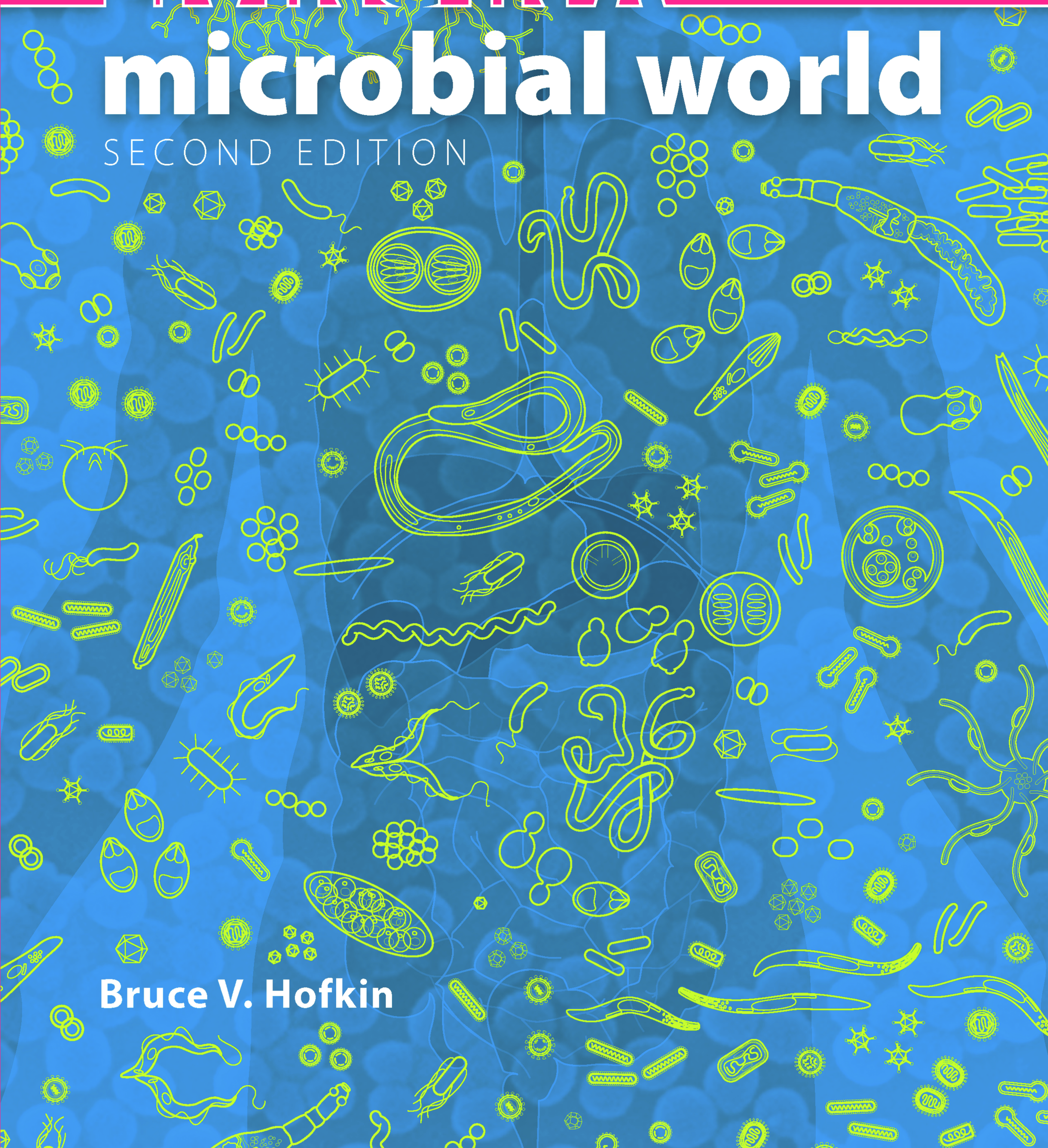

LIVING IN A microbial world

SECOND EDITION

Bruce V. Hofkin

Garland Science

LIVING IN A microbial world

SECOND EDITION

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Bruce V. Hofkin

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Preface

When the first edition of *Living in a Microbial World* was published several years ago, I felt the natural exhilaration and satisfaction that is familiar to anyone who has at last completed a complex and extensive project. Yet this feeling was tempered by the knowledge that like any life sciences textbook, it wouldn't be long before my text started to show its age. New developments in biology in general and microbiology in particular arise at a lightning pace, and writing a text that is both relevant and current is a challenging task indeed. This point was rammed home to me, within only a week or two of the first edition's publication; my Senior Editor, Mike Morales, sent me an article with a note saying that this article might prove useful for a second edition. The subject of the article instantly captured my attention: "fecal transplant." Although at the time, we were beginning to hear more and more about the importance of our microbiota, this was the first I had heard about this particular application and its potential to treat certain medical conditions. It certainly wasn't discussed in my book. Although I found the article interesting, I experienced a slight sinking feeling that my text was already dated.

Consequently, my primary task in preparing the second edition was to incorporate the new and often marvellous information that had come forward since the publication of the first edition. Every chapter was scrutinized to insure that while still providing the necessary basic information, any relevant, recent developments, especially those that change the way we think about microbes, were included. Where appropriate, examples used to illustrate key concepts were also updated, in order to provide the text with a fresh and current feel. To provide only a few examples, students are introduced in Chapter 1 to a new technique involving microorganisms in which damaged antiquities may be restored. Newly emerged pathogens such as the fungus causing white nose syndrome in bats, or the virus causing the death of baby elephants in zoos around the world are utilized in Chapters 4 and 5. In Chapter 7, students learn about quorum sensing in microorganisms, while Chapter 10 explores why coral reefs worldwide are in jeopardy and the role of symbiotic algae in this ongoing ecological crisis. In Chapter 11, readers learn more about the astonishing new findings regarding our normal microbiota, and how it might impact a remarkable range of host attributes. Chapter 14 traces the emergence and spread of Zika virus, while Chapter 15 investigates the technologies such as CRISPR/ Cas and metagenomics that are becoming increasingly important and commonplace in research laboratories.

The basic strategy of the second edition is faithful to that of the first: to present students who are new to microbiology with an understandable, scientifically meaningful, and relevant introduction to the world of microbiology. The second edition of *Living in a Microbial World* remains geared toward students taking a general microbiology or microbiology-themed course for non-science majors. The goal is still to present students with the many and often unexpected ways that microorganisms impact our daily lives, and to do so with a conversational writing style, that is not overly burdened with details. Thus the text strives to provide non-scientists with the information they need to make informed decisions about issues that affect themselves, their families, and their communities. Core topics like cell structure and function or metabolism, which have broad application to the life sciences in general, help students understand the living world in a more profound and rewarding manner.

In addition to an emphasis on how microorganisms affect us, for better or worse, in a myriad of ways, the text continues to emphasize the importance of evolutionary theory to biology in general and microbiology in particular.

The reader will find a chapter devoted to microbial evolution and evolutionary concepts are highlighted throughout the text. To streamline the text and to make it more accessible, certain traditional microbiology topics, which often receive their own chapters in other texts, have been integrated throughout other chapters. For instance, in lieu of a separate chapter on techniques, topics such as Gram and acid-fast staining are introduced in the discussion of cell wall structure.

Like the first edition, each chapter contains a number of case studies that introduce new concepts with news items, historical accounts or scenarios that are designed to engage the reader. For instance, a case added to the second edition introduces the topic of bioconversion with a case that may be of interest to those concerned with animal welfare: how an important steroid hormone used therapeutically can be produced by bacteria, rather than extracted from the urine of pregnant horses. As before, each case is followed by several questions, the answers to which should become apparent in the subsequent text section.

In these ways, I have attempted to provide readers with a meaningful and contemporary text, with which they may explore the world of microorganisms. It is my hope that after reading it, students will share my fascination with these endlessly astonishing and diverse living things.

I am excited that the second edition is able to make use of the Garland Science Learning System (GSLS) to provide additional resources that are designed to complement the book. GSLS will engage students through active learning, while instructors are able to tailor discussions to fit their class and monitor progress. There are specially written tutorials, quizzes, movies, vocabulary review, and help answering the concept questions. I encourage everyone to try it! Also new to this edition is a brief Study Skills section before the text begins, which is designed to help readers make the most of this textbook and its resources.

All textbooks are collaborative efforts, and many people have helped bring the second edition of *Living in a Microbial World* into existence. These people are recognized in the acknowledgments. Any remaining errors, however, are solely the responsibility of the author. Please help with these errors via contact at science@garland.com so that corrections can be made in subsequent printings.

Acknowledgments

No textbook is solely the work of the author whose name appears on the cover and *Living in a Microbial World*, second edition, is no exception. Microbiology educators and students from around the country reviewed drafts of each chapter, and I would like to thank them for their many helpful comments and suggestions. Specifically, I wish to thank:

Suzanne Anglehart, University of Wisconsin; Jason Arnold, Hopkinsville Community College; Linda Bruslind, Orgeon State University; Alyssa Bumbaugh, Penn State Altoona; Jean Cardinale, Alfred University; Edward Cluett, Ithaca College; David Fulford, Edinboro University of Pennsylvania; Eileen Gregory, Rollins College; Patrick Hindmarsh, Louisiana Tech University; Timothy Ladd, Millersville University; Juanita Leonhard, Illinois College; Sylvie Franke McDevitt, Skidmore College; Amy Medlock, University of Georgia; Robert Miller, Oklahoma State University; Heather Minges Wols, Columbia College Chicago; Roderick Morgan, Grand Valley State University; Karen Palin, Bates College; Carolyn Peters, Spoon River College; Greg Pryor, Francis Marion University; Rachel Robson, Morningside College; Mark Schneegurt, Wichita State University; Tammy Tobin, Susquehanna University; Jamie Welling, South Suburban College.

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Many thanks also to the dedicated staff at Garland Science, who helped to make this second edition a reality. At the top of that list is Senior Editor Elizabeth Owen, whose assistance and guidance were crucial in seeing this project to fruition. Not only did Liz oversee the entire project, but her many insightful ideas and comments were instrumental in the updating and redrafting process. The editorial process, especially with regard to the artwork, was helped greatly by Editorial Assistant Jordan Wearing. Production Editor Deepa Divakaran and I worked closely together to produce the final pages. I am grateful for her professionalism, attention to detail and thoroughness, all of which contributed to the final product being of the highest standard. All new artwork for the second edition was produced by Matthew McClements of Blink Studio, who was also the artist for the first edition. As before, I am appreciative of Matt's special talent for rendering often-complex concepts into easy-to-understand and aesthetically appealing artwork. I offer my deep and sincere gratitude to all of these individuals.

And as with the first edition, I thank Leslie for being there.

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INSTRUCTOR RESOURCES

Living in a Microbial World, second edition comes with a redemption code that gives students free access to original tutorials with assessments, quizzes, 24 movies designed to complement the book, vocabulary review, and hints to the end-of-chapter questions, all on the **Garland Science Learning System (GSLS)**. For students to receive a redemption code with free access to the GSLS, you must use the following ISBN when placing the book order: 9780815346012.

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Movies

The 24 movies include both animations that explain processes in detail and videos of biological processes. Each movie has a voice-over narration, and the text of the narration is located in the "Media Guide." Movies are provided in Windows and Macintosh-compatible formats for easy import into PowerPoint®. The movies are available to students in the GSLS modules.

Media Guide

This document overviews the multimedia package available for students and instructors. It also contains the text of the voice-over narration for all the movies.

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It is also possible to use the GSLS as an independent learner, if you don't have an instructor, or your instructor is not using the system. Information for accessing the modules independently is available at: http://garlandscience.rocketmix.com/students

The following resources for *Living in a Microbial World* are available on the GSLS:

- Every chapter features a tutorial with assessment questions to explore exciting topics and applications.
- Quizzes assess mastery of topics and provide feedback.
- Twenty-four movies illuminate molecular processes and show cells in real life.
- Vocabulary review for each chapter helps with important microbiology terminology.
- Hints for End-of-Chapter Concept Questions.

See page x for a complete list of student resources on the GSLS.

