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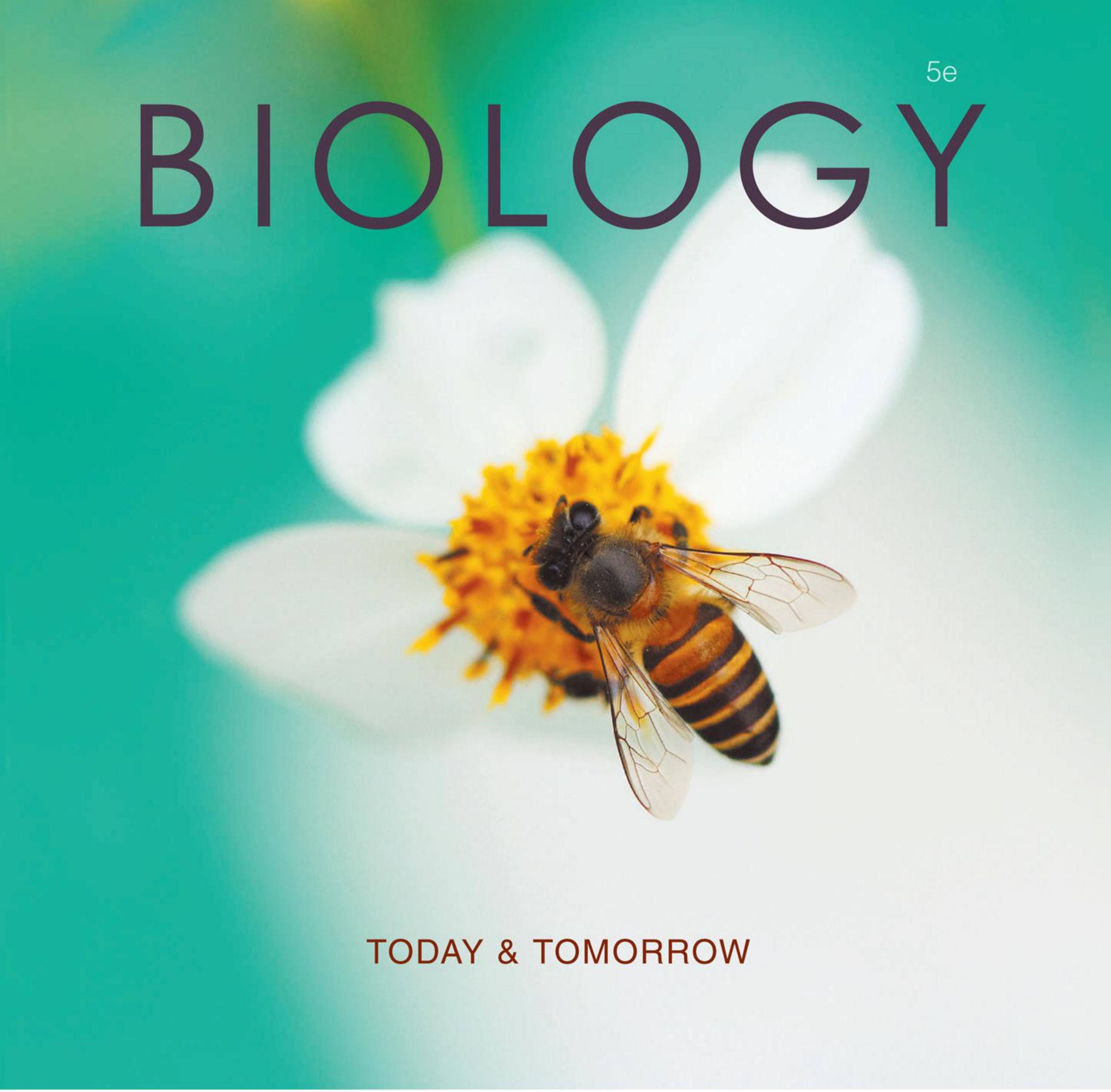
BIOLOGY



TODAY & TOMORROW

Cecie Starr | Christine A. Evers | Lisa Starr

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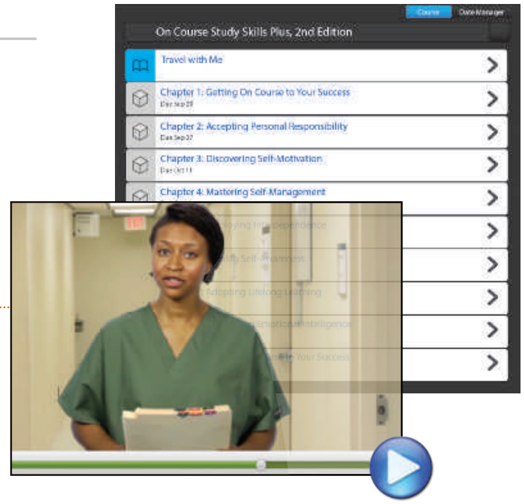

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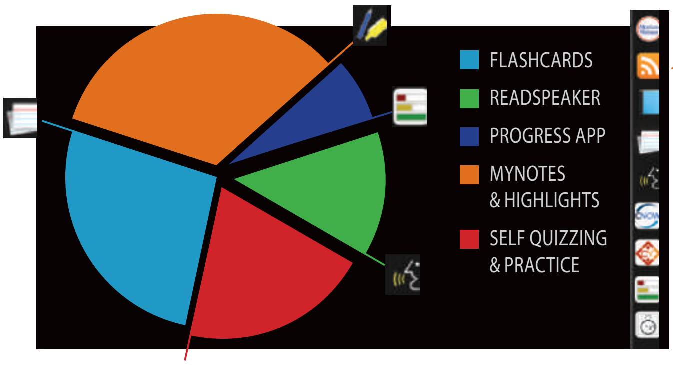

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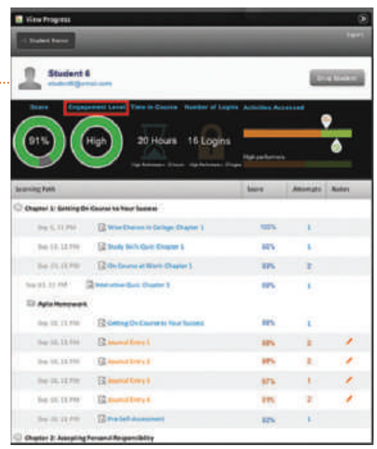

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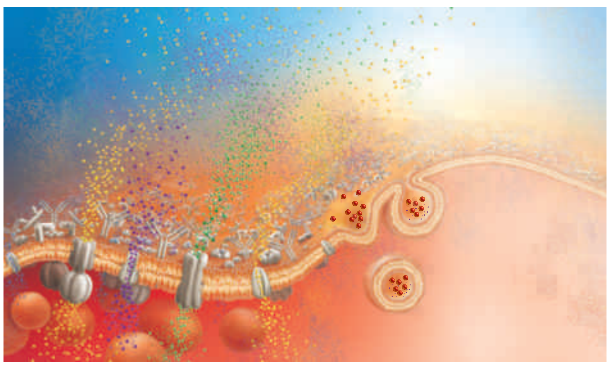
BRIEF CONTENTS

CONTENTS



4 Energy and Metabolism

5 Capturing and Releasing Energy

UNIT 2 GENETICS

6 DNA Structure and Function

7 Gene Expression and Control

8 How Cells Reproduce

9 Patterns of Inheritance

10 Biotechnology

UNIT 3 EVOLUTION AND DIVERSITY

11 Evidence of Evolution

UNIT 4 ECOLOGY

UNIT 5 HOW ANIMALS WORK

19 Animal Tissues and Organs

20 How Animals Move

21 Circulation and Respiration

22 Immunity

23 Digestion and Excretion

UNIT 6 HOW PLANTS WORK

27 Plant Form and Function

28 Plant Reproduction and Development

P

PREFACE

Biology is a huge field, with a wealth of new discoveries being made every day, and biology-related issues such as climate change, stem cell research, and personal genetics often making headlines. This avalanche of information can be intimidating to non-scientists. This book was designed and written specifically for students who most likely will not become biologists and may never again take another science course. It is an accessible and engaging introduction to biology that provides future decision-makers with an understanding of basic biology and the process of science.

A Wealth of Applications This book is packed with everyday applications of biological processes. At every opportunity, we enliven discussions of biological processes with references to their effects on human health and the environment. This edition also continues to focus on real world applications pertaining to the field of biology, including social issues arising from new research and developments. Descriptions of current research, along with photos of scientists who carry it out, underscore the concept that biology is an ongoing endeavor carried out by a diverse community of people. Discussions include not only what was discovered, but also how the discoveries were made, how our understanding has changed over time, and what remains to be discovered. These discussions are provided in the context of an accessible introduction to well-established concepts that underpin modern biology. Every topic is examined from an evolutionary perspective, emphasizing the connections between all forms of life.

Accessible Text Understanding stems from making connections between concepts and details, so a text with too little detail reads as a series of facts that beg to be memorized. However, excessive detail can overwhelm the introductory student. Thus, we constantly strive to strike the perfect balance between level of detail and accessibility. We once again revised the text to eliminate details that do not contribute to a basic understanding of essential concepts. We also know that English is a second language for many introductory students, so we avoid idioms and aim for a clear, straightforward style.

Analogies to familiar objects and phenomena will help students understand abstract concepts. For example, in the discussion of transpiration in Chapter 27 (Plant Form and Function), we explain that a column of water is drawn upward through xylem as a drinker draws fluid up through a straw.

In-Text Learning Tools To emphasize connections between biological topics, each chapter begins with an **APPLICATION** section that explores a current event or controversy directly related to the chapter's content. For example, a discussion of binge drinking on college campuses introduces the concept of metabolism in Chapter 4. This section presents an overview of the metabolic pathway that breaks down alcohol, linking the function of enzymes in the pathway to hangovers, alcoholism, and cirrhosis. The section is illustrated with a photo of a tailgate party that preceded a recent Notre Dame–Alabama football game, and also a photo of Gary Reinbach just before he died at age 22 of alcoholic liver disease. (In the index, you'll find health-related applications denoted by red squares and environmental applications by green squares.)

To strengthen a student's analytical skills and offer insight into contemporary research, each chapter includes an exercise called **DIGGING INTO DATA** that is placed in a section with relevant content. The exercise consists of a short text passage—usually about a published scientific experiment—and a table, chart, or other graphic that presents experimental data. A student can use information in the text and graphic to answer a series of questions. For example, the exercise in Chapter 2 asks students to interpret results of a study that examined the effect of dietary fat intake on "good" and "bad" cholesterol levels.

The chapter itself consists of several numbered sections that contain a manageable chunk of information. Every section ends with a boxed **TAKE-HOME MESSAGE** in which we pose a question that reflects the critical content of the section, and then answer the question in bulleted list format. Every chapter has at least one **FIGURE IT OUT QUESTION** with an answer immediately following. These questions allow students to quickly check their understanding as they read. Mastering scientific vocabulary challenges many students, so we have included an **ON-PAGE GLOSSARY** of key terms introduced in each two-page spread, in addition to a complete glossary at the book's end. The end-of-chapter material features a **VISUAL SUMMARY** that reinforces each chapter's key concepts. A **SELF-QUIZ** poses multiple choice and other short answer questions for self-assessment (answers are in Appendix I). A set of more challenging **CRITICAL THINKING QUESTIONS** provides thought-provoking exercises for the motivated student. The end matter of several chapters now includes a **VISUAL QUESTION** that reinforces learning in a nonverbal style.

Design and Content Revisions Throughout the book, text and art have been revised to help students grasp difficult concepts. The following list highlights some of the revisions to each chapter.

Introduction

1 **Invitation to Biology** Renewed and updated emphasis on the relevance of new species discovery and the process of science.

Unit 1 How Cells Work

2 **Molecules of Life** New graphic illustrates radioactive decay.

3 **Cell Structure** Application section updated with current statistics and 'pink slime' story. Micrograph comparisons now feature *Paramecia* and include a confocal image. Essay about the nature of life expanded to add Gerald Joyce's "life is squishy" concept.

4 **Energy and Metabolism** Application section now illustrated with a real-life example. Diffusion illustrated with a tea bag in hot water.

5 **Capturing and Releasing Energy** Application section updated with current statistics and illustrated with a current photo of air pollution in China. Yogurt production added to fermentation section.

Unit 2 Genetics

6 **DNA Structure and Function** Content reorganized: material on cloning folded into Application section for concept connection, and chromosome structure now appears after DNA structure. New art demonstrates how replication errors become mutations.

7 **Gene Expression and Control** Ricin discussion revised to include medical applications. New material includes hairlessness mutation (in cats), evolution of lactose tolerance, heritability of DNA methylations, telomeres.

8 **How Cells Reproduce** New material on telomeres, asexual vs. sexual mud snails. New micrograph shows multiple crossovers.

9 **Patterns of Inheritance** Epistasis is now illustrated with human skin color. New material about environmentally-triggered hemoglobin production in *Daphnia*; continuous variation in dog face length arising from short tandem repeats foreshadows DNA fingerprinting in chapter 10.

10 **Biotechnology** Updated coverage of personal genetic testing includes social impact of Angelina Jolie's response to her test. New photos illustrate genetically modified animals. New "who's the daddy" critical thinking question offers students an opportunity to analyze a paternity test based on SNPs.

Unit 3 Evolution and Diversity

11 **Evidence of Evolution** Photos of 19th century naturalists added to emphasize the process of science that led to natural selection theory. How banded iron formations provide evidence of the evolution of photosynthesis added to fossil section. Plate tectonics art updated to reflect new evidence of lava lamp mantle movements.

12 **Processes of Evolution** New opening essay on resistance to antibiotics as an outcome of agricultural overuse (warfarin material now exemplifies directional selection). New art illustrates founder effect, and hypothetical example in text replaced with reduced diversity of ABO alleles in Native Americans. New art illustrates stasis in coelacanths.

13 **Early Life Forms and the Viruses** New introductory essay about study of the human microbiome, new coverage of Ebola, and new figure depicting mechanisms of gene exchange in prokaryotes.

14 **Plants and Fungi** Additional coverage of fungal ecology, including information about white-nose syndrome in bats.

15 **Animal Evolution** New introductory essay about invertebrates as a source of medicines. Updated information about Neanderthals and added coverage of the newly discovered Dennisovans.

Unit 4 Ecology

16 **Population Ecology** Updated coverage of human demographics.

17 **Communities and Ecosystems** New photos illustrate species interactions; updated coverage of the increases in greenhouse gases.

18 **The Biosphere and Human Effects** New essay about dispersion of the radioactive material released at Fukushima and new Digging Into Data about bioaccumulation of this material in tuna.

Unit 5 How Animals Work

19 **Animal Tissues and Organs** Updated information about stem cell research and tissue regeneration in animals. Improved figures depict epithelial and connective tissues.

20 **How Animals Move** New information about how different muscle fiber types relate to animal locomotion.

21 **Circulation and Respiration** Improved coverage of insect respiration, including a new photo.

22 **Immunity** New photos show skin as a surface barrier, a cytotoxic T cell killing a cancer cell, and victims of HIV. Immune response and lymphatic system illustrations updated.

23 **Digestion and Excretion** Revised essay about obesity and new comparative information about the ruminant digestive system.

24 **Neural Control and the Senses** New opening essay about the effects of concussions. Discussion of the human nervous system has been reorganized. New information about echolocation.

25 **Endocrine Control** Opening essay now focuses on phthalates as endocrine disruptors. New Digging Into Data about BPA's effect on insulin secretion.

26 **Reproduction and Development** Updated coverage of assisted reproductive technologies. Discussion of human reproductive structure and function has been reorganized.

Unit 6 How Plants Work

27 **Plant Form and Function** Reorganization consolidates growth into a separate section. Many new photos illustrate stem, leaf, and root structure(s). Material on fire scars added to dendroclimatology.

28 **Plant Reproduction and Development** Updates reflect current research on colony collapse and ongoing major breakthroughs in the field of plant hormone function. New photos illustrate fruit classification, asexual reproduction, early growth, ABA inhibition of seed germination, and tropisms.

A

ACADEMIC ADVISORS

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Virginia White, *Riverside Community College*
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STUDENT AND INSTRUCTOR RESOURCES

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Cooperative Learning Cooperative Learning: Making Connections in General Biology, 2nd Edition, authored by Mimi Bres and Arnold Weisshaar, is a collection of separate, ready-to-use, short cooperative activities that have broad application for first year biology courses. They fit perfectly with any style of instruction, whether in large lecture halls or flipped classrooms. The activities are designed to address a range of learning objectives such as reinforcing basic concepts, making connections between various chapters and topics, data analysis and graphing, developing problem solving skills, and mastering terminology. Since each activity is designed to stand alone, this collection can be used in a variety of courses and with any text.

MindTap A personalized, fully online digital learning platform of authoritative content, assignments, and services that engages students with interactivity while also offering instructors their choice in the configuration of coursework and enhancement of the curriculum via web-apps known as MindApps. MindApps range from ReadSpeaker (which reads the text out loud to students) to Kaltura (which allows you to insert inline video and audio into your curriculum). MindTap is well beyond an eBook, a homework solution or digital supplement, a resource center website, a course delivery platform, or a Learning Management System. It is the first in a new category—the Personal Learning Experience.

New for this edition! MindTap has an integrated Study Guide, expanded quizzing and application activities, and an integrated Test Bank.

Aplia for Biology The Aplia system helps students learn key concepts via Aplia's focused assignments and active learning opportunities that include randomized, automatically graded questions, exceptional text/art integration, and immediate feedback. Aplia has a full course management system that can be used independently or in conjunction with other course management systems such as MindTap, D2L, or Blackboard.

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Writing, revising, and illustrating a biology textbook is a major undertaking for two full-time authors, but our efforts constitute only a small part of what is required to produce and distribute this one. We are truly fortunate to be part of a huge team of very talented people who are as committed as we are to creating and disseminating an exceptional science education product.

Biology is not dogma; paradigm shifts are a common outcome of the fantastic amount of research in the field. Ideas about what material should be taught and how best to present that material to students changes from one year to the next. It is only with the ongoing input of our many academic reviewers and advisors (previous page) that we can continue to tailor this book to the needs of instructors and students while integrating new information and models. We continue to learn from and be inspired by these dedicated educators.

