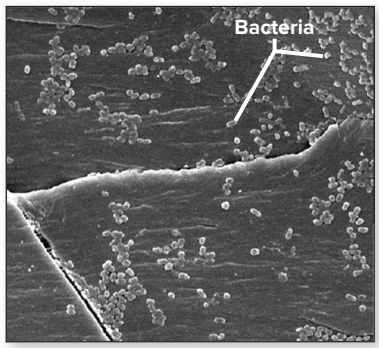
From very earliest history, humans noticed that when certain foods spoiled, they became inedible or caused illness, and yet other "spoiled" foods did no harm and even had enhanced flavor. Indeed, several centuries ago, there was already a sense that diseases such as the Black Plague and smallpox were caused by some sort of transmissible matter. But the causes of such phenomena were vague and obscure because, frankly, we couldn't *see* anything amiss. Consequently, they remained cloaked in mystery and regarded with superstition–a trend that led even well-educated scientists to believe in a concept called **spontaneous generation.** This was the belief that invisible vital forces present in matter led to the creation of life. The belief was continually reinforced as people observed that meat left out in the open soon "produced" maggots, that mushrooms appeared on rotting wood, seemingly out of nowhere, that rats and mice emerged from piles of litter, and other similar phenomena. Though some of these early ideas seem quaint and ridiculous in light of modern knowledge, we must remember that, at the time, mysteries in life were accepted and the scientific method was not widely practiced. Even after single-celled organisms

Helminth: Head (scolex) of *Taenia solium*

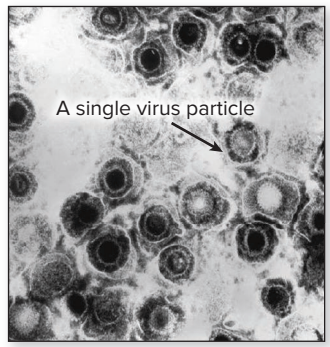


Fungus: *Mucor*

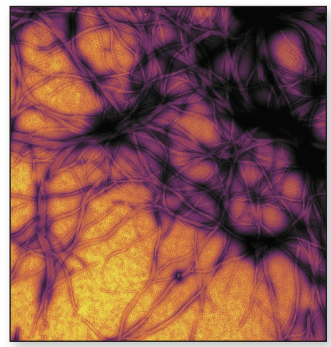
Protozoan: *Vorticella*



Bacterium: *E. coli*



Virus: Herpes simplex



Prion

Figure 1.5 Six types of microorganisms. Archaea are not pictured here.

Source: CDC/Dr. Mae Melvin (*Taenia solium*); CDC/Dr. Lucille K. Georg (*Mucor*); Nancy Nehring/E+/Getty Images (*Vorticella*); Janice Haney Carr/CDC (*E. coli*); Dr. Erskine Palmer/CDC (Herpes simplex); Cultura/Shutterstock (Prion)

Wine, cheese, and bread are each made using bacteria and fungi.

were discovered during the mid-1600s, the idea of spontaneous generation continued to exist. Some scientists assumed that microscopic beings were an early stage in the development of more complex ones.

Over the subsequent 200 years, scientists waged an experimental battle over the two hypotheses that could explain the origin of simple life forms. Some tenaciously clung to the idea of **abiogenesis** (*a* = "without"; *bio* = "life"; *genesis* = "beginning"–"beginning in absence of life"), which embraced spontaneous generation. On the other side were advocates of **biogenesis** ("beginning with life") saying that living things arise only from others of their same kind. There were serious advocates on both sides, and each side put forth what appeared on the surface to be plausible explanations of why its evidence was more correct. Finally in the mid-1800s, the acclaimed chemist and microbiologist Louis Pasteur entered the arena. He had recently been studying the roles of microorganisms in the fermentation of beer and wine, and it was clear to him that these processes were brought about by the activities of microbes introduced into the beverage from air, fruits, and grains. The methods he used to discount spontaneous generation were simple yet brilliant.

To demonstrate that air and dust were the source of microbes, Pasteur filled flasks with broth and shaped their openings into long, swan-neck-shaped tubes **(figure 1.6).** The flasks' openings were freely open to the air but were curved so that gravity would cause any airborne dust particles to deposit in the lower part of the necks. He heated the flasks to sterilize the broth and then incubated them. As long as the flask remained intact, the broth remained sterile; but if the neck was broken off so that dust fell directly down into the container, microbial growth immediately commenced.

Pasteur summed up his findings, "For I have kept from them, and am still keeping from them, that one thing which is above the power of man to make; I have kept from them the germs that float in the air, I have kept from them life."

The Role of the Microscope

True awareness of the widespread distribution of microorganisms and some of their characteristics was finally made possible by the development of the first microscopes. These devices revealed microbes as discrete entities sharing many of the characteristics of larger, visible plants and animals. Probably the earliest record of microbes is in the works of Englishman Robert Hooke. In the 1660s, Hooke studied many different materials, including household objects, plants, and trees. He described cellular structures for the first time (in tree bark) and drew sketches of "little structures" that seemed to be alive. Hooke paved the way for even more exacting observations of microbes by Antonie van Leeuwenhoek (lay′-oo-wun-hook), a Dutch linen merchant and self-made microbiologist.

Leeuwenhoek taught himself to grind glass lenses to ever-finer specifications so he could see the threads in his fabrics with better clarity. Eventually, he became interested

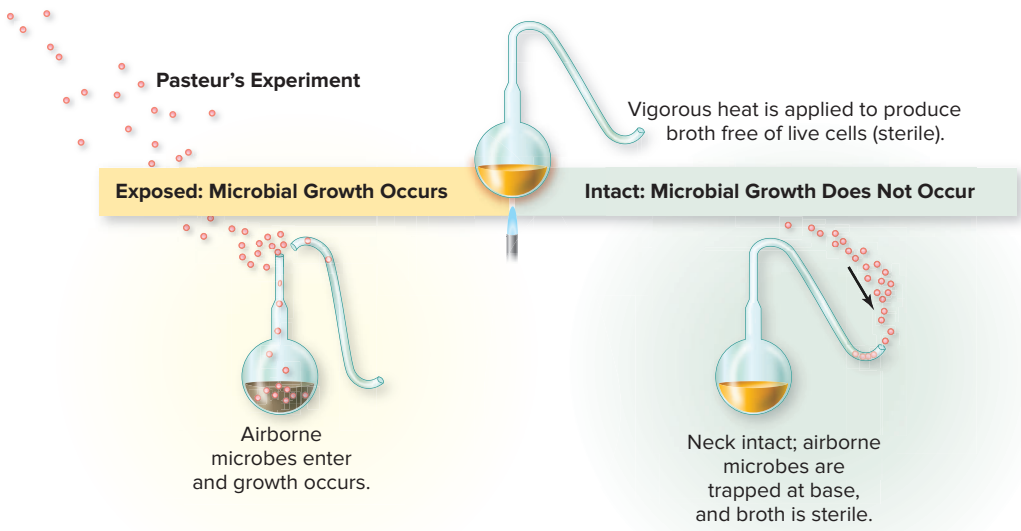


Figure 1.6 Pasteur's swan-neck flask experiment disproving spontaneous generation.
He left the flask open to air but bent the neck so that gravity would trap any airborne microbes.

in things other than thread counts. He took rainwater from a clay pot, smeared it on his specimen holder, and peered at it through his finest lens. He found "animals appearing to me ten thousand times less than those which may be perceived in the water with the naked eye."

He didn't stop there. He scraped the plaque from his teeth and from the teeth of some volunteers who had never cleaned their teeth in their lives and took a good close look at that. He recorded: "In the said matter there were many very little living animalcules, very prettily a-moving. . . . Moreover, the other animalcules were in such enormous numbers, that all the water . . . seemed to be alive." Leeuwenhoek started sending his observations to the Royal Society of London, and eventually he was recognized as a scientist of great merit.

Leeuwenhoek constructed more than 250 small, powerful microscopes that could magnify objects up to 300 times **(figure 1.7).** Considering that he had no formal training in science, his descriptions of bacteria and protozoa (which he called "animalcules") were accurate and precise.

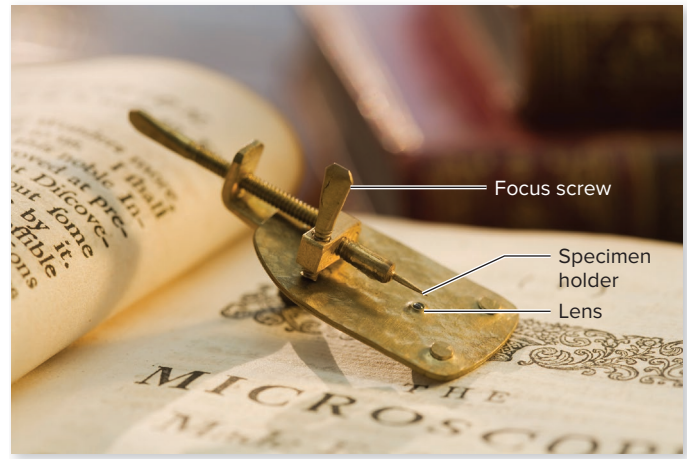


Figure 1.7 Leeuwenhoek's microscope. A brass replica of a Leeuwenhoek microscope. The lens is held in front of one eye with the specimen holder facing outward.

Tetra Images/Alamy Stock Photo

These events marked the beginning of our understanding of microbes and the diseases they can cause. Discoveries continue at a breakneck pace, however. In fact, the 2000s are being widely called the Century of Biology, fueled by our new abilities to study genomes and harness biological processes. To give you a feel for what has happened most recently, **table 1.3** provides a glimpse of some recent discoveries that have had huge impacts on our understanding of microbiology.

The changes to our view of the role of RNAs that you see in table 1.3 highlight a feature of biology–and all of science–that is perhaps underappreciated. Because we have thick textbooks containing all kinds of assertions and "facts," many people think science is an ironclad collection of facts. Wrong! Science is an ever-evolving collection of new information, gleaned from observable phenomena and combined with old information to come up with the current understandings of nature. Some of the hypotheses explaining these observations have been confirmed so many times over such a long period of time that they are, if not "fact," very close to fact. Many other hypotheses will be altered over and over again as new findings emerge. And that is the beauty of science.

It is important to understand that modern science is conducted according to a set of widely accepted "rules," termed the *scientific method* **(figure 1.8).** Researchers form a hypothesis, and then perform experiments or other types of studies that allow them to either reject or accept the hypothesis. In real life it can also get much more complicated than that. Note the blue arrows in the figure indicating that the process can stop and revisit earlier steps. After the results are communicated (last step in the figure), other scientists review and repeat the studies in order to verify them or bring them into question. This is a process that distinguishes true research from even the most educated guesses or opinions.

The Beginnings of Medical Microbiology

Early experiments on the sources of microorganisms led to the profound realization that microbes are everywhere: Not only are air and dust full of them, but the entire surface of the earth, its waters, and all objects are inhabited by them. This discovery led to immediate applications in medicine. So you see that the seeds of medical microbiology were sown in the mid to latter half of the 19th century (the 1800s) with the introduction of the germ theory of disease and the resulting use of sterile, aseptic, and pure culture techniques.

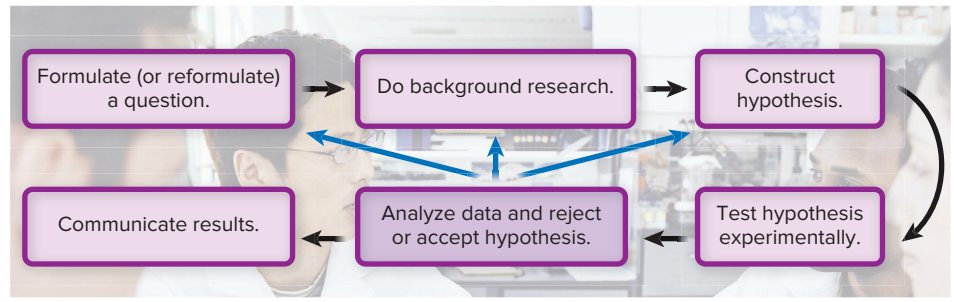
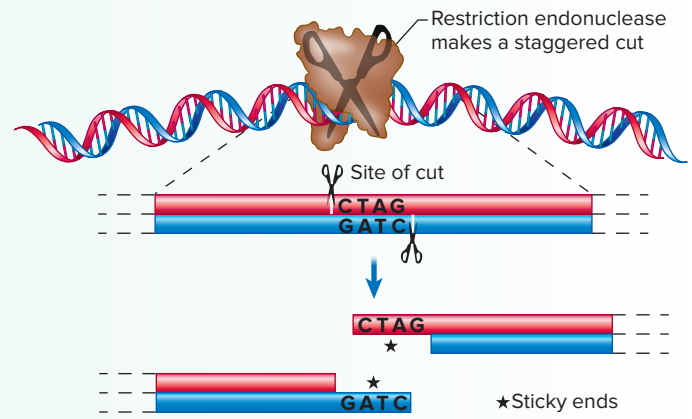


Figure 1.8 An overview of the scientific method.