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Chapter 1
- Tutorial: The Scientific Method (discover how to prove you're right scientifically and why a scientific theory isn't merely theoretical)
- Quiz with Feedback
- Hints for End-of-Chapter Concept Questions
- Vocabulary Review

Chapter 2
- Tutorial: Protein Structure and Denaturation (discover why a fried egg doesn't look like a raw egg and why it's important that proteins fold like socks in a clothes dryer)
- Movie: Glucose Molecule
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Chapter 3
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- Movie: Fluidity of the Lipid Bilayer
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Chapter 4
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- Quiz with Feedback
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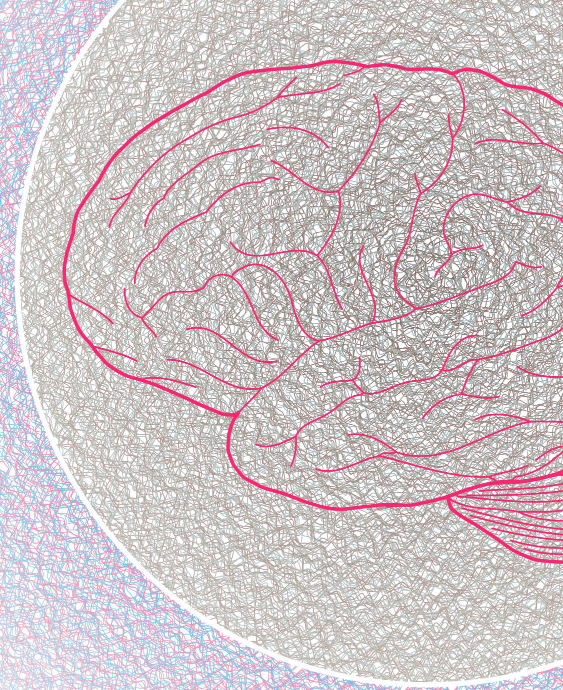
Learning Skills



Learning is a skill, so before you start to learn about microbiology, here are some tips about how to use your brain effectively ...

You have to be motivated to learn

The first step is to turn your brain on by wanting to learn and believing you can. In order to want to learn, you have to be motivated and able to answer the question "Why am I learning all this?". Motivation can be internal (driven by you) or external (driven by someone or something else), with internal motivation being by far the most powerful. Internal motivation comes from curiosity and the desire for self-improvement; you feel good when you learn something new, so learning itself is the goal. External motivations, such as passing an exam, tend to concentrate on negative thoughts, such as not passing the exam, and relying on them won't use your brain effectively. However, external motivations are a good starting point and can develop into an internal motivation to learn: subjects you find difficult or boring are simply those in which you have yet to develop interest. Once you develop an interest in a subject you'll want to learn more about it.

Memorizing is only a part of learning

Statements such as "What do I have to know?" or "What's the least I've got to study?" or "What's the minimum to pass the course?" indicate a predisposition to memorize rather than understand. Memorizing is seductive, because you can recognize and recall many facts in a short time, but they will quickly be forgotten, making memorization an inefficient use of your brain. Do not make the mistake of thinking that memorization is the key aspect of mastering a new subject. Nothing could be farther from the truth, and relying on memorization alone is a sure recipe for failure. A certain amount of memorization is necessary to provide you with the basic vocabulary in a new subject. It is valuable in the way that memorizing new words helps when your goal is to learn a new language. But memorizing vocabulary lists is not the same as actually speaking a language. Memorization simply gives you the vocabulary you need to delve into the important concepts and ideas that are the heart of any scientific field of inquiry.

Understanding is a crucial step on the road to learning

To truly learn something, you first need to understand it. Understanding comes from making connections to your existing knowledge. It is more difficult to connect unfamiliar ideas, and you probably think that the ideas in this book are unfamiliar and alien to you, but they're not. If you've had a cold, eaten yogurt, learned about the Spanish conquistadors, read Edgar Allan Poe, or noticed the "Now wash your hands" sign, you're familiar with microbiology. This book is full of examples like this and they'll help you understand and learn about microbiology.

You need time and space to learn

Once you understand an idea, you are ready to learn. Learning involves using the material and developing the skills to apply it to new situations. In other words, you need to practice with the material, just as you would practice to learn to play an instrument, a new sport, or to solve math problems. When you practice, you can take advantage of the most powerful learning tool there is; the opportunity to make mistakes in a situation where those mistakes are not costly, and then to learn from your mistakes. Over time, your performance improves, just as it always improves if you conscientiously practice a new skill. In schoolwork, this practice should take place when you study. If you make mistakes then, they will have no long-term negative impact, and you can strengthen weak spots in your knowledge, before you're asked about them in an exam or other assignment. So, how does one practice microbiology? One easy way is that after you have read about a topic, and think you understand it, try explaining it to another person. Can you do it? If you have nobody to explain it to, simply explain it out loud to an empty room or even your cat asleep on a chair. Unless the topic is very simple, you will make errors the first few times you try to explain it. In that case, simply open your book, re-examine the topic, and try again, until you can explain the topic well. Every time you correct your errors, your understanding and knowledge grow deeper.

Learning takes time, so make a good amount of time available for learning. You won't learn about any subject if you leave it until the night before the exam. Make time every week and make sure you've had enough sleep and enough to eat before you start. You also need space in your head so remove as many distractions as possible, find somewhere quiet, and turn social media off for a while.

Break it down into small chunks

Don't try and learn too much at one go: large tasks are dispiriting and demotivating because they appear insurmountable. This book is broken down into chapters, and the chapters are broken down into sections. Don't try and read the whole book in one go, don't try and learn a whole chapter in one go, take it a section at a time and you'll be amazed how far you get. Remember to have short breaks every 20 minutes or so to refresh your brain.

A wide range of resources are available to you, many of which are provided with this book. Use them all!

Use the headings (they're in blue) to get an overview of the chapter

Make notes in the book, it has wide margins for this purpose

Use the glossary and vocabulary review to explain any unfamiliar terminology

Use the case studies and tutorials to find familiar and interesting situations

Write explanations in your own words

Use the figures to follow processes

Draw your own figures

Use the videos and animations to help with visualization

Use the questions and answers to test your learning

Don't fall into the trap of thinking the answers to questions, instead, write them down and be sure any correct answers aren't lucky guesses. Be honest with yourself. The Garland Science Learning System (GSLS) resources include a quiz for each chapter, which gives you the correct answer as you go along and also lets you know why the correct answer is correct. Write down your answers to the concept questions at the end of each chapter and then look up the hints on the GSLS. Once you've answered all the questions, try and explain what you've learned to someone else.

IN SUMMARY

- **Want to learn**
- **Believe you can learn**
- **Aim for understanding not memorization**
- **Practice with the material and learn from your mistakes**
- **Make time and space to learn**
- **Use all the resources available**
- **Test yourself as you go along**
- **Enjoy it!**

LIVING IN A MICROBIAL WORLD

1

We live in a microbial world. Ask a friend to name a living thing and he or she will likely pick a dog, a daisy, or some other familiar animal or plant. The vast majority of living things on Earth, however, are **microorganisms**—bacteria, viruses, fungi, and protozoa, too small to see with the unaided eye (**Figure 1.1a**). The numerical advantage that microorganisms have over larger living things is truly mind boggling. A single teaspoon of soil can hold millions or billions of bacteria and fungi. A drop of seawater teems with microscopic life. And larger animals and plants provide shelter for literally trillions of smaller living things. At this moment, more bacteria than all the humans that have ever lived are quietly going about their business in your intestine.

Microorganisms, also frequently called **microbes**, live everywhere (**Figures 1.1b** and **1.1c**). They have been found frozen in ice and inside solid rock. They live in the deepest parts of the ocean and in boiling hot springs. They are found in habitats that are as acidic as battery acid or in briny water so salty that no fish could survive.

Many people lump all microorganisms together as germs—tiny organisms that are of little importance to us unless they make us sick. Nothing could be further from the truth. This book will not only demonstrate how diverse these fascinating organisms are but will also explore the many and often surprising ways they affect our lives. Indeed, it is difficult to open a newspaper or turn on the radio and not read or hear something about the way microorganisms impact humans.

It was recently announced, for instance, that researchers had genetically modified bacteria in a way that allows the diagnosis of liver cancer. In a nutshell, the bacteria, which normally live peacefully in the intestine, were altered in a way that allowed them to pass through the gut wall and enter the liver, where they naturally gravitate toward any cancer cells that are present. If the microbes find and colonize a liver tumor, they have been engineered to produce a chemical that is visible as a color change in the urine, when the chemical is excreted. Another surprising recent report is that each of us is surrounded by a unique microbial cloud of specific organisms that emanate from our bodies. Although we all harbor many species in common, the precise makeup of our microbial cloud is as individual as a fingerprint. The researchers at the University of Oregon who made the discovery even suggest that these clouds may have a forensic application; they could be used to detect, for example, whether someone had passed through a room. And if you visit Amsterdam, be sure you visit the Micropia Zoo, the world's first microbial zoo. Much of the zoo, which opened in 2014, looks like a laboratory, complete with rows of microscopes connected to giant television screens. Visitors can also look through a window at a genuine

All case studies have a few questions at the end, the answers to which will become apparent as you read the sections following the case.

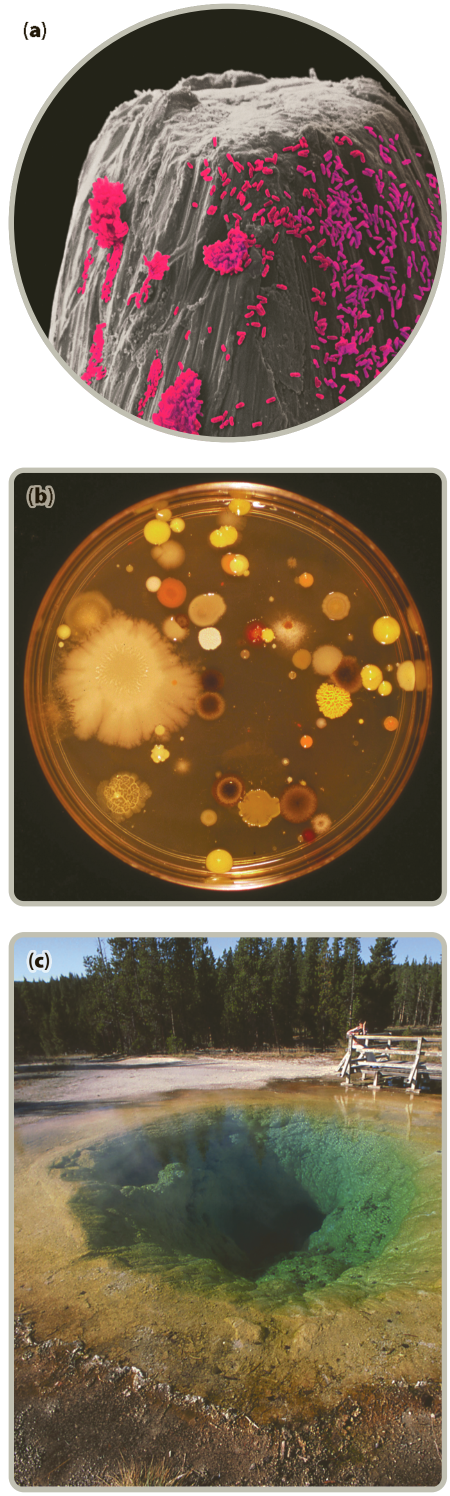


Figure 1.1 The microbial world around us. (a) Bacteria growing on the end of a pin. (b) Microorganisms live almost everywhere. When surfaces in the environment (a doorknob, a body part, or a kitchen sink, for example) are swabbed with a moist sterile swab, microorganisms that adhere to the swab can be transferred to a nutrient agar plate that supports microbial growth. After approximately 24 hours at a favorable temperature, all of these samples of environmental material show heavy microbial growth. Each visible spot on the plate represents millions of microbial cells, known as a colony. (c) Even environments such as this hot spring, too extreme to support plant or animal life, are conducive to the survival of certain microorganisms.

laboratory where different kinds of microbes are being grown in Petri dishes and test tubes.

Certainly there is no shortage of news stories to remind us that some microorganisms cause disease. In December 2013, the worst and most widespread epidemic of Ebola virus in history erupted in West Africa, riveting the world's attention. The virus kills an estimated 70% of those who become infected, and so far, there are well over 11,000 confirmed deaths. The Zika virus epidemic in the Americas, which started in Brazil in early 2015, is still a serious cause for concern and we continue to hear regularly about the ongoing AIDS crisis. And it's not just humans who are affected. North American bats, for example, are currently under siege from white nose syndrome, a disease caused by the fungus *Pseudogymnoascus destructans*. This organism, originally from Europe, was inadvertently introduced into New York in 2006. Since then it has spread to at least 25 US states and five Canadian provinces, killing over 6 million bats so far. Eleven bat species, including three endangered species have been affected. But microorganisms are not always the bad guys when it comes to our health. Consider the 2015 discovery of GB Virus C. Over a billion people are believed to be infected with this virus, but unlike viruses like measles or influenza, which cause disease, the GB Virus C actually appears to slow down the progression of certain other viral diseases such as AIDS.

The study of any living thing starts with the basics, and microorganisms are no exception. We will therefore begin by investigating the basic chemistry of microbes, their structure, and how they grow. We will learn how they pass genetic information on to the next generation and how they acquire new characteristics over time. We will take a close look at how they impact, for better or worse, our environment, our health, our diet, and even our history. Along the way we will learn the following, just to provide a few examples:

- What the designation H5N1 in reference to bird flu actually signifies
- Why biological dead zones, devoid of most sea life, are an important problem in the world's oceans
- How microorganisms contributed to the fall of Rome, the conquest of the Americas, and the development of a middle class in England
- Why hydrogen peroxide is a good thing to keep in your medicine cabinet
- How disease-causing microbes develop resistance to antibiotics and how such resistance can be reversed
- What gives Swiss cheese its particular flavor
- Why stone-washed denim has nothing to do with stones

The study of microbes provides answers to all of these questions. The reasons for studying microorganisms, however, go well beyond such examples, no matter how interesting they might be. When we learn about microorganisms, we are learning about life itself. As you proceed through this text, you will find that basic life processes are the same for all living things. Most of the major discoveries made by biologists about the nature of life and how it works were first made in microorganisms; biologists then found that the same discoveries applied to other forms of life. Biologists have been attracted to microorganisms because, in many respects, they are simpler, they are easier to work with, and they yield experimental results faster than animals or plants. Furthermore, many of the most important issues in the world today—issues that on the surface may seem to have little to do with biology, such as global warming, rising energy costs, and international terrorism—involve microorganisms to greater or lesser degrees. Consequently, for the newcomer to biology, there is no better place to start than the world of microorganisms.

