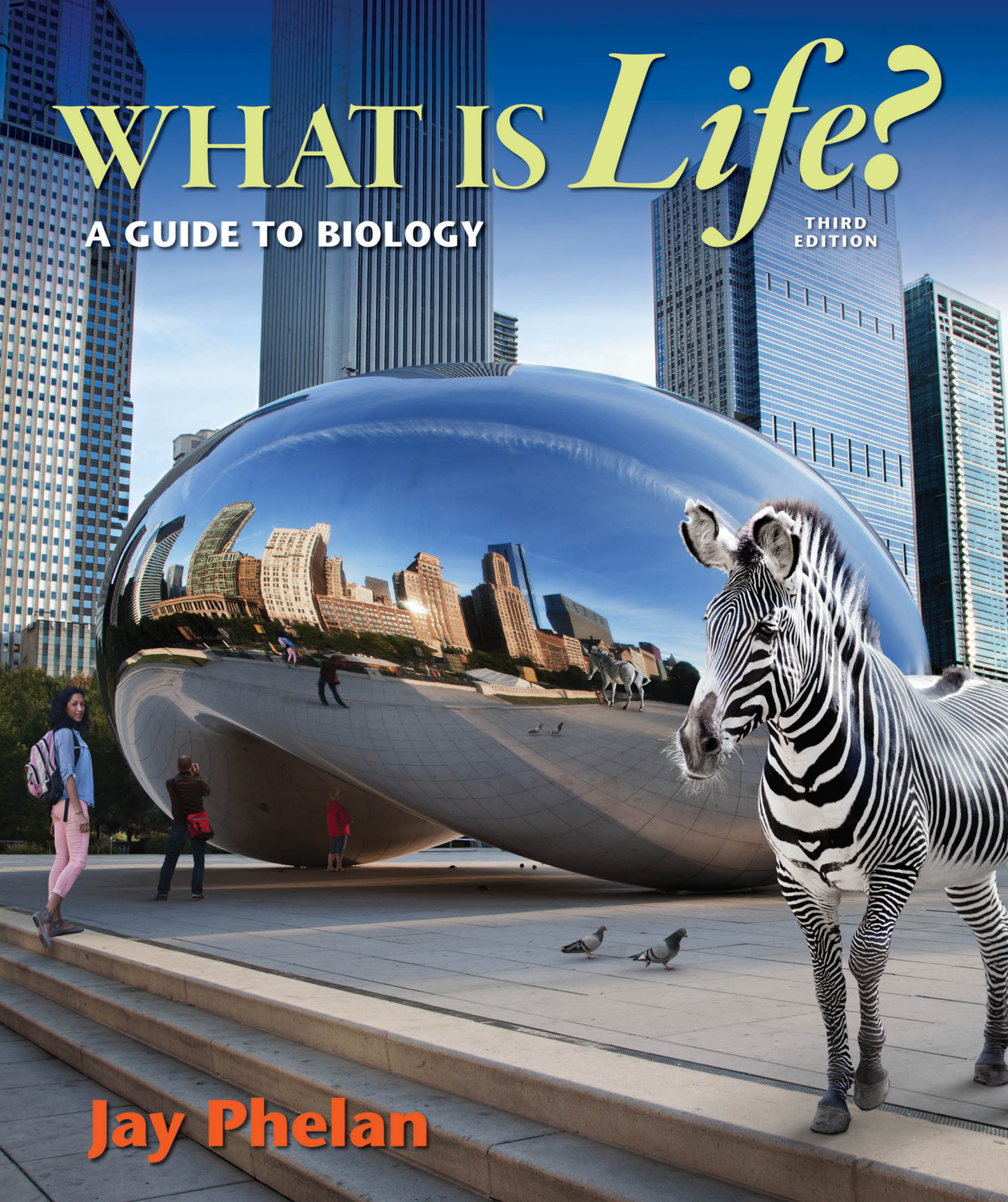
WHAT IS *Life?*

A GUIDE TO BIOLOGY

THIRD EDITION



Jay Phelan

WHAT IS *Life?*

A GUIDE TO BIOLOGY

THIRD EDITION

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University of California, Los Angeles

W. H. Freeman & Company
A Macmillan Education Imprint

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Printing and Binding: Quebecor Dubuque

Cover photo by Thomas Jackson

Library of Congress Control Number: 2014952562

Student Edition: ISBN-13: 978-1-4641-3595-8
ISBN-10: 1-4641-3595-9

Printed in the United States of America

First Printing

W. H. Freeman and Company
41 Madison Avenue, New York, NY 10010
Houndmills, Basingstoke RG21 6XS, England

www.whfreeman.com

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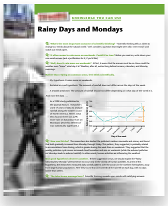

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Dear Reader,

How many days do you wake up to breaking news about a scary-sounding virus, or a potential cause of cancer, or newly identified genes that make you better at math? In a world of fast progress and easy access to information, it can be difficult to know how much confidence we should have about such reports.

My mission is to help you become more aware of the beauty and the utility of biology, and to help you evaluate the sometimes conflicting messages about science topics and science-related issues. If you could learn anything from reading this book, I hope it would be this: *Biology is about you, and it touches your life every day in dozens of ways. It's creative. And it's fun.*

There are two versions of this third edition of *What Is Life? A Guide to Biology.* One of them, *What Is Life? A Guide to Biology with Physiology,* includes all sixteen chapters of the other version, with an additional ten chapters on plant and animal physiology. It's not always possible to include these additional chapters in a one-term course, but they provide a rich introduction to the importance of biology, with particular significance for human health.

In these pages, you'll find an overview of the key themes in biology as well as detailed information and stories about meaningful topics. I hope you will find answers to questions you're curious about, and will be spurred to ask many more. You'll also find many Red **Q** questions, such as:

- Do megadoses of vitamin C reduce cancer risk?
- An onion has five times as much DNA as a human. Why doesn't that make onions more complex than humans?
- Why doesn't natural selection lead to the production of perfect organisms?
- Why are big, fierce animal species so rare in the world?

The Red **Q**s point toward passages that help uncover the answers. Often, the answer may not be apparent—but look again and think some more. Sometimes you know more than you realize. And sometimes it's possible to transfer the things you learn in one context to another, helping you to recognize new connections. Understanding and developing these abilities will help you tackle novel problems, serving you well long after you may have forgotten this or that specific fact.

