University Physics
FOR THE LIFE SCIENCES

KNIGHT JONES FIELD

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Useful Data

Earth data and gravity

M_e	Mass of the earth	5.98×10^{24} kg
R_e	Radius of the earth	6.37×10^{6} m
g	Free-fall acceleration	9.80 m/s^2
G	Gravitational constant	$6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$

Thermodynamics

k_B	Boltzmann constant	1.38×10^{-23} J/K
R	Gas constant	$8.31 \text{ J/mol} \cdot \text{K}$
N_A	Avogadro's number	6.02×10^{23} particles/mol
T_0	Absolute zero	-273°C
p_{atm}	Standard atmosphere	101,000 Pa
u	Atomic mass unit (Dalton)	1.66×10^{-27} kg

Speeds of sound and light

v_{sound}	Speed of sound in air at 20°C	343 m/s
c	Speed of light in vacuum	3.00×10^{8} m/s

Electricity and magnetism

K	Coulomb constant $(1/4\pi\epsilon_0)$	$8.99 \times 10^{9} \text{ N} \cdot \text{m}^2/\text{C}^2$
ϵ_0	Permittivity constant	$8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2$
μ_0	Permeability constant	$1.26 \times 10^{-6} \text{ T} \cdot \text{m/A}$
e	Fundamental unit of charge	1.60×10^{-19} C

Quantum and atomic physics

h	Planck constant	$6.63 \times 10^{-34} \text{ J} \cdot \text{s}$	$4.14 \times 10^{-15} \text{ eV} \cdot \text{s}$
$\hbar$	Planck constant	$1.05 \times 10^{-34} \text{ J} \cdot \text{s}$	$6.58 \times 10^{-16} \text{ eV} \cdot \text{s}$
a_B	Bohr radius	5.29×10^{-11} m	

Particle masses

m_p	Mass of the proton (and the neutron)	1.67×10^{-27} kg
m_e	Mass of the electron	9.11×10^{-31} kg

Common Prefixes

Prefix	Meaning
femto-	10^{-15}
pico-	10^{-12}
nano-	10^{-9}
micro-	10^{-6}
milli-	10^{-3}
centi-	10^{-2}
kilo-	10^{3}
mega-	10^{6}
giga-	10^{9}
terra-	10^{12}

Conversion Factors

Length

1 in = 2.54 cm
1 mi = 1.609 km
1 m = 39.37 in
1 km = 0.621 mi

Velocity

1 mph = 0.447 m/s
1 m/s = 2.24 mph = 3.28 ft/s

Mass and energy

1 u = 1.66×10^{-27} kg
1 cal = 4.19 J
1 eV = 1.60×10^{-19} J

Time

1 day = 86,400 s
1 year = 3.16×10^{7} s

Force

1 lb = 4.45 N

Pressure

1 atm = 101 kPa = 760 mm Hg
1 atm = 14.7 lb/in^2

Rotation

1 rad = 180°/π = 57.3°
1 rev = 360° = 2π rad
1 rev/s = 60 rpm

Greek Letters Used in Physics

Alpha		α	Nu		ν
Beta		β	Pi	Π	π
Gamma	Γ	γ	Rho		ρ
Delta	Δ	δ	Sigma	Σ	σ
Epsilon		ϵ	Tau		τ
Eta		η	Phi	Φ	ϕ
Theta	Θ	θ	Psi		ψ
Lambda		λ	Omega	Ω	ω
Mu		μ			

Mathematical Approximations

$(1 + x)^n \approx 1 + nx$ if $x \ll 1$
$\sin\theta \approx \tan\theta \approx \theta$ and $\cos\theta \approx 1$ if $\theta \ll 1$ radian
$\ln(1 + x) \approx x$ if $x \ll 1$

Brief Contents

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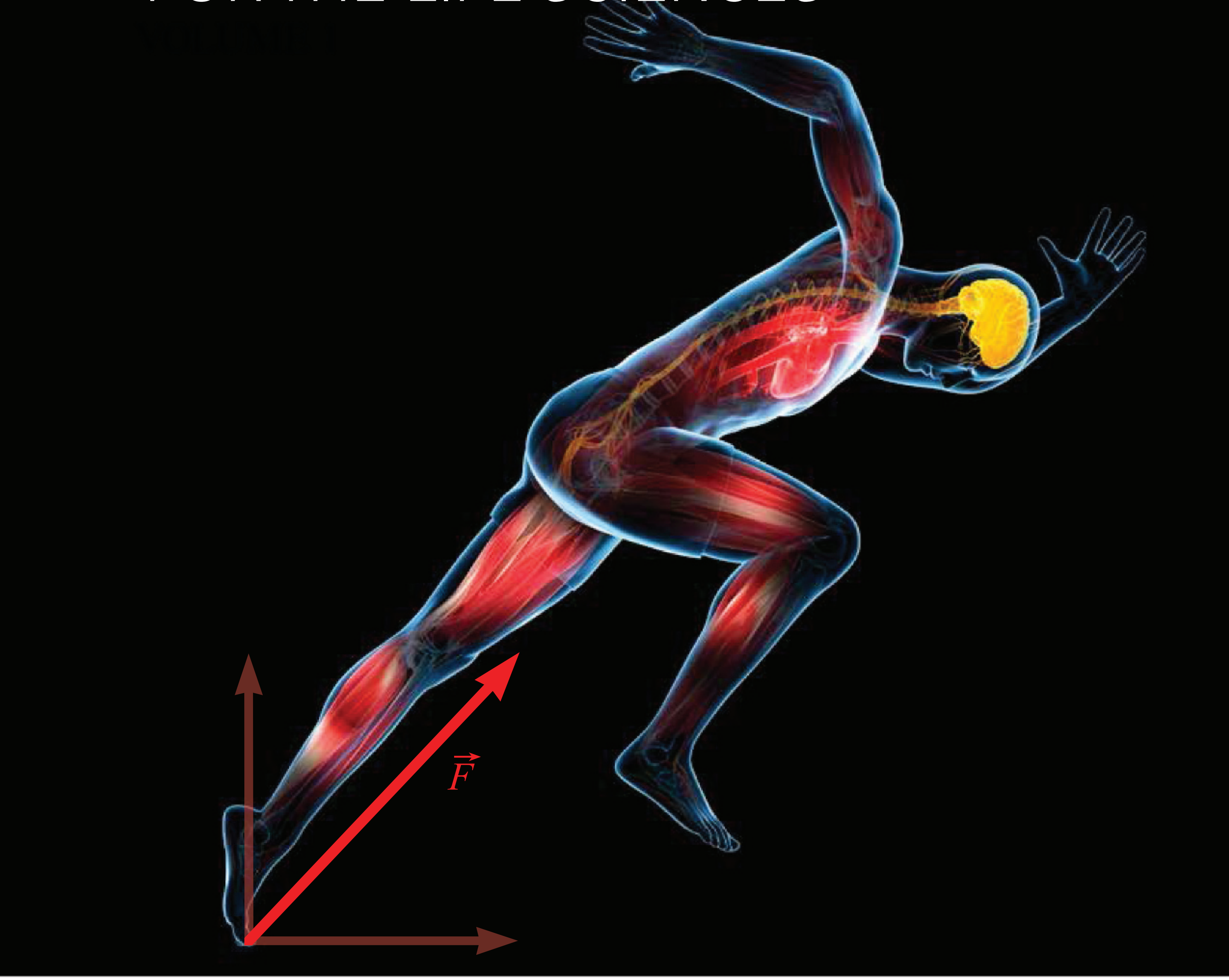