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Lisa Starr and Christine Evers, November 2014

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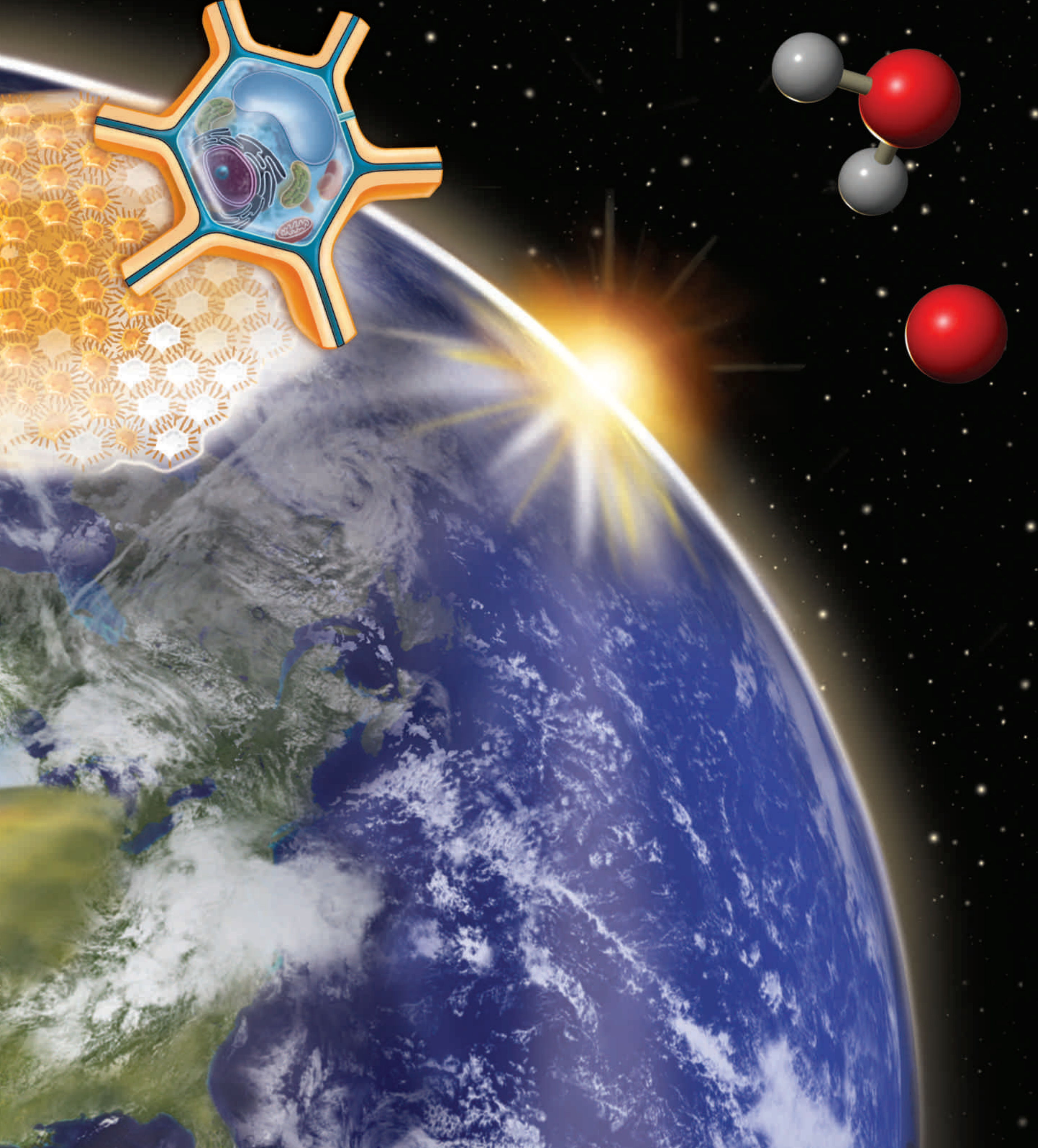
TODAY & TOMORROW

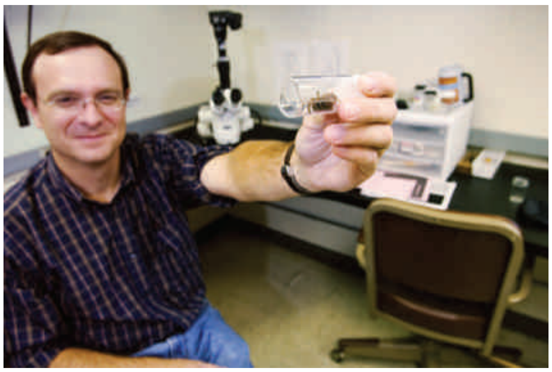
1

INVITATION TO BIOLOGY



Application ❯ 1.1 The Secret Life of Earth

A. Paul Oliver discovered this tree frog perched on a sack of rice during a rainy campsite lunch in New Guinea's Foja Mountains. The explorers dubbed the new species "Pinocchio frog" after the Disney character because the male frog's long nose inflates and points upward during times of excitement.



B. Dr. Jason Bond holds a new species of trapdoor spider he discovered in sand dunes of California beaches in 2008. Bond named the spider *Aptostichus stephencolberti*, after TV personality Stephen Colbert.

Figure 1.1 Newly discovered species.
Each of the thousands of species discovered every year is a reminder that we do not yet know all of the organisms living on our own planet. We don't even know how many to look for. Information about the 1.8 million species we do know about is being collected in The Encyclopedia of Life, an online database maintained by collaborative effort (www.eol.org).

(A) Tim Laman/National Geographic Stock; (B) Courtesy East Carolina University.

In this era of detailed satellite imagery and cell phone global positioning systems, could there possibly be any places left on Earth that humans have not yet explored? Actually, there are plenty of them. In 2005, for example, helicopters dropped a team of scientists into the middle of a vast and otherwise inaccessible cloud forest atop New Guinea's Foja Mountains. Within a few minutes, the explorers realized that their landing site, a dripping, moss-covered swamp, had been untouched by humans. Team member Bruce Beehler remarked, "Everywhere we looked, we saw amazing things we had never seen before. I was shouting. This trip was a once-in-a-lifetime series of shouting experiences."

How did the explorers know they had landed in uncharted territory? For one thing, the forest was filled with plants and animals previously unknown even to native peoples that have long inhabited other parts of the region. During the next month, the team members discovered many new species, including a rhododendron plant with flowers the size of a plate and a frog the size of a pea. They also came across hundreds of species that are on the brink of extinction in other parts of the world, and some that supposedly had been extinct for decades. The animals had never learned to be afraid of humans, so they could easily be approached. A few were discovered as they casually wandered through campsites (Figure 1.1A).

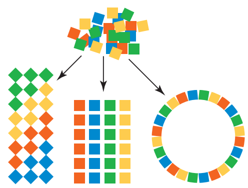
New species are discovered all the time, often in places much more mundane than Indonesian cloud forests (Figure 1.1B). How do we know what species a particular organism belongs to? What is a species, anyway, and why should discovering a new one matter to anyone other than a scientist? You will find the answers to such questions in this book. They are part of the scientific study of life, **biology**, which is one of many ways we humans try to make sense of the world around us.

Trying to understand the immense scope of life on Earth gives us some perspective on where we fit into it. For example, hundreds of new species are discovered every year, but about 20 species become extinct every minute in rain forests alone—and those are only the ones we know about. The current rate of extinctions is about 1,000 times faster than normal, and human activities are responsible for the acceleration. At this rate, we will never know about most of the species that are alive on Earth today. Does that matter? Biologists think so. Whether or not we are aware of it, humans are intimately connected with the world around us. Our activities are profoundly changing the entire fabric of life on Earth. These changes are, in turn, affecting us in ways we are only beginning to understand.

Ironically, the more we learn about the natural world, the more we realize we have yet to learn. But don't take our word for it. Find out what biologists know, and what they do not, and you will have a solid foundation upon which to base your own opinions about how humans fit into this world. By reading this book, you are choosing to learn about the human connection—your connection—with all life on Earth.

1.2 Life Is More Than the Sum of Its Parts

What, exactly, is the property we call "life"? We may never actually come up with a good definition, because living things are too diverse, and they consist of the same basic components as nonliving things. When we try to define life, we end up with a long list of properties that differentiate living from nonliving things. These properties often emerge from the interactions of basic components. To understand how that works, take a look at these groups of squares:



A property called "roundness" emerges when the squares are organized one way, but not other ways. The idea that different structures can be assembled from the same basic building blocks is a recurring theme in our world, and also in biology.

Life has successive levels of organization, with new properties emerging at each level (Figure 1.2). This organization begins with interactions between **atoms**, which are fundamental units of matter—the building blocks of all substances (1). Atoms bond together to form **molecules** (2). There are no atoms unique to living things, but there are unique molecules. In today's natural world, only living things make the "molecules of life," which are lipids, proteins, DNA, RNA, and complex carbohydrates. The emergent property of "life" appears at the next level, when many molecules of life become organized as a cell (3). A **cell** is the smallest unit of life. Cells survive and reproduce themselves using energy, raw materials, and information in their DNA.

Some cells live and reproduce independently; others do so as part of a multicelled organism (4). An **organism** is an individual that consists of one or more cells. In most multicelled organisms, cells are organized as tissues, organs, and organ systems that interact to keep the body working properly.

A **population** is a group of interbreeding individuals of the same type, or species, living in a given area (5). At the next level, a **community** consists of all populations living in a given area (6). Communities may be large or small, depending on the area defined.

The next level of organization is the **ecosystem**, which is a community interacting with its physical and chemical environment (7). The most inclusive level, the **biosphere**, encompasses all regions of Earth's crust, waters, and atmosphere in which organisms live (8).

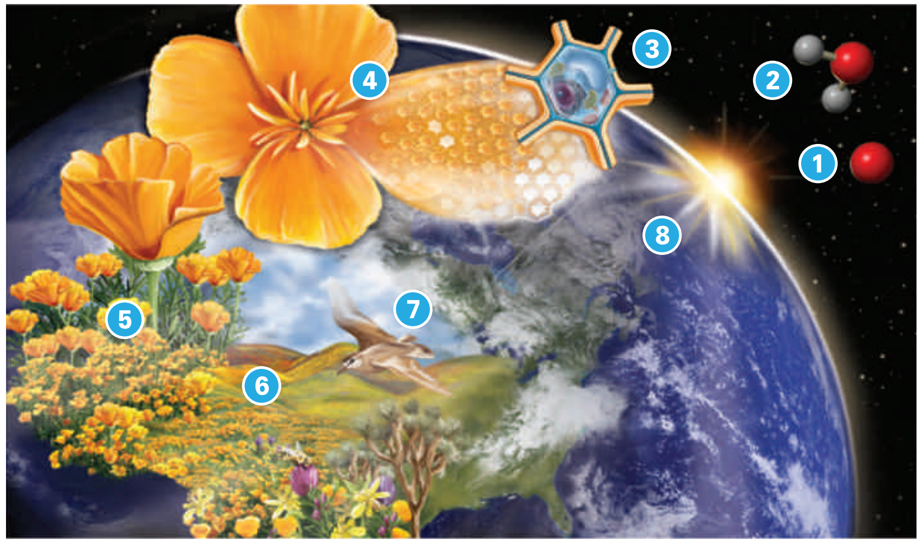


Figure 1.2 Levels of organization in nature.

1. Atoms are fundamental units of matter.
2. Molecules consist of atoms.
3. Cells consist of molecules.
4. Organisms consist of cells.
5. Populations consist of organisms.
6. Communities consist of populations.
7. Ecosystems consist of communities interacting with their environment.
8. The biosphere consists of all ecosystems on Earth.

Take-Home Message 1.2

How do living things differ from nonliving things?

- All things, living or not, consist of the same building blocks: atoms. Atoms bond together to form molecules.
- In today's natural world, only living things make lipids, proteins, DNA, RNA, and complex carbohydrates. The unique properties of life emerge as these molecules become organized into cells.
- Higher levels of life's organization include multicelled organisms, populations, communities, ecosystems, and the biosphere.

atom Fundamental building block of all matter.

biology The scientific study of life.

biosphere All regions of Earth where organisms live.

cell Smallest unit of life.

community All populations of all species in a given area.

ecosystem A community interacting with its environment.

molecule Two or more atoms bonded together.

organism Individual that consists of one or more cells.

population Group of interbreeding individuals of the same species that live in a given area.

1.3 How Living Things Are Alike

Even though we cannot precisely define "life," we can intuitively understand what it means because all living things share a particular set of key features. All require ongoing inputs of energy and raw materials; all sense and respond to change; and all pass DNA to offspring.

Organisms Require Energy and Nutrients Not all living things eat, but all require energy and nutrients on an ongoing basis. Inputs of both are essential to maintain the functioning of individual organisms and the organization of life in general. A **nutrient** is a substance that an organism needs for growth and survival but cannot make for itself.

Organisms spend a lot of time acquiring energy and nutrients (Figure 1.3). However, the source of energy and the type of nutrients acquired differ among organisms. These differences allow us to classify living things into two categories: producers and consumers. A **producer** makes its own food using energy and simple raw materials it obtains from nonbiological sources. Plants are producers; by a process called **photosynthesis**, they use the energy of sunlight to make sugars from water and carbon dioxide (a gas in air). Consumers, by contrast, cannot make their own food. A **consumer** obtains energy and nutrients by feeding on other organisms. Animals are consumers. So are decomposers, which feed on the wastes or remains of other organisms. The leftovers from consumers' meals end up in the environment, where they serve as nutrients for producers. Said another way, nutrients cycle between producers and consumers.

Unlike nutrients, energy is not cycled. It flows through the world of life in one direction: from the environment, through organisms, and back to the environment. This flow maintains the organization of every living cell and body, and it also influences how individuals interact with one another and their environment. The energy flow is one-way, because with each transfer, some energy escapes as heat, and cells cannot use heat as an energy source. Thus, energy that enters the world of life eventually leaves it (we return to this topic in Chapter 5).

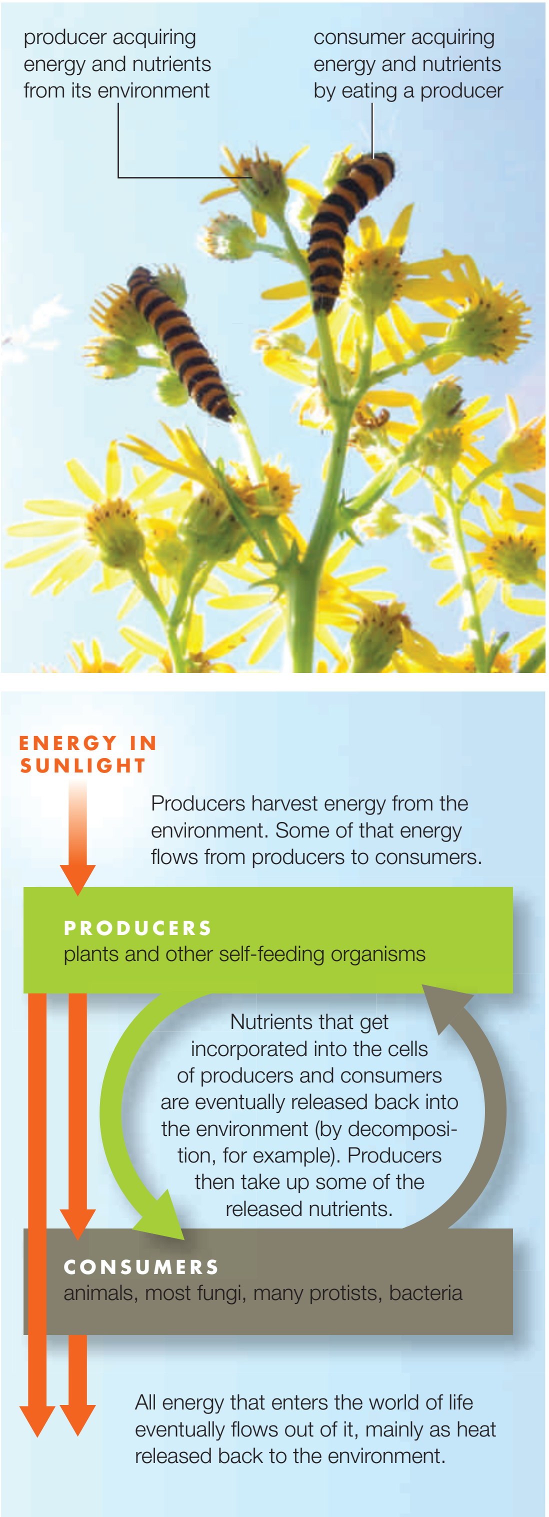


Figure 1.3 The one-way flow of energy and the cycling of materials in the world of life.

Top, © Victoria Pinder, www.flickr.com/photos/vixstarplus.

Organisms Sense and Respond to Change An organism cannot survive for very long in a changing environment unless it adapts to the changes. Thus, every living thing has the ability to sense and respond to change both inside and outside of itself (Figure 1.4). Consider how, after you eat, the sugars from your meal enter your bloodstream. The added sugars set in motion a series of events that causes cells throughout the body to take up sugar faster, so the sugar level in your blood quickly falls. This response keeps your blood sugar level within a certain range, which in turn helps keep your cells alive and your body functioning properly.

All of the fluids outside of cells make up a body's internal environment. That environment must be kept within certain ranges of temperature and other conditions, or the cells that make up the body will die. By sensing and adjusting to change, organisms keep conditions in the internal environment within a range that favors survival. **Homeostasis** is the name for this process, and it is one of the defining features of life.

Organisms Grow and Reproduce With little variation, the same types of molecules perform the same basic functions in every organism. For example, information in an organism's **DNA** (deoxyribonucleic acid) guides ongoing functions that sustain the individual through its lifetime. Such functions include **development**:

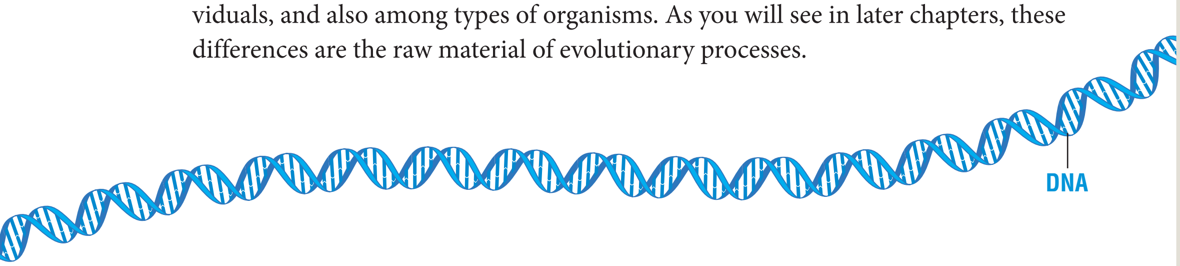
Figure 1.4 Organisms sense and respond to stimulation.
This baby orangutan is laughing in response to being tickled. Apes and humans make different sounds when being tickled, but the airflow patterns are so similar that we can say apes really do laugh.

© Dr. Marina Davila Ross, University of Portsmouth.

the process by which the first cell of a new individual becomes a multicelled adult; **growth**: increases in cell number, size, and volume; and **reproduction**: processes by which individuals produce offspring.

Individuals of every natural population are alike in certain aspects of their body form and behavior because their DNA is very similar: Orangutans look like orangutans and not like caterpillars because they inherited orangutan DNA, which differs from caterpillar DNA in the information it carries. **Inheritance** refers to the transmission of DNA to offspring. All organisms receive their DNA from one or more parents.