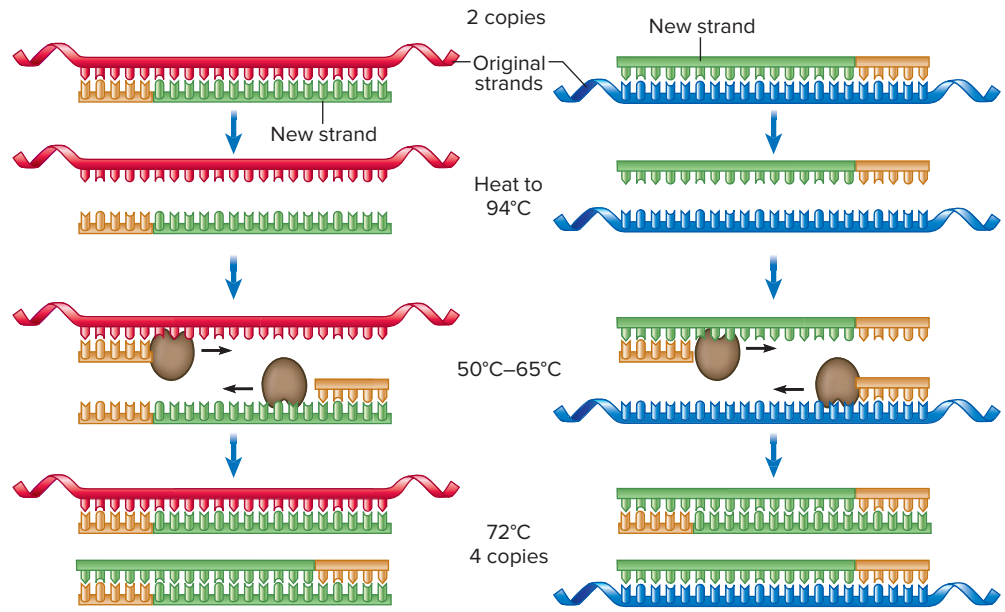
Ryan McVay/Getty Images

Table 1.3 Recent Advances in Microbiology

Discovery of restriction enzymes—1970s. Three scientists, Daniel Nathans, Werner Arber, and Hamilton Smith, discovered these little molecular "scissors" inside bacteria. They chop up DNA in specific ways. This was a huge moment that enabled scientists to use these enzymes to cut DNA in tailor-made ways. This opened the floodgates to genetic engineering–and all that has meant for the treatment of diseases, the investigation into biological processes, and the biological "revolution" of the 21st century.



The invention of the PCR technique—1980s. The polymerase chain reaction (PCR) was a breakthrough in our ability to detect tiny amounts of DNA and then amplify them into quantities sufficient for studying. It has provided a new and powerful method for discovering new organisms, diagnosing infectious diseases, and doing forensic work such as crime scene investigation. Its inventor is Kary Mullis, a scientist working at a company in California at the time. He won the Nobel Prize for this invention in 1993.



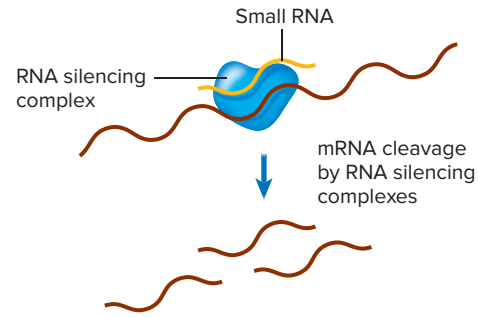
The Discovery of Spores and Sterilization

The discovery and detailed description of heat-resistant bacterial endospores by Ferdinand Cohn, a German botanist, clarified the reason that heat would sometimes fail to completely eliminate all microorganisms. The modern sense of the word **sterile,** meaning completely free of all life forms (including spores) and virus particles, was established from that point on. The capacity to sterilize objects and materials is an absolutely essential part of microbiology, medicine, dentistry, and many industries.

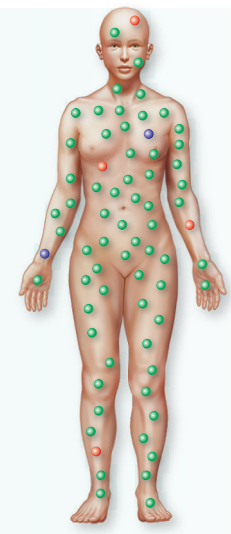
The Development of Aseptic Techniques

At the same time that spontaneous generation was being hotly debated, a few physicians began to suspect that microorganisms could cause not only spoilage and decay but also human diseases. It occurred to these rugged individualists that even the human body itself was a source of infection. In 1843, Dr. Oliver Wendell

The importance of small RNAs—2000s. Once we were able to sequence entire genomes (another big move forward), scientists discovered something that turned a concept we literally used to call "dogma" on its head. The previously held "Central Dogma of Biology" was that DNA makes RNA, which leads to the creation of proteins. Genome sequencing has revealed that perhaps only 2% of DNA actually codes for a protein. Much RNA doesn't end up with a protein counterpart. These pieces of RNA are usually small. It now appears that they have critical roles in regulating what happens in the cell. It has led to new approaches to how diseases are treated. For example, if some small RNAs are important in bacteria that infect humans, they can be new targets for antimicrobial therapy.



Genetic identification of the human microbiome—2010s and beyond. The first detailed information produced by the Human Microbiome Project (HMP) was astounding: Even though the exact types of microbes found in and on different people are highly diverse, the overall set of metabolic capabilities the bacterial communities possess is remarkably similar among people. This and other groundbreaking discoveries have set the stage for new knowledge of our microbial guests and their role in our overall health and disease.



Holmes, an American physician, published an article in which he observed that mothers who gave birth at home experienced fewer infections than did mothers who gave birth in the hospital. A few years later, the Hungarian Dr. Ignaz Semmelweis showed quite clearly that women became infected in the maternity ward after being examined by physicians coming directly from the autopsy room—without washing their hands.

In the 1860s, the English surgeon Joseph Lister took notice of these observations and was the first to introduce **aseptic** (ay-sep′-tik) **techniques** aimed at reducing microbes in a medical setting. Lister's concept of asepsis was much more limited than our modern precautions. It mainly involved disinfecting the hands and the air with strong antiseptic chemicals, such as phenol, prior to surgery. It is hard for us to believe, but as recently as the late 1800s surgeons wore street clothes in the operating room and had little idea that hand washing was important **(figure 1.9).** Lister's techniques and the application of heat for sterilization became the foundations for microbial control by physical and chemical methods, which are still in use today.

Figure 1.9 An artist's depiction of Joseph Lister's operating theater in the mid-1800s.
Bettmann/Getty Images

The Germ Theory of Disease

Louis Pasteur made enormous contributions to our understanding of the microbial role in wine and beer formation. He invented pasteurization and conducted some of the first studies showing that human diseases could arise from infection. These studies, supported by the work of other scientists, became known as the **germ theory of disease.** Pasteur's contemporary, Robert Koch, established *Koch's postulates,* a series of logical steps that verified the germ theory and could establish whether an organism was pathogenic and which disease it caused (see chapter 11). About 1875, Koch used this experimental system to show that anthrax was caused by a bacterium called *Bacillus anthracis.* So useful were his postulates that the causative agents of 20 other diseases were discovered between 1875 and 1900, and even today, they are the standard for identifying pathogens of plants and animals.

1.2 LEARNING OUTCOMES—Assess Your Progress

9. Make a time line of the development of microbiology from the 1600s to today.
10. List some recent microbiology discoveries of great impact.
11. Identify the important features of the scientific method.

1.3 Macromolecules: Superstructures of Life

In this book, we won't be presenting the basics of chemistry, though of course it is important to understand chemical concepts to understand all of biology. But that is what chemistry textbooks are for! However, there will be so much emphasis on some important *bio*chemicals in this book and in your course that we want to present a concise description of cellular macromolecules.

All microorganisms–indeed, all organisms–are constructed from just a few major types of biological molecules, called **macromolecules**–"macro" because they are often very large. They include four main families: carbohydrates, lipids, proteins, and nucleic acids **(table 1.4).** All macromolecules except lipids are formed by polymerization, a process in which repeating subunits termed **monomers** are bound into chains of various lengths termed **polymers.** For example, proteins (polymers) are composed of a chain of amino acids (monomers). In the following section and in later chapters, we consider numerous concepts relating to the roles of macromolecules in cells. **Table 1.5** presents the important structural features of the four main macromolecules.

The green specks are microorganisms in the stomach of a tube worm.
©Stephen Durr

Carbohydrates: Sugars and Polysaccharides

The term **carbohydrate** originates from the composition of members of this class: They are combinations of carbon (*carbo-*) and water. Carbohydrates can be generally represented by the formula $(CH_2O)_n$, in which *n* indicates the number of units of this combination of atoms. Some carbohydrates also contain additional atoms of sulfur or nitrogen **(figure 1.10).**

Monosaccharides and disaccharides are specified by combining a prefix that describes some characteristic of the sugar with the suffix *-ose.* For example, **hexoses** are composed of 6 carbons, and **pentoses** contain 5 carbons. **Glucose** (Gr. *glyko,* "sweet") is the most common and universally important hexose; **fructose** is named for fruit (one place where it is found); and xylose, a pentose, derives its name from the Greek word for wood. Disaccharides are named similarly: **lactose** (L. *lacteus,* "milk") is an important component of milk; **maltose** means malt sugar; and **sucrose** (Fr. *sucre,* "sugar") is common table sugar or cane sugar.

Table 1.4 Macromolecules and Their Functions

Macromolecule	Basic Structure	Examples	Notes About the Examples
Carbohydrates			
Monosaccharides	3- to 7-carbon sugars	Glucose, fructose	Sugars involved in metabolic reactions; building block of disaccharides and polysaccharides
Disaccharide	Two monosaccharides	Maltose (malt sugar)	Composed of two glucoses; an important breakdown product of starch
		Lactose (milk sugar)	Composed of glucose and galactose
		Sucrose (table sugar)	Composed of glucose and fructose
Polysaccharides	Chains of monosaccharides	Starch, cellulose, glycogen	Cell wall, food storage
Lipids			
Triglycerides	Fatty acids + glycerol	Fats, oils	Major component of cell membranes; storage
Phospholipids	Fatty acids + glycerol + phosphate	Membrane components	
Waxes	Fatty acids, alcohols	Mycolic acid	Cell wall of mycobacteria
Steroids	Ringed structure	Cholesterol, ergosterol	In membranes of eukaryotes and some bacteria
Proteins	Chains of amino acids	Enzymes; part of cell membrane, cell wall, ribosomes, antibodies	Serve as structural components and perform metabolic reactions
Nucleic acids	Nucleotides (pentose sugar + phosphate + nitrogen base) Nitrogen bases Purines: adenine (A), guanine (G) Pyrimidines: cytosine (C), thymine (T), uracil (U)		
Deoxyribonucleic acid (DNA)	Contains deoxyribose sugar and thymine, not uracil	Chromosomes; genetic material of viruses	Mediate inheritance
Ribonucleic acid (RNA)	Contains ribose sugar and uracil, not thymine	Ribosomes; mRNA, tRNA, small RNAs, genetic material of viruses	Facilitate expression of genetic traits

The Functions of Polysaccharides

Polysaccharides contribute to structural support and protection and also serve as nutrient and energy stores. The cell walls in plants and many microscopic algae derive their strength and rigidity from **cellulose,** a long, fibrous polysaccharide. Because of this role, cellulose is probably one of the most common organic substances on the earth. Interestingly, it is digestible only by certain bacteria, fungi, and protozoa. These microbes, called decomposers, play an essential role in breaking down and recycling plant materials.