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Cover Image by SCIEPRO, Science Photo Library

Library of Congress Cataloging-in-Publication Data

Names: Knight, Randall Dewey, author. | Jones, Brian, author. | Field, Stuart, author.
Title: University physics for the life sciences / Randall D. Knight, California Polytechnic State University, San Luis Obispo, Brian Jones, Colorado State University, Stuart Field, Colorado State University; with contributions by Catherine Crouch, Swarthmore College.
Description: Hoboken: Pearson, 2021. | Includes index. | Summary: "University Physics for the Life Sciences has been written in response to the growing call for an introductory physics course explicitly designed for the needs and interests of life science students anticipating a career in biology, medicine, or a health-related field"—Provided by publisher.
Identifiers: LCCN 2020053801 | ISBN 9780135822180 (hardcover) | ISBN 9780135821053 (ebook)
Subjects: LCSH: Physics—Textbooks.
Classification: LCC QC23.2 .K658 2021 | DDC 530—dc23
LC record available at https://lccn.loc.gov/2020053801

Cataloging-in-Publication Data is on file at the Library of Congress.

ScoutAutomatedPrintCode

Pearson

Access Code Card
ISBN-10: 0-135-82129-0
ISBN-13: 978-0-135-82129-9

Rental
ISBN-10: 0-135-82218-1
ISBN-13: 978-0-135-82218-0

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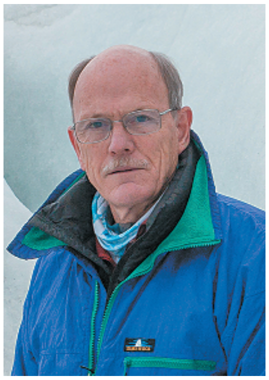
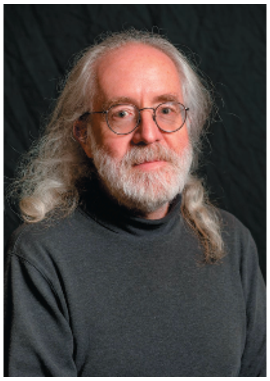


Randy Knight taught introductory physics for thirty-two years at Ohio State University and California Polytechnic State University, where he is Professor Emeritus of Physics. Professor Knight received a PhD in physics from the University of California, Berkeley, and was a postdoctoral fellow at the Harvard-Smithsonian Center for Astrophysics before joining the faculty at Ohio State University. A growing awareness of the importance of research in physics education led first to *Physics for Scientists and Engineers: A Strategic Approach* and later to *College Physics: A Strategic Approach.* Professor Knight's research interests are in the fields of laser spectroscopy and environmental science. When he's not in front of a computer, you can find Randy hiking, traveling, playing the piano, or spending time with his wife Sally and their five cats.



Brian Jones has won several teaching awards at Colorado State University during his thirty years teaching in the Department of Physics. His teaching focus in recent years has been the College Physics class, including writing problems for the MCAT exam and helping students review for this test. In 2011, Brian was awarded the Robert A. Millikan Medal of the American Association of Physics Teachers for his work as director of the Little Shop of Physics, a hands-on science outreach program. He is actively exploring the effectiveness of methods of informal science education and how to extend these lessons to the college classroom. Brian has been invited to give workshops on techniques of science instruction throughout the United States and in Belize, Chile, Ethiopia, Azerbaijan, Mexico, Slovenia, Norway, Namibia, and Uganda. Brian and his wife Carol have dozens of fruit trees and bushes in their yard, including an apple tree that was propagated from a tree in Isaac Newton's garden.

Stuart Field has been interested in science and technology his whole life. While in school he built telescopes, electronic circuits, and computers. After attending Stanford University, he earned a Ph.D. at the University of Chicago, where he studied the properties of materials at ultralow temperatures. After completing a postdoctoral position at the Massachusetts Institute of Technology, he held a faculty position at the University of Michigan. Currently at Colorado State University, Stuart teaches a variety of physics courses, including algebra-based introductory physics, and was an early and enthusiastic adopter of Knight's *Physics for Scientists and Engineers*. Stuart maintains an active research program in the area of superconductivity. Stuart enjoys Colorado's great outdoors, where he is an avid mountain biker; he also plays in local ice hockey leagues.

Contributing author **Catherine Hirshfeld Crouch** is Professor of Physics at Swarthmore College, where she has taught since 2003. Dr. Crouch's work developing and evaluating curriculum for introductory physics for life science students has been used by faculty around the country and has been supported by the National Science Foundation. She earned her PhD at Harvard University in experimental condensed matter physics, and then remained at Harvard in a dual postdoctoral fellowship in materials physics and physics education with Eric Mazur, including developing and evaluating pedagogical best practices for undergraduate physics. She has published numerous peer-reviewed research articles in physics education and experimental physics, and has involved dozens of Swarthmore undergraduate students in her work. She is married to Andy Crouch and they have two young adult children, Timothy and Amy.

To the Student

If you're taking a physics course that uses this text, chances are that you intend a career in medicine or the life sciences. What are you expected to learn in physics that's relevant to your future profession?

Understanding physics is essential to a mastery of the life sciences for two key reasons:

- Physics and physical laws underlie all physiological processes, from the exchange of gases as you breathe to the propagation of nerve impulses.
- Many of the modern technologies used in biology and medicine, from fluorescent microscopy to radiation therapy, are based on physics concepts.

Because of this critical role, physics is a major component of the MCAT.

Biological systems are also physical systems, and a deep knowledge of biology requires understanding how the laws of physics apply to and sometimes constrain biological processes. One of our goals in this text is to build on the science you've learned in biology and chemistry to provide a solid understanding of the physical basis of biology and medicine.