DNA is the basis of similarities in form and function among organisms. However, the details of DNA molecules differ, and herein lies the source of life's diversity. Small variations in the details of DNA's structure give rise to differences among individuals, and also among types of organisms. As you will see in later chapters, these differences are the raw material of evolutionary processes.



Take-Home Message 1.3

How are all living things alike?

- A one-way flow of energy and a cycling of nutrients sustain life's organization.
- Organisms sense and respond to conditions inside and outside themselves. They make adjustments that keep conditions in their internal environment within a range that favors cell survival, a process called homeostasis.
- All organisms use information in the DNA they inherited from their parent or parents to develop, grow, and reproduce. DNA is the basis of similarities and differences in form and function among organisms.

consumer Organism that gets energy and nutrients by feeding on the tissues, wastes, or remains of other organisms.

development Multistep process by which the first cell of a new multicelled organism gives rise to an adult.

DNA Deoxyribonucleic acid; carries hereditary information that guides development and other activities.

growth In multicelled species, an increase in the number, size, and volume of cells.

homeostasis Process in which an organism keeps its internal conditions within tolerable ranges by sensing and responding to change.

inheritance Transmission of DNA to offspring.

nutrient Substance that an organism needs for growth and survival but cannot make for itself.

photosynthesis Process by which a producer uses light energy to make sugars from carbon dioxide and water.

producer Organism that makes its own food using energy and nonbiological raw materials from the environment.

reproduction Process by which parents produce offspring.

1.4 How Living Things Differ

Living things differ tremendously in their observable characteristics. Various classification schemes help us organize what we understand about the scope of this variation, which we call Earth's **biodiversity**.

For example, organisms can be grouped on the basis of whether they have a nucleus, which is a saclike structure containing a cell's DNA. **Bacteria** (singular, bacterium) and **archaea** (singular, archaeon) are organisms whose DNA *is not* contained within a nucleus. All bacteria and archaea are single-celled, which means each organism consists of one cell (Figure 1.5). Collectively, these organisms are the most diverse representatives of life. Different kinds are producers or consumers in nearly all regions of Earth. Some inhabit such extreme environments as frozen desert rocks, boiling sulfurous lakes, and nuclear reactor waste. The first cells on Earth may have faced similarly hostile conditions.

Traditionally, organisms without a nucleus have been called **prokaryotes**, but the designation is now used only informally. This is because, despite the similar appearance of bacteria and archaea, the two types of cells are less related to one another than we once thought. Archaea turned out to be more closely related to **eukaryotes**, which are organisms whose DNA *is* contained within a nucleus. Some eukaryotes live as individual cells; others are multicelled (Figure 1.6). Eukaryotic cells are typically larger and more complex than bacteria or archaea.

Protists are the simplest eukaryotes, but as a group they vary dramatically, from single-celled consumers to giant, multicelled producers.

Fungi (singular, fungus) are eukaryotic consumers that secrete substances to break down food externally, then absorb nutrients released by this process. Many fungi are decomposers. Most fungi, including those that form mushrooms, are multicellular. Fungi that live as single cells are called yeasts.

Plants are multicelled eukaryotes, and the vast majority of them are photosynthetic producers that live on land. Besides feeding themselves, plants also serve as food for most other land-based organisms.

Animals are multicelled eukaryotic consumers that ingest tissues or juices of other organisms. Unlike fungi, animals break down food inside their body. They also develop through a series of stages that lead to the adult form. All animals actively move about during at least part of their lives.

What Is a Species? Each time we discover a new **species**, or unique kind of organism, we name it. **Taxonomy**, the practice of naming and classifying species, began thousands of years ago, but naming species in a consistent way did not become a priority until the eighteenth century. At the time, European explorers who were just discovering the scope of life's diversity started having more and more trouble communicating with one another because species often had multiple names. For example, the dog rose (a plant native to Europe, Africa, and Asia) was alternately known as briar rose, witch's briar, herb patience, sweet briar, wild briar, dog briar, dog berry, briar hip, eglantine gall, hep tree, hip fruit, hip rose, hip tree, hop fruit, and hogseed—and those are only the English names! Species often had multiple scientific names too, in Latin that was descriptive but often cumbersome. The scientific name of the dog rose was *Rosa sylvestris inodora seu canina* (odorless woodland dog rose), and also *Rosa sylvestris alba cum rubore, folio glabro* (pinkish white woodland rose with smooth leaves).

An eighteenth-century naturalist, Carolus Linnaeus, standardized a two-part naming system that we still use. By the Linnaean system, every species is given a

animal Multicelled consumer that develops through a series of stages and moves about during part or all of its life.

archaea Group of single-celled organisms that lack a nucleus but are more closely related to eukaryotes than to bacteria.

bacteria The most diverse and well-known group of single-celled organisms that lack a nucleus.

biodiversity Scope of variation among living organisms.

eukaryote Organism whose cells characteristically have a nucleus.

fungus Single-celled or multicelled eukaryotic consumer that breaks down material outside itself, then absorbs nutrients released from the breakdown.

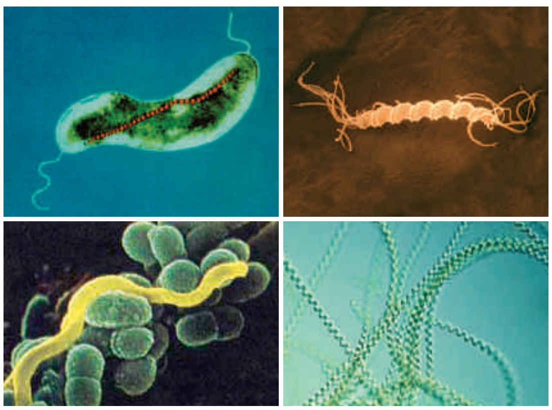
plant A multicelled, typically photosynthetic producer.

prokaryote Single-celled organism with no nucleus.

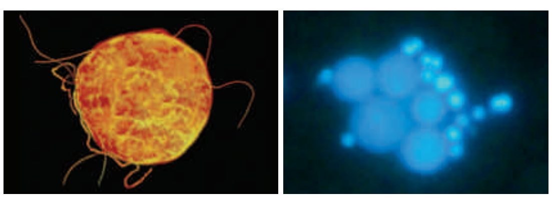
protists A group of diverse, simple eukaryotes.

species Unique type of organism.

taxonomy Practice of naming and classifying species.



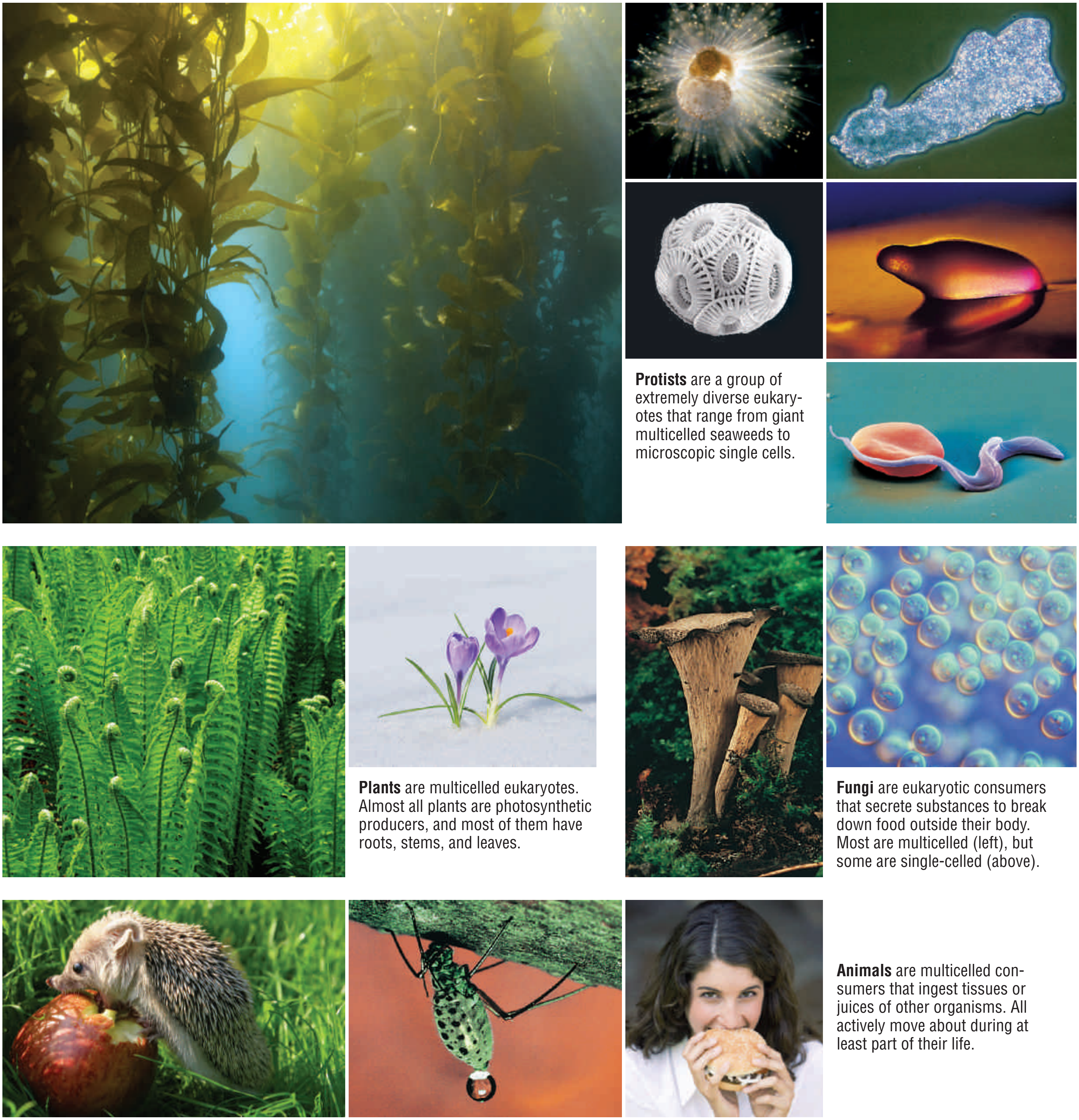
A. Bacteria are the most numerous organisms on Earth. Clockwise from upper left, a bacterium with a row of iron crystals that acts like a tiny compass; a common resident of cat and dog stomachs; spiral cyanobacteria; types found in dental plaque.



B. Archaea may resemble bacteria, but they are more closely related to eukaryotes. These are two types of archaea from a hydrothermal vent on the seafloor.

Figure 1.5 A few representative prokaryotes.

(A) top left, Dr. Richard Frankel; top right, Science Source; bottom left, www.zahnarzt-stuttgart.com; bottom right, © Susan Barnes; (B) left, Dr. Terry Beveridge, Visuals Unlimited/Corbis; right, © Dr. Harald Huber, Dr. Michael Hohn, Prof. Dr. K.O. Stetter, University of Regensburg, Germany.



Protists are a group of extremely diverse eukaryotes that range from giant multicelled seaweeds to microscopic single cells.

Plants are multicelled eukaryotes. Almost all plants are photosynthetic producers, and most of them have roots, stems, and leaves.

Fungi are eukaryotic consumers that secrete substances to break down food outside their body. Most are multicelled (left), but some are single-celled (above).

Animals are multicelled consumers that ingest tissues or juices of other organisms. All actively move about during at least part of their life.

Figure 1.6 A few representative eukaryotes.

Protists: from left, © worldswildlifewonders/Shutterstock.com; top middle, Courtesy of Allen W. H. Bé and David A. Caron; bottom middle, © Emiliania Huxleyi photograph, Vita Pariente, scanning electron micrograph taken on a Jeol T330A instrument at Texas A&M University Electron Microscopy Center; top right, M I Walker/Science Source; middle right, © Carolina Biological Supply Company; bottom right, Oliver Meckes/Science Source; Plants: left, © Jag.ca.Shutterstock.com; right, © Martin Ruegner/Radius Images/Getty Images; Fungi, left, Edward S. Ross; right, London Scientific Films/Oxford Scientific/Getty Images; Animals: left, Shironina/Shutterstock.com; middle, © Martin Zimmerman, Science, 1961, 133:73–79, © AAAS; right, © Pixtal/SuperStock.

genus A group of species that share a unique set of traits.

taxon Group of organisms that share a unique set of traits.

unique two-part scientific name. The first part of a scientific name is the **genus** (plural, genera), a group of species that share a unique set of features. The second part is the specific epithet. Together, the genus name and the specific epithet designate one species. Thus, the dog rose now has one official name, *Rosa canina*, that is recognized worldwide.

Genus and species names are always italicized. For example, *Panthera* is a genus of big cats. Lions belong to the species *Panthera leo*. Tigers belong to a different species in the same genus (*Panthera tigris*), and so do leopards (*P. pardus*). Note how the genus name may be abbreviated after it has been spelled out once.

A "species" is a convenient but artificial construct of the human mind.

A Rose by Any Other Name The individuals of a species share a unique set of inherited traits. For example, giraffes normally have very long necks, brown spots on white coats, and so on. These are morphological (structural) traits. Individuals of a species also share biochemical traits (they make and use the same molecules) and behavioral traits (they respond the same way to certain stimuli, as when hungry giraffes feed on tree leaves). We can rank species into ever more inclusive categories based on some subset of traits it shares with other species. Each rank, or **taxon** (plural, taxa), is a group of organisms that share a unique set of traits. Each category above species—genus, family, order, class, phylum (plural, phyla), kingdom, and domain—consists of a group of the next lower taxon (Figure 1.7). Using this system, we can sort all life into a few categories (Figure 1.8).

It is easy to tell that orangutans and caterpillars are different species because they appear very different. Distinguishing between species that are more closely related may be much more challenging (Figure 1.9). In addition, traits shared by members of a species often vary a bit among individuals, as eye color does among

	wild carrot	marijuana	apple	prickly rose	dog rose
domain	Eukarya	Eukarya	Eukarya	Eukarya	Eukarya
kingdom	Plantae	Plantae	Plantae	Plantae	Plantae
phylum	Magnoliophyta	Magnoliophyta	Magnoliophyta	Magnoliophyta	Magnoliophyta
class	Magnoliopsida	Magnoliopsida	Magnoliopsida	Magnoliopsida	Magnoliopsida
order	Apiales	Rosales	Rosales	Rosales	Rosales
family	Apiaceae	Cannabaceae	Rosaceae	Rosaceae	Rosaceae
genus	*Daucus*	*Cannabis*	*Malus*	*Rosa*	*Rosa*
species	*carota*	*sativa*	*domestica*	*acicularis*	*canina*

Figure 1.7 Taxonomic classification of five species that are related at different levels.
Each species has been assigned to ever more inclusive groups, or taxa: in this case, from genus to domain.

From the left, Joaquim Gaspar; © kymkemp.com; Sylvie Bouchard/Shutterstock.com; Courtesy of Melissa S. Green, www.flickr.com/photos/henkimaa; © Grodana Sarkotic.

Figure It Out: Which of the plants shown here are in the same order?

Answer: Marijuana, apple, prickly rose, and dog rose

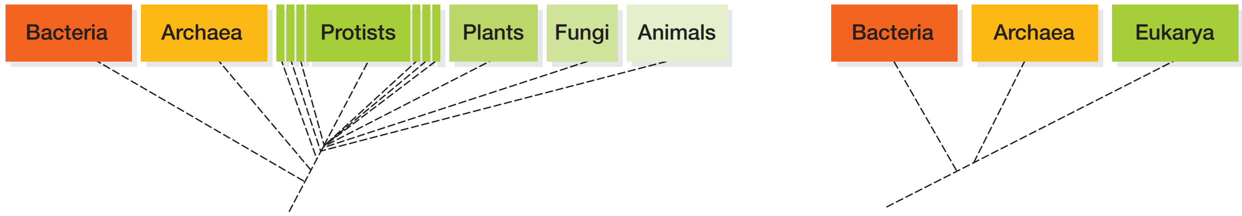


Figure 1.8 Two little ways to see the big picture of life. Lines in such diagrams indicate evolutionary connections.

A. Six-kingdom classification system. The protist kingdom includes the most ancient multicelled and all single-celled eukaryotes.

B. Three-domain classification system. The Eukarya domain includes protists, plants, fungi, and animals.

people. How do we decide whether similar-looking organisms belong to the same species? The short answer to that question is that we rely on whatever information we have. Early naturalists studied anatomy and distribution—essentially the only methods available at the time—so species were named and classified according to what they looked like and where they lived. Today's biologists are able to compare traits that the early naturalists did not even know about, including biochemical ones.

The discovery of new information sometimes changes the way we distinguish a particular species or how we group it with others. For example, Linnaeus grouped plants by the number and arrangement of reproductive parts, a scheme that resulted in odd pairings such as castor-oil plants with pine trees. Having more information today, we place these plants in separate phyla.

Evolutionary biologist Ernst Mayr defined a species as one or more groups of individuals that potentially can interbreed, produce fertile offspring, and do not interbreed with other groups. This "biological species concept" is useful in many cases, but it is not universally applicable. For example, we may never know whether two widely separated populations could interbreed if they got together. As another example, populations often continue to interbreed even as they diverge, so the exact moment at which two populations become two species is often impossible to pinpoint. We return to speciation and how it occurs in Chapter 12, but for now it is important to remember that a "species" is a convenient but artificial construct of the human mind.

Figure 1.9 Four butterflies, two species: Which are which?
The top row shows two forms of the species *Heliconius melpomene*; the bottom row, two forms of *H. erato*.

H. melpomene and *H. erato* never cross-breed. Their alternate but similar patterns of coloration evolved as a shared warning signal to predatory birds that these butterflies taste terrible.

© 2006 Axel Meyer, "Repeating Patterns of Mimicry." *PLoS Biology* Vol. 4, No. 10, e341 doi:10.1371/journal.pbio.0040341. Used with Permission.

Take-Home Message 1.4

How do organisms differ from one another?

- Organisms differ in their details; they show tremendous variation in observable characteristics.
- We divide Earth's biodiversity into broad groups based on traits such as having a nucleus or being multicellular.
- Each species is given a unique, two-part scientific name.
- Classification systems group species on the basis of shared traits.

1.5 The Science of Nature

Most of us assume that we do our own thinking, but do we, really? You might be surprised to find out how often we let others think for us. Consider how a school's job (which is to impart as much information to students as quickly as possible)

control group Group of individuals identical to an experimental group except for the independent variable under investigation.

critical thinking Evaluating information before accepting it.

data Experimental results.

experiment A test designed to support or falsify a prediction.

experimental group In an experiment, a group of individuals who have a certain characteristic or receive a certain treatment.

hypothesis Testable explanation of a natural phenomenon.

model Analogous system used for testing hypotheses.

prediction Statement, based on a hypothesis, about a condition that should exist if the hypothesis is correct.

science Systematic study of the observable world.

scientific method Making, testing, and evaluating hypotheses.

variable In an experiment, a characteristic or event that differs among individuals or over time.