Structural polysaccharides can be conjugated (chemically bonded) to amino acids, nitrogen bases, lipids, or proteins. **Agar,** an indispensable polysaccharide in preparing solid culture media, is a natural component of certain seaweeds. It is a complex polymer of galactose and sulfur-containing carbohydrates. The exoskeletons of certain fungi contain **chitin** (ky′-tun), a polymer of glucosamine (a sugar with an amino functional group). **Peptidoglycan** (pep-tih-doh-gly′-kan) is one special class of compounds in which polysaccharides (glycans) are linked to peptide fragments (a short chain of amino acids). This molecule provides the main source of structural support to the bacterial cell wall. The outer covering of gram-negative bacteria also contains **lipopolysaccharide,** a complex of lipid and polysaccharide responsible for symptoms such as fever and shock (see chapters 3 and 11).

The outer surface of many cells has a "sugar coating" composed of polysaccharides bound in various ways to proteins (this combination is termed a glycoprotein). This structure, called the **glycocalyx,** serves as a protective outer layer, and also can play a role in attachment of the cells to other cells or surfaces. Small sugar

Medical Moment

Delivering Essential Nutrients

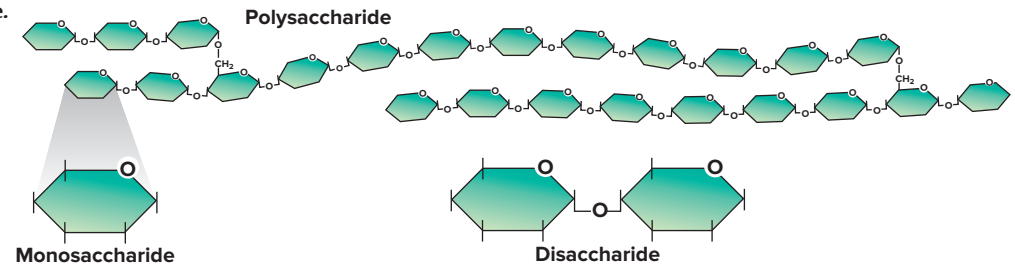
It is important to maintain homeostasis in ill patients. Supplemental nutrition is often necessary. For some patients, intake of calories by mouth or feeding tube is not possible. In order to supply essential minerals, vitamins, electrolytes, amino acids, glucose, and fluid, nutrition via intravenous (IV) line may be initiated. Total parenteral nutrition (TPN) is prescribed to meet the entirety of the patient's daily nutritional needs, accounting for their specific disease process and organ function. In addition, fatty acids might be prescribed alongside TPN because they provide essential energy stores and help with the absorption of some vitamins. This intravenous nutrition provides the body with energy patients need for maintenance of cellular processes and promotion of healing.

Q. Use context in the paragraph above to deduce what the word "parenteral" means.

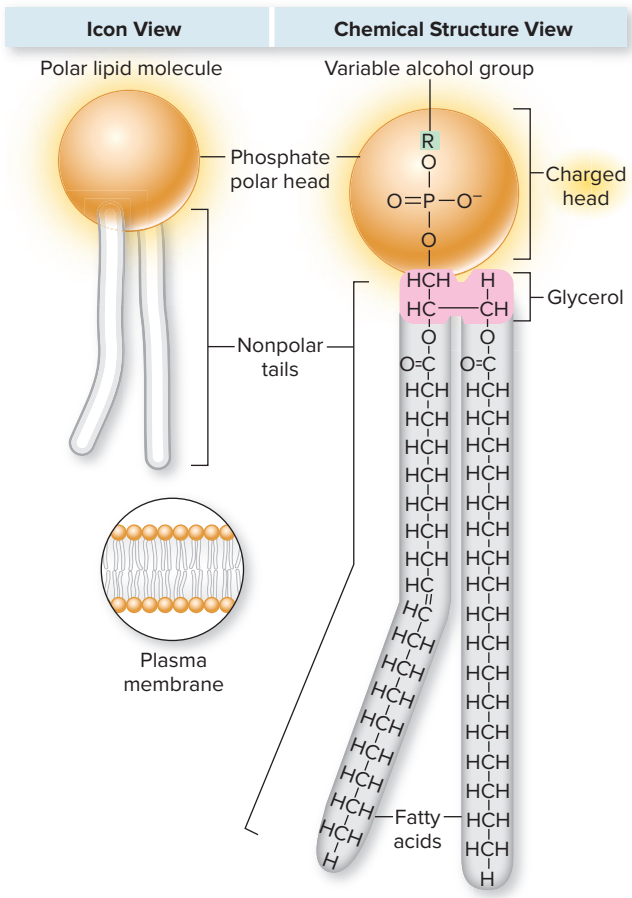
Answer in Appendix B.

Table 1.5 Macromolecules in the Cell

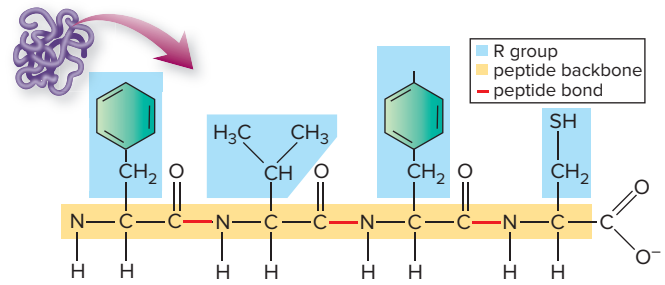
Carbohydrates. Another word for *sugar* is **saccharide.** A **monosaccharide** is a simple sugar containing from 3 to 7 carbons; a **disaccharide** is a combination of two monosaccharides; and a **polysaccharide** is a polymer of five or more monosaccharides bound in linear or branched chain patterns.



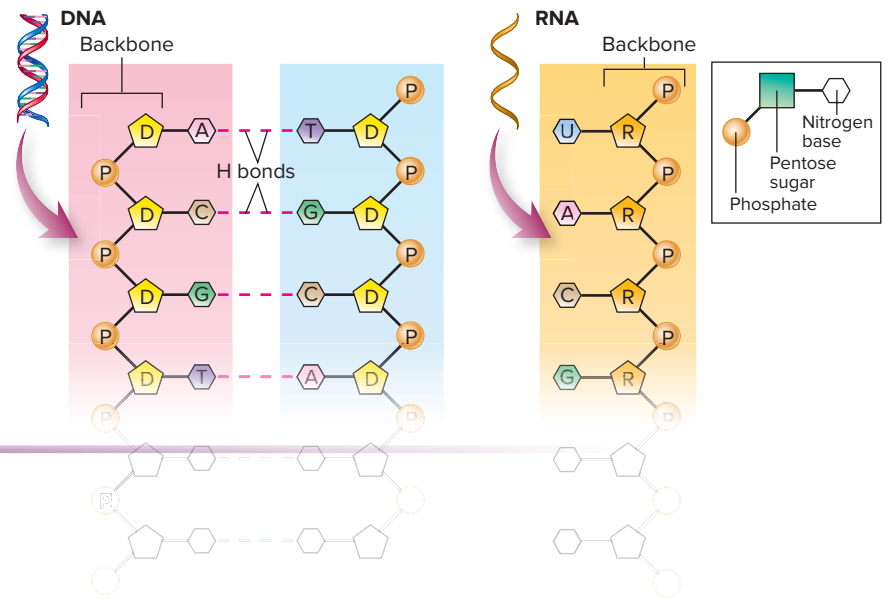
Lipids. The term **lipid,** derived from the Greek word *lipos,* meaning fat, is not a chemical designation but an operational term for a variety of substances that are not soluble in polar solvents such as water but will dissolve in nonpolar solvents such as benzene and chloroform. Here we see a model of a single molecule of a phospholipid. The phosphate-alcohol head leads a charge to one end of the molecule; its long, trailing hydrocarbon chain is uncharged.



Proteins. Proteins are chains of amino acids. Amino acids have a basic skeleton consisting of a carbon (called the α carbon) linked to an amino group (NH_2), a carboxyl group (COOH), a hydrogen atom (H), and a variable R group. The variations among the amino acids occur at the R group, which is different in each amino acid and confers the unique characteristics to the molecule and to the proteins that contain it. A covalent bond called a **peptide bond** forms between the amino group on one amino acid and the carboxyl group on another amino acid.



Nucleic acids. Both DNA and RNA are polymers of repeating units called **nucleotides,** each of which is composed of three smaller units: a **nitrogen base,** a **pentose** (5-carbon) sugar, and a **phosphate.** The nitrogen base is a cyclic compound that comes in two forms: *purines* (two rings) and *pyrimidines* (one ring). There are two types of purines–**adenine (A)** and **guanine (G)**–and three types of pyrimidines–**thymine (T), cytosine (C),** and **uracil (U).** The nitrogen base is covalently bonded to the sugar *ribose* in RNA and *deoxyribose* (because it has one less oxygen than ribose) in DNA. The backbone of a nucleic acid strand is a chain of alternating phosphate-sugar-phosphate-sugar molecules, and the nitrogen bases branch off the side of this backbone.



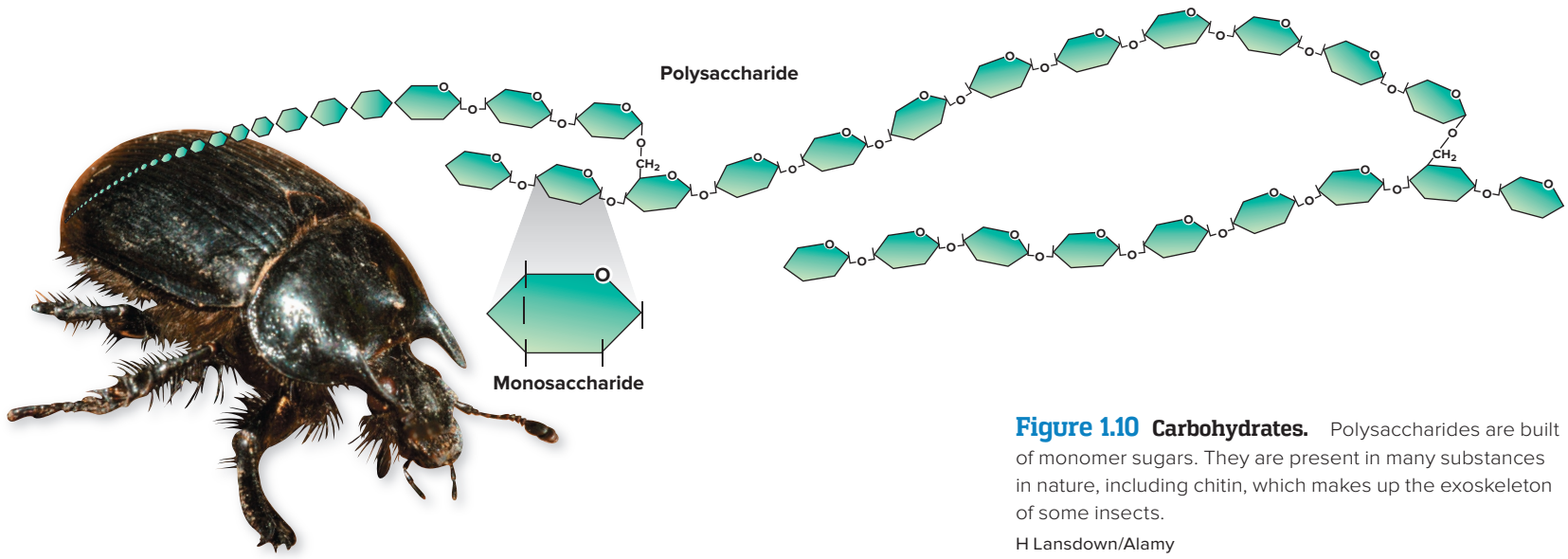


Figure 1.10 Carbohydrates. Polysaccharides are built of monomer sugars. They are present in many substances in nature, including chitin, which makes up the exoskeleton of some insects.