We will learn why life itself depends on microorganisms. Although we may not see them and although some of them cause more than their share of misery and disease, we cannot live without them. Microorganisms were here millions of years before us, and they will no doubt be here long after we are gone. Before we begin to tell their tale, however, let's consider a few key characteristics that all living things, microbial or not, have in common.

All living things are composed of one or more cells

One of the most fundamental principles in all of biology is the **cell theory**—the notion that all living things are composed of **cells**. Cells are highly organized structures that are always surrounded by a membrane. Cells are the basic unit of life, and all living things are composed of one or more cells (**Figure 1.2**). The interior of cells is a watery mixture of many molecules and structures that carry out various activities. Microorganisms are most commonly **unicellular**; they consist of only a single cell. Some microbes, on the other hand, as well as all animals and plants, are **multicellular**, meaning that they are composed of many cells.

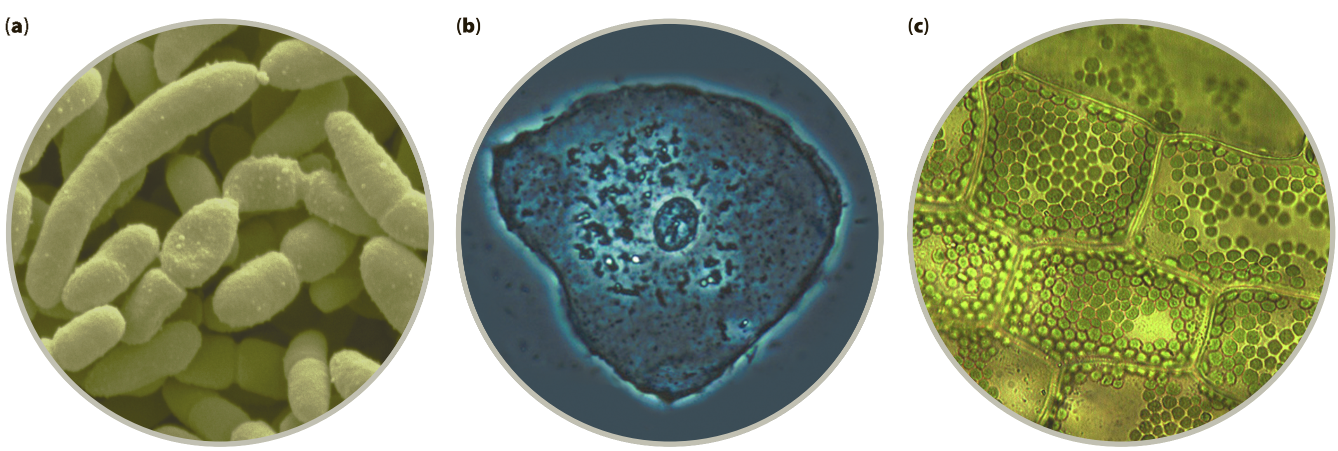


Figure 1.2 Cell types. All cells are surrounded by a cell membrane. (a) *Acetobacter*, an example of bacterial cells. These bacteria are commonly used to make vinegar. Because each individual cell constitutes an individual bacterium, most bacteria are considered to be unicellular. Like almost all bacterial cells, each cell is small and surrounded by a rigid cell wall. The genetic material of bacterial cells is not enclosed within a membrane. Cells that lack a membrane for this purpose are called prokaryotic cells. (b) An animal cell from the inside of the mouth. Note the densely stained nucleus in the cell's interior. The nucleus, which contains the cell's genetic material, is surrounded by a nuclear membrane. Cells with such a membrane are called eukaryotic cells. (c) Plant cells. In addition to a nucleus, plant cells also often contain chloroplasts (seen as green membrane-bound structures), the site of photosynthesis. Note the more regular shape of the plant cells, compared with animal cells. This is due to the presence of a cell wall, exterior to the cell membrane. Such a wall is absent in animal cells. Individual plants and animals are both composed of many cells and are consequently called multicellular organisms.

Cells fall into two general types, called prokaryotic and eukaryotic. Most microorganisms have simpler and usually smaller cells known as **prokaryotic cells** (see Figure 1.2). This name comes from the Greek for "before the nucleus," and it reminds us that in these cells the genetic material is not surrounded by a nuclear membrane. This is in contrast to the larger and more complex **eukaryotic cells** (from the Greek for "true nucleus"), in which a membrane surrounding the genetic material forms the nucleus. Eukaryotic cells also have a variety of other small structures called **organelles** (little organs), which carry out specific functions required by the cell. Eukaryotic cells are thus more compartmentalized than prokaryotic cells, with many specific activities taking place in discrete locations. In prokaryotic cells, although these same activities occur, the precise location within the cell where they occur is less defined. Eukaryotic cells are found in animals and plants, as well as some microorganisms.

All living things display other observable characteristics

What exactly is life? Perhaps surprisingly, such a simple question does not have an easy answer. One unifying characteristic of living things is that they are composed of cells (**Figure 1.3a**). These cells, prokaryotic and eukaryotic alike, share a number of defining characteristics, and the presence of these characteristics usually allows us to separate the living and nonliving worlds.

First of all, living cells typically have an internal environment that is different from their surroundings. It may be more or less salty or different in terms of acidity. Moreover, cells have mechanisms to maintain these differences, a process called **homeostasis** (**Figure 1.3b**). Just to provide one familiar example of homeostasis, your body temperature is kept relatively constant, about 37°C, regardless of the environmental temperature. In humans, critical cellular processes function best at this temperature. Should temperature-regulating homeostasis fail, a cell's ability to carry out these processes will decline, and if homeostasis cannot be reestablished, the cell will ultimately die.

Furthermore, all living things have the ability to reproduce (**Figure 1.3c**), which requires a blueprint, usually encoded in a molecule called **deoxyribonucleic acid (DNA)**. Living things can also respond to their environment; they can alter their behavior as environmental conditions change. Certain environmental cues may cause cells to move toward or away from a stimulus. Cells respond to chemical signals in their environment, and often these signals are released by other cells (**Figure 1.3d**). This represents a form of cell-to-cell communication, and such communication is also a hallmark of living systems. Another important characteristic of living things is the ability to assimilate and use energy, a process known as **metabolism** (**Figure 1.3e**). Finally, all life changes over time. Via the process of **evolution**, the characteristics of living things may change over many generations (**Figure 1.3f**).

Microbiology involves the study of several distinct groups of living things

Microbiology is distinguished from other subdisciplines within biology in that it deals primarily with microscopic organisms. It actually covers quite a bit of ground because microorganisms are such a diverse lot—far more diverse than animals or plants.

Bacteria are small, most commonly single-celled, prokaryotic organisms (**Table 1.1**). The other major group of prokaryotes is the **archaea**. Although archaea look much the same as bacteria, there are many structural differences between these two groups, and they are only distantly related.

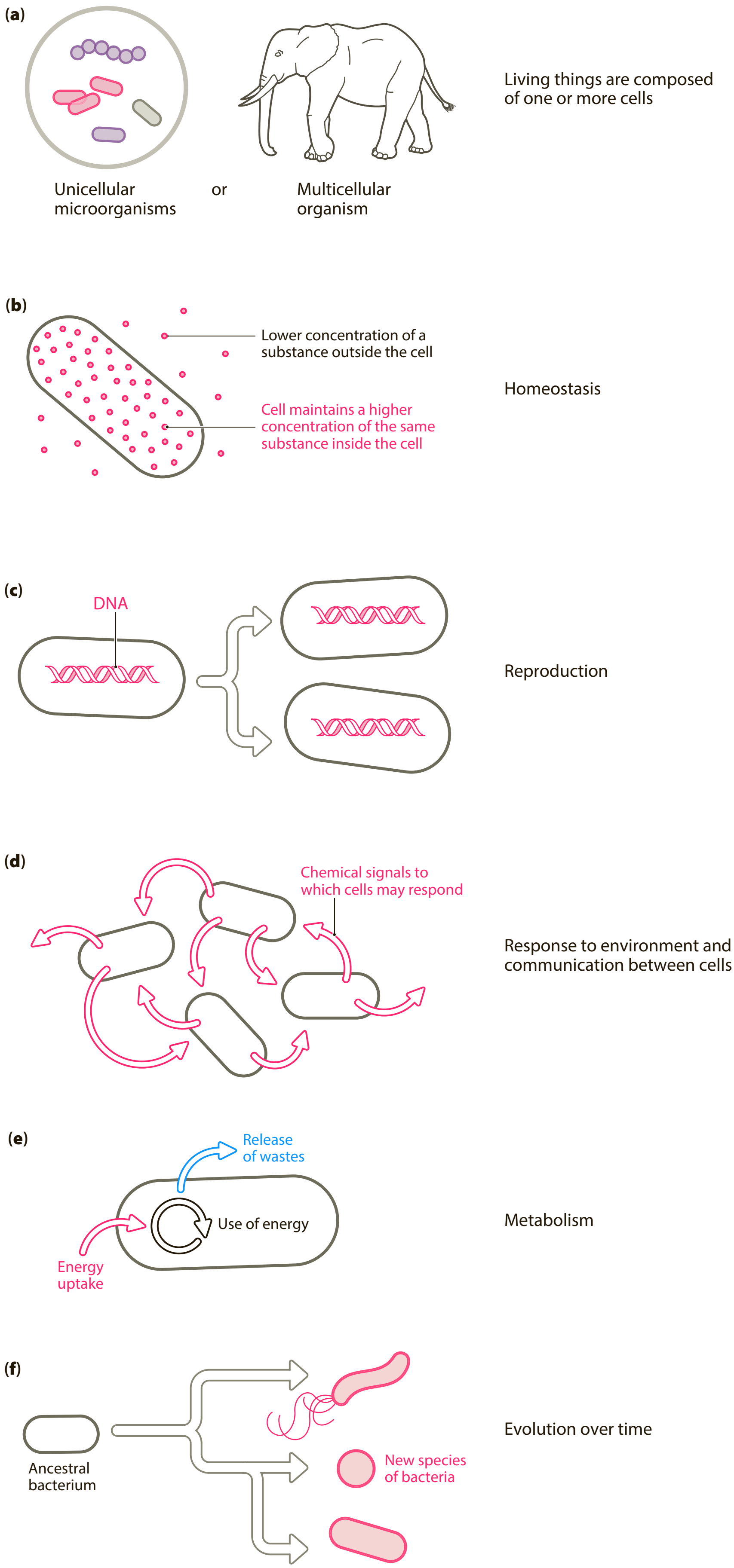


Figure 1.3 Some characteristics of life. (a) Living things are composed of one or more cells. (b) For some environmental factors, homeostasis allows cells to maintain different conditions within the cell than those of the surrounding environment. (c) All living things are able to reproduce. Genetic information is transferred between parent and offspring in the form of a molecule called DNA. (d) Cells respond to chemical signals that are released by other cells or that are present in the environment. (e) They also require energy to carry out various cellular functions. (f) They undergo evolutionary change over time.

Table 1.1 Some characteristics of major types of microorganisms. Bacteria and archaea have prokaryotic cells, while protozoa, fungi, and algae have eukaryotic cells. Neither viruses nor prions are composed of cells and are therefore termed acellular.

MICROORGANISM	CELL TYPE	CELL WALL	PHOTOSYNTHESIS
Bacteria	Prokaryotic	Yes, almost all	Some
Archaea	Prokaryotic	Some	Some
Protozoa	Eukaryotic	In some life cycle stages	No
Fungi	Eukaryotic	Yes	No
Algae	Eukaryotic	Yes	Yes
Viruses	Acellular (not composed of cells)	No	No
Prions	Acellular (protein only)	No	No

Other microorganisms have eukaryotic cells (see Table 1.1). Eukaryotic microorganisms include many fungi and the protozoa (**Figure 1.4**). Algae likewise have eukaryotic cells, and the smaller microscopic algae are considered to be microorganisms as well. Animals and plants are also composed of more complex eukaryotic cells, meaning that, in spite of the size difference, the cells of microorganisms such as baker's yeast (a fungus) and malaria parasites (protozoa) have more in common with human or other animal cells than they do with prokaryotic bacteria or archaea.