How do my own biases affect what I'm learning?

© JupiterImages Corporation.

meshes perfectly with a student's job (which is to acquire as much knowledge as quickly as possible). In this rapid-fire exchange of information, it can be very easy to forget about the quality of what is being exchanged. Any time you accept information without questioning it, you let someone else think for you.

Thinking About Thinking **Critical thinking** is the deliberate process of judging the quality of information before accepting it. "Critical" comes from the Greek *kriticos* (discerning judgment). When you use critical thinking, you move beyond the content of new information to consider supporting evidence, bias, and alternative interpretations. How does the busy student manage this? Critical thinking does not necessarily require extra time, just a bit of extra awareness. There are many ways to do it. For example, you might ask yourself some of the following questions while you are learning something new:

What message am I being asked to accept?
Is the message based on facts or opinion?
Is there a different way to interpret the facts?
What biases might the presenter have?
How do my own biases affect what I'm learning?

Such questions are a way of being conscious about learning. They can help you decide whether to allow new information to guide your beliefs and actions.

How Science Works Critical thinking is a big part of **science**, the systematic study of the observable world and how it works. A scientific line of inquiry usually begins with curiosity about something observable, such as (for example) a decrease in the number of birds in a particular area. Typically, a scientist will read about what others have discovered before making a **hypothesis**, a testable explanation for a natural phenomenon. An example of a hypothesis would be, "The number of birds is decreasing because the number of cats is increasing."

A **prediction**, or statement of some condition that should exist if the hypothesis is correct, comes next. Making predictions is often called the if–then process, in which the "if" part is the hypothesis, and the "then" part is the prediction: *If* the number of birds is decreasing because the number of cats is increasing, *then* reducing the number of cats should stop the decline.

Next, a researcher will test the prediction. Tests may be performed on a **model**, or analogous system, if working with an object or event directly is not possible. For

A. Studying the ecological benefits of weedy buffer zones on farms.

B. Measuring how much wood is produced by extremely old trees.

example, animal diseases are often used as models of similar human diseases. Careful observations are one way to test predictions that flow from a hypothesis. So are **experiments**: tests designed to support or falsify a prediction. A typical experiment explores a cause-and-effect relationship using **variables**, which are characteristics or events that can differ among individuals or over time.

Biological systems are typically complex, with many interdependent variables. It can be difficult to study one variable separately from the rest. Thus, biology researchers often test two groups of individuals simultaneously. An **experimental group** is a set of individuals that have a certain characteristic or receive a certain treatment. An experimental group is tested side by side with a **control group**, which is identical to the experimental group except for one independent variable: the characteristic or the treatment being tested. Any differences in experimental results between the two groups is likely to be an effect of changing the variable. Test results—**data**—that are consistent with the prediction are evidence in support of the hypothesis. Data inconsistent with the prediction are evidence that the hypothesis is flawed and should be revised.

A necessary part of science is reporting one's results and conclusions in a standard way, such as in a peer-reviewed journal article. The communication gives other scientists an opportunity to evaluate the information for themselves, both by checking the conclusions drawn and by repeating the experiments. Forming a hypothesis based on observation, and then systematically testing and evaluating the hypothesis, are collectively called the **scientific method** (Table 1.1).

Table 1.1 The Scientific Method

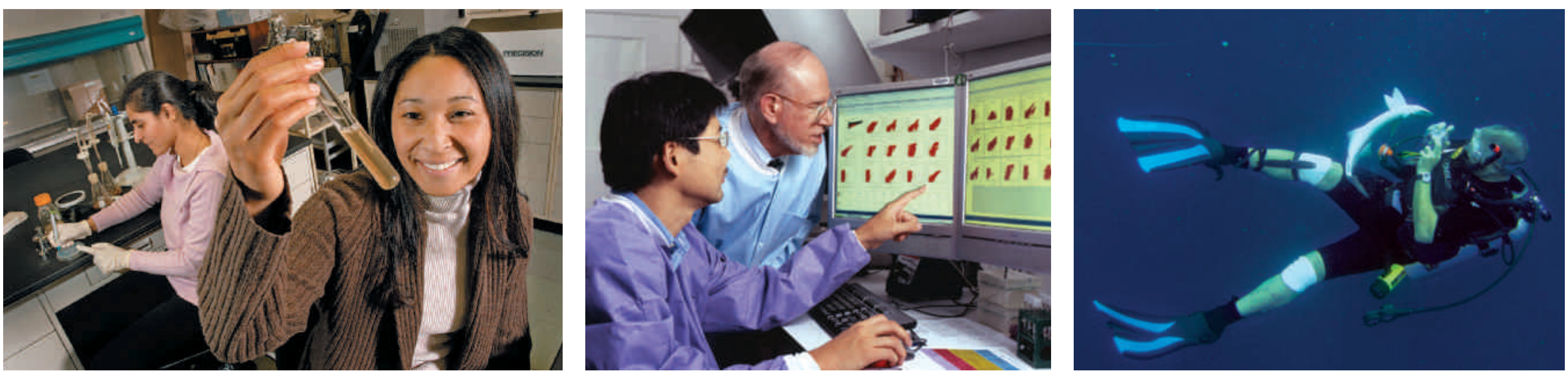
Observe some aspect of nature.
Think of an explanation for your observation (in other words, form a hypothesis).
Test the hypothesis. a. Make a prediction based on the hypothesis. b. Test the prediction using experiments or surveys. c. Analyze the results of the tests (data).
Decide whether the results of the tests support your hypothesis or not (form a conclusion).
Report your results to the scientific community.

Examples of Experiments in Biology There are many different ways to do research, particularly in biology (Figure 1.10). Some biologists survey, simply observing without making or testing hypotheses. Others make hypotheses based on observations, and leave the testing to others. However, despite a broad range of approaches, scientific experiments are typically designed in a consistent way, so the effects of changing one variable at a time can be measured. To give you a sense of how biology experiments work, we summarize two published studies here.

In 1996 the U.S. Food and Drug Administration (FDA) approved Olestra®, a fat replacement manufactured from sugar and vegetable oil, as a food additive. Potato chips were the first Olestra-containing food product to be sold in the United States. Controversy about the chip additive soon raged. Many people complained of intestinal problems after eating the chips, and thought that the Olestra was at fault. Two

Figure 1.10 A few examples of scientific research in the field of biology.

(A) Photo by Scott Bauer, USDA/ARS; (B) MICHAEL NICHOLS/National Geographic Creative; (C) © Roger W. Winstead, NC State University; (D) National Cancer Institute; (E) Courtesy of Susanna López-Legentil.



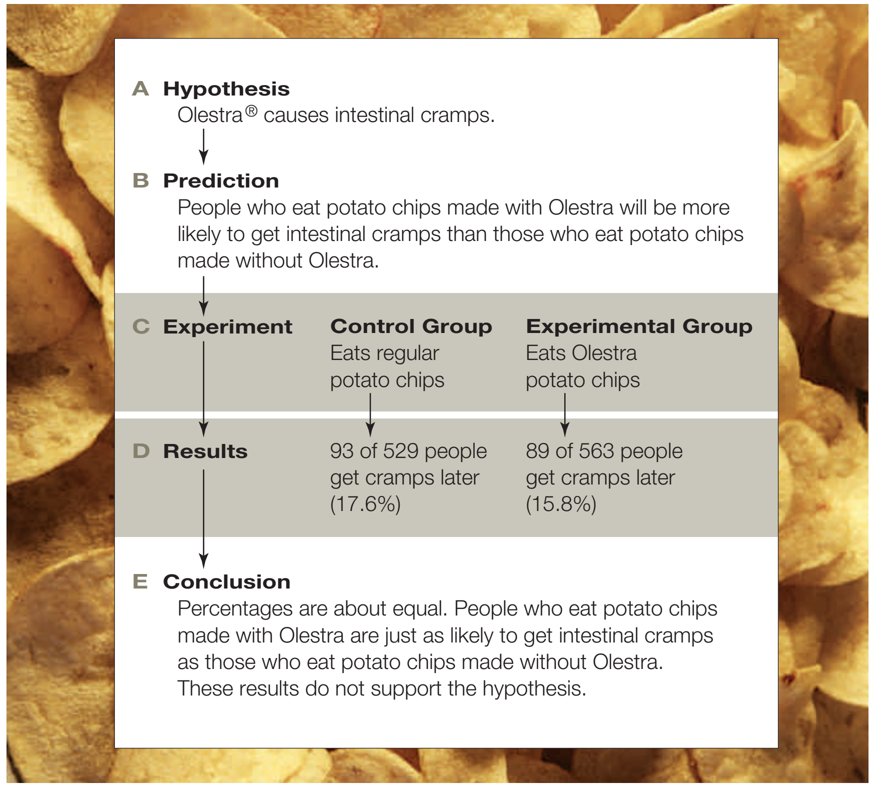
C. Improving efficiency of biofuel production from agricultural waste.

D. Devising a vaccine that helps prevent cancer.

E. Discovering medically active natural products made by marine animals.

Figure 1.11 The steps in a scientific experiment to determine whether Olestra causes intestinal cramps. A report of this study was published in the *Journal of the American Medical Association* in January 1998.

Left, © Bob Jacobson/Corbis; background right, © SuperStock.



years later, researchers at the Johns Hopkins University School of Medicine designed an experiment to test whether Olestra causes cramps. The researchers made the following prediction: *if* Olestra causes cramps, *then* people who eat Olestra should be more likely to get cramps than people who do not eat it. To test the prediction, they used a Chicago theater as a "laboratory." They asked 1,100 people between the ages of thirteen and thirty-eight to watch a movie and eat their fill of potato chips. Each person received an unmarked bag containing 13 ounces of chips. In this experiment, the individuals who received Olestra-laden potato chips were the experimental group, and the individuals who received regular chips were the control group.

A few days after the movie, the researchers contacted all of the people who participated in the experiment and collected any reports of post-movie gastrointestinal problems. Of 563 people making up the experimental group, 89 (15.8 percent) reported having cramps. However, so did 93 of the 529 people (17.6 percent) making up the control group—who had eaten the regular chips. People were about as likely to get cramps whether or not they ate chips made with Olestra. These results did not support the prediction, so the researchers concluded that eating Olestra does not cause cramps (Figure 1.11).

A different experiment that took place in 2005 investigated whether certain behaviors of peacock butterflies help the insects avoid predation by birds. The researchers performing this experiment began with two observations. First, when a peacock butterfly rests, it folds its wings, so only the dark underside shows (Figure 1.12A). Second, when a butterfly sees a predator approaching, it repeatedly flicks its wings open, while also moving them in a way that produces a hissing sound and a series of clicks (Figure 1.12B).

The researchers were curious about why the peacock butterfly flicks its wings. After they reviewed earlier studies, they came up with two hypotheses that might explain the wing-flicking behavior.

1. Wing-flicking probably attracts predatory birds, but it also exposes brilliant spots that resemble owl eyes. Anything that looks like owl eyes is known to startle small, butterfly-eating birds, so exposing the wing spots might scare off predators.

2. The hissing and clicking sounds produced when the peacock butterfly moves its wings may be an additional defense that deters predatory birds.

The researchers then used their hypotheses to make the following predictions:

1. *If* exposing brilliant wing spots startles butterfly-eating birds, *then* peacock butterflies missing their spots will be more likely to get eaten.

2. *If* hissing and clicking sounds deter birds butterfly-eating birds, *then* peacock butterflies unable to make these sounds will be more likely to get eaten.

The next step was the experiment. The researchers used a black marker to cover up the wing spots of some butterflies, and scissors to cut off the sound-making part of the wings of others. A third group had both treatments, their wings painted and also cut. The researchers then put each butterfly into a large cage with a hungry blue tit (Figure 1.12C) and watched the pair for thirty minutes.

Figure 1.12D lists the results of the experiment. All butterflies with unmodified wing spots survived, regardless of whether they made sounds. By contrast, only half of the butterflies that had spots painted out but could make sounds survived. Most

Figure 1.12 Testing peacock butterfly defenses.

(A) © Matt Rowlings, www.eurobutterflies.com; (B) © Adrian Vallin; (C) © Antje Schulte; (D) *Proceedings of the Royal Society of London*, Series B (2005) 272: 1203–1207.

Figure It Out: What percentage of butterflies with spots painted and wings cut survived the test?

Answer: 20 percent

Experimental Treatment	Number of Butterflies Eaten (of Total)
Spots painted out	5 of 10
Wings cut	0 of 8
Spots painted, wings cut	8 of 10
None	0 of 9

A. With wings folded, a resting peacock butterfly resembles a dead leaf, so it is appropriately camouflaged from predatory birds.

B. When a predatory bird approaches, a butterfly flicks its wings open and closed, revealing brilliant spots and producing hissing and clicking sounds.

C. Researchers tested whether the wing-flicking behavior of peacock butterflies affected predation by blue tits.

D. The researchers painted out the spots of some butterflies, cut the sound-making part of the wings on others, and did both to a third group; then exposed each butterfly to a hungry blue tit for 30 minutes. Results are listed on the right.

Digging Into Data

Peacock Butterfly Predator Defenses The photographs below represent the experimental and control groups used in the peacock butterfly experiment. Identify the experimental groups, and match them up with the relevant control group(s). *Hint:* Identify which variable is being tested in each group (each variable has a control).

Adrian Vallin, Sven Jakobsson, Johan Lind and Christer Wiklund, *Proc. R. Soc. B* (2005: 272, 1203, 1207). Used with permission of The Royal Society and the author.

A. Wing spots painted out

B. Wing spots visible; wings silenced

C. Wing spots painted out; wings silenced

D. Wings painted but spots visible

E. Wings cut but not silenced

F. Wings painted, spots visible; wings cut, not silenced of the silenced butterflies with painted-out spots were eaten quickly. The test results confirmed both predictions, so they support the hypotheses. Predatory birds are indeed deterred by peacock butterfly wing-flicking behavior.

Take-Home Message 1.5

How does science work?

- The scientific method consists of making, testing, and evaluating hypotheses. It is one way of critical thinking—systematically judging the quality of information before allowing it to guide one's beliefs and actions.
- Natural processes are often very complex and influenced by many interacting variables.
- Experiments help researchers unravel causes of complex natural processes by focusing on the effects of changing a single variable.

The scientific community consists of critically thinking people trying to poke holes in one another's ideas.

1.6 The Nature of Science

Bias in Interpreting Experimental Results Experimenting with a single variable apart from all others is not often possible, particularly when studying humans. For example, remember that the people who participated in the Olestra experiment were chosen randomly, which means the study was not controlled for gender, age, weight, medications taken, and so on. These variables may well have influenced the experiment's results.

Humans are by nature subjective, and scientists are no exception. Researchers risk interpreting their results in terms of what they want to find out. That is

Figure 1.13 **Example of how generalizing from a subset can lead to a conclusion that is incorrect.**

(A) Tim Laman/ National Geographic Stock; (B) © Bruce Beehler/ Conservation International.

A. The cloud forest that covers about 2 million acres of New Guinea's Foja Mountains is extremely remote and difficult to access, even for natives of the region. The first major survey of this forest occurred in 2005.

B. In science, discovery of an error is not always bad news. Kris Helgen holds a golden-mantled tree kangaroo he found during the 2005 Foja Mountains survey. This kangaroo species is extremely rare in other areas, so it was thought to be critically endangered prior to the expedition.

why they typically design experiments that will yield quantitative results, which are counts or some other data that can be measured or gathered objectively. Quantitative results minimize the potential for bias, and also give other scientists an opportunity to repeat the experiments and check the conclusions drawn from them. This last point gets us back to the role of critical thinking in science. Scientists expect one another to recognize and put aside bias in order to test hypotheses in ways that may prove them wrong. If a scientist does not, then others will, because exposing errors is just as useful as applauding insights. The scientific community consists of critically thinking people trying to poke holes in one another's ideas. Ideally, their collective efforts make science a self-correcting endeavor.

Sampling Error Researchers cannot always observe all individuals of a group. For example, the explorers you read about in Section 1.1 did not—and could not—survey every uninhabited part of the Foja Mountains. The cloud forest alone cloaks more than 2 million acres (Figure 1.13A), so surveying all of it would take unrealistic amounts of time and effort.

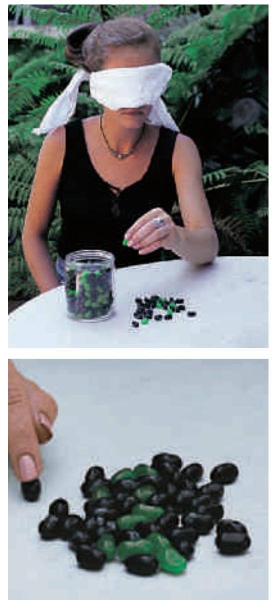
When researchers cannot directly observe all individuals of a population, all instances of an event, or some other aspect of nature, they may test or survey a subset. Results from the subset are then used to make generalizations about the whole. However, generalizing from a subset is risky because subsets are not necessarily representative of the whole. Consider the golden-mantled tree kangaroo, an animal first discovered in 1993 on a single forested mountaintop in New Guinea. For more than a decade, the species was never seen outside of that habitat, which is getting smaller every year because of human activities. Thus, the golden-mantled tree kangaroo was considered to be one of the most endangered animals on the planet. Then, in 2005, the New Guinea explorers discovered that this kangaroo species is fairly common in the Foja Mountain cloud forest (Figure 1.13B). As a result, biologists now believe its future is secure, at least for the moment.

Sampling error is a difference between results obtained from a subset, and results from the whole (Figure 1.14A). Sampling error may be unavoidable, but knowing how it can occur helps researchers design their experiments to minimize it. For example, sampling error can be a substantial problem with a small subset, so experimenters try to start with a relatively large sample, and they repeat their experiments (Figure 1.14B). To understand why these practices reduce the risk of sampling error, think about flipping a coin. There are two possible outcomes of each flip: The coin lands heads up, or it lands tails up. Thus, the chance that the coin will land heads up is one in two (1/2), or 50 percent. However, when you flip a coin repeatedly, it often lands heads up, or tails up, several times in a row. With just 3 flips, the proportion of times that the coin actually lands heads up may not even be close to 50 percent. With 1,000 flips, however, the overall proportion of times the coin lands heads up is much more likely to approach 50 percent.

Probability is the measure, expressed as a percentage, of the chance that a particular outcome will occur. That chance depends on the total number of possible outcomes. For instance, if 10 million people enter a drawing, each has the same probability of winning: 1 in 10 million, or (an extremely improbable) 0.00001 percent. Analysis of experimental data often includes probability calculations. If there is a very low probability that a result has occurred by chance alone, the result is said to be **statistically significant**. In this context, the word "significant" does not refer to the result's importance. Rather, it means that a rigorous statistical analysis has shown a very low probability (usually 5 percent or less) of the result being incorrect because of sampling error.