At the heart of scientific thinking is a determination to ask and answer questions about the world. This process of inquiry is carried out in diverse and creative ways. Within each chapter of *What Is Life?* you'll find a section called **This Is How We Do It**. In these sections we explore the diverse ways that scientists approach problems, and how they go about finding answers. Example topics include *Why do we yawn?* and *Does sunscreen use reduce skin cancer risk?*

At the end of each chapter, you'll find a section called **StreetBIO: Knowledge You Can Use**. These sections unpack some questions and issues that are particularly practical, such as *How clean is that food you just dropped?*

There's much more to biology than just words. Flip through *What Is Life?* and look at the **photographs**. Images can do much more than simply illustrate ideas; they can inspire and provide an alternative hook for remembering and understanding concepts. They can also challenge you to see ideas in new ways. I have hand-picked every photo, with a goal of provoking and engaging, while helping you make connections between complex ideas.

You'll also notice brief quotes from a variety of literary sources. There is a rich tradition of scientific imagery, references, and metaphors throughout literature. It is my hope that you will recognize that as your scientific literacy increases, your experience and appreciation of literature also will be richer.

In a world of information overload, it is more important than ever to learn how to distill ideas, examples, and implications, forming hierarchies of importance. I don't want you to lose sight of the big picture. In organizing each chapter, I have broken down the topics into **discrete, manageable sections**. And at the end of each, I provide a

Take-Home Message that concisely and precisely highlights and reinforces the section's most important ideas.

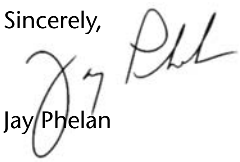
Also included in the book are four-page illustrated summaries of each chapter, integrated with multiple-choice and short-answer questions. This **Review & Rehearse (R&R)** "mash-up" of content and quizzing reflects important insights from educational research: integrating testing to hone your retrieval abilities, while reviewing the concepts themselves, enhances your learning—taking it beyond the simple recognition that comes from just revisiting the material.

The multiple-choice questions are just a tiny sampling of the thousands of questions available to you in the online adaptive quizzing system **PrepU**, and each is marked with a difficulty thermometer, which reflects the difficulty of the questions based on more than 30 million responses from students nationwide.

Increasingly, the information you consume includes graphs. It's essential to understand how to read and interpret such figures. To help you, I've included an exercise within each chapter called **Graphic Content**. This critical thinking challenge will help you become adept at reading and analyzing visual displays of information, while identifying subtle assumptions, biases, and even manipulations.

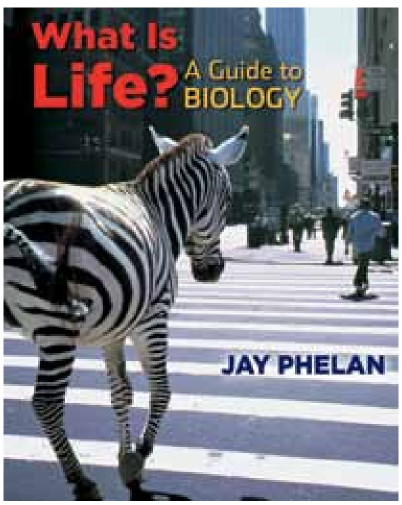
This is just a sample of some of the features in *What Is Life?* I hope that you find this book stimulates new ways of thinking about and understanding the world.

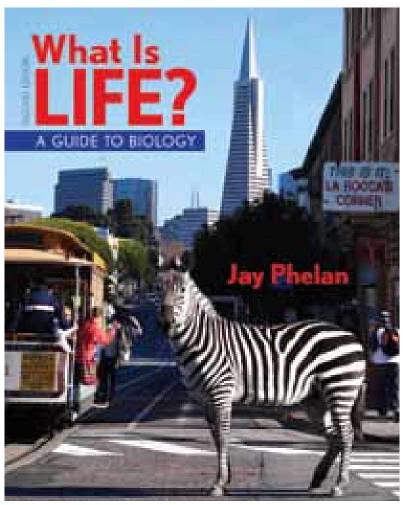
Sincerely,

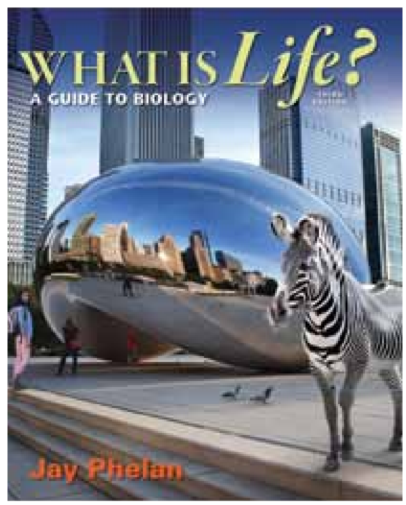


Jay Phelan

P.S. About the cover: I want to convey that biology isn't something that exists far away, separate from our personal lives. Rather, it intersects with our lives and is a central part of our world.







About the Author

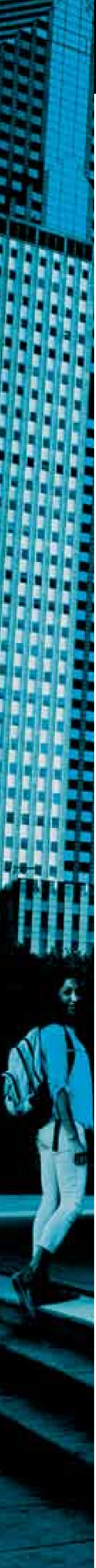
Jay Phelan teaches biology at UCLA, where he has taught introductory biology to more than 11,000 majors and non-majors students over the past seventeen years. He is the recipient of more than a dozen teaching awards, including UCLA's highest teaching honor, the Distinguished Teaching Award, in 2011. He received his Ph.D. in evolutionary biology from Harvard in 1995, a master's degree in environmental studies from Yale, and a bachelor's degree from UCLA. His primary area of research is evolutionary genetics, and his original research has been published in *Evolution, Experimental Gerontology*, and the *Journal of Integrative and Comparative Biology*, among other journals. His research has been featured on *Nightline*, CNN, the BBC, and National Public Radio; in *Science Times* and *Elle*; and in more than a hundred newspapers.

Jay lectures frequently on a variety of topics in education, including the nurturing of critical thinking skills in undergraduate students and the use and efficacy of online adaptive assessment systems. His research in these areas has been published in the *International Encyclopedia of Education* and numerous journals.

With economist Terry Burnham, Jay is co-author of the international bestseller *Mean Genes: From Sex to Money to Food—Taming Our Primal Instincts*. Written for the general reader, *Mean Genes* explains in simple terms how knowledge of the genetic basis of human nature can empower individuals to lead more satisfying lives.

(The Daily Bruin.)

