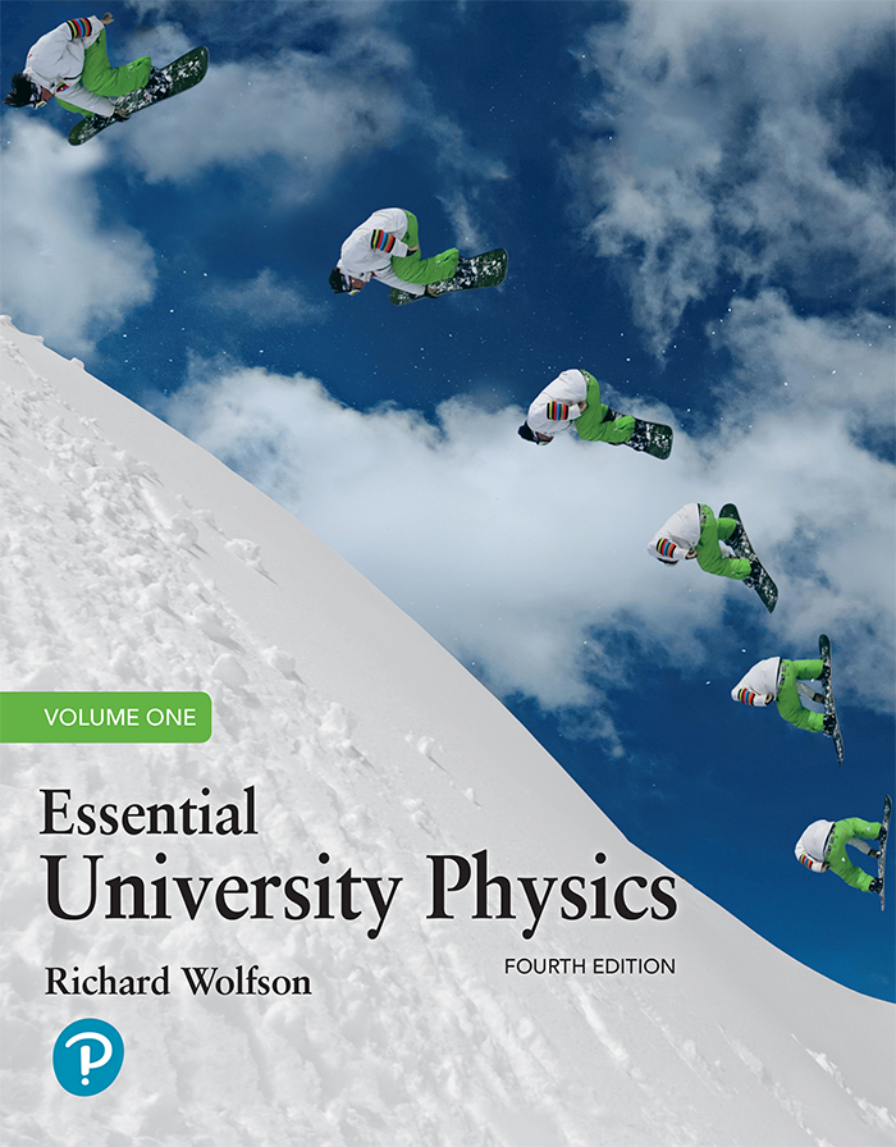


VOLUME ONE

Essential University Physics

FOURTH EDITION

Richard Wolfson

PHYSICAL CONSTANTS

CONSTANT	SYMBOL	THREE-FIGURE VALUE	BEST KNOWN VALUE*
Speed of light	c	3.00×10^{8} m/s	299,792,458 m/s (exact)
Elementary charge	e	1.60×10^{-19} C	$1.602\,176\,634 \times 10^{-19}$ C (exact)
Electron mass	m_e	9.11×10^{-31} kg	$9.109\,383\,56(11) \times 10^{-31}$ kg
Proton mass	m_p	1.67×10^{-27} kg	$1.672\,621\,898(21) \times 10^{-27}$ kg
Gravitational constant	G	6.67×10^{-11} N·m^2/kg^2	$6.67408(31) \times 10^{-11}$ N·m^2/kg^2
Permeability constant	μ_0	1.26×10^{-6} N/A^2 (H/m)	$12.566\,370\,616\,9(29) \times 10^{-7}$ N/A^2
Permittivity constant	ϵ_0	8.85×10^{-12} C^2/N·m^2 (F/m)	$8.854\,187\,815\,8(20) \times 10^{-7}$ C^2/ N·m^2
Boltzmann's constant	k	1.38×10^{-23} J/K	$1.380\,649 \times 10^{-23}$ J/K (exact)
Universal gas constant	R	8.31 J/K·mol	$N_A k$ (exact)
Stefan–Boltzmann constant	σ	5.67×10^{-8} W/m^2·K^4	$5.670\,367(13) \times 10^{-8}$ W/m^2·K^4
Planck's constant	$h\,(= 2\pi\hbar)$	6.63×10^{-34} J·s	$6.626\,070\,15 \times 10^{-34}$ J·s (exact)
Avogadro's number	N_A	6.02×10^{23} mol^{-1}	$6.022\,140\,76 \times 10^{23}$ mol^{-1} (exact)
Bohr radius	a_0	5.29×10^{-11} m	$5.291\,772\,085\,9(36) \times 10^{-11}$ m

*Parentheses indicate uncertainties in last decimal places. *Source*: U.S. National Institute of Standards and Technology, 2014, 2019 values

SI PREFIXES

POWER	PREFIX	SYMBOL
10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deca	da
10^{0}	—	—
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