Another important goal is to help you develop your quantitative reasoning skills. Quantitative reasoning is more than simply doing calculations. It is important to be able to do calculations, but our primary focus will be to discover and use *patterns* and *relationships* that occur in nature. Right away, in Chapter 1, we'll present evidence showing that there's a quantitative relationship between a mammal's mass and its metabolic rate. That is, knowing the metabolic rate of a mouse allows you to predict the metabolic rate of an elephant. Making and testing predictions are at the heart of what science and medicine are all about. Physics, the most quantitative of the sciences, is a great place to practice these skills.

Physics and biology are both sciences. They share many similarities, but learning physics requires a different approach than learning biology. In physics, exams will rarely test your ability to simply recall information. Instead, the emphasis will be on learning procedures and skills that, on exams, you will need to apply to new situations and new problems.

You may be nervous about the amount of mathematics used in physics. This is common, but be reassured that you can do it! The math we'll use is overwhelmingly the algebra, geometry, and trigonometry you learned in high school. You may be a bit rusty (see Appendix A for a review of the math we'll be using), and you almost certainly will understand this math better after using it in physics, but our many years of teaching experience find that nearly all students can handle the math.

This text does use some calculus, and your instructor will decide how much or how little of that to include. Many of the ideas of physics—how fast things happen, how things accumulate—are expressed most naturally in the language of calculus. We'll introduce the ideas gently and show you how calculus can be an important thinking and reasoning tool. In fact, many students find they understand calculus best after using it in physics. It's important to become comfortable with calculus because it is increasingly used as a quantitative tool in the life sciences.

How To Learn Physics

There's no single strategy for learning physics that works for everyone, but we can make a few suggestions that will help most students succeed:

- **Read all of each chapter!** This might seem obvious, but we know that many students focus their study on the worked examples. The worked examples are important and helpful, but to succeed on exams you will have to apply these ideas to completely new problems. To do so, you need to understand the underlying principles and logic that are explained in the body of the chapter.
- **Use the chapter summaries.** The chapter summaries are designed to help you see the big picture of how the pieces fit together. That said, the summaries are not a substitute for reading the chapter; their purpose is to help you consolidate your knowledge *after* you've read the chapter. Notice that there are also *part summaries* at the end of each of the text's six parts.
- **Actively participate in class.** Take notes, answer questions, and participate in discussions. There is ample evidence that *active participation* is far more effective for learning science than passive listening.
- **Apply what you've learned.** Give adequate time and attention to the assigned homework questions and problems. Much of your learning occurs while wrestling with problems. We encourage you to form a study group with two or three classmates. At the same time, make sure you fully understand how each problem is solved and are not simply borrowing someone else's solution.
- **Solve new problems as you study for exams.** Questions and problems on physics exams will be *entirely new problems,* not simply variations on problems you solved for homework. Your instructor wants you to demonstrate that you understand the physics by being able to apply it in new situations. Do review the solutions to worked examples and homework problems, focusing on the underlying reasoning rather than the calculations, but don't stop there. A much better use of time is to practice solving additional end-of-chapter problems while, as much as possible, referring only to the chapter summaries.

Our sincere wish is that you'll find your study of physics to be a rewarding experience that helps you succeed in your chosen field by enhancing your understanding of biology and medicine. Many of our students report this was their experience!

To the Instructor

University Physics for the Life Sciences has been written in response to the growing call for an introductory physics course explicitly designed for the needs and interests of life science students anticipating a career in biology, medicine, or a health-related field. The need for such a course has been recognized within the physics education community as well as by biological and medical professional societies. The *Conference on Introductory Physics for the Life Sciences Report* (American Association of Physics Teachers, 2014, available at compadre.org/ipls/) provides background information and makes many recommendations that have guided the development of this text.

This new text is based on Knight *Physics for Scientists and Engineers* (4th edition, 2017) and Knight, Jones, Field *College Physics* (4th edition, 2019). As such, it is a research-based text based on decades of studies into how students learn physics and the challenges they face. It continues the engaging, student-oriented writing style for which the earlier books are known. At the same time, we have fully rethought the content, ordering, examples, and end-of-chapter problems to ensure that this text matches the needs of the intended audience.

Objectives

Our goals in writing this textbook have been:

- To produce a textbook that recognizes and meets the needs of students in the life sciences.
- To integrate proven techniques from physics education research and cognitive psychology into the classroom in a way that accommodates a range of teaching and learning styles.
- To help students develop conceptual and quantitative reasoning skills that will be important in their professional lives.
- To prepare students to succeed on the Chemical and Physical Foundations of Biological Systems portion of the MCAT exam.

Content and Organization

Why develop a new textbook? What is needed to best meet the needs of life science students? The purpose of this text is to prepare students to grasp and apply physics content as needed to their discipline of choice—biology, biochemistry, and/or health sciences. However, the introductory physics course taken by most life science students has for decades covered pretty much the same topics as those taught in the course for engineering and physics majors but with somewhat less mathematics. Few of the examples or end-of-chapter problems deal with living systems. Such a course does not help life science students see the relevance of physics to their discipline.

Many topics of biological importance are missing in a standard introductory physics textbook. These include viscosity, surface tension, diffusion, osmosis, and electrostatics in salt water. Applications such as imaging, whether in the form of fluorescence microscopy or scanning electron microscopy, are barely touched on. A physics course designed for life science students must be grounded in the fundamental laws of physics, a goal to which this text remains firmly committed. But how those laws are applied to the life sciences, and the examples that are explored, differ significantly from their application to engineering and physics.

To endeavor to connect physics to the life sciences, we have added many topics that are important for biologists and physicians. To make time for these, we've scaled back some topics that are important for physicists and engineers but much less so for students in the life sciences. There's less emphasis on standard force-and-motion problems; circular and rotational motion has been de-emphasized (and the text has been written to allow instructors to omit rotation entirely); some aspects of electricity and magnetism have been reduced; and relativity is omitted. After careful consideration, and consultation with experts in biology and physics education, we've made the choice that these topics are less relevant to the audience than the new content that needed to be added.

The most significant change is in the treatment of energy and thermodynamics. Energy and entropy are crucial to all living systems, and introductory physics could play a key role to help students understand these ideas. However, physicists and biologists approach these topics in very different ways.

The standard physics approach that emphasizes conservation of mechanical energy provides little insight into biological systems, where mechanical energy is almost never conserved. Further, biologists need to understand not how work is performed by a heat engine but how useful work can be extracted from a chemical reaction. Biologists describe energy use in terms of enthalpy and Gibbs free energy—concepts from chemistry—rather than heat and entropy. A presentation of energy and entropy must connect to and elucidate reaction dynamics, enthalpy, and free energy if it is to help students see the relevance of physics to biology.