A. Natalie chooses a random jelly bean from a jar. She is blindfolded, so she does not know that the jar contains 120 green and 280 black jelly beans.

The jar is hidden from Natalie's view before she removes her blindfold. She sees one green jelly bean in her hand and assumes that the jar must hold only green jelly beans. This assumption is incorrect: 30 percent of the jelly beans in the jar are green, and 70 percent are black. The small sample size has resulted in sampling error.



B. Still blindfolded, Natalie randomly chooses 50 jelly beans from the jar. She ends up choosing 10 green and 40 black beans.

The larger sample leads Natalie to assume that one-fifth of the jar's jelly beans are green (20 percent) and four-fifths are black (80 percent). The larger sample more closely approximates the jar's actual green-to-black ratio of 30 percent to 70 percent.

The more times Natalie repeats the sampling, the greater her chance of guessing the actual ratio.

Figure 1.14 How sample size affects sampling error.

© Gary Head.

probability The chance that a particular outcome of an event will occur; depends on the total number of outcomes possible.

sampling error Difference between results derived from testing an entire group of events or individuals, and results derived from testing a subset of the group.

statistically significant Refers to a result that is statistically unlikely to have occurred by chance alone.

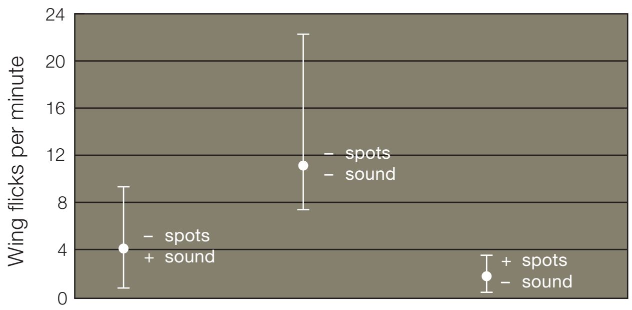


Figure 1.15 Example of error bars in a graph. This graph was adapted from the peacock butterfly research described in Section 1.5.

The researchers recorded the number of times each butterfly flicked its wings in response to an attack by a bird.

The squares represent average frequency of wing flicking for each sample set of butterflies. The error bars that extend above and below the dots indicate the range of values—the sampling error.

Figure It Out: What was the fastest rate at which a butterfly with no spots or sound flicked its wings? **Answer:** 22 times per minute

Variation in data is often shown as error bars on a graph (Figure 1.15). Depending on the graph, error bars may indicate variation around an average for one sample set, or the difference between two sample sets.

Scientific Theories Suppose a hypothesis stands even after years of tests. It is consistent with all data ever gathered, and it has helped us make successful predictions about other phenomena. When a hypothesis meets these criteria, it is considered to be a **scientific theory** (Table 1.2). To give an example, all observations to date have been consistent with the hypothesis that matter consists of atoms. Scientists no longer spend time testing this hypothesis for the compelling reason that, since we started looking 200 years ago, no one has discovered matter that consists of anything else. Thus, scientists use the hypothesis, now called atomic theory, to make other hypotheses about matter.

Science helps us communicate our experiences without bias.

Scientific theories are our best objective descriptions of the natural world. However, they can never be proven absolutely, because to do so would necessitate testing under every possible circumstance. For example, in order to prove atomic theory, the atomic composition of all matter in the universe would have to be checked—an impossible task even if someone wanted to try.

Like all hypotheses, a scientific theory can be disproven by a single observation or result that is inconsistent with it. For example, if someone discovers a form of matter that does not consist of atoms, atomic theory would have to be revised. The potentially falsifiable nature of scientific theories means that science has a built-in system of checks and balances. A theory is revised until no one can prove it to be incorrect. The theory of evolution, which states that change occurs in a line of descent over time, still holds after a century of observations and testing. As with all other scientific theories, no one can be absolutely sure that it will hold under all possible conditions, but it has a very high probability of not being wrong. Few other theories have withstood as much scrutiny.

You may hear people apply the word "theory" to a speculative idea, as in the phrase "It's just a theory." This everyday usage of the word differs from the way it is used in science. Speculation is an opinion, belief, or personal conviction that is not necessarily supported by evidence. A scientific theory is different. By definition, a scientific theory is supported by a large body of evidence, and it is consistent with all known data.

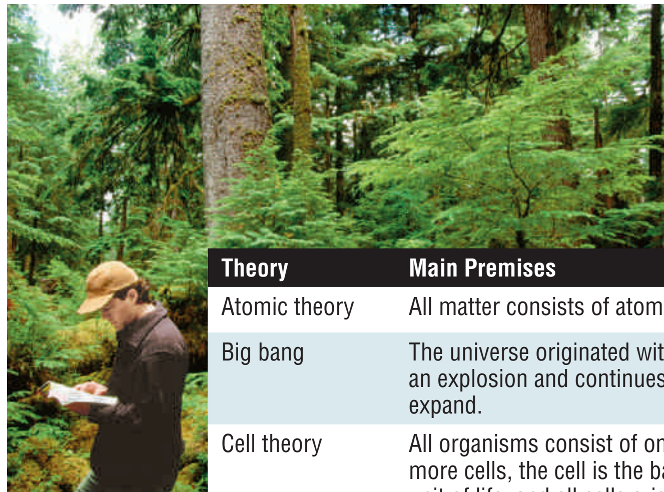
A scientific theory also differs from a **law of nature**, which describes a phenomenon that has been observed to occur in every circumstance without fail, but for which we do not have a complete scientific explanation. The laws of thermodynamics, which describe energy, are examples. We understand *how* energy behaves, but not exactly *why* it behaves the way it does.

The Scope of Science Science helps us be objective about our observations in part because of its limitations. For example, science does not address many questions, such as "Why do I exist?" Answers to such questions can only come from within as an integration of the personal experiences and mental connections that shape our consciousness. This is not to say subjective answers have no value, because no human society can function for long unless its individuals share standards for making judgments, even if they are subjective. Moral, aesthetic, and philosophical standards vary from one society to the next, but all help people decide what is important and good. All give meaning to our lives.

Neither does science address the supernatural, or anything that is "beyond nature." Science neither assumes nor denies that supernatural phenomena occur, but scientists often cause controversy when they discover a natural explanation for something that was thought to have none. Such controversy arises when a society's moral standards are interwoven with its understanding of nature. Nicolaus Copernicus proposed in 1540 that Earth orbits the sun. Today that idea is generally accepted, but the prevailing belief system had Earth as the immovable center of the universe. In 1610, Galileo Galilei published evidence for the Copernican model of the solar system, an act that resulted in his imprisonment. He was publicly forced to recant his work, spent the rest of his life under house arrest, and was never allowed to publish again.

As Galileo's story illustrates, exploring a traditional view of the natural world from a scientific perspective is often misinterpreted as a violation of morality. As a group, scientists are no less moral than anyone else, but they follow a particular set of rules that do not necessarily apply to others: Their work concerns only the natural world, and their ideas must be testable by other scientists.

Science helps us communicate our experiences of the natural world without bias. As such, it may be as close as we can get to a universal language. We are fairly sure, for example, that the laws of gravity apply everywhere in the universe. Intelligent beings on a distant planet would likely understand the concept of gravity. Thus, we might well use gravity or another scientific concept to communicate with them, or anyone, anywhere. The point of science, however, is not to communicate with aliens. It is to find common ground here on Earth.



Theory	Main Premises
Atomic theory	All matter consists of atoms.
Big bang	The universe originated with an explosion and continues to expand.
Cell theory	All organisms consist of one or more cells, the cell is the basic unit of life, and all cells arise from existing cells.
Evolution	Change occurs in the inherited traits of a population over generations.
Global warming	Human activities are causing Earth's average temperature to increase.
Plate tectonics	Earth's crust is cracked into pieces that move in relation to one another.

Table 1.2 Examples of Scientific Theories

Take-Home Message 1.6

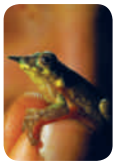
Why does science work?

- Researchers minimize sampling error by using large sample sizes and by repeating their experiments. Probability calculations can show whether a result is unlikely to have occurred by chance alone.
- Science is concerned only with testable ideas about observable aspects of nature.
- Ideally, science is a self-correcting process because it is carried out by a community of people who systematically check one another's work and conclusions.
- Because a scientific theory is thoroughly tested and revised until no one can prove it wrong, it is our best way of objectively describing the natural world.

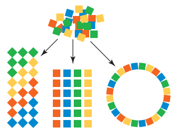
law of nature Generalization that describes a consistent natural phenomenon for which there is incomplete scientific explanation.

scientific theory Hypothesis that has not been disproven after many years of rigorous testing.

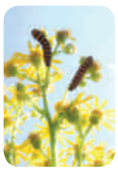
Summary



Section 1.1 **Biology** is the scientific study of life. We know about only a fraction of the organisms that live on Earth, in part because we have explored only a fraction of its inhabited regions.



Section 1.2 Biologists think about life at different levels of organization, with new properties emerging at successively higher levels. All matter consists of **atoms**, which bond together to form **molecules**. **Organisms** are individuals that consist of one or more **cells**, the organizational level at which life emerges. A **population** is a group of interbreeding individuals of a species in a given area; a **community** is all populations of all species in a given area. An **ecosystem** is a community interacting with its environment. The **biosphere** includes all regions of Earth that hold life.



Section 1.3 Life has underlying unity in that all living things have similar characteristics: (1) All organisms require energy and **nutrients** to sustain themselves. **Producers** harvest energy from the environment to make their own food by processes such as **photosynthesis**; **consumers** ingest other organisms, or their wastes or remains. (2) Organisms keep the conditions in their internal environment within ranges that their cells tolerate—a process called **homeostasis**. (3) **DNA** contains information that guides an organism's **growth**, **development**, and **reproduction**. The passage of DNA from parents to offspring is **inheritance**.

Section 1.4 The many types of organisms that currently exist on Earth differ greatly in details of body form and function. **Biodiversity** is the sum of differences among living things. **Bacteria** and **archaea** are **prokaryotes**, single-celled organisms whose DNA is not contained within a nucleus. The DNA of single-celled or multicelled **eukaryotes** (**protists**, **plants**, **fungi**, and **animals**) is contained within a nucleus.

Each **species** has a two-part name. The first part is the **genus** name. When combined with the specific epithet, it designates the particular species. With **taxonomy**, species are ranked into ever more inclusive **taxa** on the basis of shared traits.

Section 1.5 **Critical thinking**, the self-directed act of judging the quality of information as one learns, is an important part of **science**. Generally, a researcher observes something in nature, forms a **hypothesis** (testable explanation) for it, then makes a **prediction** about what might occur if the hypothesis is correct. Predictions are tested with observations, **experiments**, or both.

Experiments typically are performed on an **experimental group** as compared with a **control group**, and sometimes on **model** systems. Conclusions are drawn from **data**. A hypothesis that is not consistent with data is modified or discarded. The **scientific method** consists of making, testing, and evaluating hypotheses, and sharing results with the scientific community.

Biological systems are usually influenced by many interacting **variables**. Research approaches differ, but experiments are designed in a consistent way, in order to study a single cause-and-effect relationship in a complex natural system.

Section 1.6 Small sample size increases the potential for **sampling error** in experimental results. In such cases, a subset may be tested that is not representative of the whole. Researchers design experiments carefully to minimize sampling error and bias, and they use **probability** calculations to check the **statistical significance** of their results.

Science helps us be objective about our observations because it is concerned only with testable ideas about observable aspects of nature. Opinion and belief have value in human culture, but they are not addressed by science. A **scientific theory** is a long-standing hypothesis that is useful for making predictions about other phenomena. It is our best way of objectively describing nature. A **law of nature** is a phenomenon that occurs without fail, but has an incomplete scientific explanation.

Self-Quiz

Answers in Appendix I

1. ________ are fundamental building blocks of all matter.
   a. Cells
   b. Atoms
   c. Organisms
   d. Molecules

2. The smallest unit of life is the ________ .
   a. atom
   b. molecule
   c. cell
   d. organism

3. ________ is the transmission of DNA to offspring.
   a. Reproduction
   b. Development
   c. Homeostasis
   d. Inheritance

4. A process by which an organism produces offspring is called ________ .
   a. reproduction
   b. development
   c. homeostasis
   d. inheritance

5. Organisms require ________ and ________ to maintain themselves, grow, and reproduce.
   a. DNA; energy
   b. food; sunlight
   c. nutrients; energy
   d. DNA; cells

6. ________ move around for at least part of their life.

7. By sensing and responding to change, an organism keeps conditions in its internal environment within ranges that its cells can tolerate. This process is called ________ .
   a. sampling error
   b. development
   c. homeostasis
   d. critical thinking

8. DNA ________ .
   a. guides form and function
   b. is the basis of traits
   c. is transmitted from parents to offspring
   d. all of the above

9. A butterfly is a(n) ________ (choose all that apply).
   a. organism
   b. domain
   c. species
   d. eukaryote
   e. consumer
   f. producer
   g. prokaryote
   h. trait

10. A bacterium is ________ (choose all that apply).
   a. an organism
   b. single-celled
   c. an animal
   d. a eukaryote

11. Bacteria, Archaea, and Eukarya are three ________ .

12. A control group is ________ .
   a. a set of individuals that have a characteristic under study or receive an experimental treatment
   b. the standard against which an experimental group is compared
   c. the experiment that gives conclusive results

13. Science addresses only that which is ________ .
   a. alive
   b. observable
   c. variable
   d. indisputable

14. Match the terms with the most suitable description.

_____ life	a. if–then statement
_____ probability	b. unique type of organism
_____ species	c. emerges with cells
_____ scientific theory	d. testable explanation
_____ hypothesis	e. measure of chance
_____ prediction	f. makes its own food
_____ producer	g. time-tested hypothesis

15. In one survey, fifteen randomly selected students were found to be taller than 6 feet. This data led to the conclusion that the average height of a student is greater than 6 feet. This is an example of ________ .
   a. experimental error
   b. sampling error
   c. a subjective opinion
   d. experimental bias

Critical Thinking

1. A person is declared to be dead upon the irreversible ceasing of spontaneous body functions: brain activity, or blood circulation and respiration. However, only about 1% of a person's cells have to die in order for all of these things to happen. How can someone be dead when 99% of his or her cells are still alive?
2. Explain the difference between a one-celled organism and a single cell of a multicelled organism.
3. Why would you think twice about ordering from a restaurant menu that lists only the second part of the species name (not the genus) of its offerings? *Hint:* Look up *Ursus americanus, Ceanothus americanus*, *Bufo americanus*, *Homarus americanus*, *Lepus americanus*, and *Nicrophorus americanus*.
4. Once there was a highly intelligent turkey that had nothing to do but reflect on the world's regularities. Morning always started out with the sky turning light, followed by the master's footsteps, which were always followed by the appearance of food. Other things varied, but food always followed footsteps. The sequence of events was so predictable that it eventually became the basis of the turkey's theory about the goodness of the world. One morning, after more than 100 confirmations of this theory, the turkey listened for the master's footsteps, heard them, and had its head chopped off.

   Any scientific theory is modified or discarded upon discovery of contradictory evidence. The absence of absolute certainty has led some people to conclude that "theories are irrelevant because they can change." If that is so, should we stop doing scientific research? Why or why not?
5. In 2005, researcher Woo-suk Hwang reported that he had made immortal stem cells from human patients. His research was hailed as a breakthrough for people affected by degenerative diseases, because stem cells may be used to repair a person's own damaged tissues. Hwang published his results in a peer-reviewed journal. In 2006, the journal retracted his paper after other scientists discovered that Hwang's group had faked their data. Does the incident show that results of scientific studies cannot be trusted? Or does it confirm the usefulness of a scientific approach, because other scientists discovered and exposed the fraud?

2

MOLECULES OF LIFE

Application 2.1 Fear of Frying

The human body requires only about a tablespoon of fat each day to stay healthy, but most people in developed countries eat far more than that. The average American eats about 70 pounds of fat per year, which may be part of the reason why the average American is overweight. Being overweight increases one's risk for many chronic illnesses. However, the total quantity of fat in the diet may have less impact on health than the types of fats. Fats are more than inert molecules that accumulate in strategic areas of our bodies. They are the main constituents of cell membranes, and as such they have powerful effects on cell function.

The typical fat molecule has three fatty acid tails, each a long chain of carbon atoms that can vary a bit in structure. Fats with a certain arrangement of hydrogen atoms around those carbon chains are called *trans* fats. Small amounts of *trans* fats occur naturally in red meat and dairy products, but the main source of these fats in the American diet is an artificial food product called partially hydrogenated vegetable oil. Hydrogenation is a manufacturing process that adds hydrogen atoms to oils in order to change them into solid fats. In 1908, Procter & Gamble Co. developed partially hydrogenated soybean oil as a substitute for the more expensive solid animal fats they had been using to make candles. By 1911, more households in the United States became wired for electricity, so the demand for candles was waning. P & G needed another way to sell its proprietary fat. Partially hydrogenated vegetable oil looks a lot like lard, so the company began aggressively marketing it as a revolutionary new food: a solid cooking fat with a long shelf life, mild flavor, and lower cost than lard or butter.

Figure 2.1 **Unhealthy *trans* fats are abundant in partially hydrogenated oils commonly used to make manufactured and fast foods.**

© Kentoh/Shutterstock.com.

By the mid-1950s, hydrogenated vegetable oil had become a major part of the American diet. For decades, it was considered to be healthier than animal fats because it was made from plants, but we now know otherwise. *Trans* fats, which are abundant in hydrogenated vegetable oils, raise the level of cholesterol in our blood more than any other fat, and they directly alter the function of our arteries and veins. The effects of such changes are quite serious. Eating as little as 2 grams per day (about 0.4 teaspoon) of hydrogenated vegetable oil measurably increases one's risk of atherosclerosis (hardening of the arteries), heart attack, and diabetes. A small serving of french fries made with hydrogenated vegetable oil contains about 5 grams of *trans* fat (Figure 2.1). At this writing, hydrogenated oil is still a component of many manufactured and fast foods: french fries, stick margarines, ready-to-use frostings, cookies, crackers, cakes and pancakes, peanut butter, pies, doughnuts, muffins, chips, microwave popcorn, pizzas, burritos, chicken nuggets, fish sticks, and so on.

All organisms consist of the same kinds of molecules, but small differences in the way those molecules are put together can have big effects. With this concept, we introduce you to the chemistry of life. This is your chemistry. It makes you far more than the sum of your body's molecules.

2.2 Start With Atoms

REMEMBER: Atoms are fundamental units of matter—the building blocks of all substances (Section 1.2).