To Julia



Q: HOW DOES *WHAT IS LIFE?* SO THOROUGHLY CAPTIVATE NON-MAJORS? IT WAS CREATED WITH THEM IN MIND.

Engaging Examples Showcase Biology in Everyday Life

What Is Life? A Guide to Biology threads fascinating, relevant, contemporary examples of the science throughout each chapter.

Brief Sections Make the Material Manageable

Each chapter is broken down into a series of short, accessible sections.

Clear and Consistent Illustrations

Fresh and easy-to-understand figures bring the concepts to life. Collaboratively developed by the author and the scientific illustrator, the text and illustrations are seamlessly integrated, effective learning tools.

FIGURE 11-2 Two equally successful organisms: the earthworm and the tiger.

Vivid Photos Capture the Story of Biology

Striking images appear as unit openers and are combined with illustrations of biological processes, concepts, and experimental techniques to engage the imagination of the student.

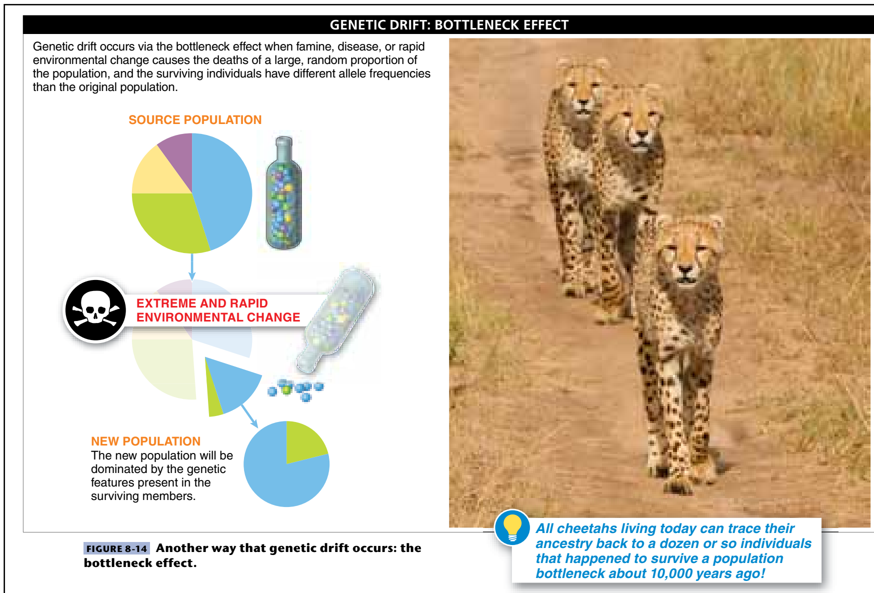


FIGURE 8-14 Another way that genetic drift occurs: the bottleneck effect.

Intriguing, Often Surprising Q Questions Motivate Readers

Q Questions spark students' interest and encourage critical thinking.

Q Animations (interactive versions of these questions) are available in LaunchPad.

Q Mammals get bigger and bigger the more they eat. Why don't insects?

Take-Home Messages Provide a Quick Summary

Each section of the chapter includes a concise, memorable summary of key ideas.

> **TAKE-HOME MESSAGE 14·8**
>
> Because constraints limit evolution, life histories are characterized by trade-offs between investments in growth, reproduction, and survival.

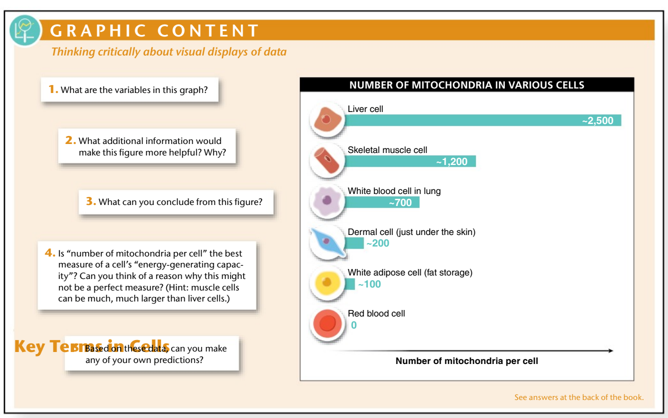
StreetBIOs Make Biology Memorable

StreetBIO: KNOWLEDGE YOU CAN USE features are found in every chapter, and demonstrate the practicality and fun of biology.

> **StreetBIO** KNOWLEDGE YOU CAN USE
>
> **Mixing aspirin and alcohol can lead to metabolic interference and unexpected inebriation.**

End-of-Chapter Study Tools

Each chapter includes **Key Terms,** an **R&R** visual summary with embedded questions, and a **Graphic Content** feature that gives students practice in thinking critically about visual displays of data.



Q: WHAT'S NEW IN THE NEW EDITION?
INNOVATIVE NEW STUDY TOOLS

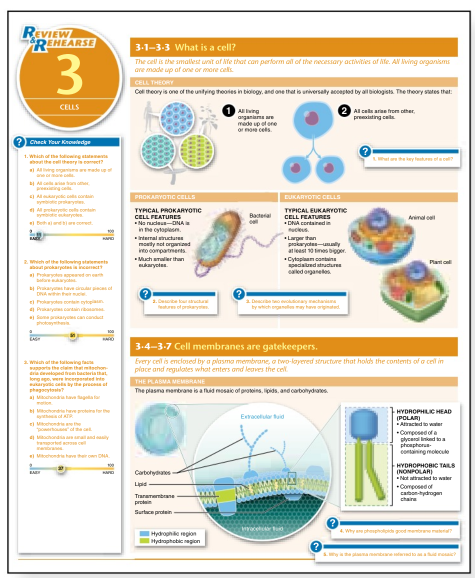
This Is How We Do It

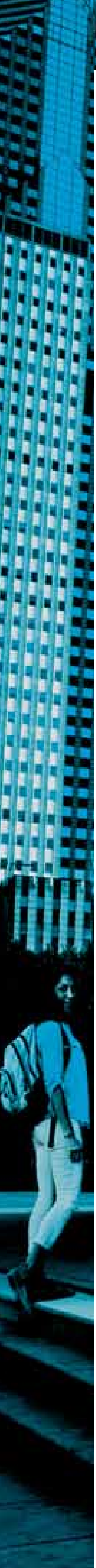
In each chapter, Jay Phelan highlights an intriguing question—for example, *Does sunscreen use reduce skin cancer risk?*—and shows how scientists have approached the problem and thought it through. It's an effective new way to guide students through the process of science and develop their science literacy skills.