Thus we've developed a new unit on energy and thermodynamics that provides a coherent development of energy ideas, from work and kinetic energy through the laws of thermodynamics. Students bring a knowledge of atoms and molecules to the course, so a kinetic-theory perspective is emphasized. Molecular energy diagrams and the Boltzmann factor are used to understand what happens in a chemical reaction, and ideas about randomness lead not only to entropy but also to Gibbs free energy and what that tells us about the energetics of reactions.

This text does use simple calculus, but more lightly than in the calculus-based introductory course for physicists and engineers. Calculus is now a required course for biology majors at many universities, it is increasingly used as a quantitative analysis tool in biological research, and many medical schools expect at least a semester of calculus. Few results depend on calculus, and it can easily be sidestepped if an instructor desires an algebra-based course. Similarly, there are topics where the instructor could supplement the text with a somewhat more rigorous use of calculus if his or her students have the necessary math background.

Although this text is oriented toward the life sciences, it assumes no background in biology on the part of the instructor. Examples and problems are self-contained. A basic familiarity with chemistry and chemical reactions is assumed.

Key Features

Many of the key features of this textbook are grounded in physics education research.

- **Annotated figures,** now seen in many textbooks, were introduced to physics in the first edition of Knight's *Physics for Scientists and Engineers.* Research shows that the "instructor's voice" greatly increases students' ability to understand the many figures and graphs used in physics.
- **Stop to Think Questions** throughout the chapters are based on documented student misconceptions.
- **NOTES** throughout the chapters call students' attention to concepts or procedures known to cause difficulty.
- **Tactics Boxes** and **Problem-Solving Strategies** help students develop good problem-solving skills.
- **Chapter Summaries** are explicitly hierarchical in design to help students connect the ideas and see the big picture.

Instructor Resources

A variety of resources are available to help instructors teach more effectively and efficiently. Most can be downloaded from the Instructor Resources area of Mastering™ Physics.

- **Ready-To-Go Teaching Modules** are an online instructor's guide. Each chapter contains background information on what is known from physics education research about student misconceptions and difficulties, suggested teaching strategies, suggested lecture demonstrations, and suggested pre- and post-class assignments.
- **Mastering Physics** is Pearson's online homework system through which the instructor can assign pre-class reading quizzes, tutorials that help students solve a problem with hints and wrong-answer feedback, direct-measurement videos, and end-of-chapter questions and problems. Instructors can devise their own assignments or utilize pre-built assignments that have been designed with a good balance of problem types and difficulties.
- **PowerPoint Lecture Slides** can be modified by the instructor but provide an excellent starting point for class preparation. The lecture slides include QuickCheck questions.
- **QuickCheck "Clicker Questions"** are conceptual questions, based on known student misconceptions. They are designed to be used as part of an active-learning teaching strategy. The Ready-To-Go teaching modules provide information on the effective use of QuickCheck questions.
- The **Instructor's Solution Manual** is available in both Word and PDF formats. We do require that solutions for student use be posted only on a secure course website.

Instructional Package

University Physics for the Life Sciences provides an integrated teaching and learning package of support material for students and instructors.

NOTE For convenience, instructor supplements can be downloaded from the Instructor Resources area of Mastering Physics.

Supplement	Print	Online	Instructor or Student Supplement	Description
Mastering Physics with Pearson eText		✓	Instructor and Student Supplement	This product features all of the resources of Mastering Physics in addition to the new Pearson eText 2.0. Now available on smartphones and tablets, Pearson eText 2.0 comprises the full text, including videos and other rich media.
Instructor's Solutions Manual		✓	Instructor Supplement	This comprehensive solutions manual contains complete solutions to all end-of-chapter questions and problems.
TestGen Test Bank		✓	Instructor Supplement	The Test Bank contains more than 2,000 high-quality problems, with a range of multiple-choice, true/false, short answer, and regular homework-type questions. Test files are provided in both TestGen® and Word format.
Instructor's Resource Materials	✓	✓	Instructor Supplement	All art, photos, and tables from the book are available in JPEG format and as modifiable PowerPoints™. In addition, instructors can access lecture outlines as well as "clicker" questions in PowerPoint format, editable content for key features, and all the instructor's resources listed above.
Ready-to-Go Teaching Modules		✓	Instructor Supplement	Ready-to-Go Teaching Modules provide instructors with easy-to-use tools for teaching the toughest topics in physics. Created by the authors and designed to be used before, during, and after class, these modules demonstrate how to effectively use all the book, media, and assessment resources that accompany *University Physics for the Life Sciences.*

Acknowledgments

We have relied on conversations with and the written publication of many members of the physics education community and those involved in the Introductory Physics for Life Sciences movement. Those who may recognize their influence include the late Lillian McDermott and members of the Physics Education Research Group at the University of Washington, Edward "Joe" Redish and members of the Physics Education Research Group at the University of Maryland, Ben Dreyfus, Ben Geller, Bob Hilborn, Dawn Meredith, and the late Steve Vogel. Ben Geller of Swarthmore College provided useful insights into teaching thermodynamics and contributed to the Ready-To-Go Teaching Modules.

We are especially grateful to our contributing author Catherine Crouch at Swarthmore College for many new ideas and examples, based on her experience developing a course for life science majors, and for a detailed review of the entire manuscript.

Thanks to Christopher Porter, The Ohio State University, for the difficult task of writing the *Instructor's Solutions Manual*; to Charlie Hibbard for accuracy checking every figure and worked example in the text; to Elizabeth Holden, University of Wisconsin-Platteville, for putting together the lecture slides; and to Jason Harlow, University of Toronto, for updating the QuickCheck "clicker" questions.

We especially want to thank Director HE Content Management Science & Health Sciences, Jeanne Zalesky; Product Manager Science–Physical Sciences, Darien Estes; Senior Analyst HE Global Content Strategy–Physical Sciences, Deborah Harden; Senior Development Editor, Alice Houston; Development Editor, Edward Dodd; Senior Content Producer, Martha Steele; Senior Associate Content Analyst Physical Science, Pan-Science, Harry Misthos; and all the other staff at Pearson for their enthusiasm and hard work on this project. It has been very much a team effort.

Thanks to Margaret McConnell, Project Manager, and the composition team at Integra for the production of the text; Carol Reitz for her fastidious copyediting; Joanna Dinsmore for her precise proofreading; and Jan Troutt and Tim Brummett at Troutt Visual Services for their attention to detail in the rendering and revising of the art.

And, last but not least, we each want to thank our wives for their encouragement and patience.