H Lansdown/Alamy

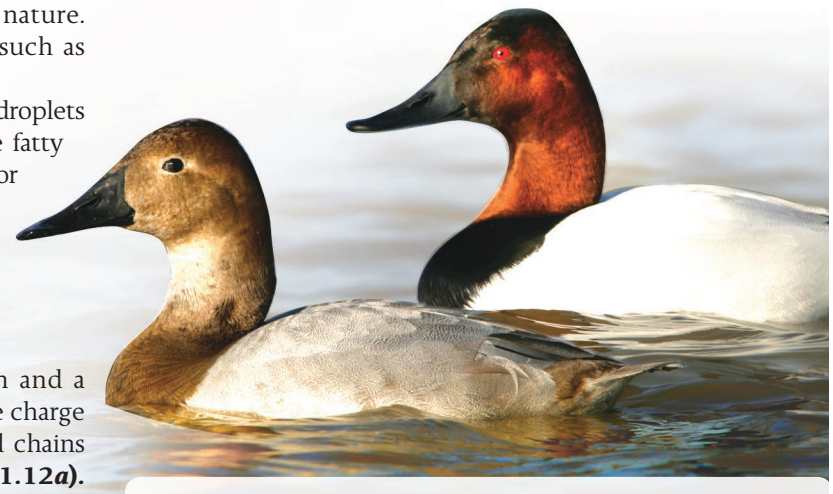
molecules on cell surfaces also account for the differences in human blood types. Viruses also have glycoproteins on their surface with which they bind to and invade their host cells.

Lipids: Fats, Phospholipids, Steroids, and Waxes

There are four main types of compounds classified as lipids: triglycerides, phospholipids, steroids, and waxes.

The **triglycerides** are an important storage lipid. This category includes fats and oils. Triglycerides are composed of a single molecule of glycerol bound to three fatty acids **(figure 1.11). Glycerol** is a 3-carbon alcohol with three OH groups, and fatty acids are long-chain hydrocarbon molecules with a carboxyl group (COOH) at one end that is free to bind to the glycerol. The hydrocarbon portion of a fatty acid can vary in length from 4 to 24 carbons–and, depending on the fat, it may be saturated or unsaturated. If all carbons in the chain are single-bonded to 2 other carbons and 2 hydrogens, the fat is saturated. If there is at least one C=C double bond in the chain, it is unsaturated. The structure of fatty acids is what gives fats and oils (liquid fats) their greasy, insoluble nature. In general, solid fats (such as butter) are more saturated, and liquid fats (such as oils) are more unsaturated.

In most cells, triglycerides are stored in long-term concentrated form as droplets or globules. When they are acted on by digestive enzymes called lipases, the fatty acids and glycerol are freed to be used in metabolism. Fatty acids are a superior source of energy, yielding twice as much per gram as other storage molecules (carbohydrates). Soaps are K^+ or Na^+ salts of fatty acids whose qualities make them excellent grease removers and cleaners (see chapter 9).



Oils on duck feathers keep these two canvasback ducks insulated and dry, no matter how much time they spend in the water.

©Guy Crittenden/Getty Images

Membrane Lipids

Phospholipids in membranes have a hydrophilic ("water-loving") region and a hydrophobic ("water-fearing") region. The hydrophilic region carries a negative charge due to a phosphate group attached to an alcohol group. The long fatty acid chains are uncharged and make that portion of the molecule hydrophobic **(figure 1.12*a*).** When exposed to an aqueous solution, the charged heads are attracted to the water phase, and the nonpolar tails are repelled from the water phase **(figure 1.12*b*).** This property causes lipids to naturally form into single and double layers (bilayers). When two single layers of polar lipids come together to form a double layer, the outer

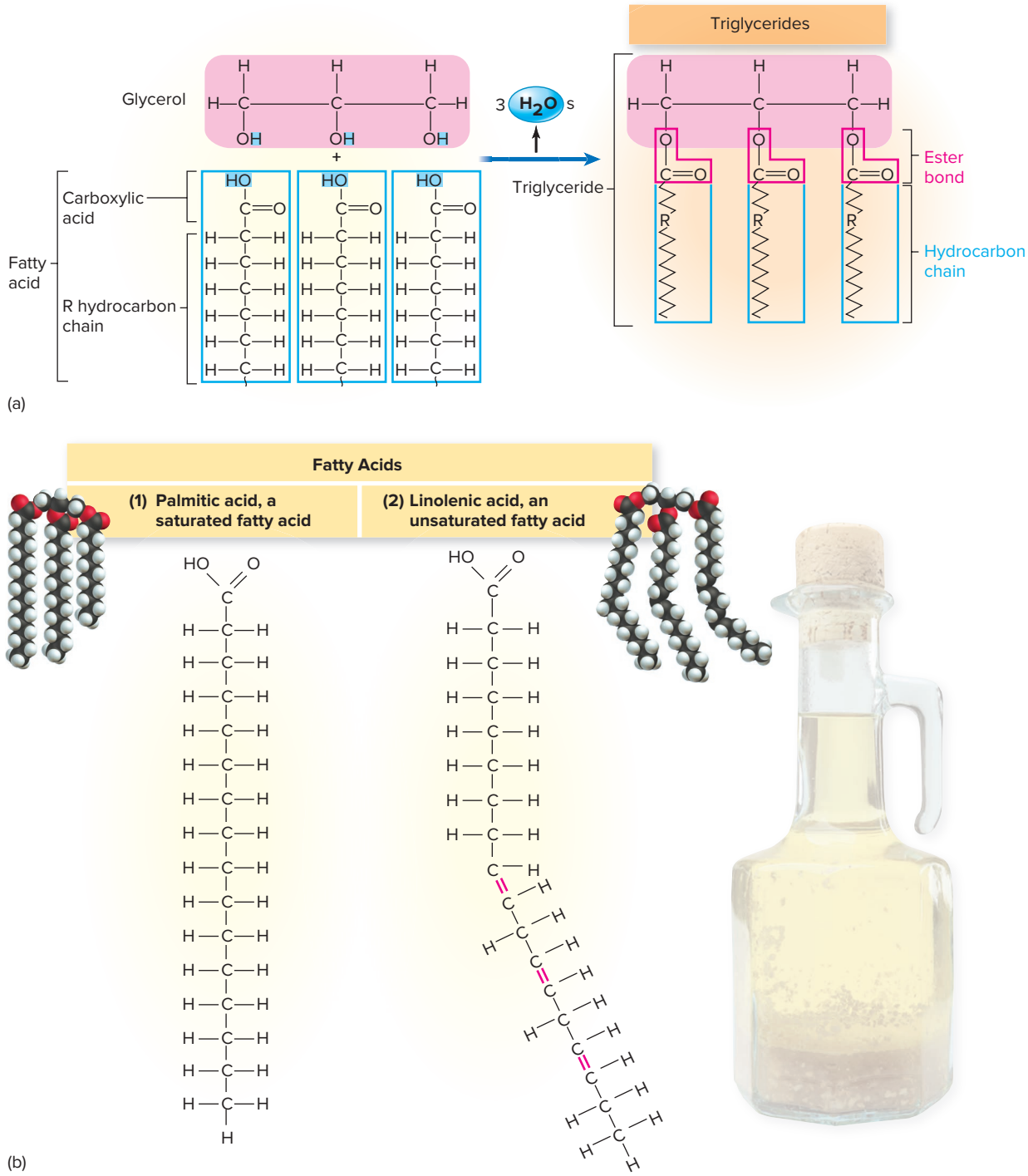


Figure 1.11 Synthesis and structure of a triglyceride. **(a)** Because a water molecule is released at each ester bond, this is an example of dehydration synthesis. The jagged lines and R symbol represent the hydrocarbon chains of the fatty acids, which are commonly very long. **(b)** Structural and three-dimensional models of fatty acids and triglycerides. (1) A saturated fatty acid has long, straight chains that readily pack together and form solid fats. (2) An unsaturated fatty acid—here a polyunsaturated one with 3 double bonds—has a bend in the chain that prevents packing and produces oils (right).

Stockbyte/PunchStock

hydrophilic face of each single layer will orient itself toward the solution, and the hydrophobic portions will become immersed in the core of the bilayer. This behavior allows phospholipids to be the main constituent of all cell membranes.

Steroids and Waxes

Steroids are complex ringed compounds commonly found in cell membranes and as animal hormones. The best known of these is the sterol called **cholesterol (figure 1.13).** (A sterol is a steroid that has an OH group.) Cholesterol reinforces the structure of the

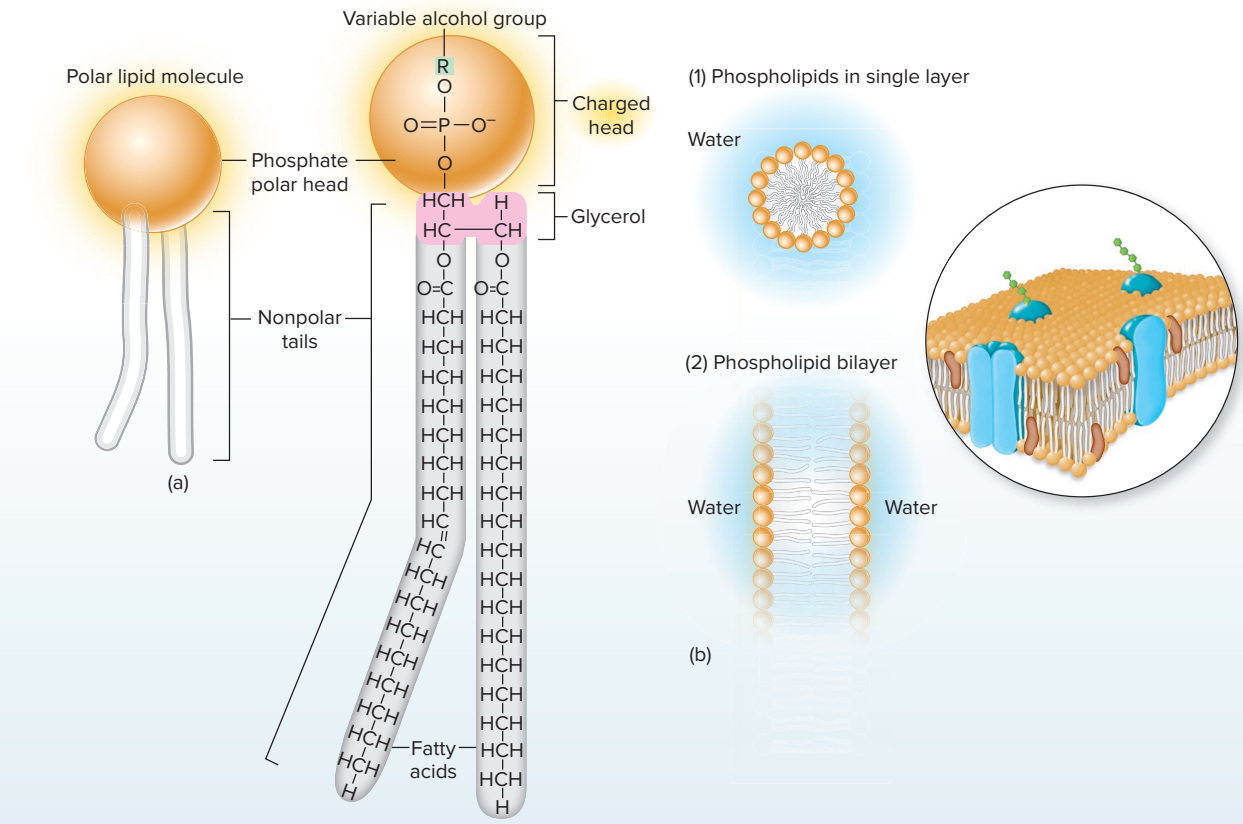


Figure 1.12 Phospholipids—membrane molecules. **(a)** A model of a single molecule of a phospholipid. The phosphate-alcohol head lends a charge to one end of the molecule; its long, trailing hydrocarbon chain is uncharged. **(b)** The behavior of phospholipids in water-based solutions causes them to become arranged (1) in single layers called micelles, with the charged head oriented toward the water phase and the hydrophobic nonpolar tail buried away from the water phase, or (2) in double-layered phospholipid systems with the hydrophobic tails sandwiched between two hydrophilic layers.