> **14·9 THIS IS HOW WE DO IT**
>
> **Life history trade-offs: rapid growth comes at a cost.**
>
> Sometimes it's tricky to collect experimental evidence supporting a theoretical prediction, even when it seems extremely likely that the prediction is accurate. This is the case for the idea that there must be a trade-off between growth and longevity.
>
> Collecting the appropriate evidence is challenging due to several confounding factors.
>
> 1. If you look at the slowest-growing organisms in a population, they may turn out not to have the greatest longevity simply because their slow growth is due to poor nutrition—which tends to reduce longevity.
>
> 2. If you look at the fastest-growing organisms, they may have the greatest longevity simply because their faster growth reflects access to better nutrition.
>
> 3. And, because growth rate is often positively correlated with adult body size—which is, in turn, positively correlated with longevity—the fastest-growing organisms may end up having the greatest longevity.
>
> **Why is it useful to randomize subjects to experimental treatments?**
>
> In each of these cases, the data aren't appropriate for evaluating whether there is a trade-off specifically between growth and longevity. Testing that prediction requires extremely well-controlled experiments.
>
> In a 2013 paper in the *Proceedings of the Royal Society of London,* some researchers reported a clever experimental approach that enabled them to evaluate,

R&R (Review and Rehearse)

Each chapter now concludes with a four-page visual summary that represents the key ideas, with a brief recap and central illustration from each section. **R&R** also includes short-answer and multiple-choice questions, making it ideal for chapter review, for exam preparation, or as assignments.





NEW! FOR THE INSTRUCTOR AND FOR THE CLASSROOM

From the front of the classroom to the top of the bestseller list, award-winning educator Jay Phelan knows how to tell the story of how scientists investigate the big questions about life. He is also a master at using biology as a springboard for developing the critical thinking skills and scientific literacy that are essential to students through college and throughout their lives.

Phelan's dynamic approach to teaching biology is the driving force behind *What Is Life?*—the most successful new non-majors biology textbook of the millennium. The rigorously updated new edition brings forward the features that made the book a classroom favorite (chapters anchored to intriguing questions about life, spectacular original illustrations, innovative learning tools). The third edition also includes enhanced art and full integration with its own dedicated version of LaunchPad—W. H. Freeman's breakthrough online course space. LaunchPad fully integrates an interactive e-Book, all student media, and a wide range of assessment and course management features, in a new interface in which power and simplicity go hand in hand.

LaunchPad

Developed with extensive feedback from instructors and students, W. H. Freeman's new online course space offers:

- **Pre-built units for each chapter**, curated by experienced educators, with media for that chapter organized and ready to assign or customize to suit your course.
- **All online resources for the text in one location**, including an interactive e-Book, LearningCurve adaptive quizzing (see below), Bio 101 Tutorials, **Q** Animations, graph-reading and data analysis activities, assessment questions (written by the author), all instructor resources, and more.
- **Intuitive and useful analytics**, with a Gradebook that lets you see how your class is doing individually and as a whole.
- **A streamlined interface** that lets you build an entire course in minutes.

LearningCurve

In a game-like format, LearningCurve adaptive and formative quizzing provides an effective way to get students involved in the coursework. It offers:

- A unique learning path for each student, with quizzes shaped by each individual's correct and incorrect answers.
- A Personalized Study Plan, to guide students' preparation for class and for exams.
- Feedback for each question with live links to relevant e-Book pages, guiding students to the reading they need to do to improve their areas of weakness.

Acknowledgments

As a new graduate student at Harvard, I heard from experienced teaching fellows that if you were interested in learning how to be an effective teacher, it was essential to seek out extraordinary mentors. Based on word of mouth, I became involved with E. O. Wilson's course in Evolutionary Biology and Irven DeVore's course in Human Behavioral Biology. Both were known to be unusually provocative, challenging, and entertaining classes for non-science majors. I aggressively pursued teaching positions in both classes—which I held onto tightly for twelve semesters. Working under these legendary educators, I was set on a course that inspired and prepared me to write this book.

The two courses were quite different from each other, but at their core both were built on two beliefs that are central to this book and to my thinking about education: (1) Biology is creative, interesting, and fun. (2) Biology is relevant to the daily life of every person. There was a palpable sense that, in teaching non-science majors especially, we had a responsibility to provide our students with the tools to thrive in a society increasingly permeated by scientific ideas and issues, and that one of our most effective strategies would be to convey the excitement we felt for biology and the enormous practical value it has to help us understand the world. I thank Professors Wilson and DeVore for all that they have shared with me.

My development as a scientist and, particularly, my appreciation for rigorous and methodical critical thinking have been shaped by the kind support and wise guidance of Richard Lewontin. I have also been fortunate to have as a long-time mentor and collaborator Michael Rose, who has instilled in me a healthy skepticism about any observation in life that is not fivefold replicated. And for almost daily insightful input on matters relating to scientific content, teaching, writing, and more, I thank Terry Burnham.

There are many other friends and colleagues I wish to thank for helping me with *What Is Life?*

In researching and writing the book and in developing the numerous courses I teach, I have benefited from more than a decade of perceptive and valuable contributions, too numerous to list, from Glenn Adelson, Alon Ziv, and Michael Cooperson. I am tremendously appreciative of all they have done for me.

For a project covering so many topics and years, it is essential to have a close group of trusted, tolerant, and knowledgeable colleagues. I am grateful to Alicia Moretti, Harold Owens, Greg Graffin, Brian Swartz, Greg Laden, Jeff Egger, Andy Tobias, Elisabeth Tobias, Joshua Malina, Melissa Merwin-Malina, Bill U'ren, Chris Bruno, and Michelle Richmond, who have offered advice, guidance, and support, far beyond the call of duty.

Numerous colleagues at UCLA provided assistance and support, including Steve Strand, Cliff Brunk, Fred Eiserling, Victoria Sork, Deb Pires, Lianna Johnson, Gaston Pfluegl, Frank Laski, Jeff Thomas, and Tracy Knox. As a result of their commitment to excellence in the UCLA Department of Life Science Core Education, I have been able to acquire a wealth of experiences that have helped me continue improving as a teacher.

I owe a tremendous debt to Sara Tenney, without whose encouragement and support this project could never have been begun or completed.