The **viruses** are particularly interesting and unusual. Viruses are the ultimate parasite; they are utterly unable to reproduce unless they gain access to the interior of an appropriate cell. Once inside, however, they essentially hijack the cell and use the cell's machinery to carry out their own replication. The cell, forced to divert energy and other resources to viral replication, may eventually die. Once they have successfully replicated, new viral particles leave the cell and go on to infect other cells to repeat the replicative cycle. Because they rely so heavily on the cells that they parasitize, viruses are unusually simple. They consist of little more than genetic material surrounded by a protein coat, and they have few of the structures found in other microorganisms. Many of humanity's worst scourges are various viruses, such as influenza and HIV

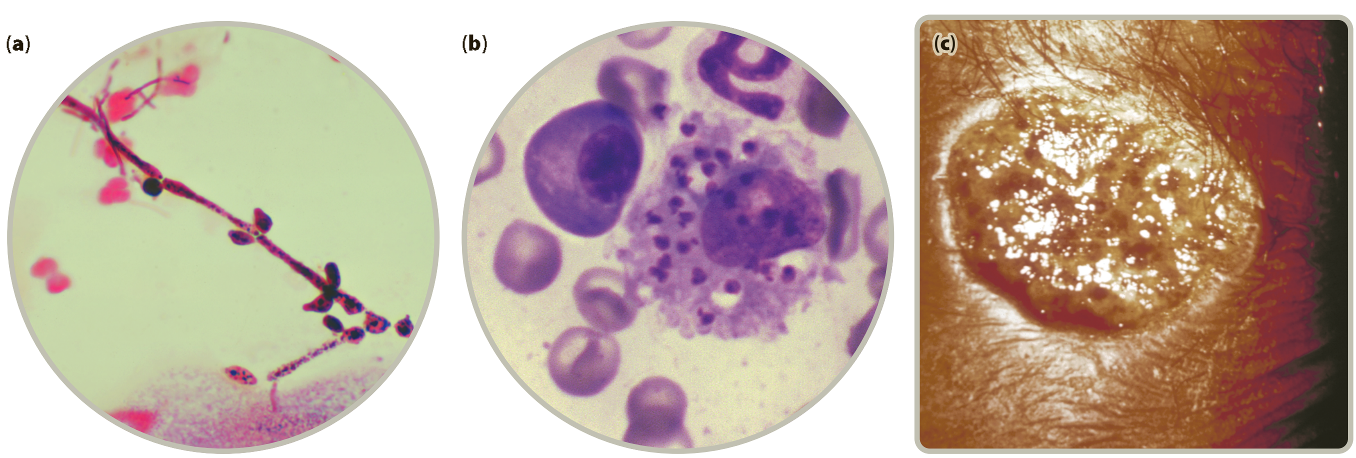


Figure 1.4 Eukaryotic microorganisms. (a) *Candida albicans*, the fungal pathogen responsible for vaginal yeast infections. (b) *Leishmania donovani* (small purple bodies) inside larger mammalian white blood cells. This protozoan parasite is transmitted through the bite of infected sand flies. (c) A skin lesion in a patient suffering from a *Leishmania* infection.

(**Figure 1.5**). Finally, there are the **prions**, infectious proteins, which make even viruses look complex by comparison (**Figure 1.6**). Prions are responsible for a set of odd diseases that includes mad cow disease.

Viruses strain our notion of what it means to be alive

Not all living things display all the characteristics of life, and microorganisms especially test the boundaries separating the living from the nonliving world. Sometimes, for instance, the capacity for independent movement is considered a characteristic of life, but many microorganisms are incapable of such movement. Viruses are particularly problematic; they seem to straddle the border between life and nonlife. Viruses are not composed of cells. On their own, they cannot reproduce, and they carry out little if any independent metabolism. Yet viruses are able to attach to and gain entry into the cells of other organisms. Once inside, they begin to replicate and certainly act like living things. So, are they alive? Such a question is perhaps more philosophical than biological, but it highlights the fact that the division between life and nonlife is not as sharp as one might think.

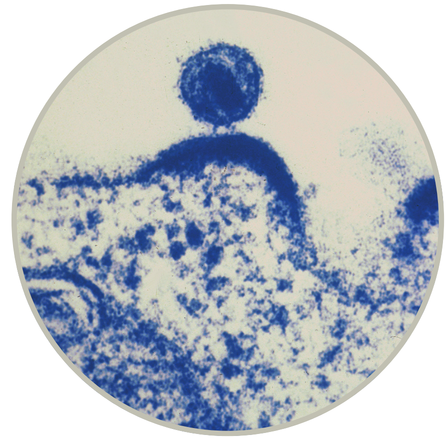


Figure 1.5 Human immunodeficiency virus (HIV). Newly formed viral particles can be seen leaving the much larger infected human cell. Unlike other microorganisms, viruses are not composed of cells, and they cannot replicate outside an appropriate cell of another organism. Consequently, they are called obligate parasites (parasitism is an absolute requirement). Once inside an appropriate cell, viruses commandeer the host-cell machinery to facilitate their own replication. Depending on the virus, such cellular hijacking may or may not kill the cell.

Microbiology is closely intertwined with the study of non-microorganisms

The scope of microbiology does not end with the microorganisms themselves. In many areas of microbiology, we cannot neglect the biology of multicellular eukaryotes such as ourselves. When we discuss how certain microorganisms cause disease, for example, it is important to understand not only what infectious microbes do to us but also how we defend against them. Consequently, we must also consider the immune system and how it helps us fend off a never-ending microbial onslaught.

Because microbiology is such a large and complex field, most microbiologists specialize within one of many specific fields of expertise. Before we begin our study of the organisms themselves, let us briefly consider some of the diverse areas of study within the science of microbiology. To do so, we will begin with a case study.

Figure 1.6 Prions. (a) Prion proteins. Prions are unique infectious agents, consisting of protein only. (b) Prions cause neurological disorders. This sheep suffers from a prion disease known as scrapie. Infected sheep behave erratically, often scraping themselves against hard objects, causing the loss of their wool coat.

Microbiology is composed of both basic and applied components

CASE: BEAUTY AND THE BACTERIA

Many of the greatest artistic masterpieces have suffered greatly from the passage of time. Modern museums are designed to protect these priceless artifacts, but in many cases, the damage is already done; centuries of storage or display under less-than-optimal conditions, such as an old cathedral, where artworks may be exposed to soot from burning candles, moisture, light, and air pollutants take their toll, resulting in the accumulation of dirt and the degradation of the original paint. Here to help is *Pseudomonas stutzeri*, a common bacterium that digests many of the common pollutants found in artwork. Italian scientists have found that small amounts of these bacteria applied to damaged frescos can remove up to 80% of the accumulated contaminants in as little as 12 hours. To cite one example, *The Conversion of St Efisio*, painted in the late fourteenth century by the Italian artist Spinello Aretino, was on display for hundreds of years on the interior wall of the famed Camposanto Cemetery in Pisa and was badly damaged. By applying *P. stutzeri* to the fresco, the original beauty of the artwork has been largely restored.

1. **What type of microbiologists would concern themselves with studies of this kind?**
2. **How does *Pseudomonas stutzeri* dissolve away accumulated material from the artwork?**
3. **Are there other types of microorganisms that damage, rather than help protect, artwork?**

Microbiology, like biology in general, has both **basic** and **applied** components. A biologist studying topics in basic biology is interested in a more complete understanding of life processes. Learning exactly how specific cells utilize energy, or how different organisms are related to each other, are both examples of basic biological questions.

Much of our understanding of basic biological processes comes from the study of microorganisms (**Figure 1.7a**). With their simpler cellular structure, microorganisms provide the microbiologist with a useful starting point for teasing apart cellular processes. They are also easier to maintain in the laboratory than plants or animals, and they are relatively easy to manipulate experimentally. Because they reproduce so quickly, experimental results can be obtained far more rapidly with them than with slower growing and more slowly reproducing multicellular organisms. And finally, as we have already noted and as we will highlight throughout this text, many fundamental biological processes are very similar whether we are talking about a single-celled bacterium or a large animal composed of trillions of cells. Consequently, lessons learned from microorganisms are often useful in understanding the basic biology of animals, plants, and other organisms.

Certain bacteria and other living things that have been closely studied for these and similar reasons are referred to as **model organisms**. The bacterium *Escherichia coli*, for example, is sometimes referred to as the microbial lab rat (rats are an animal model organism), because of the intensity with which it has been studied. Many seminal biological discoveries, such as the discovery of DNA and how it functions, were first elucidated by the use of this bacterial species. *E. coli* continues to reveal secrets with applications to living things in general. For instance, in Chapter 15 we will see how many breakthroughs of the biotechnology revolution came to us courtesy of this microorganism.

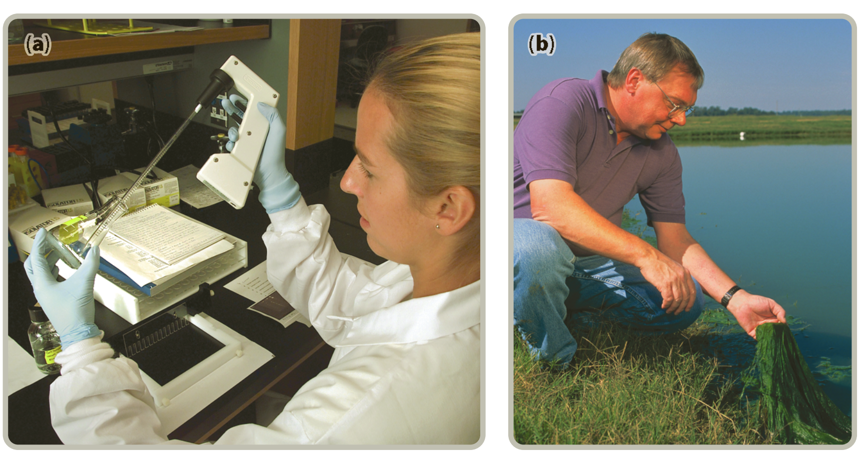


Figure 1.7 Microbiologists at work. (a) Basic microbiology seeks to gain a more complete understanding of biological processes, focusing on microorganisms. Here, a microbiologist uses a device called a pipetter to transfer material from one tube to another. (b) Using knowledge gained through basic research, the applied microbiologist attempts to solve practical problems. Here, an environmental microbiologist investigates the effect of microorganisms on a lake's water quality.

The basic biologist is not trying to solve a practical problem. That's the job of the applied biologist. Applied biologists use the knowledge gained in basic biology to solve real-world problems. For example, a basic researcher might determine the exact way that a certain virus enters human cells. An applied scientist may then use this information to design a new antiviral drug that would thwart the entry of the virus. The division between basic and applied science, however, is not a sharp one, and it is not uncommon for a scientist to work on both basic and applied aspects of a particular problem.

Both basic and applied microbiology consist of many subdisciplines

Within the broad area of basic microbiology, a scientist might wish to study any number of specific topics. A microbial geneticist, for example, may choose to study how the genetic material of a particular microorganism is turned on or shut off in response to changing environmental conditions. A microbial ecologist might opt to investigate how a community of microorganisms living in the soil influences the availability of nutrients for plants. A microbiologist interested in adaptations to extreme environments may wish to know how certain microorganisms withstand levels of radiation that would kill an animal.

Applied microbiology likewise encompasses many diverse areas of interest. Medical microbiologists try to better understand the role of microorganisms in infectious disease, with an eye toward prevention or treatment. Public health microbiologists help educate the public about how to best avoid such disease, whereas epidemiologists track the spread of disease in the community and attempt to predict future outbreaks.

Food microbiologists, on the other hand, utilize microorganisms to produce a large portion of what we eat, from cheese to bread to soy sauce. Agricultural microbiologists often utilize knowledge gained through the study of microbial ecology to enhance crop growth or reduce the likelihood that valuable food plants will suffer from disease (**Figure 1.7b**). Industrial microbiologists investigate the manner in which bacteria and fungi can be used to produce a wide variety of industrial and commercial products.

Increasingly, microbiologists, along with other biologists, have entered the new biological frontier of genetic engineering and recombinant DNA technology. Using a variety of techniques and molecular tools provided by microbes, these scientists have been able to introduce foreign DNA into new organisms, creating cells with novel capabilities. As we will discover, because of this powerful new technology, we now have bacteria that produce insulin for human diabetics and potential cures for genetic diseases, as well as a whole host of other potentially exciting, sometimes scary applications.

These are just a few of the many avenues of investigation open to the microbiologist. We will discover others as we proceed through the text. And what about the scientists who are using bacteria to restore irreplaceable artwork (**Figure 1.8a**)? Those who work to protect paintings and other art objects from

Figure 1.8 Microorganisms and art; friends and foes. (a) A portion of the fresco *The Conversion of St Efisio* by the Italian artist Spinello Aretino (1350–1410). The upper photo has yet to be restored. The lower photo is following treatment with *Pseudomonas stutzeri*. (b) *Starry Night* by Vincent van Gogh (1853–1890). Faint areas of brownish and greenish discoloration are due to the breakdown of crocoite, a mineral used by many artists in the nineteenth century to formulate certain colors. Bacteria are responsible for crocoite digestion and consequently the discoloration. (c) The dark discoloration of these Mayan ruins in Yucatan, Mexico, is likewise caused by various microorganisms.

damage of any sort are generally called restoration scientists. This new field, utilizing microbial assistance, as yet has no formal name. Perhaps it should be called restoration microbiology or artifact microbiology. Regardless, this is an example of applied microbiology. Like other applied microbiologists, these scientists are grounded in basic microbiology—in this instance, the precise manner in which certain bacteria break down the art contaminants.