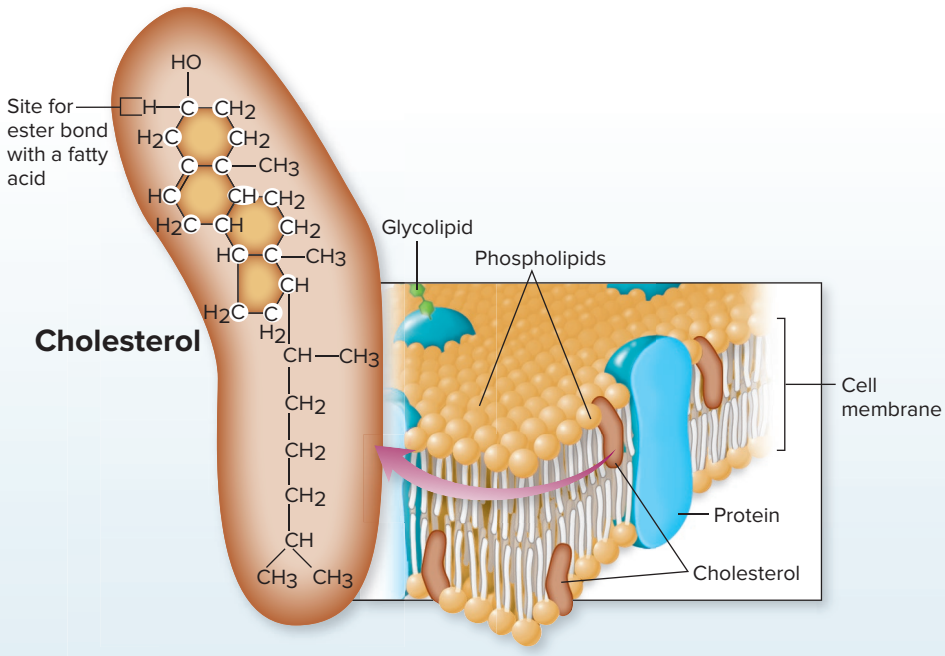


Figure 1.13 Cutaway view of a membrane with its bilayer of lipids. The primary lipid is phospholipid—however, cholesterol is inserted in some membranes.

Table 1.6 Twenty Amino Acids and Their Abbreviations

Acid	Abbreviation	Characteristic of Their R Groups
Alanine	Ala	nonpolar
Arginine	Arg	+
Asparagine	Asn	polar
Aspartic acid	Asp	−
Cysteine	Cys	polar
Glutamic acid	Glu	−
Glutamine	Gln	polar
Glycine	Gly	polar
Histidine	His	+
Isoleucine	Ile	nonpolar
Leucine	Leu	nonpolar
Lysine	Lys	+
Methionine	Met	nonpolar
Phenylalanine	Phe	nonpolar
Proline	Pro	nonpolar
Serine	Ser	polar
Threonine	Thr	polar
Tryptophan	Trp	nonpolar
Tyrosine	Tyr	polar
Valine	Val	nonpolar

+ = positively charged; − = negatively charged.

cell membrane in animal cells and in an unusual group of cell-wall-deficient bacteria called the mycoplasmas. The cell membranes of fungi also contain a sterol, called ergosterol.

Chemically, a *wax* is an ester formed between a long-chain alcohol and a saturated fatty acid. The resulting material is typically pliable and soft when warmed but hard and water resistant when cold (think of a wax candle). Among living things, fur, feathers, fruits, leaves, human skin, and insect exoskeletons are naturally waterproofed with a coating of wax. Bacteria that cause tuberculosis and leprosy produce a wax that repels ordinary laboratory stains and contributes to their disease-causing potential.

Proteins: Shapers of Life

The predominant organic molecules in cells are **proteins.** To a large extent, the structure, behavior, and unique qualities of each living thing are a consequence of the proteins they contain. The building blocks of proteins are **amino acids,** which exist in 20 different naturally occurring forms **(table 1.6).** Various combinations of these amino acids account for the nearly infinite variety of proteins.

Various terms are used to denote the nature of proteins. **Peptide** usually refers to a molecule composed of short chains of amino acids, such as a dipeptide (two amino acids), a tripeptide (three), and a tetrapeptide (four). A **polypeptide** contains an unspecified number of amino acids but usually has more than 20 and is often a smaller subunit of a protein. A protein is the largest of this class of compounds and usually contains a minimum of 50 amino acids. It is common for the term *protein* to be used to describe all of these molecules. In chapter 8, we see that protein synthesis is not just a random connection of amino acids; it is directed by information provided in DNA.

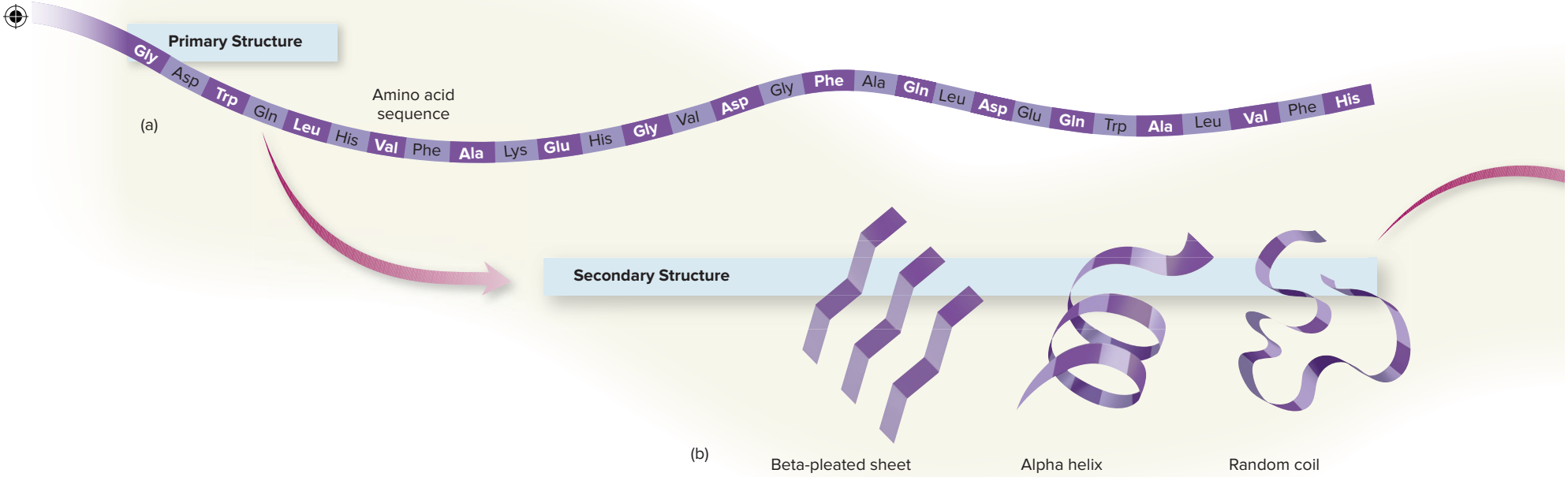
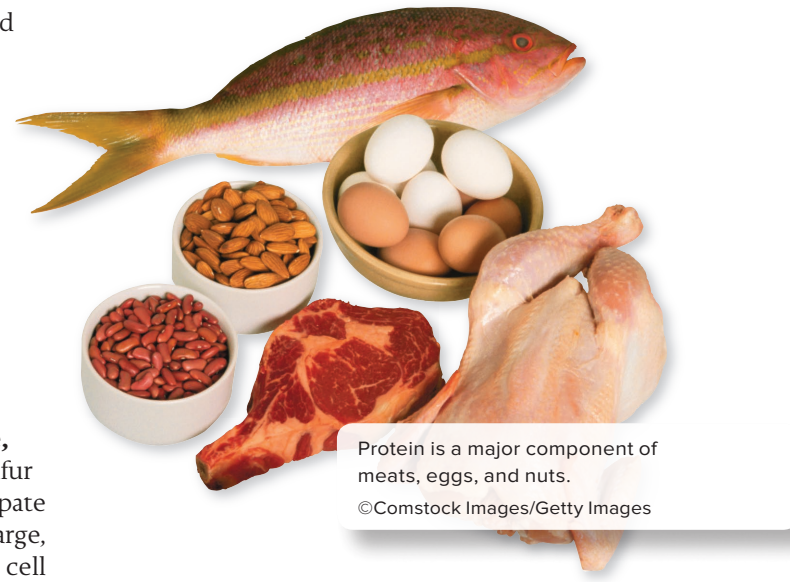


Figure 1.14 Stages in the formation of a functioning protein. **(a)** Its primary structure is a series of amino acids bound in a chain. **(b)** Its secondary structure develops when the chain forms hydrogen bonds that fold it into one of several configurations such as an α *helix* or β*-pleated sheet.* Some proteins have several configurations in the same molecule. **(c)** A protein's tertiary structure is due to further folding of the molecule into a three-dimensional mass that is stabilized by hydrogen, ionic, and disulfide bonds between functional groups. **(d)** The quaternary structure exists only in proteins that consist of more than one polypeptide chain. Each of the separate chains in this protein has a different color.

Protein Structure and Diversity

The reason that proteins are so varied and specific is that the way they are folded makes all the difference with respect to their function. A protein has a natural tendency to assume more complex levels of organization, called the secondary, tertiary, and quaternary structures **(figure 1.14).** The **primary (1°) structure** is the type, number, and order of amino acids in the chain, which varies extensively from protein to protein. The **secondary (2°) structure** arises when various functional groups (called R groups) exposed on the outer surface of the molecule interact by forming hydrogen bonds. This interaction causes the amino acid chain to twist into a coiled configuration called the *alpha helix* (α helix) or to fold into an accordion pattern called a *beta-pleated sheet* (β-pleated sheet). Many proteins contain both types of secondary configurations. Proteins at the secondary level undergo a third degree of torsion called the **tertiary (3°) structure** created by additional bonds between functional groups (figure 1.14*c*). In proteins with the sulfur-containing amino acid **cysteine,** further tertiary stability is achieved through covalent disulfide bonds between sulfur atoms on two different parts of the molecule. Some complex proteins also participate in a **quaternary (4°) structure,** in which more than one polypeptide forms a large, multiunit protein. This is typical of antibodies and some enzymes that act in cell synthesis.



Protein is a major component of meats, eggs, and nuts.