W. H. Freeman is an extremely author-centric publisher. Throughout the process of creating this book, Liz Widdicombe, John Sargent, and Susan Winslow have been tremendously supportive. I am grateful for their welcoming me into their publishing family. Publisher Peter Marshall has been a tenacious, versatile, and skillful manager of the entire team. I am very fortunate to have such a wise leader and friend overseeing all aspects of this project. The team of editors that worked with me on this book improved it immeasurably. Most importantly, development editor Beth Marsh oversaw every aspect of the writing and production of the book, attending to issues of content, production, and design while making insightful contributions throughout and expertly managing the thousand details necessary to put everything together. I could not have completed this book without Beth's commitment and guidance. I must also convey my gratitude to development editor Jane Tufts, whose meticulous attention to detail, commitment to accuracy, and almost obsessive drive to create a thorough and readable book are apparent on every page.

It is impossible to teach biology without illustrations. My deepest gratitude goes to Tommy Moorman for creating such innovative and effective figures for the book. Tommy's vision for an elegant and beautiful art program completely integrated with the text is apparent on every page. Working with him to develop each illustration in this book has been (and continues to be) one of my most enjoyable and satisfying professional collaborations. Thanks also go to Alison Kendall, Tamara Lau, and Erin Daniel for assisting with the creation of the illustrations. For the design of the book, I thank Tom Carling. And for excellent assistance with photo research, thanks to Julia Phelan, Jennifer Atkins, and Christine Buese.

For creating the innovative media and print materials that accompany the book, I am thankful for the contributions of Mike Jones and for the extensive input of Amanda Dunning and Elaine Palucki. I thank all of the contributors and advisors who helped create the student and instructor resources; your efforts have been invaluable. I thank Jennifer Warner and Meredith Norris

for their work on the Student Success Guide. I also appreciate the contributions of Troy Williams and the PrepU team. Sheri Snavely provided significant input in developing pedagogical strategies throughout the book; I also appreciate her thoughtful and wise advice at nearly every step in the publishing process. Copyeditor Linda Strange helped to ensure consistency, accuracy, and readability throughout the text. The rest of the life sciences editorial team at W. H. Freeman, too, have been knowledgeable and supportive, particularly Anna Bristow, Lisa Samols, Susan Moran, Kate Parker, and Elaine Palucki. For their efficiency and commitment to producing a beautiful book, I am most grateful to the W. H. Freeman production team: Sheridan Sellers, Elizabeth Geller, Paul Rohloff, Diana Blume, and Catherine Woods.

The people on the marketing team at W. H. Freeman have contributed enormously in helping with the challenging task of introducing this book to students and instructors across the country. John Britch, Shannon Howard, and Todd Elder have been enthusiastic and dedicated in creating materials and strategies to assist instructors in evaluating the ways in which *What Is Life?* can aid them as they develop their own courses and strategies for success.

Finally, I thank my family—Kevin Phelan, Patrick Phelan, Erin Enderlin, and my parents—for their unwavering support and interest as I wrote this book. Reading draft after draft and following each revision, they made valuable contributions at every stage. I thank Charlie, Jack, and Sam, too. Most of all, for her generous and passionate support of this project from day one, her substantive contributions to both the content and presentation of ideas, and so much more, I thank Julia.

Contact the author with your feedback.

The content of this book has been greatly improved through the comments of reviewers and students. Your comments, suggestions, and criticism are also welcome; they are essential in guiding its ongoing evolution. Please contact the author at jay@jayphelan.com. I'm serious.

We thank the many reviewers who aided in the development of this text.

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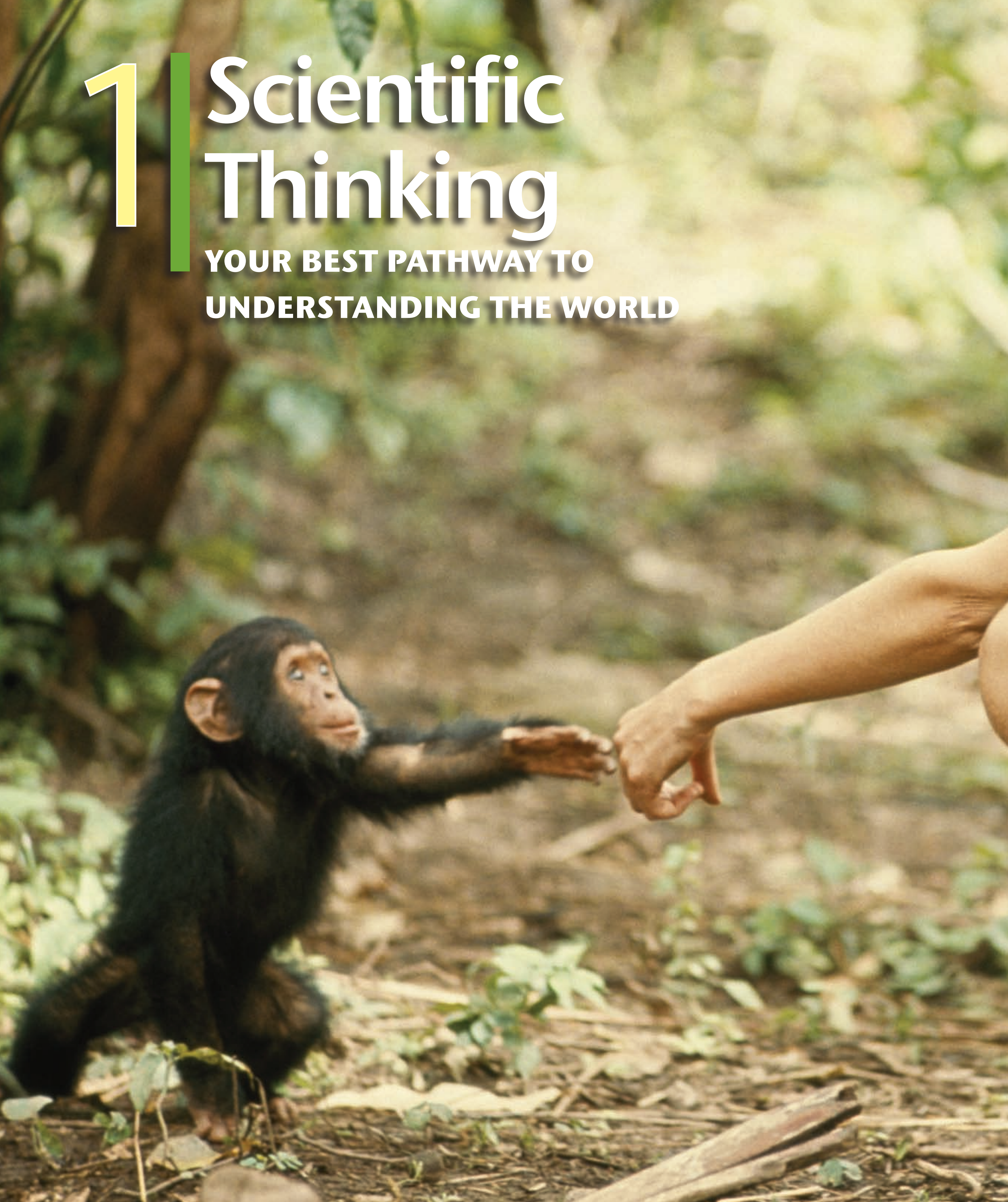
1 Scientific Thinking

YOUR BEST PATHWAY TO UNDERSTANDING THE WORLD



More than just a collection of facts, science is a process for understanding the world.