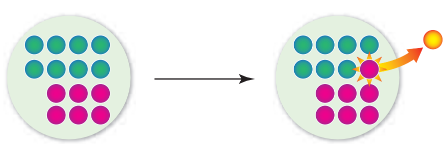
Even though atoms are about 20 million times smaller than a grain of sand, they consist of even smaller subatomic particles. Positively charged **protons** (p^+) and uncharged **neutrons** occur in an atom's core, or **nucleus**. Negatively charged **electrons** (e^-) move around the nucleus (Figure 2.2). **Charge** is an electrical property: Opposite charges attract, and like charges repel. A typical atom has about the same number of electrons and protons. The negative charge of an electron is the same magnitude as the positive charge of a proton, so the two charges cancel one another. Thus, an atom with the same number of electrons and protons carries no charge.

All atoms have protons. The number of protons in the nucleus is called the **atomic number**, and it determines the type of atom, or element. **Elements** are pure substances, each consisting only of atoms with the same number of protons in their nucleus. For example, the element carbon has an atomic number of 6 (Figure 2.3). All atoms with six protons in their nucleus are carbon atoms, no matter how many electrons or neutrons they have. Elemental carbon (the substance) consists only of carbon atoms, and all of those atoms have six protons. Each of the 118 known elements has a symbol that is typically an abbreviation of its Latin or Greek name (see Appendix II). Carbon's symbol, C, is from *carbo*, the Latin word for coal. Coal is mostly carbon.

All atoms of an element have the same number of protons, but they can differ in the number of other subatomic particles. Those that differ in the number of neutrons are called **isotopes**. The total number of neutrons and protons in the nucleus of an isotope is its **mass number**. Mass number is written as a superscript to the left of the element's symbol. For example, the most common isotope of hydrogen has one proton and no neutrons, so it is designated ^{1}H. Other hydrogen isotopes include deuterium (^{2}H, one proton and one neutron) and tritium (^{3}H, one proton and two neutrons).

The most common carbon isotope has six protons and six neutrons (^{12}C). Another naturally occurring carbon isotope, ^{14}C, has six protons and eight neutrons ($6 + 8 = 14$). Carbon 14 is an example of a **radioisotope**, or radioactive isotope. Atoms of a radioisotope have an unstable nucleus that breaks up spontaneously. As a nucleus breaks up, it emits radiation (subatomic particles, energy, or both), a process called **radioactive decay**. The atomic nucleus cannot be altered by ordinary means, so radioactive decay is unaffected by external factors such as temperature, pressure, or whether the atoms are part of molecules.

Each radioisotope decays at a predictable rate into predictable products. For example, when carbon 14 decays, one of its neutrons splits into a proton and an electron. The nucleus emits the electron as radiation. Thus, a carbon atom with eight neutrons and six protons (^{14}C) becomes a nitrogen atom, with seven neutrons and seven protons (^{14}N):



This process is so predictable that we can say with certainty that about half of the atoms in any sample of ^{14}C will be ^{14}N atoms after 5,730 years. The predictability of

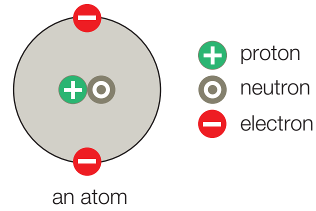


Figure 2.2 Atoms consist of subatomic particles. Models such as this do not show what atoms really look like. Electrons move in defined, three-dimensional spaces about 10,000 times bigger than the nucleus. Protons and neutrons occur in the nucleus.

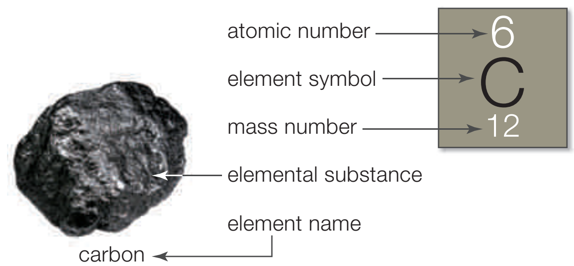


Figure 2.3 Example of an element: carbon.

Left, Theodore Gray/Visuals Unlimited, Inc.

atomic number Number of protons in the atomic nucleus; determines the element.

charge Electrical property; opposite charges attract, and like charges repel.

electron Negatively charged subatomic particle.

element A pure substance that consists only of atoms with the same number of protons.

isotopes Forms of an element that differ in the number of neutrons their atoms carry.

mass number Of an isotope, the total number of protons and neutrons in the atomic nucleus.

neutron Uncharged subatomic particle in the atomic nucleus.

nucleus Core of an atom; occupied by protons and neutrons.

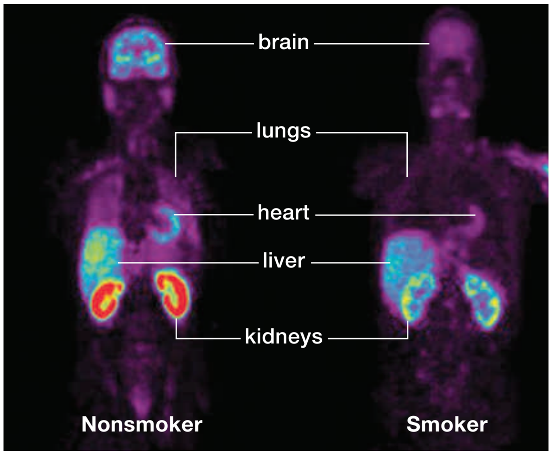
proton Positively charged subatomic particle that occurs in the nucleus of all atoms.

radioactive decay Process by which atoms of a radioisotope emit energy and subatomic particles when their nucleus spontaneously breaks up.

radioisotope Isotope with an unstable nucleus.

Figure 2.4 PET scans.
PET scans use radioactive tracers to form a digital image of a process in the body's interior. These two PET scans reveal the activity of a molecule called MAO-B in the body of a nonsmoker (left) and a smoker (right). The activity is color-coded from red (highest activity) to purple (lowest). Low MAO-B activity is associated with violence, impulsiveness, and other behavioral problems.

Brookhaven National Laboratory.



radioactive decay makes it possible for scientists to estimate the age of a rock or fossil by measuring its isotope content (we return to this topic in Section 11.4).

Radioisotopes are often used in **tracers**, which are substances with a detectable component. For example, a molecule in which an atom (such as ^{12}C) has been replaced with a radioisotope (such as ^{14}C) can be used as a radioactive tracer. When delivered into a biological system, a radioactive tracer may be followed as it moves through the system with instruments that detect radiation (Figure 2.4).

Why Electrons Matter The more we learn about electrons, the weirder they seem. Consider that an electron has mass but no size, and its position in space is described as more of a smudge than a point. It carries energy, but only in incremental amounts (this concept will be important to remember when you learn how cells harvest and release energy). An electron gains energy only by absorbing the precise amount needed to boost it to the next energy level. Likewise, it loses energy only by emitting the exact difference between two energy levels.

Imagine that an atom is a multilevel apartment building with a nucleus in the basement. Each "floor" of the building corresponds to a certain energy level, and each has a certain number of "rooms" available for rent. Two electrons can occupy each room. Pairs of electrons populate rooms from the ground floor up. The farther an electron is from the nucleus in the basement, the greater its energy. An electron can move to a room on a higher floor if an energy input gives it a boost, but it immediately emits the extra energy and moves back down.

A. The first shell corresponds to the first energy level, and it can hold up to 2 electrons. Hydrogen has one proton, so it has 1 electron and one vacancy. A helium atom has 2 protons, 2 electrons, and no vacancies.

B. The second shell corresponds to the second energy level, and it can hold up to 8 electrons. Carbon has 6 electrons, so its first shell is full. Its second shell has 4 electrons and four vacancies. Oxygen has 8 electrons and two vacancies. Neon has 10 electrons and no vacancies.

C. The third shell corresponds to the third energy level, and it can hold up to 8 electrons. A sodium atom has 11 electrons, so its first two shells are full; the third shell has one electron. Thus, sodium has seven vacancies. Chlorine has 17 electrons and one vacancy. Argon has 18 electrons and no vacancies.

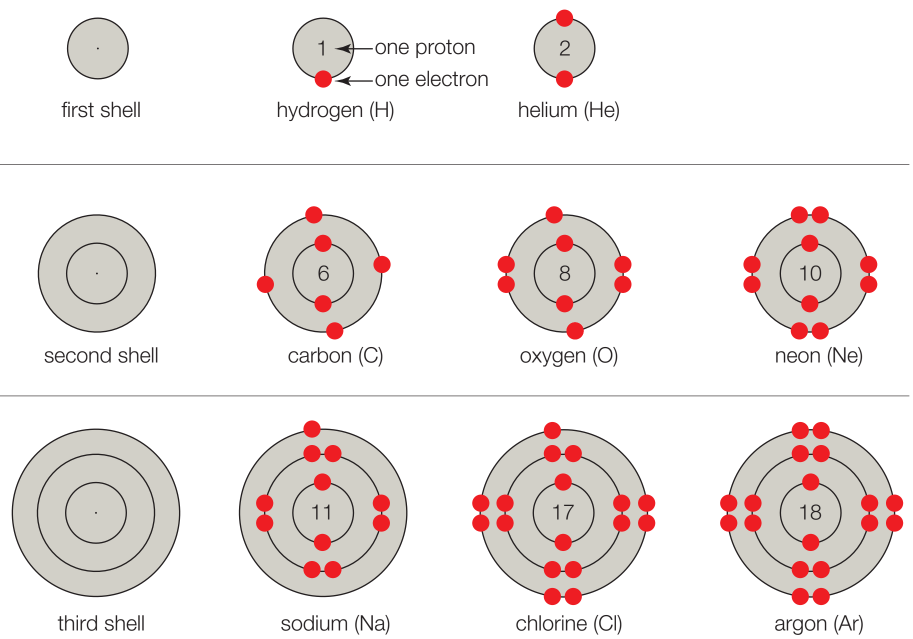


Figure 2.5 Shell models.
Each circle (shell) represents one energy level. To make these models, we fill the shells with electrons from the innermost shell out, until there are as many electrons as the atom has protons. The number of protons in each model is indicated.

Figure It Out: Which of these models have unpaired electrons in their outer shell?

Answer: Hydrogen, carbon, oxygen, sodium, and chlorine

A **shell model** helps us visualize how electrons populate atoms (Figure 2.5). In this model, nested "shells" correspond to successively higher energy levels. Thus, each shell includes all of the rooms on one floor (energy level) of our atomic apartment building. We draw a shell model of an atom by filling it with electrons from the innermost shell out, until there are as many electrons as the atom has protons. There is only one room on the first floor, and it fills up first. In hydrogen, the simplest atom, a single electron occupies that room (Figure 2.5A). Helium, with two protons, has two electrons that fill the room—and the first shell. In larger atoms, more electrons rent the second-floor rooms (Figure 2.5B). When the second floor fills, more electrons rent third-floor rooms (Figure 2.5C), and so on.

When an atom's outermost shell is filled with electrons, we say that it has no vacancies, and it is in its most stable state. Helium, neon, and argon are examples of elements with no vacancies. Atoms of these elements are chemically stable, which means they have very little tendency to interact with other atoms. Thus, these elements occur most frequently in nature as solitary atoms. By contrast, when an atom's outermost shell has room for another electron, it has a vacancy. Atoms with vacancies tend to get rid of them by interacting with other atoms; in other words, they are chemically active. For example, the sodium atom (Na) in Figure 2.5C has one electron in its outer (third) shell, which can hold eight. With seven vacancies, we can predict that this atom is chemically active. In fact, this particular sodium atom is not just active, it is extremely so. Why? The shell model shows that a sodium atom has an unpaired electron, but in the real world, electrons really like to be in pairs when they populate atoms. Atoms that have unpaired electrons are called **free radicals**. With a few exceptions, free radicals are very unstable, easily forcing electrons upon other atoms or ripping electrons away from them. This property makes free radicals dangerous to life. A sodium atom with 11 electrons (a sodium radical) quickly evicts the one unpaired electron, so that its second shell—which is full of electrons—becomes its outermost, and no vacancies remain. This is the atom's most stable state. The vast majority of sodium atoms on Earth are like this one, with 11 protons and 10 electrons.

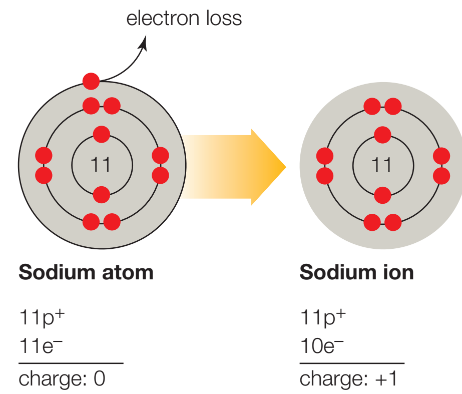
Atoms with an unequal number of protons and electrons are ions. An **ion** carries a net (or overall) charge. Sodium ions (Na^+) offer an example of how atoms gain a positive charge by losing an electron (Figure 2.6A). Other atoms gain a negative charge by accepting an electron (Figure 2.6B).

Take-Home Message 2.2

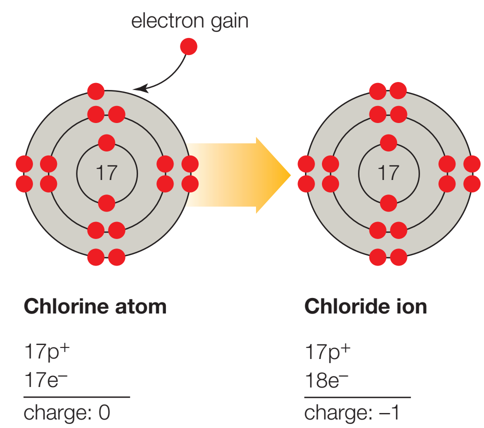
What are atoms?

- Atoms consist of electrons moving around a nucleus of protons and neutrons. The number of protons determines the element. Isotopes are forms of an element that have different numbers of neutrons.
- Unstable nuclei of radioisotopes emit radiation as they spontaneously break down (decay). Radioisotopes decay at a predictable rate to form predictable products.
- An atom's electrons are the basis of its chemical behavior. When an atom's outermost shell is not full of electrons, it has a vacancy and it is chemically active. Atoms that get rid of vacancies by gaining or losing electrons become ions (charged).

Figure 2.6 Ion formation.



A. A sodium atom (Na) becomes a positively charged sodium ion (Na^+) when it loses the single electron in its third shell. The atom's full second shell is now its outermost, so it has no vacancies.



B. A chlorine atom (Cl) becomes a negatively charged chloride ion (Cl^-) when it gains an electron and fills the vacancy in its third, outermost shell.

Figure It Out: Does a chloride ion have an unpaired electron?
Answer: No

free radical Atom with an unpaired electron.

ion Atom or molecule that carries a net charge.

shell model Model of electron distribution in an atom.

tracer A substance that can be traced via its detectable component.

Figure 2.7 The water molecule.
Each water molecule has two hydrogen atoms bonded to the same oxygen atom.

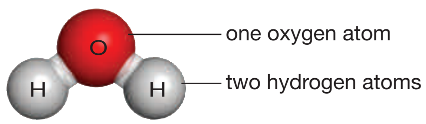
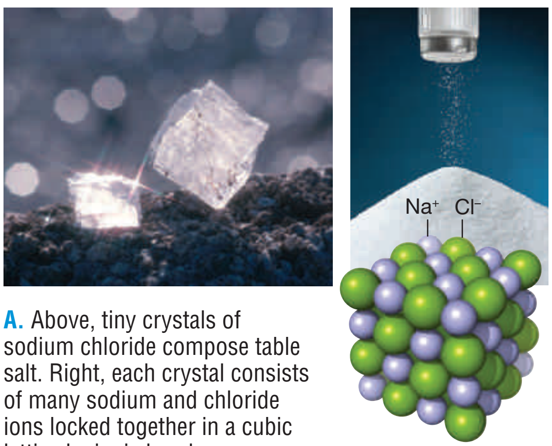
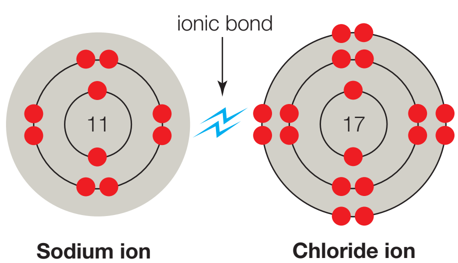


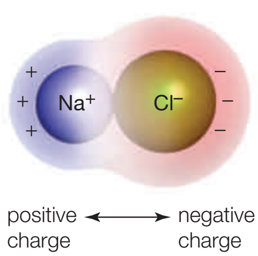
Figure 2.8 Ionic bonds in table salt, or NaCl.
(A) left, Francois Gohier/Science Source; top right, Melica/Shutterstock.



A. Above, tiny crystals of sodium chloride compose table salt. Right, each crystal consists of many sodium and chloride ions locked together in a cubic lattice by ionic bonds.



B. The strong mutual attraction of opposite charges holds a sodium ion and a chloride ion together in an ionic bond.



C. Ions taking part in an ionic bond retain their charge, so the molecule itself is polar. One side is positively charged (represented by a blue overlay); the other side is negatively charged (red overlay).

2.3 From Atoms to Molecules

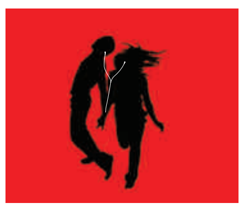
REMEMBER: The same building blocks, arranged different ways, form different products; atoms bond together to form molecules (Section 1.2).

A **chemical bond** is an attractive force that arises between two atoms, and it is one way that atoms rid themselves of vacancies. Chemical bonds make molecules out of atoms. A molecule consists of atoms held together in a particular number and arrangement by chemical bonds. For example, a water molecule consists of three atoms: two hydrogen atoms bonded to the same oxygen atom (Figure 2.7). Because a water molecule has atoms of two or more elements, it is called a **compound**. Other molecules, including molecular oxygen (a gas in air), have atoms of one element only.

The term "bond" applies to a continuous range of atomic interactions. However, we can categorize most bonds into distinct types based on their different properties. Which type forms depends on the atoms taking part in the molecule.

Ionic Bonds Two ions may stay together by the mutual attraction of their opposite charges, an association called an **ionic bond**. Ionic bonds can be quite strong. Ionically bonded sodium and chloride ions make sodium chloride (NaCl), which we know as table salt; a crystal of this substance consists of a lattice of sodium and chloride ions interacting in ionic bonds (Figure 2.8A).

Ions retain their respective charges when participating in an ionic bond (Figure 2.8B). Thus, one "end" of an ionically bonded molecule has a positive charge, and the other "end" has a negative charge. Any such separation of charge into distinct positive and negative regions is called **polarity** (Figure 2.8C).