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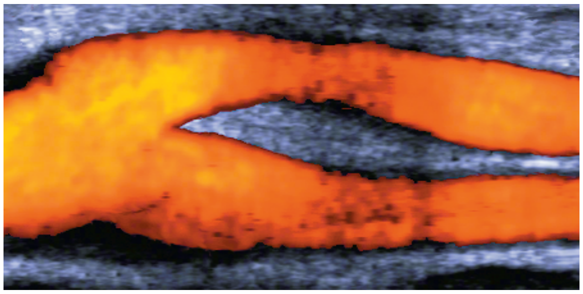
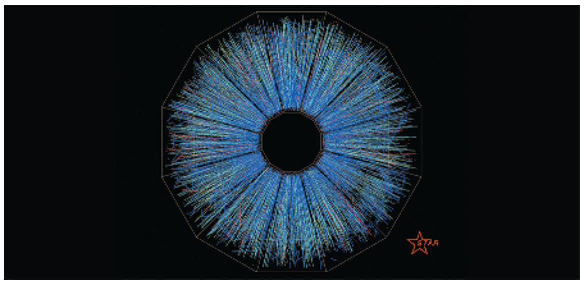




PART

I

Force and Motion

Elite athletes push the human body's physical limits. What forces act on this sprinter as she accelerates? How much force can her muscles, tendons, and bones endure? How much air can flow into her lungs? How rapidly can blood be pumped through her veins? These are physics questions that help us understand human performance, questions we'll address in Part I.

OVERVIEW

The Science of Physics

Physics is the foundational science that underlies biology, chemistry, earth science, and all other fields that attempt to understand our natural world. Physicists couple careful experimentation with theoretical insights to build powerful and predictive models of how the world works. A key aspect of physics is that it is a *unifying* discipline: A relatively small number of key concepts can explain a vast array of natural phenomena. In this text, we have organized the chapters into parts according to six of these unifying principles. Each of the six parts opens with an overview that gives you a look ahead, a glimpse of where your journey will take you in the next few chapters. It's easy to lose sight of the big picture while you're busy negotiating the terrain of each chapter. In Part I, the big picture is, in a word, *change*.

Why Things Change

Simple observations of the world around you show that most things change. Some changes, such as aging, are biological. Others, such as the burning of gasoline in your car, are chemical. In Part I, we will look at changes that involve *motion* of one form or another—from running and jumping to swimming microorganisms.

There are two big questions we must tackle to study how things change by moving:

- **How do we describe motion?** How should we measure or characterize the motion if we want to analyze it quantitatively?
- **How do we explain motion?** Why do objects have the particular motion they do? When you toss a ball upward, why does it go up and then come back down rather than keep going up? What are the "laws of nature" that allow us to predict an object's motion?

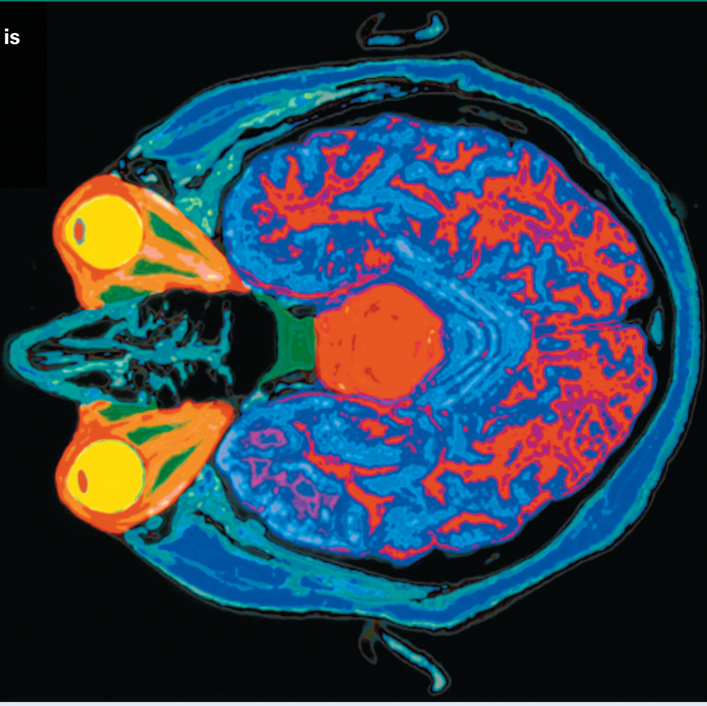
Two key concepts that will help answer these questions are *force* (the "cause") and *acceleration* (the "effect"). Our basic tools will be three laws of motion worked out by Isaac Newton to relate force and motion. We will use Newton's laws to explore a wide range of problems—from how a sprinter accelerates to how blood flows through the circulatory system. As you learn to solve problems dealing with motion, you will be learning techniques that you can apply throughout this text.

Using Models

Another key aspect of physics is the importance of models. Suppose we want to analyze a ball moving through the air. Is it necessary to analyze the way the atoms in the ball are connected? Or the details of how the ball is spinning? Or the small drag force it experiences as it moves? These are interesting questions, of course. But if our task is to understand the motion of the ball, we need to simplify!

We can conduct a perfectly fine analysis of the ball's motion by treating the ball as a single particle moving through the air. This is a *model* of the situation. A model is a simplified description of reality that is used to reduce the complexity of a problem so it can be analyzed and understood. Both physicists and biologists make extensive use of models to simplify complex situations, and in Part I you'll begin to learn where and how models are employed and assessed. Learning how to simplify a situation is the essence of successful problem solving.

1 Physics for the Life Sciences

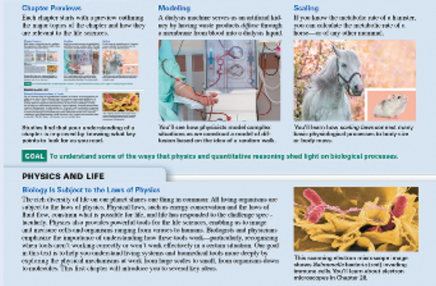


Magnetic resonance imaging (MRI) is just one of many ways that physics has contributed to biology and medicine. We'll look at how images like this are created in Chapter 26.

LOOKING AHEAD

Chapter Previews

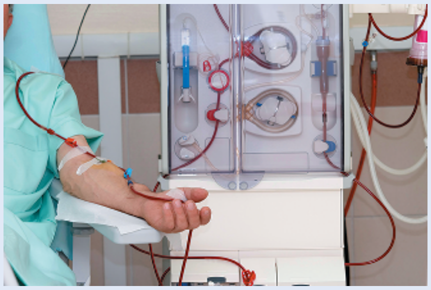
Each chapter starts with a preview outlining the major topics of the chapter and how they are relevant to the life sciences.



Studies find that your understanding of a chapter is improved by knowing what key points to look for as you read.

Modeling

A dialysis machine serves as an artificial kidney by having waste products *diffuse* through a membrane from blood into a dialysis liquid.



You'll see how physicists model complex situations as we construct a model of diffusion based on the idea of a random walk.