A beginner's guide: what are the steps of the scientific method?

Well-designed experiments are essential to testing hypotheses.

Scientific thinking can help us make wise decisions.

On the road to biological literacy: what are the major themes in biology.

1·1–1·3
More than just a collection of facts, science is a process for understanding the world.

A walk through Carnarvon National Park, Australia.

1·1 What is science? What is biology?

You are already a scientist. You may not have realized this yet, but it's true. Because humans are curious, you have no doubt asked yourself or others questions about how the world works and wondered how you might find the answers.

- Does the radiation released by cell phones cause brain tumors?
- Do large doses of vitamin C reduce the likelihood of getting a cold?

These are important and serious questions. But you've probably also pondered some less weighty issues, too.

- Why is morning breath so stinky? And can you do anything to prevent it?
- Why is it easier to remember gossip than physics equations?

And if you really put your mind to the task, you will start to find questions all around you whose answers you might like to know (and some whose answers you'll learn as you read this book).

- Which parent determines a baby's sex? Why?
- Why do so few women get into barroom brawls?
- What is "blood doping," and does it really improve athletic performance?
- Why is it so much easier for an infant to learn a complex language than it is for a college student to learn biology?

Still not convinced you're a scientist? Here's something important to know: science doesn't require advanced degrees or secret knowledge dispensed over years of technical training. It does, however, require an important feature of our species: a big brain, as well as curiosity and a desire to learn. But curiosity, casual observations, and desire can take you only so far.

Explaining how something works or why something happens requires methodical, objective, and rational observations and analysis that are not clouded with emotions or preconceptions. **Science** is not simply a body of knowledge or a list of facts to be remembered. It is an intellectual activity, encompassing observation, description, experimentation, and explanation of natural phenomena. Put another way, science is a pathway by which we can come to discover and better understand our world.

Later in this chapter, we explore specific ways in which we can most effectively use scientific thinking in our lives. But first let's look at a single powerful question that underlies scientific thinking:

How do you know that is true?

FIGURE 1-1 **Some products claim to improve our health, but how do we know whether they work?**

Once you begin asking this question—of others and of yourself—you are on the road to a better understanding of the world.

The following two stories about popular and successful products show the importance of questioning the truth of many "scientific" claims you see on merchandise packages or read in a newspaper or on the internet.

Dannon yogurt. According to the Federal Trade Commission (FTC), a U.S. government agency with the mission of consumer protection, the Dannon Company claimed in nationwide advertisements that its Activia yogurt relieves irregularity and helps with "slow intestinal transit time." Dannon also claimed that its DanActive dairy drink helps prevent colds and flu (**FIGURE 1-1**). The FTC charged that the ads were deceptive because there was no substantiation for the claims and, further, that the claims had been clinically proven to be false. In an agreement finalized in 2011, Dannon agreed to pay $21 million in fines and to stop making those claims unless the company gets reliable scientific evidence demonstrating the claims.

Airborne. For more than 15 years, the product Airborne has been marketed and sold to millions of customers. On the packaging and in advertisements, the makers originally asserted that Airborne tablets could ward off colds and boost your immune system (see Figure 1-1). Not surprisingly, Airborne quickly became a great success; it has generated more than $500 million in revenue. Then some consumers posed a reasonable question to the makers of Airborne: *How do you know that it wards off colds?*

Q Can we trust the packaging claims that companies make?

To support their claims, the makers of Airborne pointed to the results of a "double-blind, placebo-controlled study" conducted by a company specializing in clinical drug trials. We'll discuss exactly what those terms mean later in the chapter; for now we just need to note that as a result of a class-action lawsuit, it became clear that no such study had been conducted and that there was *no* evidence to back up Airborne's claims. The Airborne company removed the claims from the packaging and agreed to refund the purchase price to anyone who had bought Airborne. It also removed any reference to its "clinical trials," with the company's CEO saying that people "are really not scientifically minded enough to be able to understand a clinical study."

Are you insulted by the CEO's assumption about your intelligence? You should be. Did you or your parents fall for Airborne's false claims? Possibly. But here's some more good news: you can learn to be skeptical and suspicious (in a good way) of product claims. You can learn exactly what it means to have scientific proof or evidence for something. And you can learn this by learning what it means to think scientifically.

Scientific thinking is important in the study of a wide variety of topics: it can help you understand economics, psychology, history, and many other subjects. Our focus in this book is **biology,** the study of living things. Taking a scientific approach, we investigate the facts and ideas in biology that are already known and study the process by which we come to learn new things. As we move through the book, we explore the most important questions in biology.

- What is the chemical and physical basis for life and its maintenance?
- How do organisms use genetic information to build themselves and to reproduce?
- What are the diverse forms that life on earth takes, and how has that diversity arisen?
- How do organisms interact with each other and with their environment?

In this chapter, we explore how to think scientifically and how to use the knowledge we gain to make wise decisions. Although we generally restrict our focus to biology, scientific thinking can be applied to nearly every endeavor, so in this chapter we use a wide range of examples—including some from beyond biology—as we learn how to think scientifically. Although the examples vary greatly, they all convey a message that is key to scientific thinking: it's okay to be skeptical.

Fortunately, learning to think scientifically is not difficult—and it can be fun, particularly because it is so empowering. **Scientific literacy,** a general, fact-based understanding of the basics of biology and other sciences, is increasingly important in our lives, and literacy in matters of biology is especially essential.

TAKE-HOME MESSAGE 1·1

Through its emphasis on objective observation, description, and experimentation, science is a pathway by which we can discover and better understand the world around us.

1·2 Biological literacy is essential in the modern world.

A brief glance at any magazine or newspaper will reveal just how much scientific literacy has become a necessity (**FIGURE 1-2**). Many important health, social, medical, political, economic, and legal issues pivot on complex scientific data and theories. For example, why are unsaturated fats healthier for you than saturated fats? And why do allergies strike children from clean homes more than children from dirty homes? And why do new agricultural pests appear faster than new pesticides?