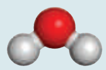
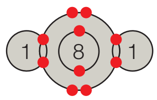
Covalent Bonds In a **covalent bond**, two atoms share a pair of electrons, so each atom's vacancy becomes partially filled (Figure 2.9). Sharing electrons links the two atoms, just as sharing a pair of earphones links two friends (left). Covalent bonds can be stronger than ionic bonds, but they are not always so.

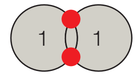
Table 2.1 shows some of the different ways we represent molecules that are held together with covalent bonds. In structural formulas, a line between two atoms represents a single covalent bond, in which two atoms share one pair of electrons. For example, molecular hydrogen (H_2) has one covalent bond between hydrogen atoms (H—H).

Two, three, or even four covalent bonds may form between atoms when they share multiple pairs of electrons. For example, two atoms sharing two pairs of electrons are connected by two covalent bonds. Such double bonds are represented by a double line between the atoms. A double bond links the two oxygen atoms in molecular oxygen (O═O). Three lines indicate a triple bond, in which two atoms share three pairs of electrons. A triple covalent bond links the two nitrogen atoms in molecular nitrogen (N≡N).

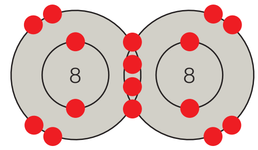
Double and triple bonds are not distinguished from single bonds in structural models, which show positions and relative sizes of the atoms in three dimensions. The bonds are shown as one stick connecting two balls, which represent atoms. Elements are usually coded by color:

Table 2.1 Representing Covalent Bonds in Molecules

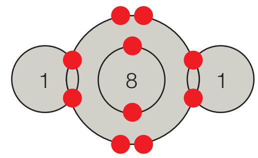
Common name	Water	Familiar term
Chemical name	Dihydrogen monoxide	Describes elemental composition.
Chemical formula	H_2O	Indicates unvarying proportions of elements. Subscripts show number of atoms of an element per molecule. The absence of a subscript means one atom.
Structural formula	H—O—H	Represents each covalent bond as a single line between atoms.
Structural model		Shows relative sizes and positions of atoms in three dimensions.
Shell model		Shows how pairs of electrons are shared in covalent bonds.



Molecular hydrogen (H—H)
Two hydrogen atoms, each with one proton, share two electrons in a nonpolar covalent bond.



Molecular oxygen (O═O)
Two oxygen atoms, each with eight protons, share four electrons in a double covalent bond.



Water (H—O—H)
Two hydrogen atoms share electrons with an oxygen atom in two covalent bonds. The bonds are polar because the oxygen exerts a greater pull on the shared electrons than the hydrogens do.

Figure 2.9 Covalent bonds, in which atoms fill vacancies by sharing electrons.
Two electrons are shared in each covalent bond. When sharing is equal, the bond is nonpolar. When one atom exerts a greater pull on the electrons, the bond is polar.

Atoms share electrons unequally in a polar covalent bond. A bond between an oxygen atom and a hydrogen atom in a water molecule is an example: One atom (the oxygen, in this case) pulls the electrons a little more toward its side of the bond, so that atom bears a slight negative charge. The atom at the other end of the bond (the hydrogen, in this case) bears a slight positive charge. Covalent bonds in most compounds are polar. By contrast, atoms participating in a nonpolar covalent bond share electrons equally. There is no difference in charge between the two ends of such bonds. Molecular hydrogen (H_2), oxygen (O_2), and nitrogen (N_2) are examples.

Take-Home Message 2.3

How do atoms interact in chemical bonds?

- A chemical bond forms between atoms when their electrons interact. Depending on the atoms taking part in it, the bond may be ionic or covalent.
- An ionic bond is a strong mutual attraction between ions of opposite charge.
- Atoms share a pair of electrons in a covalent bond. When the atoms share electrons unequally, the bond is polar.

2.4 Hydrogen Bonds and Water

Life evolved in water. All living organisms are mostly water, many of them still live in it, and all of the chemical reactions of life are carried out in water-based fluids. What makes water so fundamentally important for life?

Water has unique properties that arise from the two polar covalent bonds in each water molecule. Overall, the molecule has no charge, but the oxygen atom

chemical bond An attractive force that arises between two atoms when their electrons interact. Links atoms into molecules.

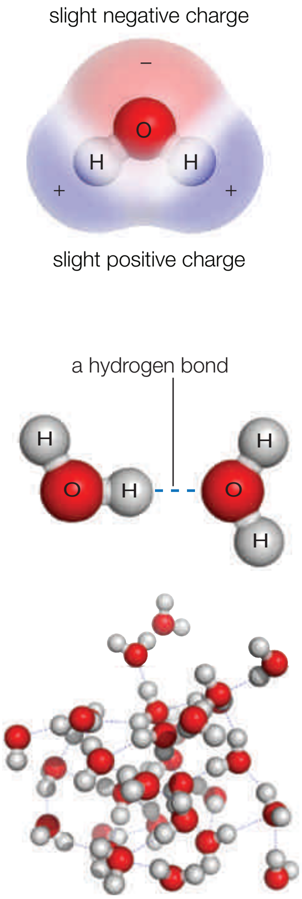
compound Molecule that has atoms of more than one element.

covalent bond Type of chemical bond in which two atoms share a pair of electrons.

ionic bond Type of chemical bond in which a strong mutual attraction links ions of opposite charge.

polarity Any separation of charge into distinct positive and negative regions.

Figure 2.10 Hydrogen bonds and water.



A. Polarity of the water molecule. Each of the hydrogen atoms in a water molecule bears a slight positive charge (represented by a blue overlay). The oxygen atom carries a slight negative charge (red overlay).

B. A hydrogen bond is an attraction between a hydrogen atom and another atom taking part in a separate polar covalent bond.

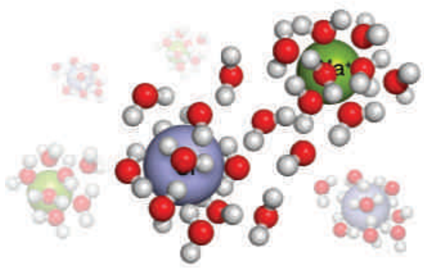
C. The many hydrogen bonds that form among water molecules impart special properties to liquid water.

carries a slight negative charge, and the two hydrogen atoms carry a slight positive charge. Thus, the molecule itself is polar (Figure 2.10A).

The polarity of individual water molecules attracts them to one another. The slight positive charge of a hydrogen atom in one water molecule is drawn to the slight negative charge of an oxygen atom in another. This type of interaction is called a hydrogen bond. A **hydrogen bond** is an attraction between a covalently bonded hydrogen atom and another atom taking part in a separate polar covalent bond (Figure 2.10B). Like ionic bonds, hydrogen bonds form by the mutual attraction of opposite charges. However, unlike ionic bonds, hydrogen bonds do not make molecules out of atoms, so they are not chemical bonds.

Hydrogen bonds lie on the weaker end of the spectrum of atomic interactions; they form and break much more easily than covalent or ionic bonds. Even so, many of them form, and collectively they can be quite strong. As you will see, hydrogen bonds stabilize the characteristic structures of biological molecules such as DNA and proteins. They also form in tremendous numbers among water molecules (Figure 2.10C). Extensive hydrogen bonding among water molecules gives liquid water the special properties that make life possible.

Water Is an Excellent Solvent The polarity of the water molecule and its ability to form hydrogen bonds make water an excellent **solvent**, which means that many other substances can dissolve in it. Substances that dissolve easily in water are **hydrophilic** (water-loving). Ionic solids such as sodium chloride (NaCl) dissolve in water because the slight positive charge on each hydrogen atom in a water molecule attracts negatively charged ions (Cl^-), and the slight negative charge on the oxygen atom attracts positively charged ions (Na^+). Hydrogen bonds among many water molecules are collectively stronger than an ionic bond between two ions, so the solid dissolves as water molecules tug the ions apart and surround each one (right).



When a substance such as NaCl dissolves, its component ions disperse uniformly among the molecules of liquid, and it becomes a **solute**. Sodium chloride is called a **salt** because it releases ions other than H^+ and OH^- when it dissolves in water (more about this in the next section). A uniform mixture such as salt dissolved in water is called a **solution**. Chemical bonds do not form between molecules of solute and solvent, so the proportions of the two substances in a solution can vary. The amount of a solute that is dissolved in a given volume of fluid is its **concentration**.

Many nonionic solids also dissolve easily in water. Sugars are examples. Molecules of these substances have one or more polar covalent bonds, and atoms participating in a polar covalent bond can form hydrogen bonds with water molecules. Hydrogen bonding with water pulls individual molecules of the solid away from one another and keeps them apart. Unlike ionic solids, these substances retain their molecular integrity when they dissolve, which means they do not dissociate into atoms.

Water does not interact with **hydrophobic** (water-dreading) substances such as oils. Oils consist of nonpolar molecules, and hydrogen bonds do not form between nonpolar molecules and water. When you mix oil and water, the water breaks into small droplets, but quickly begins to cluster into larger drops as new hydrogen bonds form among its molecules. The bonding excludes molecules of oil and pushes them together into drops that rise to the surface of the water. The very same interactions occur at the thin, oily membrane that separates the watery fluid inside cells from the watery fluid outside of them. Such interactions give rise to the structure of cell membranes.

© Herbert Schnekenburger.

Water Has Cohesion Molecules of some substances resist separating from one another, and the resistance gives rise to a property called **cohesion**. Water has cohesion because hydrogen bonds collectively exert a continuous pull on its individual molecules. You can see cohesion in water as surface tension, which means that the surface of liquid water behaves a bit like a sheet of elastic (left).

Cohesion is a part of many processes that sustain multicelled bodies. Consider how sweating helps keep your body cool during hot, dry weather. Sweat, which is about 99 percent water, cools the skin as it evaporates. Why? **Evaporation** is the process in which molecules escape from the surface of a liquid and become vapor. Evaporation of water is resisted by hydrogen bonding among individual water molecules. In other words, overcoming water's cohesion takes energy. Thus, evaporation sucks energy (in the form of heat) from liquid water, and this lowers the water's surface temperature.

Another example of cohesion's importance to life involves plants. Water molecules evaporate from leaves, and replacements are pulled upward from roots. Cohesion makes it possible for columns of liquid water to rise from roots to leaves inside narrow pipelines of vascular tissue. In some trees, these pipelines extend hundreds of feet above the soil (Section 27.4 returns to this topic).

Water Stabilizes Temperature All atoms jiggle nonstop, so the molecules they make up jiggle too. We measure the energy of this motion as degrees of **temperature**. Adding energy (in the form of heat, for example) makes the jiggling faster, so the temperature rises. Hydrogen bonding keeps water molecules from moving as much as they would otherwise, so it takes more heat to raise the temperature of water compared with other liquids. Temperature stability is an important part of homeostasis because most of the molecules of life function properly only within a certain range of temperature.

Below 0°C (32°F), water molecules do not jiggle enough to break hydrogen bonds between them, and they become locked in the rigid, lattice-like bonding pattern of ice (Figure 2.11). Individual water molecules pack less densely in ice than they do in water, which is why ice floats on water. Sheets of ice that form on the surface of ponds, lakes, and streams can insulate the water under them from subfreezing air temperatures. Such "ice blankets" protect aquatic organisms during long, cold winters.

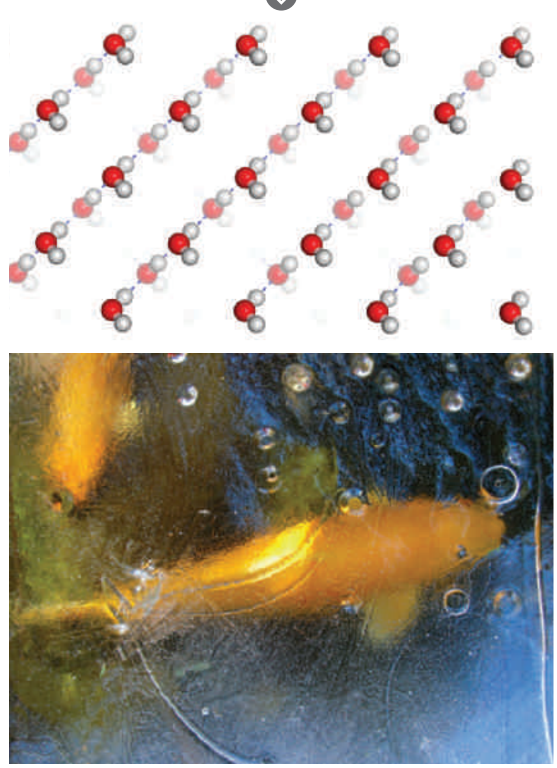
Take-Home Message 2.4

What gives water the special properties that make life possible?

- Extensive hydrogen bonding among water molecules arises from the polarity of the individual molecules.
- Hydrogen bonding among water molecules imparts cohesion to liquid water, and gives it the ability to stabilize temperature and dissolve many substances.

Figure 2.11 Ice.
Top, hydrogen bonds lock water molecules in a rigid lattice in ice. The molecules in this lattice pack less densely than in liquid water (compare Figure 2.10C), so ice floats on water. Bottom, a covering of ice can insulate water underneath it, thus keeping aquatic organisms from freezing during harsh winters.

Bottom, www.flickr.com/photos/roseofredrock.



cohesion Property of a substance that arises from the tendency of its molecules to resist separating from one another.

concentration Amount of solute per unit volume of solution.

evaporation Transition of a liquid to a vapor.

hydrogen bond Attraction between a covalently bonded hydrogen atom and another atom taking part in a separate covalent bond.

hydrophilic Describes a substance that dissolves easily in water.

hydrophobic Describes a substance that resists dissolving in water.

salt Ionic compound that releases ions other than H^+ and OH^- when it dissolves in water.

solute A dissolved substance.

solution Uniform mixture of solute completely dissolved in a solvent.

solvent Liquid in which other substances dissolve.

temperature Measure of molecular motion.

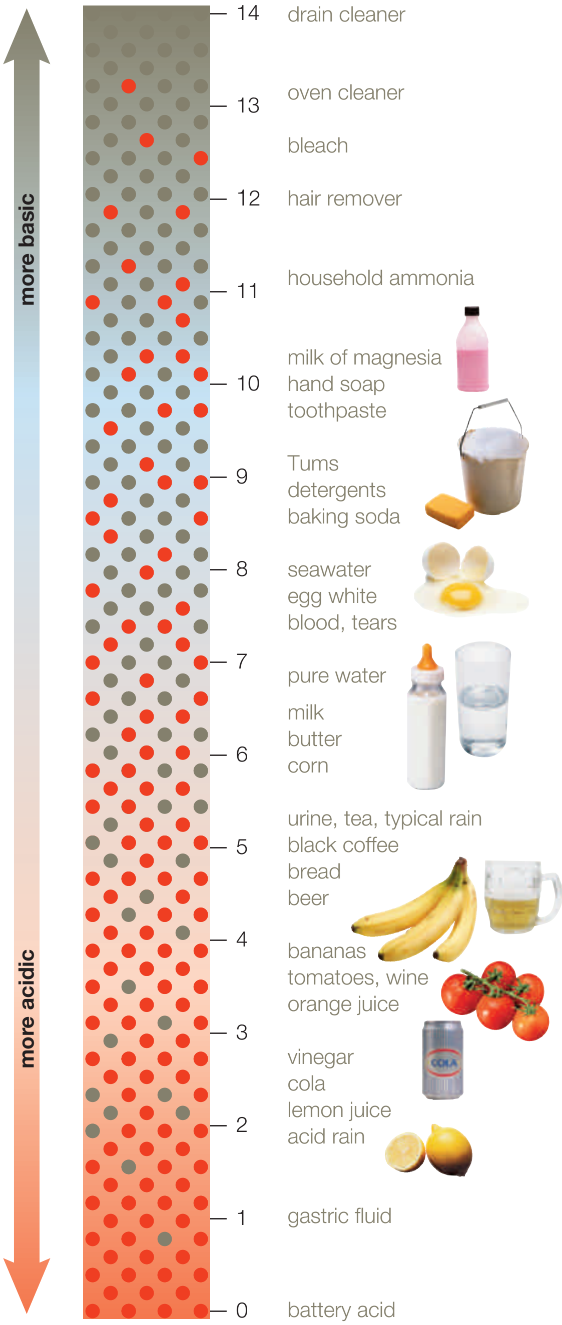


Figure 2.12 A pH scale.
Here, red dots signify hydrogen ions (H^+) and blue dots signify hydroxyl ions (OH^-). Also shown are the approximate pH values for some common solutions.

This pH scale ranges from 0 (most acidic) to 14 (most basic). A change of one unit on the scale corresponds to a tenfold change in the amount of H^+ ions.

Photos, © JupiterImages Corporation.

Figure It Out: What is the approximate pH of cola?

Answer: 2.5

2.5 Acids and Bases

A hydrogen atom, remember, is just a proton and an electron. When a hydrogen atom participates in a polar covalent bond, the electron is pulled away from the proton, just a bit. Hydrogen bonding in water tugs on that proton even more, so much that the proton can be pulled right off of the molecule. The electron stays with the rest of the molecule, which becomes negatively charged (ionic), and the proton becomes a hydrogen ion (H^+). For example, a water molecule that loses a proton becomes a hydroxyl ion (OH^-). The loss is more or less temporary, because these two ions easily get back together to form a water molecule (H_2O). With other molecules, the loss of a hydrogen ion in water is essentially permanent.

We use a value called **pH** to measure of the number of hydrogen ions in a water-based fluid. In pure water, the number of H^+ ions is the same as the number of OH^- ions, and the pH is 7, or neutral. The higher the number of hydrogen ions, the lower the pH. A one-unit decrease in pH corresponds to a tenfold increase in the number of H^+ ions (Figure 2.12). One way to get a sense of the pH scale is to taste dissolved baking soda (pH 9), distilled water (pH 7), and lemon juice (pH 2).

An **acid** is a substance that gives up hydrogen ions in water. Acids can lower the pH of a solution and make it acidic (below pH 7). **Bases** accept hydrogen ions from water, so they can raise the pH of a solution and make it basic (above pH 7). Nearly all of life's chemistry occurs near pH 7. Under normal circumstances, fluids inside cells and bodies stay within a certain range of pH because they are buffered. A **buffer** is a set of chemicals that can keep pH stable by alternately donating and accepting ions that affect pH. For example, two chemicals, carbonic acid and bicarbonate, are part of a homeostatic mechanism that normally keeps your blood pH between 7.3 and 7.5. Carbonic acid forms when carbon dioxide gas dissolves in the fluid portion of blood. It can dissociate into a hydrogen ion and a bicarbonate ion, which in turn recombine to form carbonic acid:

$$\underset{\text{carbonic acid}}{H_2CO_3} \longrightarrow H^+ + \underset{\text{bicarbonate}}{HCO_3^-} \longrightarrow \underset{\text{carbonic acid}}{H_2CO_3}$$

An excess of OH^- ions in the blood causes the carbonic acid in it to release H^+ ions. These combine with the excess OH^- ions to form water, which does not affect pH. Excess H^+ in blood combines with the bicarbonate, so it does not affect pH either.