Scaling

If you know the metabolic rate of a hamster, you can calculate the metabolic rate of a horse—or of any other mammal.

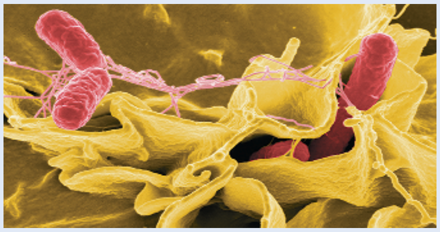
You'll learn how *scaling laws* connect many basic physiological processes to body size or body mass.

GOAL **To understand some of the ways that physics and quantitative reasoning shed light on biological processes.**

PHYSICS AND LIFE

Biology Is Subject to the Laws of Physics

The rich diversity of life on our planet shares one thing in common: All living organisms are subject to the laws of physics. Physical laws, such as energy conservation and the laws of fluid flow, constrain what is possible for life, and life has responded to the challenge spectacularly. Physics also provides powerful tools for the life sciences, enabling us to image and measure cells and organisms ranging from viruses to humans. Biologists and physicians emphasize the importance of understanding how these tools work—particularly, recognizing when tools aren't working correctly or won't work effectively in a certain situation. Our goal in this text is to help you understand living systems and biomedical tools more deeply by exploring the physical mechanisms at work from large scales to small, from organisms down to molecules. This first chapter will introduce you to several key ideas.



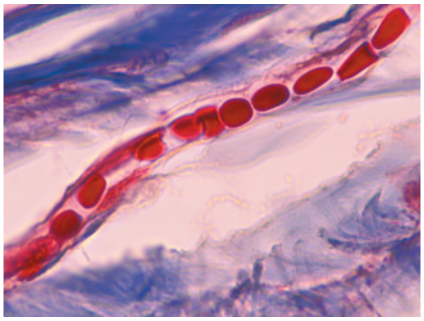
This scanning electron microscope image shows *Salmonella* bacteria (red) invading immune cells. You'll learn about electron microscopes in Chapter 28.

1.1 Why Physics?

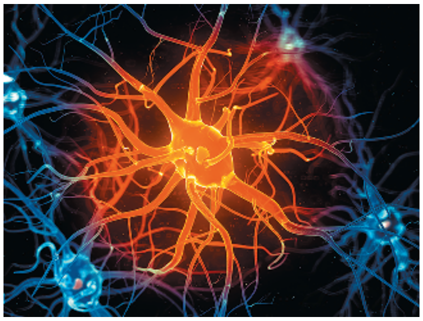
Why take physics? Does knowing about projectiles, pendulums, or magnetic fields help you understand biological systems? Do doctors or microbiologists or ecologists think about or use the principles of physics?

Actually, the answer to these questions is Yes. The existence of separate biology, chemistry, and physics departments may make it seem like these are distinct sciences, but that couldn't be further from the truth. Our overarching goal in this text is to help you discover the central importance of physics to the life sciences. Biological systems are part of the physical world, and biological processes are physical processes, so the laws of physics can help you understand a great deal about biology, biochemistry, and medicine. Let's look at some examples:

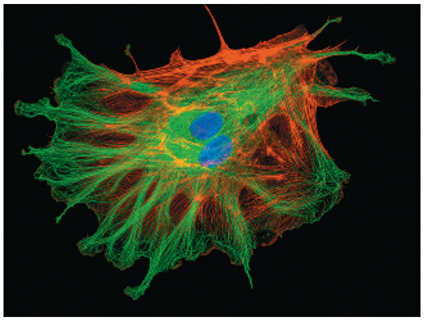
Physics in biology



The circulatory system, from the heart to the capillaries, is governed by fluid dynamics. You'll study the physics of circulation in Chapter 9.



Neurons signal each other via electric pulses that travel along axons. This is a topic we'll visit in Chapter 25.

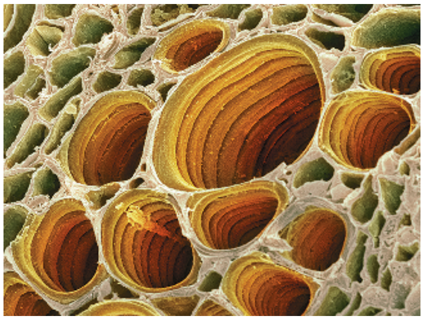


The light-emitting properties of the green fluorescent protein are used to visualize cell structure. Fluorescence is covered in Chapter 29.

Physics in biomechanics

The physics of locomotion affects how fast an animal can run. Locomotion is the topic of several chapters in Part I.

Physics helps us understand the limits of athletic performance. Chapter 11 looks at how the body uses energy.

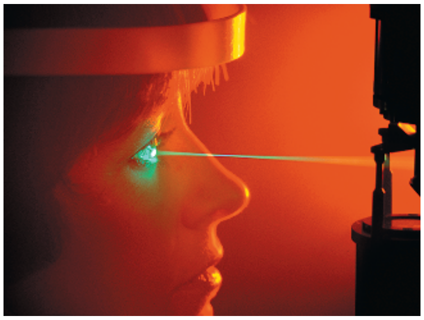


And physics explains how sap rises in trees through the xylem. This somewhat counterintuitive fluid flow is described in Chapter 9.

Physics in medicine

Pulse oximetry measures blood oxygen with a clip-on device. Chapter 29 discusses how blood absorbs different colors of light.

A patient prepares to have cancer treated by proton irradiation. Radiation and radiation therapy are topics in Chapter 30.



Lasers are used for high-precision eye surgery of both the cornea and the retina. Chapter 20 covers the optics of the human eye.

These are among the many applications of physics to the life sciences that you'll learn about in this book. That said, this is a physics textbook, not a biology textbook. We need to develop the underlying principles of physics before we can explore the applications, so we will often start with rolling balls, oscillating springs, and other simple systems that illustrate the physical principles. Then, after laying the foundations, we will move on to see how these ideas apply to biology and medicine. As authors, our sincere hope is that this course will help you see why many things in biology happen as they do.

Physics and Biology

TABLE 1.1 Characteristics of biology and physics

Biology	Physics
Irreducibly complex systems	Simple models
More qualitative	More quantitative
Focus on specific examples	Focus on broad principles

Physicists and biologists are scientists: They share many common views of what science is and how science operates. At the same time, as TABLE 1.1 illustrates, physicists and biologists often see the world in rather different ways. Your physics course will be less stressful and more productive if you're aware of these differences.