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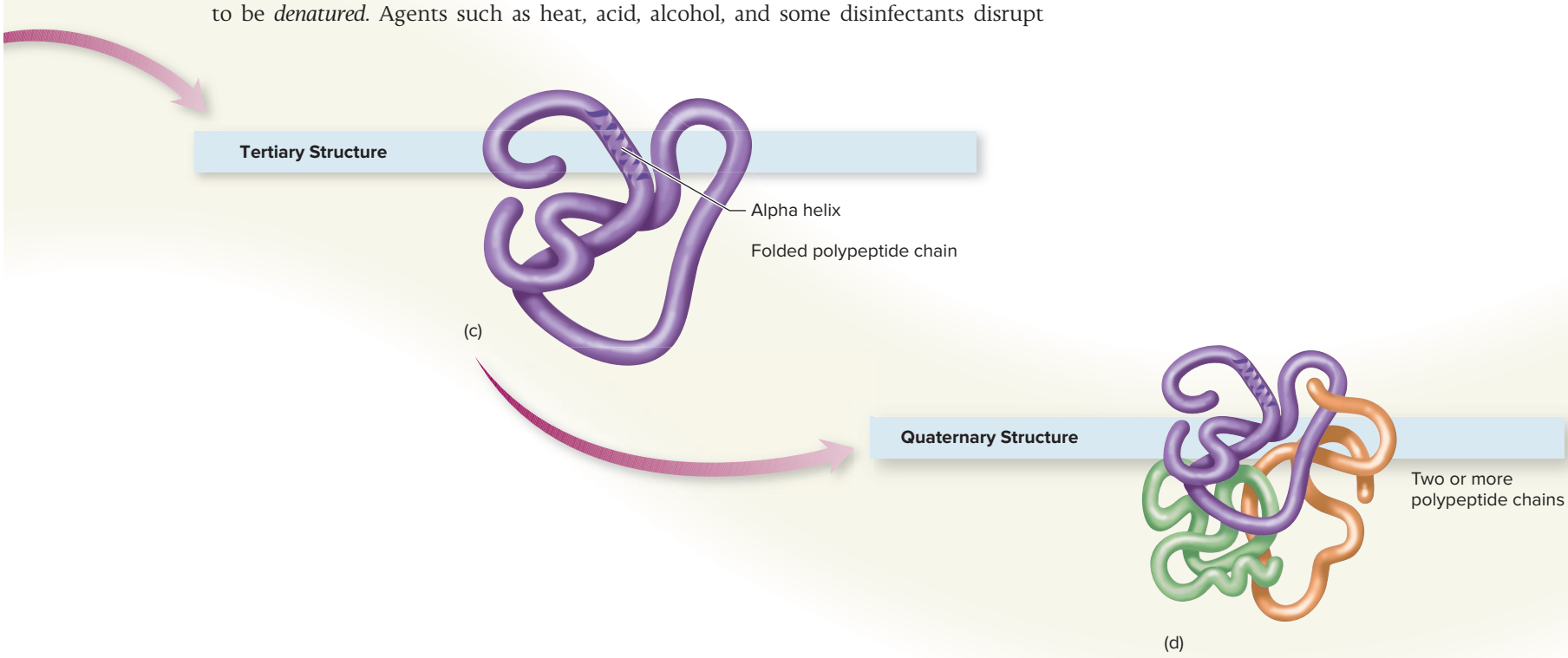
The most important outcome of the various forms of bonding and folding is that each different type of protein develops a unique shape, and its surface displays a distinctive pattern of pockets and bulges. As a result, a protein can react only with molecules that complement or fit its particular surface features like a lock and key. Such a degree of specificity can provide the functional diversity required for many thousands of different cellular activities. For example, **enzymes** serve as the catalysts for all chemical reactions in cells, and nearly every reaction requires a different enzyme (see chapter 7). This specificity comes from the architecture of the binding site, which determines which molecules fit it. The same is true of antibodies: **Antibodies** are complex glycoproteins with specific regions of attachment for bacteria, viruses, and other microorganisms. The functional three-dimensional form of a protein is termed the *native state.* If it is disrupted by some means, the protein is said to be *denatured.* Agents such as heat, acid, alcohol, and some disinfectants disrupt



Curly hair is the result of particular protein folding patterns as described in figure 1.14.

(i.e., denature) the stabilizing bonds within the chains and cause the molecule to become nonfunctional, as described in chapter 9.

The Nucleic Acids: A Cell Computer and Its Programs

The fourth type of macromolecule is **nucleic acid.** DNA and RNA are two major representatives of this group. DNA contains a special coded genetic program with detailed and specific instructions for each organism's heredity. It transfers the details of its program to RNA, "helper" molecules responsible for carrying out DNA's instructions and translating the DNA program into proteins that can perform life functions. For now, let us briefly consider the structure and some functions of DNA, RNA, and a close relative, adenosine triphosphate (ATP).

The Double Helix of DNA

DNA is a huge molecule formed by two long nucleotide strands linked along their length by hydrogen bonds between nitrogen bases. The pairing of the nitrogen bases occurs according to a predictable pattern: Adenine always pairs with thymine, and cytosine with guanine. The bases are attracted in this way because each pair shares oxygen, nitrogen, and hydrogen atoms exactly positioned to align perfectly for hydrogen bonds **(figure 1.15).**

Owing to the manner of nucleotide pairing and stacking of the bases, the actual configuration of DNA is a *double helix* that looks somewhat like a spiral staircase. Just as with proteins, the structure of DNA is intimately related to its function. DNA molecules are usually extremely long.

RNA: Organizers of Protein Synthesis

Like DNA, RNA consists of a long chain of nucleotides. However, RNA is usually a single strand, except in some viruses. It contains ribose sugar instead of deoxyribose and uracil instead of thymine (see table 1.5). Several functional types of RNA are formed using the DNA template through a process called transcription. Three major types of RNA are directly used for protein synthesis. Messenger RNA (mRNA) is a copy of a gene (a single functional part of the DNA) that provides the order and type of amino acids in a protein; transfer RNA (tRNA) is a carrier that delivers the correct amino acids for protein assembly; and ribosomal RNA (rRNA) is a major component of ribosomes (described in chapter 3). A fourth type of RNA is the RNA that acts to regulate the genes and gene expression. More information on these important processes is presented in chapter 8.

ATP: The Energy Molecule of Cells

A relative of RNA involved in an entirely different cell activity is **adenosine triphosphate (ATP).** ATP is a nucleotide containing adenine, ribose, and three phosphates rather than just one **(figure 1.16).** It belongs to a category of high-energy compounds (also including guanosine triphosphate [GTP]) that gives off energy when the bond is broken between the second and third (outermost) phosphate. The presence of these high-energy bonds makes it possible for ATP to release and store energy for cellular chemical reactions. Breakage of the bond of the terminal phosphate releases energy to do cellular work and also generates adenosine diphosphate (ADP). ADP can be converted back to ATP when the third phosphate is restored, thereby serving as an energy depot. Carriers for oxidation-reduction activities (nicotinamide adenine dinucleotide [NAD], for instance) are also derivatives of nucleotides (see chapter 8).

Cells: Where Chemicals Come to Life

As we proceed in this chemical survey from the level of simple molecules to increasingly complex levels of macromolecules, at some point we cross a line from the realm of lifeless molecules and arrive at the fundamental unit of life called a **cell.** A cell is indeed a huge aggregate of carbon, hydrogen, oxygen, nitrogen, and many other

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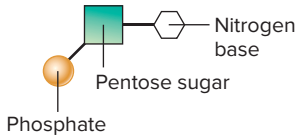
2. A nurse is caring for a patient with refractory epilepsy. To enhance medical management, a ketogenic diet has been prescribed. In educating the patient about dietary energy sources, all of the following statements are true, except:

a. *Proteins consist of polymers of nucleic acids.*
b. *Fat provides more kilocalories per gram than protein.*
c. *A high-fat diet may cause increased serum cholesterol levels.*
d. *Starch is an example of a carbohydrate.*



(a) A nucleotide is the monomer of both DNA and RNA. Nucleotides are composed of a phosphate, a pentose sugar, and a nitrogen base (A, T, C, G, or U).

(b) DNA molecules are composed of alternating deoxyribose (D) and phosphates (P). Nitrogen bases (A, T, C, G) are attached to the deoxyribose. DNA almost always exists in pairs of strands, oriented so that the bases are paired across the central axis of the molecule.

(c) RNA molecules are composed of alternating ribose (R) and phosphates (P) attached to nitrogen bases (A, U, C, G), but it is usually a single strand.

Figure 1.15 The general structure of nucleic acids.

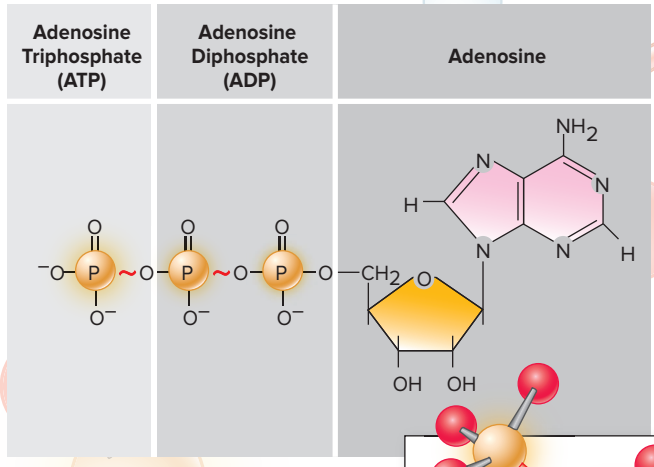


Figure 1.16 An ATP molecule. **(a)** The structural formula. Wavy lines connecting the phosphates represent bonds that release large amounts of energy. **(b)** A ball-and-stick model.

atoms, and it follows the basic laws of chemistry and physics, but it is much more. The combination of these atoms produces characteristics, reactions, and products that can only be described as *living*.

Fundamental Characteristics of Cells

The bodies of some living things, such as bacteria and protozoa, consist of only a single cell, whereas those of animals and plants contain trillions of cells. Regardless of the organism, all cells have a few common characteristics. They tend to be spherical, polygonal, cubical, or cylindrical; and their protoplasm (internal cell contents) is encased in a cell or cytoplasmic membrane. They have chromosomes containing DNA, and ribosomes for protein synthesis, and they are exceedingly complex in function. Aside from these few similarities, the contents and structure of the three different cell types–bacterial, archaeal, and eukaryotic–differ significantly.

Animals, plants, fungi, and protozoa are all made up of eukaryotic cells. Such cells contain a number of complex internal parts called organelles that perform useful functions for the cell involving growth, nutrition, or metabolism. Organelles are distinct cell components that perform specific functions and are enclosed by membranes. Organelles also partition the eukaryotic cell into smaller compartments. The most visible organelle is the nucleus, a roughly ball-shaped mass surrounded by a double membrane that contains the DNA of the cell. Other organelles include the Golgi apparatus, endoplasmic reticulum, vacuoles, and mitochondria.

Bacterial and archaeal cells may seem to be the cellular "have nots" because, for the sake of comparison, they are described by what they lack. They have no nucleus and generally no other organelles. This apparent simplicity is misleading, however, because the fine structure of these cells is complex. Overall, bacterial and archaeal cells can engage in nearly every activity that eukaryotic cells can, and many can function in ways that eukaryotes cannot. Chapters 3 and 4 delve deeply into the properties of bacterial, archaeal, and eukaryotic cells.

A chicken egg is a single large cell.

1.3 LEARNING OUTCOMES—Assess Your Progress

12. Name the four main families of biochemicals.
13. Provide examples of cell components made from each of the families of biochemicals.
14. Differentiate among primary, secondary, tertiary, and quaternary levels of protein structure.
15. List the three components of a nucleotide.
16. Name the three nitrogen bases of DNA and RNA.
17. List the three components of ATP.
18. Recall three characteristics common to all cells.

1.4 Naming, Classifying, and Identifying Microorganisms

The science of classifying living beings is **taxonomy.** It originated more than 250 years ago when Carl von Linné (also known as Linnaeus; 1701–1778), a Swedish botanist, laid down the basic rules for *classification* and established taxonomic categories, or **taxa** (singular, *taxon*).

Von Linné realized early on that a system for recognizing and defining the properties of living beings would prevent chaos in scientific studies by providing each organism with a unique name and an exact "slot" in which to catalog it. This classification would then serve as a means for future identification of that same organism and permit people working in many biological fields to know if they were indeed discussing the same organism.

The primary concerns of modern taxonomy are still naming, classifying, and identifying. These three areas are interrelated and play a vital role in keeping a dynamic inventory of the extensive array of living and extinct beings. In general,

Nomenclature (naming) is the assignment of scientific names to the various taxonomic categories and to individual organisms.

Classification is the orderly arrangement of organisms into a hierarchy.

Identification is the process of discovering and recording the traits of organisms so that they may be recognized or named and then classified.

Nomenclature

Many macroorganisms are known by a common name suggested by their dominant features. For example, a bird species may be called a "red-headed blackbird" or a flowering plant species a "black-eyed Susan." Some species of microorganisms are also called by informal names, including human pathogens such as "gonococcus" (*Neisseria gonorrhoeae*) or fermenters such as "brewer's yeast" (*Saccharomyces cerevisiae*), or the recent "Iraqiabacter" (*Acinetobacter baumannii*), but this is not the usual practice. If we were to adopt common names such as the "little yellow coccus," the terminology would become even more cumbersome and challenging than scientific names.