Pseudomonas stutzeri do not offer their services out of the goodness of their hearts. The bacteria are simply digesting materials that they can then use themselves to meet their nutritional or metabolic needs. They do so by secreting proteins called enzymes that catalyse biological reactions—in this case, the digestion of the molecules accumulating on the artwork. We will take a close look at enzymes and how they function in Chapter 2.

Other microbes are not so accommodating. Many bacteria and fungi are capable of colonizing artwork, and digesting components of the paint (**Figure 1.8b**). Others cause discoloration to stone relics as they grow on or even beneath their surfaces (**Figure 1.8c**). It is not always clear how to prevent such damage without further damaging the artwork itself. It appears that restoration microbiologists will have plenty to keep them busy for years to come.

Microbiology, like all fields of biology, is a **science**. By this we mean that microbiology is a process of learning about nature by observation and experiment. Scientists gain knowledge about the natural world in a precise manner known as the **scientific method**. Before we end this introductory chapter and begin our study of microorganisms in earnest, let us consider exactly how scientific knowledge is acquired.

A proper scientific experiment involves a series of well-defined steps

CASE: FLEMING REVISITED

The British scientist Alexander Fleming discovered the first antibiotic in 1929. He noticed that when certain molds contaminated his bacterial culture plates, the bacteria were unable to grow close to the mold. Fleming reasoned that the mold was secreting a substance that killed the bacteria. This proved to be the case, and the mold was identified as *Penicillium notatum*, now called *Penicillium chrysogenum.* Fleming named the secreted antibiotic penicillin (**Figure 1.9a**).

Two microbiology students, Eleonora and John, learn of Fleming's work in their class, and later, when they must perform a small, independent research project as part of their laboratory grade, they decide to repeat Fleming's work with a different yet closely related mold, *Penicillium roqueforti*. This mold is commonly used in the production of blue cheese. The mold digests milk sugars, and the waste products that are released contribute to the taste of the cheese. The mold also gives blue cheese its characteristic blue streaks (**Figure 1.9b**). Does it also, like *P. chrysogenum,* have antibacterial properties?

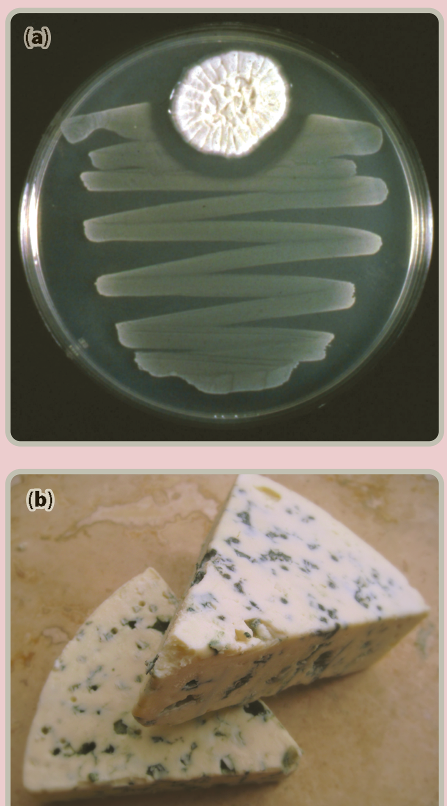


Figure 1.9 ***Penicillium*** **molds.** (a) Penicillin secreted by the mold *Penicillium chrysogenum* prevents the bacteria from growing near the mold colony. (b) *Penicillium roqueforti*, seen as blue streaks, is used to make blue cheese.

To find out, Eleonora and John buy a block of blue cheese and transfer mold cells onto nutrient agar plates, which will support the growth of a wide range of bacteria as well as the *P. roqueforti* mold. They inoculate 12 plates with lawns of the bacterium *Staphylococcus epidermidis*. Lawns are prepared by swabbing a plate with a uniform coating of bacteria. The bacteria then grow over the entire surface of the plate (**Figure 1.10a**). Eleonora and John, using an inoculating loop, next streak *P. roqueforti* in a zigzag pattern over six of their plates (**Figure 1.10b**). The other six plates are streaked with an uninoculated loop without the mold. All 12 plates are then incubated at 35°C for 24 hours. The two students then examine their plates, comparing those with and without *P. roqueforti* for evidence of antimicrobial activity.

1. **What hypothesis are Eleonora and John testing?**
2. **Which of their nutrient agar plates are serving as controls? Which are the experimental plates? Why are the control plates critical?**
3. **What is the experimental variable in this experiment? What are the important control variables?**
4. **Why is it important to use six plates with and six plates without the mold, rather than just one of each?**

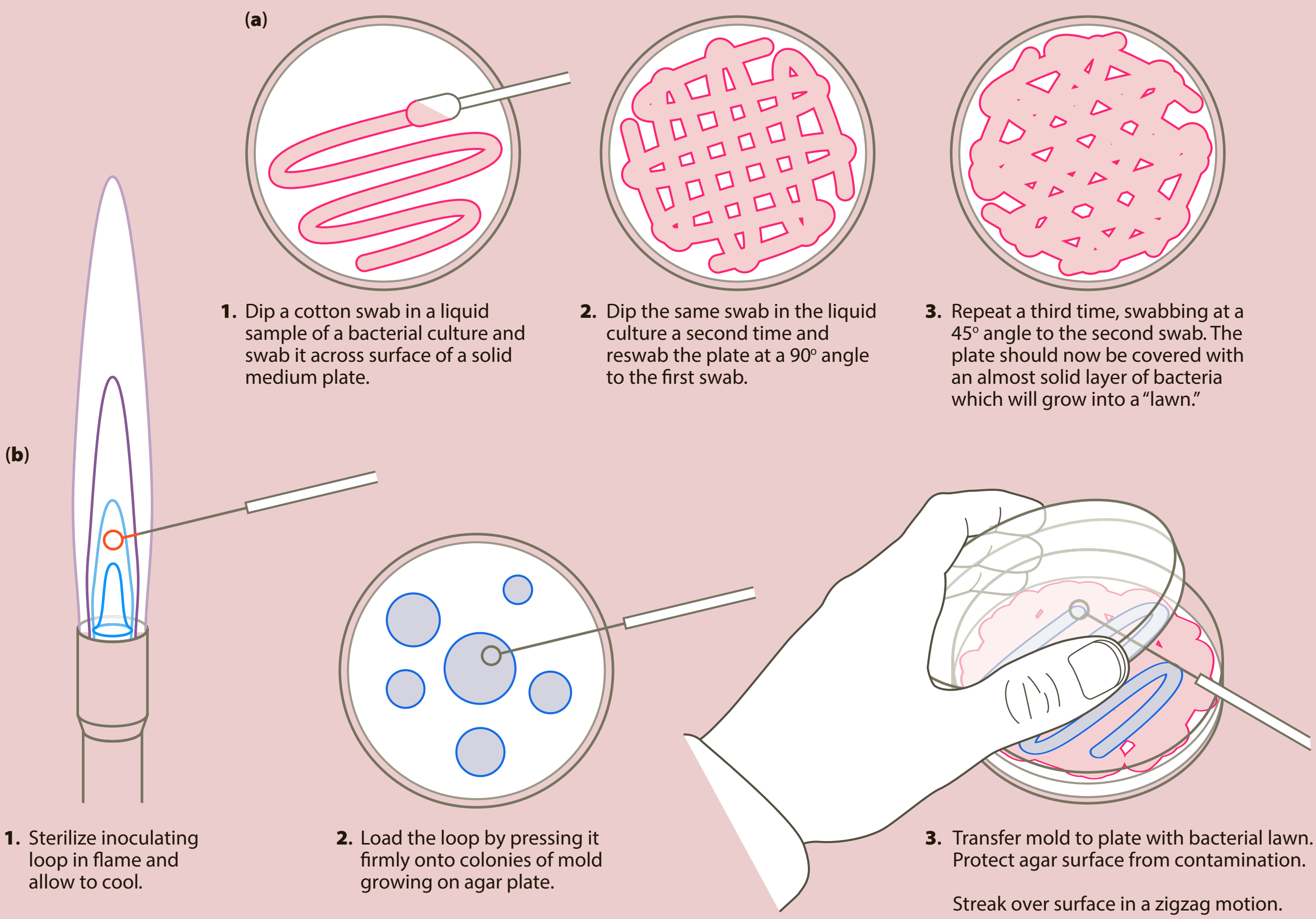


Figure 1.10 Testing a mold for antimicrobial activity. (a) Prepare bacterial lawns on several agar plates. (b) Inoculate some of the plates with mold. After an incubation period, compare the inoculated and the uninoculated plates for evidence of inhibited bacterial growth.

The scientific method and the process of scientific inquiry begin with an observation. Fleming noticed that *Staphylococcus* was unable to grow close to a mold contaminant. Observations such as these lead to questions. How did the mold inhibit bacterial growth?

To answer such questions, the scientist formulates an appropriate **hypothesis**. A hypothesis is a tentative explanation for a specific question. To be valid, a hypothesis must be testable. In other words, it must be possible to collect evidence that either supports or refutes the hypothesis. To gather such evidence, one must be able to make predictions based on the hypothesis. Experiments or observations of future events are then used to determine whether the prediction was realized. If so, the hypothesis is supported. If the prediction proves to be inaccurate, the hypothesis is rejected as false. In the case of the mold Eleonora and John are testing, their hypothesis is that *P. roqueforti* produces compounds that can inhibit bacterial growth. They therefore predict that *Staphylococcus* will be unable to grow close to the mold.

The next step is to test the hypothesis with a valid experiment. Such an experiment will compare an **experimental group** with a **control group** (**Figure 1.11**). The experimental group is the group in which a crucial factor will be manipulated. In the control group, that same factor will be left

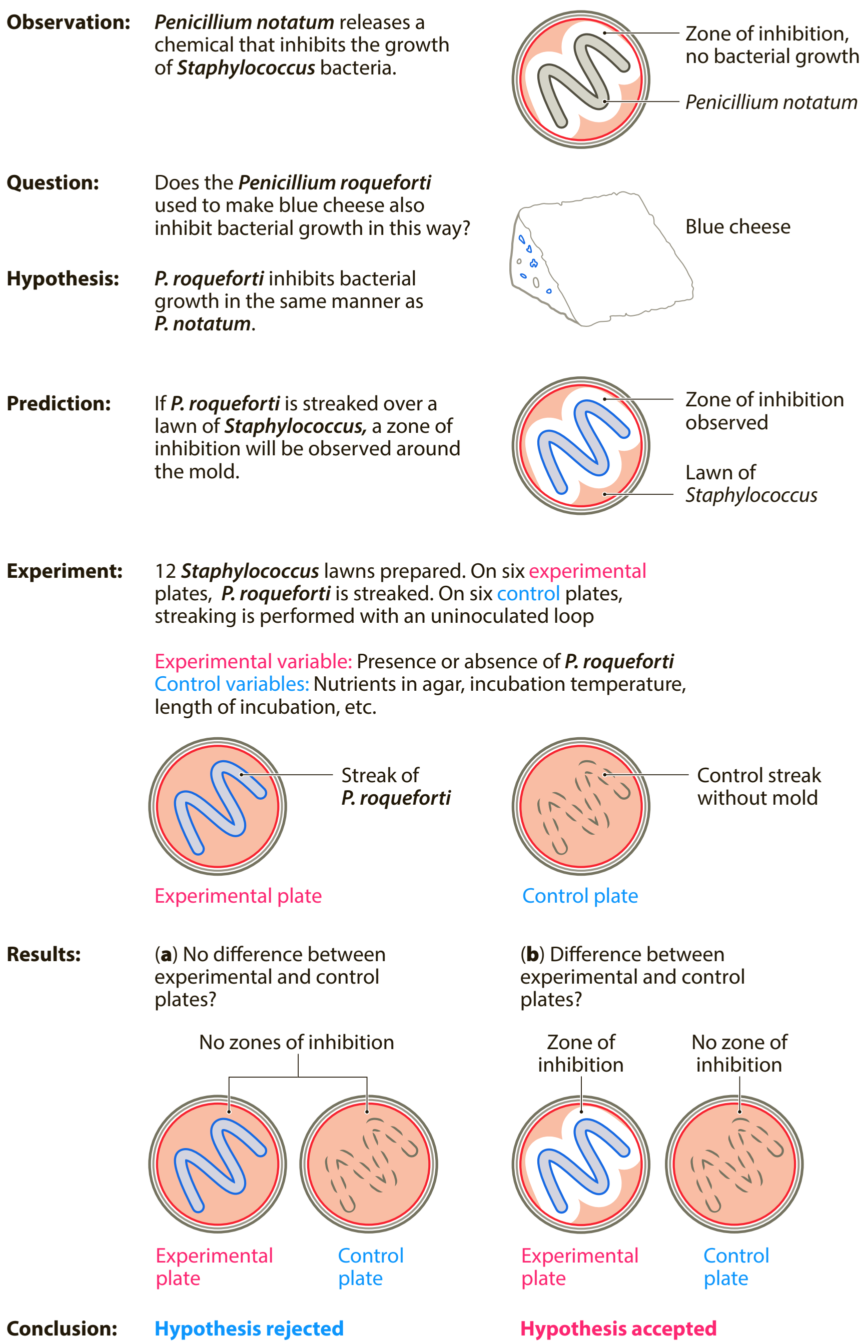


Figure 1.11 A controlled experiment to test a hypothesis. After making an initial observation that leads to a specific question, the scientist formulates a proper hypothesis. A proper hypothesis is a tentative answer to the question that has been posed and it must predict future events. If these events do not occur, the hypothesis is rejected and a new hypothesis must be generated. If the events predicted by the hypothesis occur, the hypothesis is supported. In this example, the hypothesis that *P. roqueforti* can inhibit bacterial growth by secreting antibacterial compounds is being tested experimentally. The experimenter prepares bacterial lawns and streaks *P. roqueforti* on half of these lawns. These represent the experimental group. On the remaining bacterial lawns, no *P. roqueforti* is added. These represent the control group, which will be compared with the experimental group to determine whether the added *P. roqueforti* has had any effect on bacterial growth. The only difference between the two groups of plates is the presence or absence of *P. roqueforti*. This difference is the experimental variable. All other factors (for example, temperature or provided nutrients) must be the same in the two groups. These are the control variables.

unchanged, as a means of comparison. If the manipulation of this factor results in a specific change as predicted by the hypothesis, and if that change does not occur in the unmanipulated control group, the hypothesis is supported.