As you read and study this book, you will be developing **biological literacy,** the ability to (1) use the process of scientific inquiry to think creatively about real-world issues that have a biological component, (2) communicate these thoughts to others, and (3) integrate these ideas into your decision making. Biological literacy doesn't involve just the big issues facing society or just abstract ideas. It also matters to you personally. Should you take aspirin when you have a fever? Are you using the wrong approach if you

FIGURE 1-2 **In the news.** Every day, news sources report on social, political, medical, and legal issues related to science.

try to lose weight and, after some initial success, you find your rate of weight loss diminishing? Is it a good idea to consume moderate amounts of alcohol? Lack of biological literacy will put you at the mercy of "experts" who may try to confuse you or convince you of things in the interest of (their) personal gain. Scientific thinking will help you make wise decisions for yourself and for society.

TAKE-HOME MESSAGE 1·2

Biological issues permeate all aspects of our lives. To make wise decisions, it is essential for individuals and societies to attain biological literacy.

1·3 Scientific thinking is a powerful approach to understanding the world.

It's a brand new age, and science, particularly biology, is everywhere. To illustrate the value of scientific thinking in understanding the world, let's look at what happens in its absence, by considering some unusual behaviors in the common laboratory rat.

Rats can be trained, without much difficulty, to push a lever to receive a food pellet from a feeding mechanism (FIGURE 1-3). When the mechanism is altered so that there is a 10-second delay between the lever being pushed and the food pellet being dispensed, however, strange things start to happen. In one cage, the rat will push the lever and then, very methodically, run and push its nose into one corner of the cage. Then it moves to another corner and again pushes its nose against the cage. It repeats this behavior at the third and fourth corners of the cage, after which the rat stands in front of the feeder and the pellet is dispensed. Each time the rat pushes the lever it repeats the nose-in-the-corner sequence before moving to the food tray.

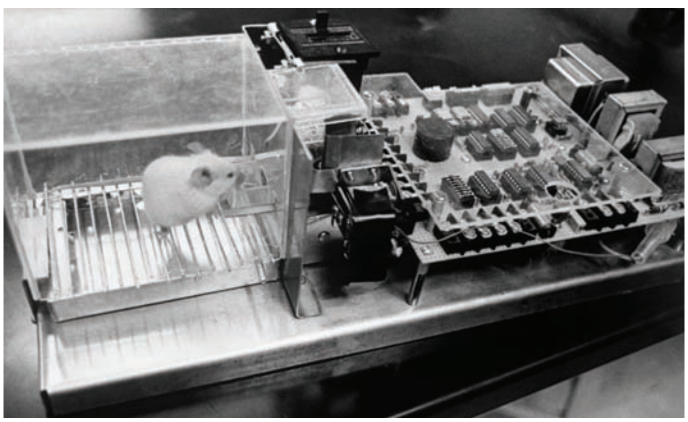


FIGURE 1-3 **"In the absence of the scientific method . . ."** Rats develop strange, superstition-like behaviors if there is a 10-second delay between when they push a lever and when food is delivered.

In another cage, with the same 10-second delay before the food pellet is dispensed, a rat pushes the lever and then proceeds to do three quick back-flips in succession. It then moves to the food tray for the food pellet when the 10 seconds have elapsed. Like the nose-in-the-corner rat, the back-flip rat will repeat this exact behavior each time it pushes the lever.

In cage after cage of rats with these 10-second-delay food levers, each rat eventually develops its own peculiar series of behaviors before moving to the food dish to receive the pellet. Why do they do this? Because it seems to work! They have discovered a method by which they can get a food pellet. To some extent, the rats' behaviors are reasonable. They associate two events—pushing the lever and engaging in some sequence of behaviors—with another event: receiving food. In a sense, they have taken a step toward understanding their world, even though the events are not actually related to each other.

Q Why do people develop superstitions? Can animals be superstitious?

Humans can also mistakenly associate actions with outcomes in an attempt to understand and control their world. The irrational belief that actions or circumstances that are not logically related to a course of events can influence its outcome is called **superstition** (FIGURE 1-4). For example, Nomar Garciaparra, a former major league baseball player, always engaged in a precise series of toe taps and adjustments to his batting gloves before he would bat.

Thousands of different narratives, legends, fairy tales, and epics from all around the globe exist to help people understand the world around them. These stories explain everything from birth and death to disease and healing.

FIGURE 1-4 **Superstitions abound.** As comforting as myths and superstitions may be, they are no substitute for really understanding how the world works.

As helpful and comforting as stories and superstitions may be (or seem to be), they are no substitute for understanding achieved through the process of examination and discovery called the **scientific method.**

The scientific method usually begins with someone observing a phenomenon and proposing an explanation for it. Next, the proposed explanation is tested through a series of experiments. If the experiments reveal that the explanation is accurate, and if others complete the experiments with the same result, then the explanation is considered to be valid. If the experiments do not support the proposed explanation, then the explanation must be revised or alternative explanations must be proposed and tested. This process continues as better, more accurate explanations are found.

While the scientific method reveals much about the world around us, it doesn't explain everything. There are many other methods through which we can gain an understanding of the world. For example, much of our knowledge about plants and animals does not come from the use of the scientific method, but rather comes from systematic, orderly observation, without the testing of any explicit hypotheses. Other disciplines also involve understandings of the world based on non-scientific processes. Knowledge about history, for example, comes from the systematic examination of past events as they relate to humans, while the "truths" in other fields, such as religion, ethics, and even politics, often are based on personal faith, traditions, and mythology.

Scientific thinking can be distinguished from these alternative ways of acquiring knowledge about the world in that it is **empirical.** Empirical knowledge is based on experience and observations that are rational, testable, and repeatable. The empirical nature of the scientific approach makes it self-correcting: in the process of analyzing a topic, event, or phenomenon with the scientific method, incorrect ideas are discarded in favor of more accurate explanations. In the next sections, we look at how to put the scientific method into practice.

TAKE-HOME MESSAGE 1·3

There are numerous ways of gaining an understanding of the world. Because it is empirical, rational, testable, repeatable, and self-correcting, the scientific method is a particularly effective approach.

1·4–1·10 A beginner's guide: what are the steps of the scientific method?

Eugenie Clark (at left), a pioneering investigator of shark behavior since the 1940s.

1·4 Thinking like a scientist: how do you use the scientific method?

"Scientific method"—this term sounds like a rigid process to follow, much like following a recipe. In practice, however, the scientific method is an adaptable process that can be done effectively in numerous ways. This flexibility makes the scientific method a powerful process that can be used to explore a wide variety of thoughts, events, or phenomena, not only in science but in other areas as well.