The method of assigning a scientific or specific name is called the **binomial** (two-name) **system** of nomenclature. The scientific name is always a combination of the genus name followed by the species name. The genus part of the scientific name is capitalized, and the species part begins with a lowercase letter. Both should be italicized (or underlined if using handwriting), as follows:

Escherichia coli

The treehopper and its discoverer, Sylvie (below.). Sylvie, at the age of 5, with her mother the biologist Dr. Laura Sullivan-Beckers (above).

The two-part name of an organism is sometimes abbreviated to save space, as in *E. coli*, but only if the genus name has already been stated. The inspiration for names is extremely varied and often rather imaginative. A biology professor from Murray State University in Kentucky was planting flowers in her garden with her 2-year-old daughter Sylvie, when Sylvie discovered something. It was a species of treehopper insect that her mother was not familiar with. It turns out that it was an as-yet-undiscovered species, and Sylvie's mom, Dr. Laura Sullivan-Beckers, named it in honor of its discoverer, her daughter. Its binomial name is now *Hebetica sylviae*. Some species of microbes have also been named in honor of a microbiologist who originally discovered the microbe or who has made outstanding contributions to the field. Other names may designate a characteristic of the microbe (shape, color), a location where it was found, or a disease it causes. Two examples of specific names, their pronunciations, and their origins are

- *Staphylococcus aureus* (staf′-i-lo-kok′-us ah′-ree-us) Gr. *staphule*, "bunch of grapes," *kokkus*, "berry," and Gr. *aureus*, "golden." The species looks like a bunch of grapes under a microscope, and its colonies are golden yellow on agar. It is a common bacterial pathogen of humans.
- *Lactobacillus sanfrancisco* (lak′-toh-bass-ill′-us san-fran-siss′-koh) L. *lacto*, "milk," and *bacillus*, "little rod." A bacterial species used to make sourdough bread, for which San Francisco is known.

Here's a helpful hint: These names may seem difficult to pronounce and the temptation is to simply "slur over them." But when you encounter the names of microorganisms in the chapters ahead, it will be extremely useful to take the time to sound them out and repeat them until they seem familiar. Even experienced scientists stumble the first few times through new names. Stumbling out loud is a great way to figure them out, and you are much more likely to remember them that way–they are less likely to end up in a tangled heap with all of the new language you will be learning.

Classification

Classification schemes are organized into several descending ranks, beginning with the most general all-inclusive taxonomic category and ending with the smallest and most specific category. This means that all members of the highest category share only one or a few general characteristics, whereas members of the lowest category are essentially the same kind of organism–that is, they share the majority of their characteristics. The taxonomic categories from top to bottom are **domain, kingdom, phylum** or **division, class, order, family, genus,** and **species.** That means that each kingdom can be subdivided into a series of phyla or divisions, each phylum is made up of several classes, each class contains several orders, and so on. Because taxonomic schemes are to some extent artificial, certain groups of organisms may not exactly fit into the main categories. In such a case, additional taxonomic levels can be imposed above (super) or below (sub) a taxon, giving us such categories as "superphylum" and "subclass."

Let's compare the taxonomic breakdowns of a human and a protozoan (pro-tuh-zoh′-un) to illustrate the fine points of this system **(figure 1.17).** Humans and protozoa are both organisms with nucleated cells (eukaryotes); therefore, they are in the same domain (Eukarya), but they are in different kingdoms. Humans are multicellular animals (kingdom Animalia), whereas protozoa are single-cellular organisms that, together with algae, belong to the kingdom Protista. To emphasize just how broad the category "kingdom" is, ponder the fact that we humans belong to the same kingdom as jellyfish. Of the several phyla within this kingdom, humans belong to the phylum Chordata, but even a phylum is rather all-inclusive, considering that humans share it with other vertebrates as well as with creatures called sea squirts. The next level, class Mammalia, narrows the field considerably by grouping only those vertebrates that have hair and suckle their young. Humans belong to the order Primates, a group that also includes apes, monkeys, and lemurs. Next comes the family Hominoidea, containing only humans and apes. The final levels are our genus, *Homo*

DOMAIN: Eukarya (all eukaryotic organisms)

Eukaryotic, heterotrophic and mostly multicellular

Kingdom: Animalia

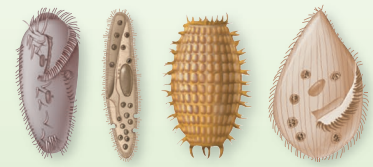
Kingdom: Protista

Includes protozoa and algae

Possess notochord, dorsal nerve cord, pharyngeal slits (if only in embryo)

Phylum: Chordata

Phylum: Ciliophora

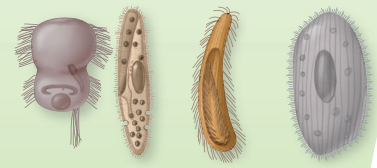


Only protozoa with cilia

Possess hair, mammary glands

Class: Mammalia

Class: Hymenostomea



Single cells with regular rows of cilia; rapid swimmers

Digital dexterity, large cerebral cortex, slow reproductive rate, long life span

Order: Primates

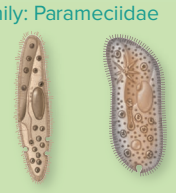
Order: Hymenostomatida

Elongated oval cells with cilia in the oral cavity

Large brain, no tail, long upper limbs

Family: Hominoidea

Family: Parameciidae



Cells rotate while swimming and have oral grooves

Genus: *Homo*
Erect posture, large cranium, opposable thumbs

Species: *sapiens*
Humans

Genus: *Paramecium*
Pointed, cigar-shaped cells with macronuclei and micronuclei

Species: *caudatum*
Cells cylindrical, long, and pointed at one end

Figure 1.17 Sample taxonomy. Two organisms belonging to the Eukarya domain, traced through their taxonomic series. On the left, modern humans, *Homo sapiens*. On the right, a common protozoan, *Paramecium caudatum*.

(all modern and ancient humans), and our species, *sapiens* (meaning "wise"). Notice that for the human as well as the protozoan, the taxonomic categories in descending order become less inclusive and the individual members more closely related. In this text, we are usually concerned with only the most general (domain, kingdom, phylum) and specific (genus, species) taxonomic levels.

Identification

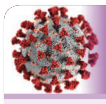
Discovering the identity of microbes we find in the environment or in diseases is an art and a science. The methods used in this process are extensively described in chapter 2 and in chapter 15.

The Origin and Evolution of Microorganisms

As we indicated earlier, *taxonomy*, the science of classification of biological species, is used to organize all of the forms of modern and extinct life. In biology today, there are different methods for deciding on taxonomic categories, but they all rely on the degree of relatedness among organisms. The scheme that represents the natural relatedness (relation by descent) between groups of living beings is called their *phylogeny* (Gr. *phylon*, "race or class"; L. *genesis*, "origin or beginning"). Biologists use phylogenetic relationships to refine the system of taxonomy.

To understand the natural history of and the relatedness among organisms, we must understand some fundamentals of the process of evolution. Evolution is an important theme that underlies all of biology, including the biology of microorganisms. As we said earlier, evolution states that the hereditary information in living beings changes gradually through time and that these changes result in various structural and functional changes through many generations. The process of evolution is selective in that those changes that most favor the survival and reproduction of a particular organism or group of organisms tend to be retained, whereas those that are less beneficial to survival tend to be lost. This is not always the case, but it often is. Charles Darwin called this process *natural selection*.

Usually, evolution progresses toward greater complexity, but there are many examples of evolution toward lesser complexity. (This is called reductive evolution.) This is because individual organisms almost never evolve in isolation but as populations of organisms in their specific environments, which exert the functional pressures of selection. Because of the nature of the evolutionary process, the phylogeny, or relatedness by descent, of organisms is often represented by a diagram of a tree. The trunk of the tree represents the origin of ancestral lines, and the branches show offshoots into specialized groups of organisms. This sort of arrangement places taxonomic groups with less divergence (less change in the heritable information) from the common ancestor closer to the root of the tree and taxa with lots of divergence closer to the top.



COVID-19

During the COVID-19 pandemic, it was declared that the virus had evolved from being able to infect non-human animals to being able to infect humans. This is an example of small (random) changes in the genetic information that happened to provide the virus a new "skill": the ability to infect a new species.

A handful of soil is home to thousands of different kinds of organisms, including a wide diversity of fungi, bacteria, viruses, and protozoa.

A Universal Web of Life

The first trees of life were constructed a long time ago on the basis of just two kingdoms–plants and animals–by Charles Darwin and Ernst Haeckel. These trees were chiefly based on visible morphological (shape) characteristics. It became clear that certain (micro)organisms such as algae and protozoa, which only existed as single cells, did not truly fit either of those categories, so a third kingdom was added. It was named Protista (or Protozoa). Eventually, when significant differences became evident among even the unicellular organisms, a fourth kingdom was established in the 1870s by Haeckel and named Monera. Almost a century passed before Robert Whittaker extended this work and added a fifth kingdom for fungi during the period of 1959 to 1969. The relationships that were used in Whittaker's tree were those based on structural similarities and differences, and the way these organisms obtained their nutrition. These criteria indicated that there were five major taxonomic units, or kingdoms: the monera, protists, plants, fungi, and animals. Each organism in these five categories consisted

of one of the two cell types, those cells lacking a nucleus and the eukaryotic cells. Whittaker's five-kingdom system quickly became the standard.

With the rise of genetics as a molecular science, newer methods for determining phylogeny have led to the development of a differently shaped tree–with important implications for our understanding of evolutionary relatedness. Molecular genetics allowed an in-depth study of the structure and function of the genetic material at the molecular level. In 1975, Carl Woese discovered that one particular macromolecule, the *ribonucleic acid in the small subunit of the ribosome* (abbreviated "ssu rRNA, or "16S rRNA""), was highly conserved–meaning that it was nearly identical in organisms within the smallest taxonomic category, the species. Based on a vast amount of experimental data, Woese hypothesized that 16S rRNA provides a "biological chronometer" or a "living record" of the evolutionary history of a given organism. Extended analysis of this molecule in prokaryotic and eukaryotic cells indicated that all members in a certain group of bacteria, then known as archaebacteria, had 16S rRNA with a sequence that was significantly different from the 16S rRNA found in other bacteria and in eukaryotes. This discovery led Carl Woese and collaborator George Fox to propose a separate taxonomic unit for the archaebacteria, which they named **Archaea.** Under the microscope, they resembled the structure of bacteria, but molecular biology has revealed that the archaea, though seemingly bacterial in nature, were actually more closely related to eukaryotic cells. To reflect these relationships, Woese and Fox proposed an entirely new system that assigned all known organisms to one of the three major taxonomic units, the domains, each being a different type of cell. Turn to the beginning of this chapter and reexamine figure 1.1, which is a depiction of the three-domain system.

The domains are the highest level in hierarchy and can contain many kingdoms and superkingdoms. Cell types lacking a nucleus are represented by the domains Archaea and **Bacteria,** whereas eukaryotes are all placed in the domain **Eukarya.** Analysis of the 16S rRNAs from all organisms in these three domains suggests that all modern and extinct organisms on earth arose from a common ancestor. Therefore, eukaryotes did not emerge from bacteria and archaea. Instead, it appears that bacteria, archaea, and eukaryotes all emerged separately from a different, now extinct, cell type.

To add another level of complexity, the most current data suggest that "trees" of life do not truly represent the relatedness of organisms in their totality. It has become obvious that genes travel horizontally–meaning from one species to another in nonreproductive ways–and that the tidy generation-to-generation changes are complicated by neighbor-to-neighbor exchanges of DNA. For example, it is estimated that 40% to 50% of human DNA has been carried to humans from other species (by viruses). For these reasons, most scientists like to think of a *web* as the proper representation of life these days. Nevertheless, this new scheme does not greatly affect our presentation of most microbes because we will discuss them at the genus or species level. Keep in mind that our methods of classification or evolutionary schemes reflect our current understanding and will change as new information is uncovered.

Please note that viruses and prions are not included in any of the classification or evolutionary schemes because they are not cells or organisms. Their special taxonomy is discussed in chapter 5.