For example, in Eleonora and John's experiment, the experimental group consists of those bacterial lawns onto which the mold was streaked. No mold was placed on the control plates. Consequently, if their hypothesis that *P. roqueforti* is able to produce antibiotic compounds is correct, bacterial growth on the experimental and control plates should be different. If the hypothesis is incorrect, bacterial growth on the two types of plates will be similar, and the hypothesis can be rejected.

The experimental and control groups in any experiment should be identical for all factors except one. In our students' experiment, all plates contained the same nutrients and they were incubated at identical temperatures. These represent **controlled variables**. The only difference was the **experimental variable**—in this case, the presence or absence of mold. After 24 hours, the two students compared bacterial growth on their experimental plates streaked with mold with their control plates lacking it. Because they carefully controlled all variables except one, any differences in bacterial growth on the two groups of plates could be attributed to the mold rather than some other factor. Note that Eleonora and John even streaked the control plates with an empty inoculating loop. This added controlled variable ensures that if they do see reduced bacterial growth on experimental plates, it must be due to the mold rather than the physical act of streaking.

Following completion of the experiment, the experimental and control plates are compared. Without the control group there would be no way to interpret the effect of the experimental variable. A significant inhibition of growth on the experimental plates indicates that the hypothesis may be tentatively accepted. No difference in bacterial growth on the two sets of plates indicates that the hypothesis should be rejected. When hypotheses are rejected in this way, a scientist has to develop a new hypothesis to explain the initial observation. A new experiment with a different experimental variable is then conducted. Keep in mind that in most situations there may be numerous plausible hypotheses. The task of the scientist, in this case, is to rule out as many of these competing hypotheses as possible. Ideally, only a single hypothesis remains to explain the initial observation.

Recall that the students in our case inoculated several experimental and control plates, rather than just one of each. It is almost always true that the larger the number of treatments, the more meaningful the results. Replication reduces the amount of variance due to unaccounted-for events. For example, the students might have accidentally prepared one of their bacterial lawns improperly. If they put too few organisms on an experimental plate, they may have incorrectly assumed that *P. roqueforti* was unable to inhibit the growth of *S. epidermidis*. In truth, these results might merely have reflected improper inoculation. By repeating the experiment, the likelihood of such erroneous interpretation can be reduced.

If a hypothesis cannot be disproved, it may eventually become a theory

If a hypothesis is rigorously and repeatedly tested and is never rejected, it may in time become part of a **theory**. A theory, such as the theory of gravity, is an important principle supported by a large body of experimental evidence. In this text we have already mentioned the cell theory, and we will encounter other biological theories, such as the theory of biological evolution and the germ theory of disease. A theory can never be proven beyond all doubt, but a scientific theory is a powerful concept; a large body of evidence has accumulated to support it. Until proven otherwise, it remains the best explanation available to account for a given phenomenon. In other words, a theory has withstood the test of time. In everyday speech, however, a theory may refer to merely an idea or a guess that has not been tested or lacks any supporting evidence. Because the word has two very different meanings, it is often a source of great confusion among the general public. Indeed, it is common to hear nonscientists erroneously dismiss a fundamental scientific principle as “only a theory,” when in fact it has the weight of scientific evidence behind it.

Looking back and looking forward

In this chapter we have laid the groundwork for what is to come. In these first few pages we have learned a little about who the microorganisms are, and something about where they are found and what characteristics they possess. We have also come to know what a microbiologist is, the sorts of things such a scientist might study, and how scientific inquiry is conducted.

Having gained some insight into exactly what we will be studying, it is time to begin. In Chapter 2 we introduce some of the basic chemical principles that are necessary for an understanding of microbiology. As we proceed through the fundamentals of biological chemistry, we will see that even when discussing atoms, the basic units of all matter, the implications for microorganisms and the manner in which they interact with us are ever-present and often unexpected.

Garland Science Learning System

- http://garlandscience.rocketmix.com/students/
- Discover how (scientifically) to prove you’re right and why a scientific theory isn’t merely theoretical
- Test your knowledge of this chapter by taking the quiz
- Familiarize yourself with the terminology used in this chapter by using the vocabulary review
- Get help with the answers to the Concept questions

Concept questions

These questions are designed to help you start thinking like a microbiologist. The answers are not always simply found in the text. Instead, you will need to take the concepts about which you have learned and apply them to new situations. Some of the questions may not even have just a single correct answer. Help is provided as part of the GSLS resources, which can be accessed through http://garlandscience.rocketmix.com/students/.

1. It is stated in this chapter that the question of whether or not viruses are alive might be more of a philosophical question than a biological one. Explain what you think is meant by this.

2. Nonscientists often refer to all microorganisms as “germs.” Is it reasonable to lump all microorganisms together with this catch-all term? Why or why not?

3. Open a newspaper or magazine, or go to an online news site and find a story that in some way discusses bacteria, a virus, or another microorganism. Are the scientists whom the story describes engaged in basic or applied microbiology?
4. A drug manufacturer develops a new antiviral drug, which it hopes will be effective in preventing colds. First, a group of 1000 volunteers is assembled. All are comparable in terms of age and general health. Of these volunteers, 500 (group A) are given the drug and told to take it as prescribed throughout the cold season. The remaining 500 individuals (group B) are given a placebo (a sugar pill that has no antiviral activity) to take. None of the volunteers know whether they are getting the drug or the placebo. After 5 months, all 1000 volunteers are asked whether or not they developed colds.
   a. What is the hypothesis being tested in this experiment?
   b. Which group is the experimental group? Which group is the control group?
   c. What is the experimental variable? What might some of the controlled variables be?
   d. What results might allow us to tentatively accept the hypothesis?
   e. What results would cause us to reject the hypothesis?
5. In a class you read an article that describes the prevailing theory as to why the dinosaurs went extinct. Data are provided to show that dinosaur eradication was caused by the impact of a gigantic meteorite that threw enormous quantities of dust into the atmosphere. This caused both a decline in Earth's temperature and a loss of photosynthetic vegetation, resulting in dinosaur extinction. Animals that were both better able to survive the cooler temperatures and less dependent on a huge diet of plant matter, such as primitive mammals, for example, survived. You tell a friend about this, and his response is, "That's just a theory. I don't believe it." In what way is your friend misunderstanding you?

THE CHEMISTRY OF LIFE

2

Shamokin Creek drains approximately 350 km^2 in east-central Pennsylvania. It used to be prime fishing habitat, with large populations of pike, sunfish, and other aquatic species. But the Shamokin Creek basin is also rich in coal, which was mined extensively from about 1840–1950. In the late 1990s, surveys were conducted to determine the ecological health of Shamokin Creek, as well as other streams in the area. Certain stretches of the creek were found to be extremely acidic and utterly devoid of all fish (**Figure 2.1**). Other indicators of ecological health, such as populations of aquatic plants and invertebrates, were also absent or greatly decreased. Restoration efforts began in 2000. Although the goal is a return to environmental health by 2020, Shamokin Creek remains one of the most polluted waterways in Pennsylvania.

And Shamokin Creek is unfortunately not unique. Mines can be death-traps as far as fish living in nearby streams are concerned. The culprits are bacteria called *Acidithiobacillus ferrooxidans*, which utilize chemical compounds in mine waste, releasing their own acidic waste product. Yet as depressing as this story is, it does remind us how vital chemistry is when it comes to understanding the microbial world and how micro-organisms affect us.

Figure 2.1 Damage to a stream resulting from mining. This stream has been badly acidified through the activity of bacteria. Mining activity releases sulfur compounds into the environment, and certain bacteria thrive on these compounds. Acids are released as a waste product of bacterial metabolism, and as bacterial numbers explode, nearby streams become increasingly acidic.

All case studies have a few questions at the end, the answers to which will become apparent as you read the sections following the case.

Indeed, all matter is composed of chemical compounds and the rules governing how these compounds form or interact are identical, whether that matter is living or nonliving. That means that if we really want to understand biological processes, some introductory chemistry is essential. This may be particularly true in microbiology. Most of the organisms we will discuss in this text owe their impact to the chemical changes they cause in their environments. When we consider the role microorganisms play in composting, how bacteria in your mouth cause cavities, why certain bacteria are harmless while others can cause serious health problems, or how specific microorganisms are used to produce sourdough bread or sauerkraut, we will really be considering aspects of microbial chemistry.

A comprehensive study of chemistry is well beyond the scope of this text. Rather, our goal here in Chapter 2 is to review those basic chemical principles necessary for us to fully appreciate how microorganisms interact with the world around them. We will begin by looking at atoms, the basic structural units of matter, and then investigate how atoms combine with each other to form molecules. One familiar molecule is water, and we will pay special attention to this remarkable substance, upon which all life depends. Finally, we will discuss the important biological molecules that are found in all living things, including microbes, and the roles they play in the chemistry of life.

Atoms are the basic building blocks of matter

All matter in the universe is composed of one or more **elements**. An element is a substance that cannot be broken down into other substances by chemical reaction. There are 94 naturally occurring elements known. Many, such as sulfur and calcium, are quite familiar to us. Others, including lanthanum and vanadium, are more obscure. The basic unit of an element is the **atom**. In other words, an atom is the smallest unit that can be identified as a specific element. We can speak, for instance, about an atom of magnesium, but if that atom is broken into its smaller component parts, it is no longer recognizable as magnesium.

Only about 25 elements are commonly found in microorganisms and other living things. The four most important are hydrogen, carbon, nitrogen, and oxygen, which make up approximately 96% of an organism's mass. The remaining 4% is composed of small amounts of other elements such as potassium and iron.

Atoms are made up of smaller components called subatomic particles

Atoms themselves are composed of still smaller subatomic particles. It is the number and kind of these particles in an atom that determine what kind of element it is and the chemical properties it possesses. Three of these subatomic particles, **electrons**, **neutrons**, and **protons**, are of particular importance. The smallest atoms, those of the element hydrogen, have only one proton, no neutrons, and one electron. An atom of uranium, on the other hand, is relatively large and is composed of 92 protons, 146 neutrons, and 92 electrons. Carbon typically has six protons, six neutrons, and six electrons. Nitrogen has seven each of these subatomic particles, while oxygen has eight.

The core of an atom, called the **nucleus**, is composed of protons and neutrons (**Figure 2.2a**). All atoms have a characteristic **atomic number**, which

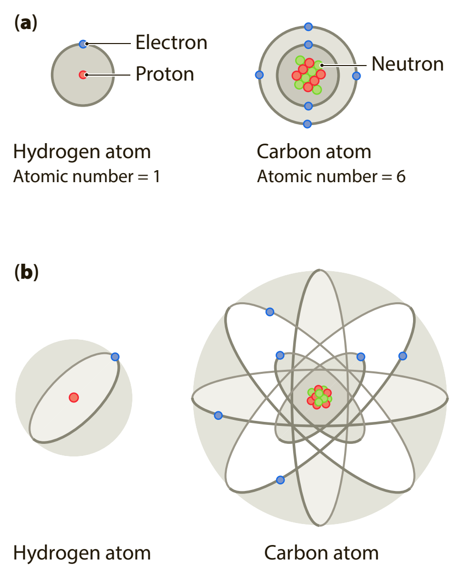


Figure 2.2 Hydrogen and carbon contain different numbers of subatomic particles. (a) A hydrogen atom, with a single positively charged proton in its nucleus, has an atomic number of 1. Its atomic mass is also equal to 1. Carbon, with a nucleus consisting of six protons and six uncharged neutrons, has an atomic number of 6 and an atomic mass of 12. A complete atom consists of the tightly packed nucleus, composed of protons and neutrons, surrounded by orbiting, negatively charged electrons. The schematic representation is highly simplified. (b) Electrons are located in specific electron shells surrounding the nucleus, and at any one time electrons may be in any of many possible locations.

corresponds to the number of protons in the nucleus. A proton carries a positive charge, while neutrons are electrically neutral. Electrons have negative charges and typically move around the nucleus at a specified distance in what is referred to as the electron's shell (**Figure 2.2b**). The protons and neutrons in the nucleus make up almost 100% of an atom's mass, and a given atom's **atomic mass** is simply the sum total of its neutrons and protons. Thus, the atomic masses of hydrogen, carbon, nitrogen, and oxygen are typically 1, 12, 14, and 16, respectively (**Table 2.1**; also see Figure 2.2).