The basic steps in the scientific method are:

Step 1. Make observations.

Step 2. Formulate a hypothesis.

Step 3. Devise a testable prediction.

Step 4. Conduct a critical experiment.

Step 5. Draw conclusions and make revisions.

Once begun, though, the process doesn't necessarily continue linearly through the five steps until it is concluded (**FIGURE 1-5**). Sometimes, observations made in the first step can lead to more than one hypothesis and several testable predictions and experiments. And the conclusions drawn from experiments often suggest new observations, refinements to hypotheses, and, ultimately, increasingly precise conclusions.

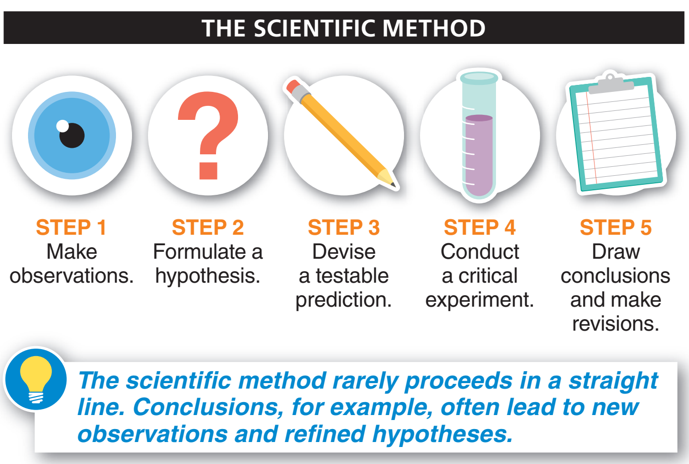


FIGURE 1-5 The scientific method: five basic steps and one flexible process.

An especially important feature of the scientific method is that its steps are self-correcting. As we continue to make new observations, a hypothesis about how the world works might change (**FIGURE 1-6**). If our observations do not support our current hypothesis, that hypothesis must be given up in favor of one that is not contradicted by any observations. This may be the most important feature of the scientific method: *it tells us when we should change our minds.*

Q What should you do when something you believe in turns out to be wrong?

> "If science proves some belief of Buddhism wrong, then Buddhism will have to change."
>
> — THE 14TH DALAI LAMA, *New York Times,* December 2005

FIGURE 1-6 **Hold the fries.** We apply an understanding of science when we choose foods from the menu that have fewer calories and less saturated fat.

FIGURE 1-7 **"With your own two eyes . . ."?** How reliable is eyewitness testimony in criminal courts?

Because the scientific method is a general strategy for learning, it needn't be used solely to learn about nature or scientific things. In fact, we can analyze an important criminal justice question using the scientific method:

- How reliable is eyewitness testimony in criminal courts?

For more than 200 years, courts in the United States have viewed eyewitness testimony as unassailable. Few things are seen as more convincing to a jury than an individual testifying that she can identify the person she saw commit a crime (FIGURE 1-7). But is eyewitness identification always right? Can the scientific method tell us whether this perception—or some other commonly held idea—is supported by evidence? As we describe how to use the scientific method to answer questions about the world, it will become clear that the answer is a resounding *yes*. In the coming sections of this chapter, we also look at how the scientific method can be used to address a variety of issues.

In addition to our criminal justice question, we'll answer two additional questions:

- Does echinacea reduce the intensity or duration of the common cold?
- Does shaving hair from your face, legs, or anywhere else cause it to grow back coarser or darker?

TAKE-HOME MESSAGE 1·4

The scientific method (observation, hypothesis, prediction, test, and conclusion) is a flexible, adaptable, and efficient pathway to understanding the world, because it tells us when we must change our beliefs.

1·5 Step 1: Make observations.

Scientific study always begins with observations: we simply look for interesting patterns or cause-and-effect relationships. This is where a great deal of the creativity of science comes from. In the case of eyewitness testimony, DNA technologies have made it possible to assess whether tissue such as hair or blood from a crime scene came from a particular suspect. Armed with these tools, the U.S. Justice Department recently reviewed 28 criminal convictions that had been overturned by DNA evidence. It found that in most of the cases, the strongest evidence against the defendant had been eyewitness identification. The observation here is that many defendants who are later found to be innocent were initially convicted based on eyewitness testimony.

Opportunities for other interesting observations are unlimited. Using the scientific method, we can (and will) also answer our two other questions.

STEP 1: MAKE OBSERVATIONS

OBSERVATION
To many people, consuming echinacea extract seems to reduce the intensity or duration of symptoms of the common cold.

FIGURE 1-8 The first step of science: making observations about the world.

Many people have claimed that consuming extracts of the herb echinacea can reduce the intensity or duration of symptoms of the common cold (FIGURE 1-8). We can ask: how do you know this is true?

- Does taking echinacea reduce the intensity or duration of the common cold?

Some people have suggested that shaving hair from your face, legs, or anywhere else causes the hair to grow back coarser and darker. Is this true?

- Does hair that is shaved grow back coarser or darker?

Using the scientific method, we can answer these questions.

TAKE-HOME MESSAGE 1·5

The scientific method begins by making observations about the world, noting apparent patterns or cause-and-effect relationships.

1·6 Step 2: Formulate a hypothesis.

Based on observations, we can develop a **hypothesis** (*pl.* **hypotheses**), a proposed explanation for observed phenomena. What hypotheses could we make about the eyewitness-testimony observations described in the previous section? We could start with the hypothesis "Eyewitness testimony is always accurate." We may need to modify our hypothesis later, but this is a good start. At this point, we can't draw any conclusions. All we have done is summarize some interesting patterns we've seen in a possible explanation.

To be most useful, a hypothesis must accomplish two things.

1. It must establish an alternative explanation for a phenomenon. That is, it must be clear that if the proposed explanation is not supported by evidence or further observations, a different hypothesis is a more likely explanation.

2. It must generate testable predictions (FIGURE 1-9). This characteristic is important because we can evaluate the validity of a hypothesis only by putting it to the test. For example, we could disprove the "Eyewitness testimony is always accurate" hypothesis by demonstrating that, in certain circumstances, individuals who have witnessed a crime might misidentify someone as the criminal when asked to select the suspect from a lineup.

Researchers often pose a hypothesis as a negative statement, proposing that there is no relationship between two factors, such as "Echinacea has no effect on the duration and severity of cold symptoms." Or "There is no difference in the coarseness or darkness of hair that grows after shaving." A hypothesis that states a *lack* of relationship between two factors is called a **null hypothesis.** Both types of hypothesis are equally valid, but a null hypothesis is easier to disprove. This is because a single piece of evidence or a