Any buffer can neutralize only so many ions. Even slightly more than that limit and the pH of the fluid will change dramatically. Buffer failure can be catastrophic in a biological system because most biological molecules can function properly only within a narrow range of pH. Consider what happens when breathing is impaired suddenly. Carbon dioxide gas accumulates in tissues, and too much carbonic acid forms in blood. If the excess acid reduces blood pH below 7.3, a dangerous level of unconsciousness called coma can be the outcome.

Take-Home Message 2.5

Why are hydrogen ions important in biological systems?

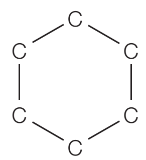
- The number of hydrogen ions in a fluid determines its pH. Most biological systems function properly only within a narrow range of pH. Buffers help keep pH stable.
- Acids release hydrogen ions in water; bases accept them.

2.6 Organic Molecules

The same elements that make up a living body also occur in nonliving things, but their proportions differ. For example, compared to sand or seawater, a human body has a much larger proportion of carbon atoms. Why? Unlike sand or seawater, a body contains a lot of the molecules of life—complex carbohydrates and lipids, proteins, and nucleic acids—and these molecules consist of a high proportion of carbon atoms. Compounds that consist primarily of carbon and hydrogen atoms are said to be **organic**. The term is a holdover from a time when such molecules were thought to be made only by living things, as opposed to the "inorganic" molecules that formed by nonliving processes. We now know that organic compounds were present on Earth long before organisms were.

Carbon's importance to life arises from its versatile bonding behavior. Carbon has four vacancies in its outer shell, so it can form four covalent bonds with other atoms, including other carbon atoms. Many organic molecules have a chain of carbon atoms, and this backbone often forms rings (Figure 2.13). Small molecular groups that attach to the backbone impart chemical properties to the molecule. For example, carboxyl groups (—COOH) make amino acids and fatty acids acidic; hydroxyl groups (—OH) make sugars polar. Carbon's ability to form chains and rings, and also to bond with many other elements, means that atoms of this element can be assembled into a wide variety of organic compounds.

As you will see shortly, the function of an organic molecule depends on its structure. The structure of even a small organic molecule can be quite complicated (Figure 2.14A), so representations are typically simplified. Hydrogen atoms and some of the bonds may not be shown, but are understood to exist where they should. Carbon rings such as the ones that occur in glucose and other sugars are often depicted as polygons (Figure 2.14B). If no atom is shown at a corner or at the end of a bond, a carbon is implied there. Ball-and-stick models are used to depict an organic molecule's three-dimensional arrangement of atoms (Figure 2.14C); space-filling models are used to show its overall shape (Figure 2.14D). Proteins and nucleic acids are often modeled as ribbon structures, which, as you will see in Section 2.9, show how the molecule folds and twists.



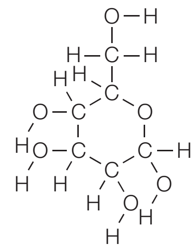
A. Carbon's versatile bonding behavior allows it to form a variety of structures, including rings.

B. Carbon rings form the backbone of many sugars, starches, and fats, such as those found in foods.

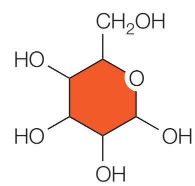
Figure 2.13 Carbon rings.

(B) Getty Images.

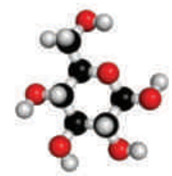
Figure 2.14 Structural models of an organic molecule. All of these models represent the same molecule: glucose.



A. A structural formula for an organic molecule—even a simple one—can be very complicated. The overall structure is obscured by detail.



B. Structural formulas of organic molecules are often simplified by using polygons as symbols for rings, and omitting some bonds and element labels.



C. A ball-and-stick model shows the arrangement of atoms and bonds in three dimensions.

D. A space-filling model can be used to show a molecule's overall shape. Individual atoms are visible in this model. Space-filling models of larger molecules often show only the surface contours.

What Cells Do to Organic Compounds All biological systems are based on the same organic molecules, but the details of those molecules differ among organisms. Just as atoms bonded in different numbers and arrangements form different molecules, simple organic building blocks bonded in different numbers and arrangements form different versions of the molecules of life.

Cells assemble complex carbohydrates, lipids, proteins, and nucleic acids from small organic molecules. These small organic molecules—sugars, fatty acids, amino acids, and nucleotides—are called **monomers** when they are used as subunits of larger molecules. A molecule that consists of multiple monomers is a **polymer**. Cells build polymers from monomers, and break down polymers to release

acid Substance that releases hydrogen ions in water.

base Substance that accepts hydrogen ions in water.

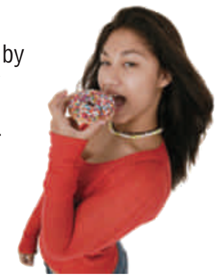
buffer Set of chemicals that can keep the pH of a solution stable by alternately donating and accepting ions that contribute to pH.

monomer Molecule that is a subunit of polymers.

organic Describes a compound that consists mainly of carbon and hydrogen atoms.

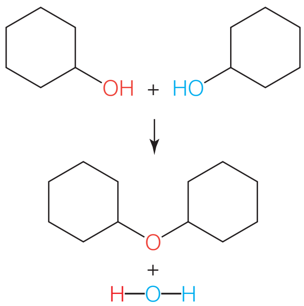
pH Measure of the amount of hydrogen ions in a fluid.

polymer Molecule that consists of multiple monomers.

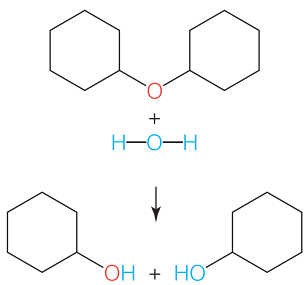


Exactostock/SuperStock.

A. Metabolism refers to processes by which cells acquire and use energy as they make and break down molecules. Humans and other consumers break down the molecules in food. Their cells use energy and raw materials from the breakdown to maintain themselves and to build new components.



B. Cells often build a large molecule from small ones by condensation. In this reaction, an enzyme removes a hydroxyl group from one molecule and a hydrogen atom from another. A covalent bond forms between the two molecules; water forms too.



C. Cells use a water-requiring reaction called hydrolysis to split a large molecule into smaller ones. An enzyme attaches a hydroxyl group and a hydrogen atom (both from water) at the cleavage site.

Figure 2.15 Metabolism.
Two common reactions by which cells build and break down organic molecules are shown.

monomers. These and other processes of molecular change are called **reactions**. Cells constantly run reactions as they acquire and use energy to stay alive, grow, and reproduce—activities collectively called **metabolism** (Figure 2.15A). Metabolism also requires **enzymes**, which are organic molecules (usually proteins) that speed up reactions without being changed by them. For example, in a common reaction called condensation, an enzyme covalently bonds two monomers together (Figure 2.15B). In hydrolysis, the reverse of condensation, an enzyme splits an organic polymer into its component monomers (Figure 2.15C).

Take-Home Message 2.6

How are all of the molecules of life alike?

- The molecules of life (carbohydrates, lipids, proteins, and nucleic acids) are organic, which means they consist mainly of carbon and hydrogen atoms.
- The structure of an organic molecule starts with a chain of carbon atoms (the backbone) that may form one or more rings.
- By processes of metabolism, cells assemble the molecules of life from monomers. They also break apart polymers into component monomers.

2.7 Carbohydrates

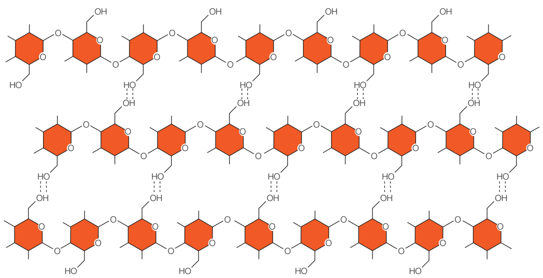
A **carbohydrate** is an organic compound that consists of carbon, hydrogen, and oxygen in a 1:2:1 ratio. The term can apply to a sugar molecule or a polymer of them, so these compounds are also called saccharides (saccharide means sugar). Cells use different kinds for fuel, as structural materials, and for storing energy.

Monosaccharides (one sugar) are the simplest carbohydrates, and common types have a backbone of five or six carbon atoms. Glucose, shown in Figure 2.14, is a monosaccharide. Sucrose, which is our table sugar, is a disaccharide (two sugars) that consists of glucose and fructose monomers. Monosaccharides and disaccharides are very soluble in water, so they can move easily through the water-based internal environments of all organisms.

Breaking the bonds of a monosaccharide releases energy that can be harnessed to power other reactions (Chapter 5 returns to this topic). Monosaccharides are also remodeled into other important compounds. For example, cells of plants and many animals make vitamin C from glucose. Human cells are unable to make vitamin C, so we need to get it from our food.

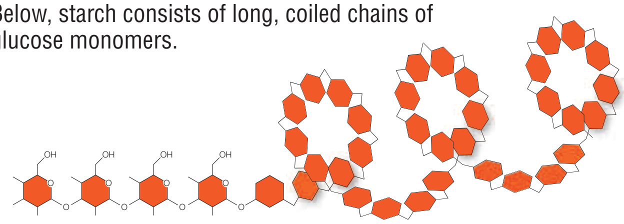
Foods that we call "complex" carbohydrates consist mainly of polysaccharides, which are chains of hundreds or thousands of monosaccharide monomers. The chains may be straight or branched, and can have one or many types of monosaccharides. The most common polysaccharides are cellulose, starch, and glycogen. All consist only of glucose monomers, but as substances their properties are very different. Why? The answer begins with differences in patterns of covalent bonding that link their monomers.

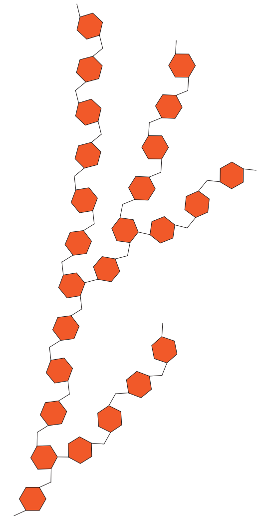
Cellulose, the major structural material of plants, is the most abundant organic molecule on Earth. Hydrogen bonding locks its long, straight chains of covalently bonded glucose monomers into tight, sturdy bundles (Figure 2.16A). The bundles form tough fibers that act like reinforcing rods inside stems and other plant parts, helping these structures resist wind and other forms of mechanical stress. Cellulose



A. Cellulose is the main structural component of plants. Above, in cellulose, hydrogen bonds stabilize chains of glucose monomers in tight bundles that form long fibers. Few organisms can digest this tough, insoluble material.

B. Starch is the main energy reserve in plants, which store it in their roots, stems, leaves, seeds, and fruits. Below, starch consists of long, coiled chains of glucose monomers.





C. Glycogen functions as an energy reservoir in animals, including people. It is especially abundant in the liver and muscles. Above, glycogen consists of highly branched chains of glucose monomers.

Figure 2.16 Three of the most common complex carbohydrates and their locations in a few organisms. Each polysaccharide consists only of glucose units, but different bonding patterns that link the subunits result in substances with very different properties.

Middle photo, © JupiterImages Corporation.

is insoluble (it does not dissolve) in water, and it is not easily broken down. Some bacteria and fungi make enzymes that can break it apart into its component sugars, but humans and other mammals do not. Dietary fiber, or "roughage," usually refers to the indigestible cellulose in our vegetable foods. Bacteria that live in the guts of termites and grazers such as cattle and sheep help these animals digest the cellulose in plants. (Chapter 23 returns to the topic of animal digestion.)

In starch, a different covalent bonding pattern between glucose monomers makes a chain that coils up into a spiral (Figure 2.16B). Like cellulose, starch does not dissolve readily in water, but it is easier to break down. These properties make the molecule ideal for storing sugars in the watery, enzyme-filled interior of plant cells. Most plant leaves make glucose during the day, and their cells store it by building starch. At night, hydrolysis enzymes break the bonds between starch's glucose monomers. The released glucose can be broken down immediately for energy, or converted to sucrose that is transported to other parts of the plant. Humans also have hydrolysis enzymes that break down starch, so this carbohydrate is an important component of our food.

Animals store sugars in the form of glycogen, a polysaccharide that consists of highly branched chains of glucose monomers (Figure 2.16C). Muscle and liver cells contain most of the body's glycogen. When the blood sugar level falls, liver cells break down the glycogen, and the released glucose subunits enter the blood.

Take-Home Message 2.7

What is a carbohydrate?

- Cells use simple carbohydrates (sugars) for energy and to build other molecules.
- Sugar monomers, bonded different ways, form complex carbohydrates such as cellulose, starch, and glycogen.

carbohydrate Molecule that consists primarily of carbon, hydrogen, and oxygen atoms in a 1:2:1 ratio.

cellulose Tough, insoluble carbohydrate that is the major structural material in plants.

enzyme Organic molecule that speeds up a reaction without being changed by it.

metabolism All the enzyme-mediated chemical reactions by which cells acquire and use energy as they build and break down organic molecules.

reaction Process of molecular change.

2.8 Lipids

Lipids are fatty, oily, or waxy organic compounds. They vary in structure, but all are hydrophobic. Many lipids incorporate **fatty acids**, which are small organic molecules that consist of a carbon chain "tail" of variable length, and a carboxyl group "head" (Figure 2.17). The tail is hydrophobic (hence the name "fatty"); the carboxyl group makes the head hydrophilic (and acidic). You are already familiar with the properties of fatty acids because these molecules are the main component of soap. The hydrophobic tails of fatty acids in soap attract oily dirt, and the hydrophilic heads dissolve the dirt in water.

Saturated fatty acids have only single bonds linking the carbons in their tails. In other words, their carbon chains are fully saturated with hydrogen atoms (Figure 2.17A). The tail of a saturated fatty acid is flexible and it wiggles freely. Double bonds between carbons limit the flexibility of the tails of an **unsaturated fatty acid** (Figure 2.17B,C). These bonds are *cis* or *trans*, depending on the way the hydrogens are arranged around them (Figure 2.17D,E).

Figure 2.17 Fatty acids.
Double bonds in the tails are highlighted in red.

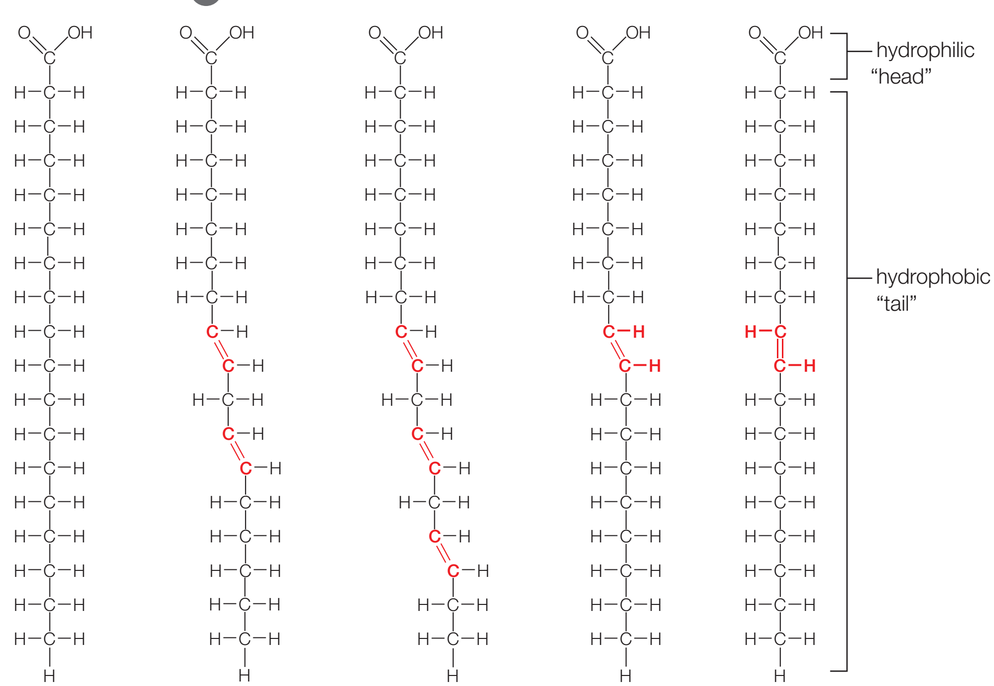
A. The tail of stearic acid is fully saturated with hydrogen atoms.

B. Linoleic acid, with two double bonds, is unsaturated. The first double bond occurs at the sixth carbon from the end of the tail, so linoleic acid is called an omega-6 fatty acid. Omega-6 and **C** omega-3 fatty acids are "essential fatty acids," which means your body does not make them and they must come from food.

D. The hydrogen atoms around the double bond in oleic acid are on the same side of the tail. Most other naturally occurring unsaturated fatty acids have these *cis* bonds.

E. Hydrogenation creates abundant *trans* bonds, with hydrogen atoms on opposite sides of the tail.

Figure It Out: Are the double bonds in linolenic acid *cis* or *trans*? **Answer:** *cis*



A. stearic acid (saturated) **B.** linoleic acid (omega-6) **C.** linolenic acid (omega-3) **D.** oleic acid (*cis*) **E.** elaidic acid (*trans*)

Fats The carboxyl group head of a fatty acid can easily form a covalent bond with another molecule. When it bonds to a glycerol, a type of alcohol, it loses its hydrophilic character. Three fatty acids bonded to the same glycerol form a **triglyceride**, a molecule that is entirely hydrophobic and therefore does not dissolve in water. Triglycerides are the most abundant and richest energy source in vertebrate bodies; gram for gram, they store more energy than carbohydrates.

A **fat** is a substance that consists mainly of triglycerides. Butter and other fats derived from animals have a high proportion of triglycerides in which all three fatty acid tails are saturated. These triglycerides are commonly called saturated fats, and substances that consist of them are solid at room temperature because floppy saturated fatty acid tails can pack tightly together. Vegetable oils, by contrast, have a high proportion of unsaturated fats, the common term for triglycerides in which at least one of the three fatty acid tails is unsaturated. Each double bond makes a rigid kink, and kinky tails cannot pack tightly. This is why most substances that consist of unsaturated fats are liquid at room temperature. The partially hydrogenated vegetable oils that you learned about in Section 2.1 are an exception. They are solid at room temperature because the special *trans* double bond keeps their fatty acid tails straight, allowing them to pack tightly just like saturated fatty acid tails do.

Phospholipids A **phospholipid** has two fatty acid tails and a head that contains a phosphate group (Figure 2.18A). The tails are hydrophobic, but the phosphate group is highly polar and it makes the head very hydrophilic. These opposing properties give rise to the basic structure of cell membranes,