1.4 LEARNING OUTCOMES—Assess Your Progress

19. Differentiate among the terms *nomenclature*, *taxonomy*, and *classification*.
20. Create a mnemonic device for remembering the taxonomic categories.
21. Correctly write the binomial name for a microorganism.
22. Draw a diagram of the three major domains.
23. Explain the difference between traditional and molecular approaches to taxonomy.

CASE FILE WRAP-UP

©Michael Williams (photo of Kelly Cowan with student); Science Photo Library RF/Getty Images (white blood cell)

If you have a bacterial infection, your doctor is likely (but not in all cases) to prescribe an antibiotic. Antibiotics are drugs that are designed to harm microbes but not harm the human host. That is their specific job—to target the microorganism. So if you have an illness that is not caused by a microorganism, you should not take antibiotics.

If you decide to go into health care as a profession, you will see a few common infections very frequently, but there will also be a wide variety of infections that you will likely only encounter once or a few times in your career. No one expects you to remember everything about every possible infection you study here. What's important is that you become familiar with important patterns of disease and the ways that our body—and the treatments we apply—affect them.

Stephen Durr

Meet Your Microbiome

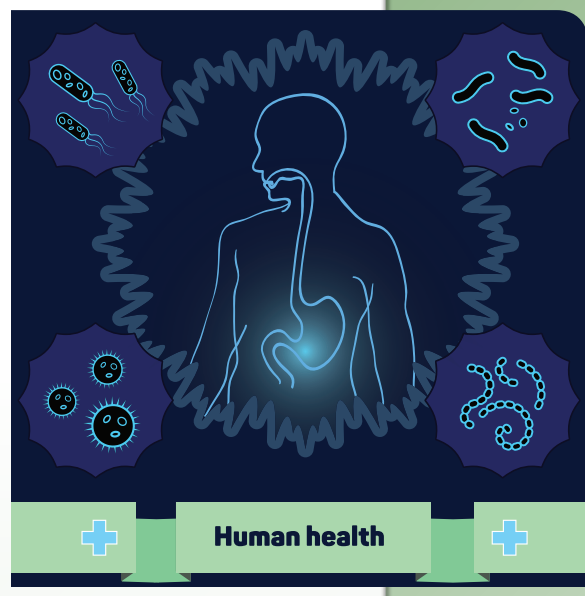
In the past few years, a new word has popped up on newsfeeds and websites: ***microbiome***. It refers to the sum total of all the microbes in a certain environment. The human microbiome consists of all the viruses, bacteria, fungi, and protozoa that call the human body home. Trillions of these microorganisms live on our body, as part of our natural biology. Unless something goes wrong, they do not cause disease, and, in fact, are necessary parts of human development and ongoing life.

The Human Microbiome Project (HMP) began in 2008, using techniques to identify body microbes that did not require growing the microbes separately in the lab (a technique scientists have relied on since the mid-1800s), but instead identified them on the basis of their genetic material. The HMP produced a staggering array of results, and they keep coming at breakneck pace.

We have learned that the microbiome may differ whether you were delivered via cesarean or vaginal birth. We have learned that the gut microbiome—the microbes living in your intestinal tract—may influence not just your intestinal health but also your likelihood to experience autoimmune disease, your weight, and even your mood! We know how the composition of the microbiome of different body systems (your skin, your eyes, your lungs) differs in health and in disease.

In short, we have learned that the characteristics of your microbiome determine your own, human, biology—and what types of experiences you will have as an organism. But there is a big note of caution here: The explosion of information about the human microbiome has led to some very preliminary science, and a lot of careless journalism. One leading microbiome researcher even calls it "Microbiomania." Many journalists gloss over the difference between correlation (these two things were observed at the same time) and causation (this thing *led to* this other thing). So we get reporting that suggests that elite cyclists should be "poop-doping" (getting transplanted fecal material that contains the donor's gut microbiome) to improve their performance, when there is no real evidence for it. Right here at the end of every chapter in this book, we will tell a short story about the microbiome as it pertains to the subject matter in the chapter, and try to address the quality of the science - and the reporting - behind the story.

The Microbiome



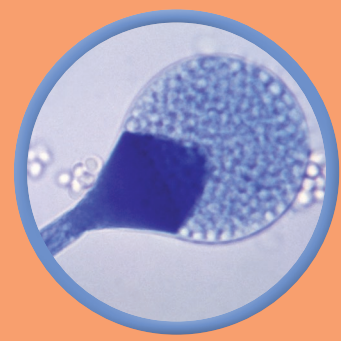
Source: Shutterstock/Barbo

INTRODUCTION TO MICROBES AND THEIR BUILDING BLOCKS

Chapter Summary

1.1 MICROBES: TINY BUT MIGHTY

Microorganisms in this book are: archaea, bacteria, fungi, protozoa, helminths, viruses, and prions. Some are cellular and some are not cells. Microbes are everywhere on the planet and are critical for nutrient and energy cycling.



CDC/Dr. Lucille K. Georg

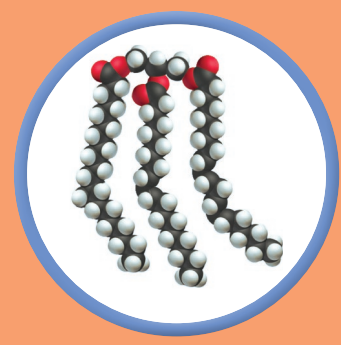
lynx/ iconotec.com/Glow Images

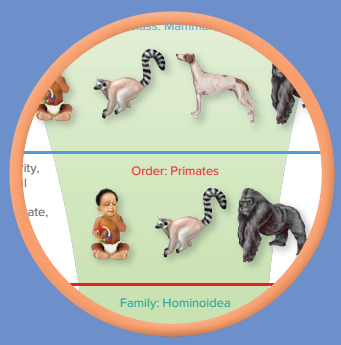
The first golden age of microbiology was in the mid-1800s, when scientists developed culturing methods and the germ theory of disease.

1.2 MICROBES IN HISTORY

1.3 MACROMOLECULES: SUPERSTRUCTURES OF LIFE

Cells and microbes are constructed of four main macromolecules: carbohydrates, lipids, proteins, and nucleic acids. Macromolecules are generally built up by polymerization of smaller molecular subunits (monomers).





Naming, classifying, and identifying microorganisms is called taxonomy. All cellular organisms belong to one of three domains: Eukarya, Bacteria, and Archaea.

1.4 NAMING, CLASSIFYING, AND IDENTIFYING MICROORGANISMS

SmartGrid: From Knowledge to Critical Thinking

This *21 Question Grid* takes the topics from this chapter and arranges them with respect to the American Society for Microbiology's Undergraduate Curriculum guidelines—all six of the important "Concepts" as well as the important "Competency" of scientific literacy. Three questions are supplied about chapter content that refer to the Concept or Competency, in increasing levels of Bloom's taxonomy for learning.

ASM Concept/ Competency	A. Bloom's Level 1, 2—Remember and Understand (Choose one.)	B. Bloom's Level 3, 4—Apply and Analyze	C. Bloom's Level 5, 6—Evaluate and Create
Evolution	**1.** Which of the following is an acellular microorganism lacking a nucleus? **a.** bacterium **b.** helminth **c.** protozoan **d.** virus	**2.** Name seven types of microorganisms that we are studying in this book and use each one in a sentence.	**3.** Defend the argument that a web of life is a more accurate representation of evolutionary relatedness than a tree of life.
Cell Structure and Function	**4.** Which of the following is a macromolecule that assembles into bilayers? **a.** protein **b.** phospholipid **c.** nucleic acid **d.** carbohydrate	**5.** Often when there is a local water main break, a town will post an advisory to boil water before ingesting it. Identify the biological basis behind the effectiveness of this procedure in minimizing illness.	**6.** Imagine a way you might design a drug to destroy microbes that will not harm human cells.
Metabolic Pathways	**7.** Identify the process or environment in this list that is not affected by microorganisms. **a.** oxygen cycles **b.** global temperatures **c.** human health **d.** all of the above have microbial involvement	**8.** Provide an argument about why metabolic capabilities are so much more diverse in single-celled organisms like bacteria and archaea than they are in multicellular eukaryotes.	**9.** Provide a possible interpretation of the finding that the identity of microbes found in different people may differ, but the metabolic pathways that they bring are similar in different people.
Information Flow and Genetics	**10.** DNA leads to RNA, which can lead to the creation of **a.** proteins. **b.** lipids. **c.** cells. **d.** oxygen.	**11.** Compare and contrast the RNA molecule with the DNA molecule.	**12.** Suggest an argument for why eukaryotic cells have developed an enclosed nucleus unlike bacteria and archaea.
Microbial Systems	**13.** Microbes are found in which habitat? **a.** human body **b.** earth's crust **c.** oceans **d.** all of the above	**14.** Defend or refute this statement: *Microbes intend to cause human disease*.	**15.** *Coevolution* is a term describing the influence that two organisms occupying the same niche have on each other. Sketch a scenario for coevolution between a bacterium and a human living in the same environment.

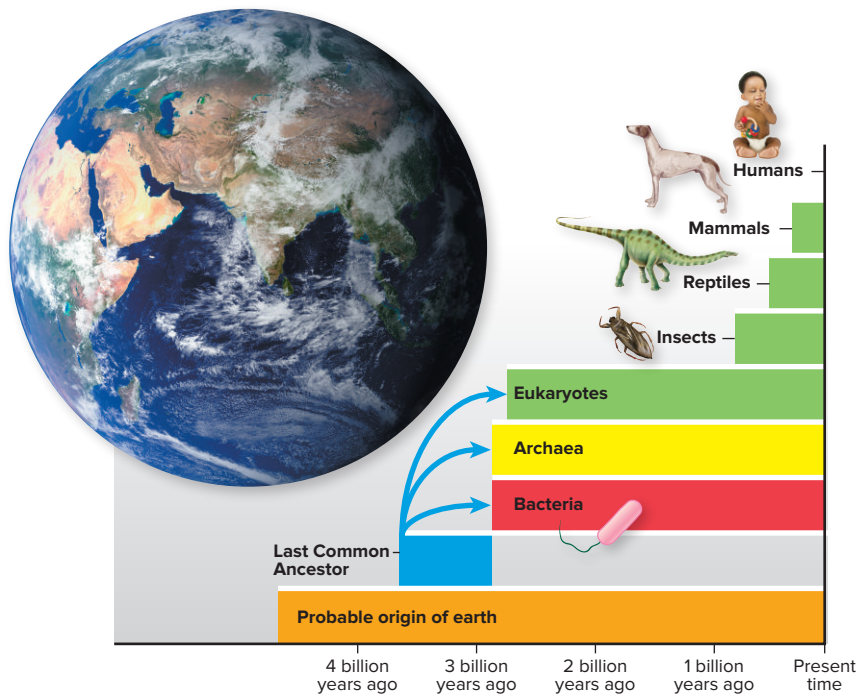
ASM Concept/ Competency	A. Bloom's Level 1, 2—Remember and Understand (Choose one.)	B. Bloom's Level 3, 4—Apply and Analyze	C. Bloom's Level 5, 6—Evaluate and Create
Impact of Microorganisms	**16.** Which of the following processes can be the result of human manipulation of microbial genes? **a.** the central dogma **b.** natural selection **c.** bioremediation **d.** abiogenesis	**17.** Speculate about why scientists believe there are more microbial species that we do not yet know about than those that we do know about.	**18.** Imagine you are a guest speaker in a middle school science class. Explain to the students why human life would not be possible without microorganisms.
Scientific Thinking	**19.** When a hypothesis has been thoroughly supported by long-term study and data, it is considered **a.** a law. **b.** a speculation. **c.** a theory. **d.** proven.	**20.** Defend the use of complicated-sounding names for identifying microorganisms.	**21.** Identify the most important component of the scientific method and defend your answer.

Answers to the multiple-choice questions appear in Appendix A.

Visual Connections

This question connects content within and between chapters.

Figure 1.2. Look at the red bar (the time that bacteria have been on earth) and at the time that humans appeared. Speculate on the probability that we will be able to completely eliminate all bacteria from our planet, and discuss whether or not this would even be a beneficial action.



Source: NASA/Goddard Space Flight Center (Earth)

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