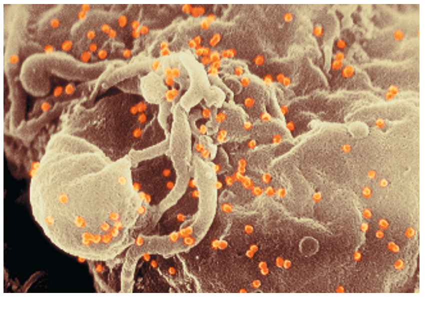
Physics tries to get at the essence of a process by identifying broad principles, such as energy conservation, and applying them to systems that have been greatly simplified by stripping away superfluous details. This approach is less common in biology, where systems often can't be simplified without throwing out details that are essential to biological function. You may have taken biology courses in which you were expected to memorize a great deal of information; there's much less to memorize in physics. Instead, most physicists agree that students demonstrate their understanding of physics by using general principles to solve unfamiliar problems.

With that in mind, we can establish four large-scale goals for this text. By the end, you should be able to:

- Recognize and use the principles of physics to explain physical phenomena.
- Understand the importance of models in physics.
- Reason quantitatively.
- Apply the principles of physics to biological systems.

The examples in this text will help you at each step along the way, and the end-of-chapter problems will provide many opportunities for practice.

Mathematics



Seeing the details A *scanning electron microscope* produces highly detailed images of biological structures only a few nanometers in size. The level of detail in this image of a budding HIV virus can provide new understanding of how the virus spreads and how it might be stopped. Physics has been at the forefront of developing a wide variety of imaging technologies.

Physics is the most quantitative of all the sciences. As physics has developed, the laws of physics have come to be stated as mathematical equations. These equations can be used to make quantitative, testable predictions about nature, whether it's the orbit of a satellite or the pressure needed to pump blood through capillaries. This approach to science has proven to be extremely powerful; much of modern biomedical technology—from electron microscopes to radiation therapy—depends on the equations of physics.

But math is used in physics for more than simply doing calculations. The equations of physics tell a story; they're a shorthand way to describe how different concepts are related to one another. So, while we can use the ideal-gas law to calculate the pressure in a container of gas, it's more useful to recognize that the pressure of a gas in a rigid container (one that has a constant volume) increases in exactly the same proportion as the absolute temperature. Consequently, doubling the temperature causes the pressure to double. The ideal-gas law expresses a set of deep ideas about how gases behave.

So, yes, we will often use equations to calculate values. But, more fundamentally, physics is about using math to reason and to analyze; that is, math is a *thinking tool* as much as it is a calculation tool. This may be a new way of using math for you, but—with some practice and experience—we think you'll come to recognize the power of this way of thinking.

The math used in this book is mostly math you already know: algebra, geometry, and some trigonometry. You might need some review (see Appendix A), but we're confident that you can handle the math. Physics does use many *symbols* to represent quantities, such as F for force, p for pressure, and E for energy, so many of our equations—like the ideal-gas law—are algebraic equations that show how quantities are related to one another. It's customary to use Greek letters to represent some quantities, but we'll let you know what those letters are when we introduce them.

We will, in some chapters, use a little bit of the calculus of derivatives and integrals. Don't panic! Our interest, once again, is not so much in doing calculations as in understanding how different physical quantities are related to one another. And we'll remind you, at the appropriate times, what derivatives and integrals are all about. In fact, most students feel that they come to understand calculus much better after studying physics because physics provides a natural context for illustrating why calculus is useful.

1.2 Models and Modeling

The real world is messy and complicated. A well-established procedure in physics is to brush aside many of the real-world details in order to discern *patterns* that occur over and over. For example, an object oscillating back and forth on a spring, a swinging pendulum, a vibrating guitar string, a sound wave, and an atom jiggling in a crystal seem very different—yet perhaps they are not really so different. Each is an example of a system oscillating around an equilibrium position. If we focus on understanding the properties of a very simple oscillating system, we'll find that we understand quite a bit about the many real-world manifestations of oscillations.

Stripping away the details to focus on essential features is a process called *modeling*. A **model** is a simplified picture of reality, but one that still captures the essence of what we want to study. Thus "mass on a spring" is a model of almost all oscillating systems. Models allow us to make sense of complex situations by providing a framework for thinking about them.

A memorable quote attributed to Albert Einstein is that physics "should be as simple as possible—but not simpler." We want to use the simplest model that allows us to understand the phenomenon we're studying, but we can't make the model so simple that essential features of the phenomenon are lost. That's somewhat of a problem in this text because understanding the *physics* of a biological system is not the same as understanding the biology. Our models of biological systems may seem to throw out much of the relevant biology, but keep in mind that our goal is to understand the ways in which the *physical* properties of the system have a meaningful effect on aspects of the biology.

We'll develop and use many models throughout this textbook; they'll be one of our most important thinking tools. These models will be of two types:

- *Descriptive models*: What are the essential characteristics and properties of a phenomenon? How do we describe it in the simplest possible terms? For example, we will often model a cell as a water-filled sphere. This omits all the details about what's inside, but for some purposes, such as estimating a cell's mass or volume, we don't need to know what's inside.
- *Explanatory models*: Why do things happen as they do? What causes what? Explanatory models have predictive power, allowing us to test—against experimental data—whether a model provides an adequate explanation of an observed phenomenon. A spring-like model of molecular bonds will allow us to explain many of the thermal properties of materials.

The eyes have it We study a *model organism* not to learn details about the organism but because the organism lends itself to the understanding of broad biological principles. *Drosophila melanogaster,* a common fruit fly, has provided immeasurable insights into genetics for more than a century.

Biologists also use models. A biological model, often qualitative rather than quantitative, is a simplified representation of the structure and function of a biological system or a biological process. The *cell model* is a simplified presentation of an immensely complex system, but it allows you to think logically about the key pieces and processes of a cell. Mice, fruit flies, and nematodes are important *model organisms* that lend themselves to the study of particular biological questions without unnecessary complications.

At the same time, biology and medicine are becoming increasingly quantitative, with models more and more like those constructed by physicists. For example:

- Mathematical models of enzyme kinetics provide quantitative predictions of complex biochemical pathways.
- Neural network models improve our understanding of both real brains and artificial intelligence.
- Epidemiological models increase our knowledge of how disease spreads.
- Global climate models that illustrate the earth's climate and how it is changing depend on a complex interplay between living (e.g., photosynthesis) and nonliving (e.g., solar radiation) processes.

These models skip over many details in order to provide a big-picture understanding of the system. That's the purpose of a model. This is not to say that details are unimportant—most scientists spend most of their careers studying the details—but that we don't want to let the trees obscure our view of the forest.

1.3 Case Study: Modeling Diffusion

Diffusion is one of the most important physical processes in biology. Oxygen diffuses from your lungs to your blood, and neurotransmitters diffuse across the synapses that connect one neuron to the next. We'll study diffusion extensively in Chapter 13, but as a case study let's see how a physicist might *model* diffusion and conclude when diffusion has biological significance. That is, our goal is to create a model that makes testable predictions of *how far* molecules can diffuse and *how long* it takes them to do so.