Because electrons have a negative charge, they are attracted to the positively charged protons in the nucleus. However, because electrons are in motion around the nucleus and therefore have energy, they are not pulled into the nucleus. Electrons are found in characteristic **electron shells** at specific distances from the nucleus. Those electrons closest to the nucleus are held by the nucleus most tightly and have less energy than those electrons farther away from the nucleus. Each shell can hold only a specific number of electrons. In larger atoms with more electrons, additional shells are needed, and electrons in more distant shells are under less nuclear attraction. These more distant electrons consequently have more energy.

The first electron shell holds a maximum of two electrons. Hydrogen, with only one electron, has its single electron in this first shell (see Figure 2.2a). Helium, with two electrons, fills up this first shell, while lithium, which has three electrons, has a full innermost shell and a single electron in the second shell. The second shell holds a maximum of eight electrons. Neon, with a total of 10 electrons, has a full first and second shell. Sodium (11 electrons) and magnesium (12 electrons) begin the process of filling up the third shell. The largest known atoms require up to eight shells to hold all their electrons.

As an atom's stability increases, its energy decreases

Energy always tends toward its lowest state. Consider the water in a river as it reaches a waterfall. As the water falls down, it loses energy; it cannot flow back up the waterfall on its own. It would have to be pumped back up through an input of mechanical energy. By moving down the waterfall, the water has moved from a higher to a lower energy state. Since it is easier for water to lose energy than it is to gain it, the lower energy state is less likely to change; it is therefore more stable.

The same is true of atoms. They are more likely to interact with other atoms when they have more energy and are therefore less chemically stable. Atoms reach their lowest possible energy level, and thus their greatest chemical stability, when their outermost electron shell is full. When this shell is *not* full, an atom is **reactive**, meaning it will tend to gain or lose electrons (**Figure 2.3**). An atom tends to interact with other atoms and remain reactive until it either

Table 2.1 Atomic characteristics of elements common in living things.

ELEMENT	PROTONS	NEUTRONS	ELECTRONS	ATOMIC NUMBER	ATOMIC WEIGHT
Hydrogen (H)	1	0	1	1	1
Carbon (C)	6	6	6	6	12
Nitrogen (N)	7	7	7	7	14
Oxygen (O)	8	8	8	8	16

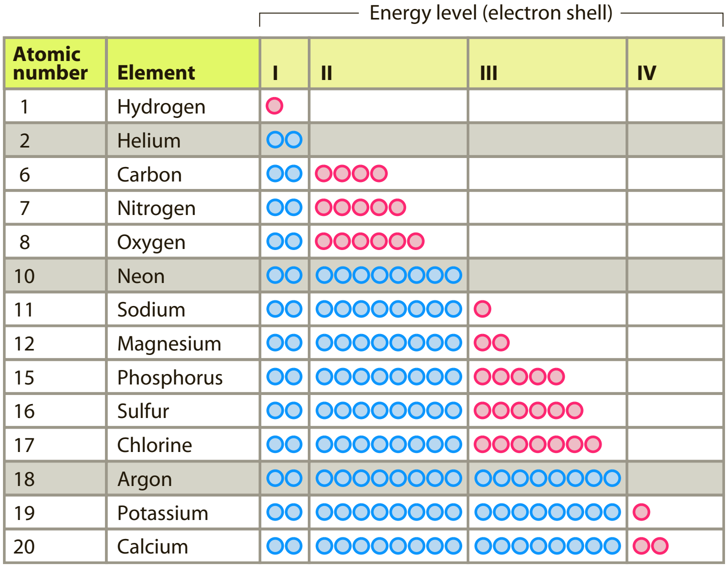


Figure 2.3 Shell configurations of some atoms. The number of electrons in an atom's outermost shell determines its chemical reactivity. The red circles indicate electrons in unfilled outermost electron shells. Atoms with such electrons are chemically reactive. Electrons in filled shells are indicated by blue circles. Atoms with no reactive outer electrons, such as helium, neon, and argon, are unreactive. Notice that the four elements most common in living organisms—hydrogen, carbon, nitrogen, and oxygen—are all chemically reactive.

gains enough electrons to fill the outermost shell or loses enough outer electrons to lose its outer shell entirely. Either way, an atom becomes stable and will no longer interact with other atoms.

Sodium, for instance, with 11 electrons, typically has a full inner shell (two electrons), a full second shell (eight electrons), and one electron in the third shell. In this uncombined state, sodium is electrically neutral because the 11 negative electrons are perfectly balanced by the 11 positively charged protons in the nucleus (**Figure 2.4**). Sodium, however, is reactive in this form, and because of its lack of stability, it tends to lose its outermost electron. If this occurs, sodium becomes stable because its 10 electrons fill both the first and second shells. But it is no longer electrically neutral. It has lost a negatively charged electron, so there are now 11 protons but only 10 electrons, giving sodium a charge of +1. Charged yet stable atoms are called **ions**. Calcium, in its reactive state, has two electrons in its outermost shell. To achieve stability, a calcium atom loses both of these electrons. Because it now has two more protons than it has electrons, the charge on a stable calcium ion is +2. Fluorine, on the other hand, has seven outer electrons in a shell that can hold eight. Fluorine can become stable by gaining a single electron, and in the process it becomes an ion with a charge of –1. Note that some atoms such as helium and neon are stable without gaining or losing electrons, because their outermost shells are already filled (see Figures 2.3 and 2.4). Such atoms are already at maximum stability and do not form ions. Because they are so stable, they do not interact with other atoms.

Perhaps the most important property of an atom is how it interacts or combines with other atoms. When two or more atoms combine, the linkage between them is called a **chemical bond**. An atom's electrons are of critical importance in determining the types of bonds an atom can form and with which other atoms it can form them. Not all bonds form in exactly the same way and we will next inspect the principal types of bonds that atoms may form with each other.

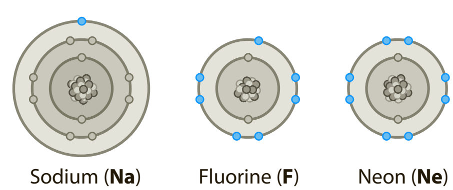


Figure 2.4 Atoms of three elements. A sodium atom becomes stable by losing one electron from its outermost shell. Once this negatively charged electron is lost, the sodium atom becomes a *positively* charged ion. A fluorine atom becomes stable by gaining an electron to complete its outermost shell. By gaining an electron, the fluorine atom becomes a *negatively* charged ion. A neon atom with a complete outermost shell neither gains nor loses electrons and is unreactive.

An ionic bond is formed when electrons are transferred from one atom to another

CASE: BACTERIA, SALT, AND CYSTIC FIBROSIS

Cystic fibrosis (CF) is an inherited disease affecting about one in every 3000 people of Northern European descent. In normal individuals, chlorine atoms, which exist as negatively charged chloride ions, can easily cross the membrane of lung cells because these cells have special chlorine-transporting proteins on their surfaces. Various mutations can affect these transport proteins and in those with CF, these transporters do not function properly. Chlorine therefore cannot enter cells efficiently. Prevented from entering lung cells, the ions readily bind to sodium ions, which carry a positive charge. The combined chlorine and sodium form the salt sodium chloride. High salt levels help to explain why bacteria proliferate in the lungs of CF sufferers. Normally, cells lining the lungs produce natural protein antibiotics that protect the lungs from bacterial colonization. However, the high salt concentration in the lungs of CF patients inactivates many of these proteins, allowing the bacteria to proliferate (Figure 2.5). Current research is underway to synthesize similar antibacterial proteins that are salt-resistant and that may be used therapeutically in CF patients to help control bacterial infections.

1. **Why do chlorine atoms form negatively charged ions, while sodium atoms form positively charged ions?**
2. **What exactly is a salt? Why do these charged atoms combine to form salt in the manner described?**
3. **How does the salt interfere with the antibacterial protein in the lungs of cystic fibrosis patients and thus increase the likelihood of bacterial infections?**

Figure 2.5 Chest X-ray of a cystic fibrosis patient. Light-colored areas in the lungs indicate areas of bacterial infection. Cystic fibrosis patients are often plagued by salty, thick mucus in the lining of the lungs and associated air passages that is difficult to cough up.

If atoms become stable simply by gaining or losing electrons, why don't they just go ahead and gain or lose them? Why should we ever encounter unstable, uncharged atoms in nature? An atom will not ordinarily lose electrons unless another atom that tends to gain electrons is nearby. The atom that requires an electron to achieve stability literally takes the electron from the atom that tends to lose electrons, forming both a positive and a negative ion in the process. In other words, atoms typically do not spontaneously gain or lose electrons. They do so because they are close to other atoms that attract their electrons more strongly or weakly than they do. The degree to which an atom attracts electrons is described as that atom's **electron affinity**. Atoms that attract electrons strongly are said to have high electron affinity. Those that attract electrons weakly have low affinity.

When one or more electrons are transferred in this manner, the positive and negative ions attract each other by virtue of their opposite charges. Such an attraction, called an **ionic bond**, holds the two ions formed in just this way. Sodium (chemical symbol Na) has one outermost electron, which it can lose to chlorine (chemical symbol Cl) with seven outer electrons. Sodium thus forms a +1 ion (Na^+), while chlorine forms a –1 ion (Cl^-). The opposing charges hold the two atoms together. The ionic compound formed, sodium chloride (Na^+Cl^-), is shown in Figure 2.6. Note that even though each atom in the compound is charged, the negative and positive charges balance each other exactly, making the **salt** electrically neutral. In the case of cystic fibrosis (CF), since the chlorine ions cannot enter the cells, they combine with the sodium in this way.

Sodium chloride is the chemical name for common table salt, one crystal of which contains many sodium and chlorine ions packed together. Sodium chloride is just one type of salt. Magnesium fluoride (MgF_2) is another salt, containing one magnesium and two fluorine atoms ionically bonded.

Now that we know why sodium chloride forms in the lungs of CF patients, we can better understand part of the reason why such patients often suffer from bacterial lung infections. Cells lining the lungs produce proteins that act as natural antibiotics, protecting the lungs from bacterial colonization. Many of these compounds only work efficiently in relatively low-salt environments. In the lungs of CF patients, salt tends to interfere with and inactivate these proteins, opening the door to infection. Interestingly, the faulty chlorine transporters that result in salt formation in the lungs of CF patients are also found in other parts of the body. This explains why the saliva and perspiration of people with this disease are also unusually salty.

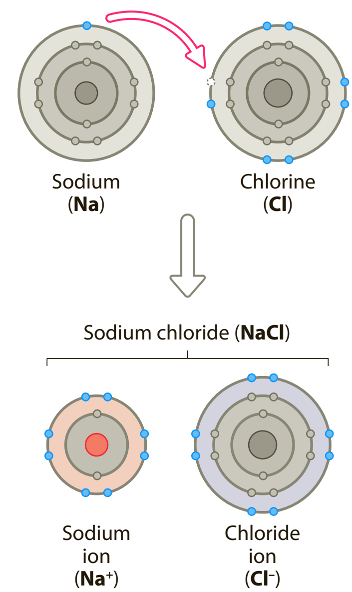


Figure 2.6 Ionic bonding. Ionic bonds form between negative and positive ions, forming salts. The red arrow in this figure indicates the transfer of electrons from one atom to another. The atom losing one or more electrons becomes a positively charged ion, while the atom gaining one or more electrons becomes a negatively charged ion. Ions with opposing charges attract each other, forming an ionic bond. In order to achieve its stability, sodium transfers its outermost electron to one chorine atom, which becomes stable by gaining the electron. Sodium forms a +1 ion, while chlorine forms a –1 ion; the two are attracted and form the salt sodium chloride.

Covalent bonds form when atoms share electrons in their outermost shells

Ionic bonds are not the only way atoms can interact. Consider two reactive atoms, both of which tend to achieve chemical stability by gaining rather than losing electrons. In this case, neither atom is likely to completely donate an electron to the other. The two atoms may obtain a full outer shell, however, and thus become stable, by sharing outer electrons. Consider hydrogen, the most abundant element in the universe. Hydrogen rarely exists as individual H atoms. A hydrogen atom, however, can bond to another hydrogen atom to form hydrogen gas (H_2).