NOTE ▶ The analysis in this section is more complex than you are expected to do on your own. However, it is expected that you will follow the reasoning and be able to answer questions about the procedure and the results. ◀

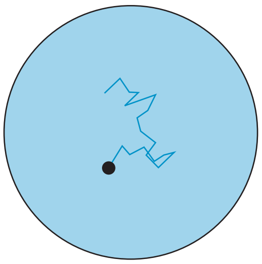


FIGURE 1.1 The possible motion of one molecule as it collides with other molecules.

On a microscopic scale, molecules are constantly jostling around and colliding with one another, an atomic-level motion we'll later associate with thermal energy. Any one molecule moves only a short distance before a collision sends it off in a different direction. Its trajectory, if we could see it, might look something like FIGURE 1.1: lots of short, straight segments of apparently random lengths in what appear to be random directions.

This is a chaotic and complex motion. The essence of modeling is to make simplifying assumptions, so how might we begin? The photographs in FIGURE 1.2 provide a clue. The left photo shows blue dye carefully deposited as a thin layer in a test tube of agar gel. The right photo is the same test tube one week later. It's a slow process, but the dye has diffused both up and down in a symmetrical pattern. This suggests that we start not with the complex three-dimensional motion of a molecule but with the simpler case of diffusion along a one-dimensional linear axis.

FIGURE 1.2 Vertical diffusion of blue dye.

A sidewalk is a linear axis. Suppose you stand at one location on an east-west sidewalk and flip a coin. If it's heads, you take one step to the east; if tails, one step to the west. Then you toss the coin again, and again, and again, each time randomly taking a step to the east or to the west. You would be engaged in what physicists and mathematicians call a one-dimensional **random walk.** Because collisions randomly redirect molecules, let's see what we can learn by modeling molecular motion as a random walk.

NOTE ▶ Variations on the random-walk model are used in applications ranging from protein folding and genetic drift to predicting share prices on the stock market. ◀

In particular, let's imagine a molecule that starts at the origin, $x = 0$, and then takes a random walk along the x-axis. That is, the molecule, at regular intervals, randomly takes a step whose length we'll call d in either the $+x$-direction or the $-x$-direction. At each step there's a 50% chance of going either way. To help make this clear, **FIGURE 1.3** shows what might be the first 10 steps of the molecule. The first two steps are to the right, the third back to the left, and so on. The molecule seems to wander aimlessly—that's the essence of random motion—and after 10 steps its position is $x_{10} = -2d$.

Now diffusion involves not one molecule but many, so imagine that we have a very large number of molecules that each move in one dimension along the x-axis. Assume that each molecule starts at the origin and then undergoes a random walk. What can we say about the collective behavior of a large number of random-walking molecules?

This is a problem that can be worked out exactly by using statistics, but the mathematical manipulations are a bit tricky. Instead, we'll explore the model as a computer simulation, one that you could do yourself in a spreadsheet. Suppose you put a zero in a spreadsheet cell to show a molecule's starting position. In the cell to the right, you use the spreadsheet's random-number generator—a digital coin flip—to either add d to the initial position (a step to the right) or subtract d from the initial position (a step to the left). Then you do the same thing in the next cell to the right, and then the next cell to the right of that, and so on, each time adding or subtracting d from the previous cell with a 50% chance of each. The 101st cell will be the molecule's position after taking 100 random steps.

Now you can add a second row of cells for a second molecule, a third row for a third molecule, and so on. It might take a big spreadsheet, but you can have as many molecules and as many steps as you wish. We've used exactly this procedure to simulate the random walks of 1000 molecules for 100 steps each. **FIGURE 1.4** gives the result by using dots to show the final positions of each of these molecules. Note that all molecules must be at an even multiple of d after an even number of steps, so the possible positions after 100 steps are 0, $\pm 2d$, $\pm 4d$, and so on. You can see that the first molecule—the top row—ends up at $x_{100} = 4d$ while the 453rd molecule in the 453rd row ends at $x_{100} = 24d$.

FIGURE 1.3 The first 10 steps of one possible random walk.

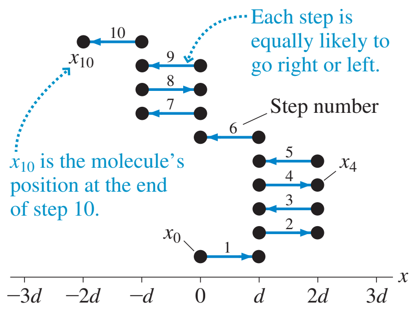
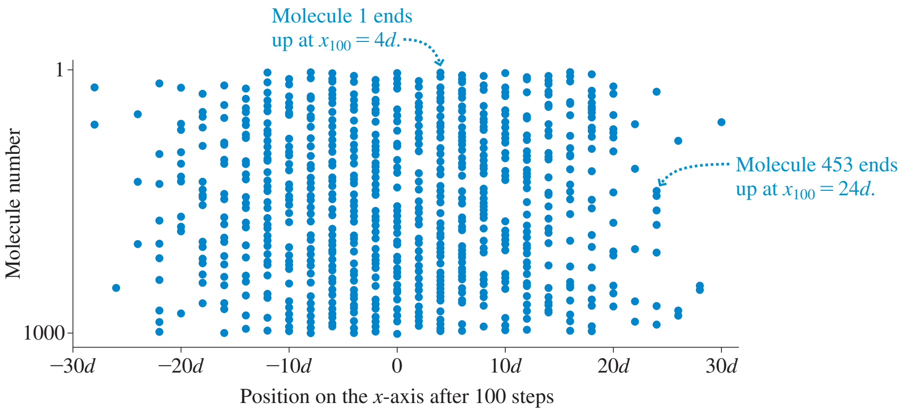


FIGURE 1.4 The result of 1000 molecules following a random walk for 100 steps.



The motion may be random, but the collective motion of many molecules reveals a pattern. Figure 1.4 shows that roughly half the molecules end up to the right of the origin and half to the left. That's exactly what we would expect from randomly taking steps to the right or left. Mathematically, we can say that the *average position* of all 1000 molecules is $x_{avg} = 0$. That is, the center of this array of dots is at the origin. You can see this in the second photo of Figure 1.2: The dye has spread, but it has done so symmetrically so that the center of the dye, its average position, is still in the middle of the test tube.

The center may not have moved, but the molecules are *spreading out,* which is exactly what diffusion is. However, the spreading is perhaps not as much as you might have expected. After 100 steps, a molecule could have reached $x = 100d$, but