Recall that each hydrogen atom has only a single electron in its first electron shell, which holds a maximum of two electrons. When two hydrogen atoms come in contact, neither can take an electron from the other, because their ability to attract electrons is exactly the same (that is, they have the same affinity). Instead, the two hydrogen atoms share their electrons, providing each atom with the two outer electrons required to achieve stability. When two atoms share electrons in their outer shells in this way, they have formed a **covalent bond** (**Figure 2.7**).

Hydrogen can bond with other atoms as well. An important example is water, the molecular formula of which is H_2O. A reactive oxygen atom has six outer electrons in a shell that holds a maximum of eight. Oxygen thus needs two additional electrons to become stable, and it can obtain them by sharing two electrons—one with each of two hydrogens (**Figure 2.7b**).

Hydrogen also commonly bonds to carbon, forming an important class of molecules called **hydrocarbons**. The simplest hydrocarbon is methane, which is composed of one carbon atom and four hydrogens (CH_4). Carbon, with four outer electrons, can form four covalent bonds by sharing each of these electrons with hydrogen (**Figure 2.7c**). Methane is an important greenhouse gas that contributes to global warming. Because much of the methane in our atmosphere is a microbial waste product, we will discuss this gas more fully in Chapter 10, where we investigate the role that microbes play in environmental processes.

Two atoms may form more than one covalent bond with each other in certain cases. For instance, atmospheric oxygen generally is in the form of O_2. Each oxygen atom has six outer electrons in its second shell. Both atoms require an additional two electrons to become stable. Consequently, they will share a total of four electrons, resulting in two covalent bonds. In carbon dioxide (CO_2),

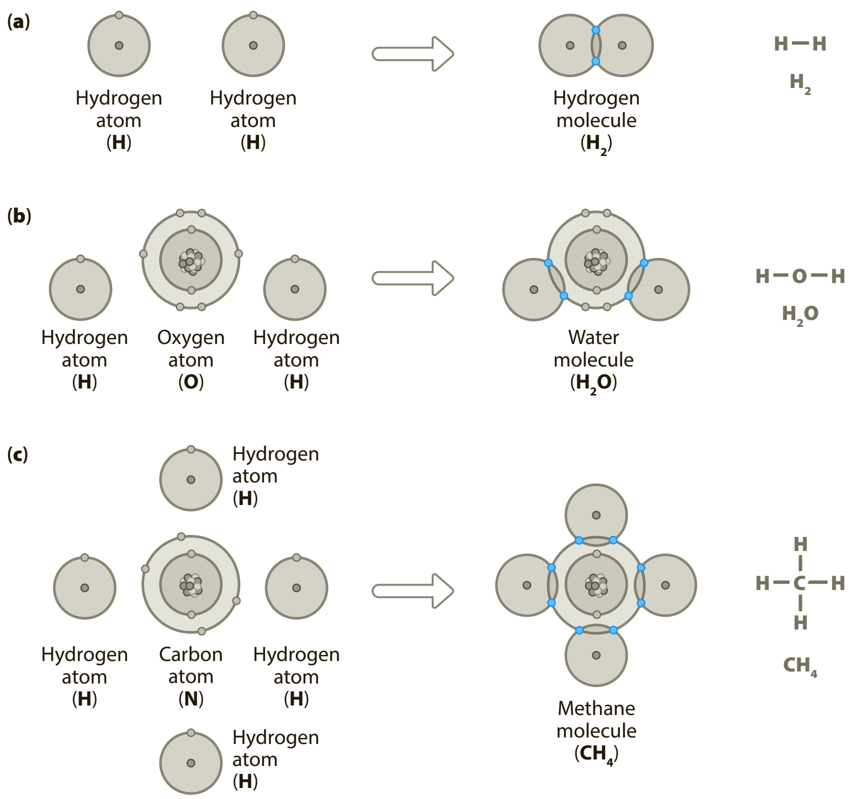


Figure 2.7 Covalent bonding. Covalent bonds form between reactive atoms that share electrons. Note that in all examples the shared electrons (in blue) are in the outermost shells of the atoms involved. Unshared electrons are in gray. The nucleus is depicted in the center of each atom. In the simplified stick models next to each atomic model, each line represents a shared electron pair. (a) Each hydrogen atom needs one additional electron to achieve stability. To gain the necessary electron, the two atoms share their electrons to form a molecule of stable hydrogen gas (H_2). (b) Oxygen has a full inner shell, but in its second shell, which can hold eight electrons, there are only six. Oxygen can become stable by sharing two outer electrons with two atoms of hydrogen, forming a molecule of water (H_2O). (c) Carbon, with four outer electrons, can form four covalent bonds with hydrogen, forming methane (CH_4).

recall that each carbon atom can form four covalent bonds, while each oxygen can form two. The single carbon thus forms two bonds with each oxygen.

Covalent bonds can be classified as either polar or nonpolar

You are no doubt familiar with the word "polar." The Earth with its north and south poles and a magnet with positively and negatively charged ends are common examples of polar objects, because they are different at their two ends. Likewise, some covalent bonds are termed **polar covalent bonds**, because the combination of participating atoms carries a slight positive charge at one end and a slight negative charge at the other. Other covalent bonds lack these opposing charges at the opposite ends. In other words, in terms of charge, the two ends are both neutral. Such bonds are called **nonpolar covalent bonds**.

Why do some covalently bound molecules have slight opposing charges at opposite ends while others do not? To explain, consider the examples of hydrogen gas (H_2), in which the covalent bond is nonpolar, and ammonia (NH_3), in which the single nitrogen atom is bound to three hydrogens by three polar covalent bonds.

When two hydrogen atoms are covalently bonded, each atom has an identical affinity for the shared electrons. In other words, the electrons are attracted equally to the nucleus of each hydrogen atom, and they are shared equally. This is not the case, however, when nitrogen binds hydrogen to form NH_3. Remember that protons in the nucleus attract the negatively charged electrons. Nitrogen has seven protons in its nucleus, whereas hydrogen has only one. Therefore, when nitrogen forms covalent bonds with hydrogen, the electrons are actually more attracted to the nitrogen than they are to the hydrogen. The difference in attraction is slight. Even though hydrogen has only a single proton to attract its shared electrons, those electrons are in hydrogen's first shell, and thus closer to the nucleus than they are in nitrogen; nitrogen's edge in number of positively charged protons is to some degree offset by the closeness of hydrogen's nucleus to its electrons. Nevertheless, the difference in attraction is large enough to ensure that the shared electrons are not equally shared. The nitrogen tends to pull the electrons away from hydrogen and toward itself. Because the electrons are negatively charged and tend to cluster closer to nitrogen, the nitrogen atom gains a very slight, partial negative charge. At the same time, the three hydrogens to which nitrogen is bound obtain partial positive charges, because the negatively charged electrons are pulled away from them and toward the nitrogen.

This gives ammonia a polarity, meaning that there is a difference in electrical charge at each of its ends. The covalent bonds holding nitrogen to each hydrogen are therefore polar covalent bonds (Figure 2.8a). When there is no charge difference at either end of a molecule, as is the case with H_2 gas, the result is a nonpolar covalent bond (Figure 2.8b). Oxygen gas (O_2) and the carbon–hydrogen bonds found in hydrocarbons such as methane are also nonpolar. This may sound like a fairly trivial point, but in reality the consequences of this are enormous. As we will see, molecules that are composed of mostly polar covalent bonds and those that are composed of mostly nonpolar covalent bonds behave very differently.

Water is an important example of a polar molecule (see Figure 2.8a). The partial positive charges on the hydrogen atoms of one molecule will be attracted to the partial negative charge on the oxygen of a different water molecule. This means that all water molecules are attracted to each other because of opposing partial charges. Such interactions between separate molecules are termed **hydrogen bonds** (Figure 2.9). Each hydrogen bond

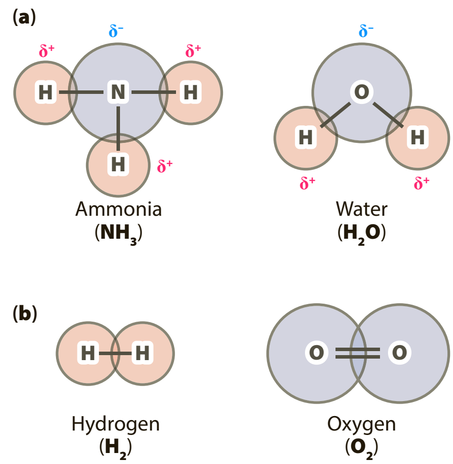


Figure 2.8 Polar and nonpolar covalent bonds. (a) Ammonia and water molecules are held together by polar covalent bonds. Because nitrogen in ammonia or oxygen in water attracts electrons more strongly than hydrogen, nitrogen and oxygen both obtain partial negative charges, represented by δ–. The hydrogens in these molecules, with less attraction (lower affinity) for the electrons, each obtain a partial positive (δ+) charge. (b) In hydrogen and oxygen molecules, electrons are shared equally. Because there are no partial charges, the covalent bonds holding the atoms together are nonpolar covalent bonds.

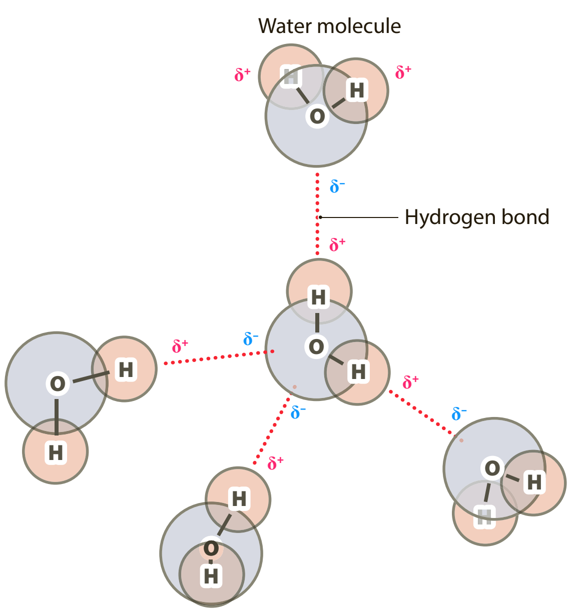


Figure 2.9 Hydrogen bonding between water molecules. Partial charges on separate water molecules attract each other, forming hydrogen bonds. Note that hydrogen bonds are bonds between separate molecules, while a covalent bond is a bond within a single molecule.

is very weak, but collectively, many hydrogen bonds can exert considerable attraction. For instance, when water is boiled, individual water molecules will not break off and leave solution as vapor until enough heat is applied to disrupt the hydrogen bonds holding the water molecules together.

It is not just water molecules that attract each other. Ammonia, as we have seen, has a partial negative charge on nitrogen and a partial positive charge on each hydrogen. Ammonia will form hydrogen bonds not only with water but also with other ammonia molecules. Nonpolar compounds, on the other hand, which lack partial charges, cannot form hydrogen bonds with water and other polar compounds.

Water is essential in life processes

Water is fundamental to all life. As we will discuss in Chapter 9, life itself evolved in water and all biochemical reactions take place in an aqueous or water environment. Environments that are totally lacking in water are devoid of living things. If water is present, it is likely that life will be present as well. For instance, researchers have found microorganisms in pockets of liquid water over 10 meters deep in frozen Antarctic lakes, in boiling hot oceanic volcanic vents, and even in water vapor found in clouds.

The ability or inability of a compound to interact with water is a crucial characteristic of that compound. We have already seen that polar compounds can interact with water. Nonpolar molecules cannot; lacking partial charges, they are unable to form hydrogen bonds with water. A simple example is ordinary table sugar, also called sucrose ($C_{12}H_{22}O_{11}$). Sucrose is largely polar in nature. When you place a teaspoon of sugar in water, the individual sugar molecules form hydrogen bonds with the water and disperse through the solution; the sugar dissolves. Alternatively, when you drop a piece of fat into water, nothing happens. Fat molecules are mostly made of hydrocarbons, which are nonpolar and consequently cannot dissolve in water.

It is not only polar compounds that will dissolve in water; anything with electrical charges will be attracted to water's partial positive and negative charges. For instance, when you place an ionically bonded compound such as table salt (NaCl) into water, positively charged sodium ions are attracted to the partial negative charges on the oxygen in water molecules. Similarly, negatively charged chlorine ions are attracted by the partial positive charges on the hydrogens. Ultimately these attractive forces pull apart the ionic compound, separating it into individual ions. Hence, the salt also dissolves in water. Consider the odd fact that even in saltwater there is little or no actual salt; it is largely dissolved into individual ions. It is only when water is removed, for instance by evaporation, that the positive and negative ions reassociate to form salt.

Polar covalent and ionic compounds that interact well with water in this fashion are termed **hydrophilic**, from the Greek term for "water loving." Nonpolar covalent compounds that cannot dissolve in water are referred to as **hydrophobic** or "water fearing." While molecules such as salt or oil are purely hydrophilic or hydrophobic, respectively, many molecules have both hydrophilic and hydrophobic regions and will consequently interact with water to greater or lesser degrees.