THE GREEK ALPHABET

	UPPERCASE	LOWERCASE
Alpha	Α	α
Beta	Β	β
Gamma	Γ	γ
Delta	Δ	δ
Epsilon	Ε	ϵ
Zeta	Ζ	ζ
Eta	Η	η
Theta	∫	θ
Iota	Ι	ι
Kappa	Κ	κ
Lambda	Λ	λ
Mu	Μ	μ
Nu	Ν	ν
Xi	Ξ	ξ
Omicron	Ο	o
Pi	Π	π
Rho	Ρ	ρ
Sigma	Σ	σ
Tau	Τ	τ
Upsilon	Υ	υ
Phi	Φ	ϕ
Chi	Χ	χ
Psi	Ψ	ψ
Omega	Ω	ω

Conversion Factors (more conversion factors in Appendix C)

Length

1 in = 2.54 cm
1 mi = 1.609 km
1 ft = 0.3048 m
1 light year = 9.46×10^{15} m

Velocity

1 mi/h = 0.447 m/s
1 m/s = 2.24 mi/h = 3.28 ft/s

Mass, energy, force

1 u = 1.661×10^{-27} kg
1 cal = 4.184 J
1 Btu = 1.054 kJ
1 kWh = 3.6 MJ
1 eV = 1.602×10^{-19} J
1 pound (lb) = 4.448 N
= weight of 0.454 kg

Time

1 day = 86,400 s
1 year = 3.156×10^{7} s

Pressure

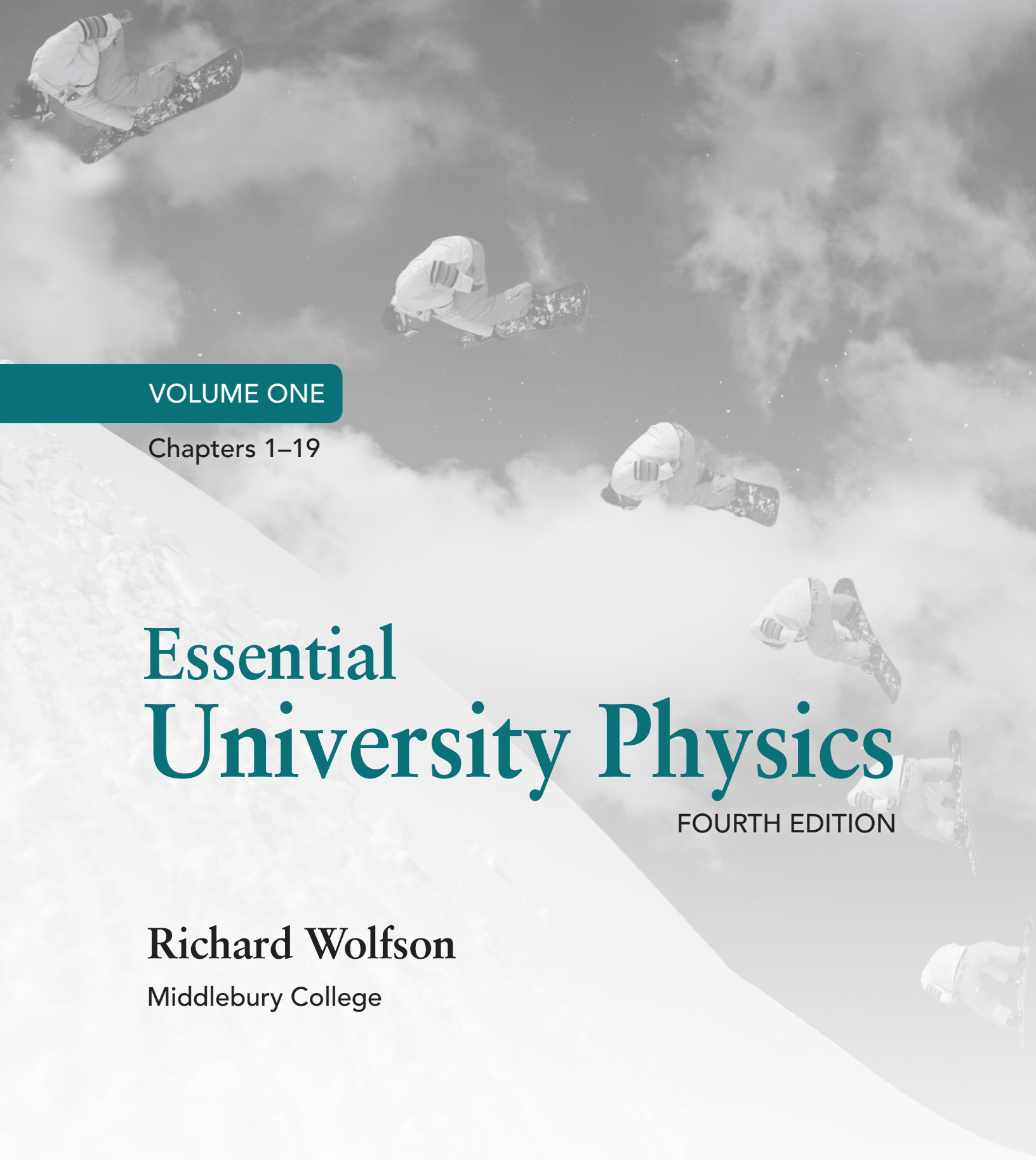
1 atm = 101.3 kPa = 760 mm Hg
1 atm = 14.7 lb/in^2

Rotation and angle

1 rad = $180°/\pi = 57.3°$
1 rev = $360° = 2\pi$ rad
1 rev/s = 60 rpm

Magnetic field

1 gauss = 10^{-4} T



VOLUME ONE

Chapters 1–19

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FOURTH EDITION

Richard Wolfson

Middlebury College

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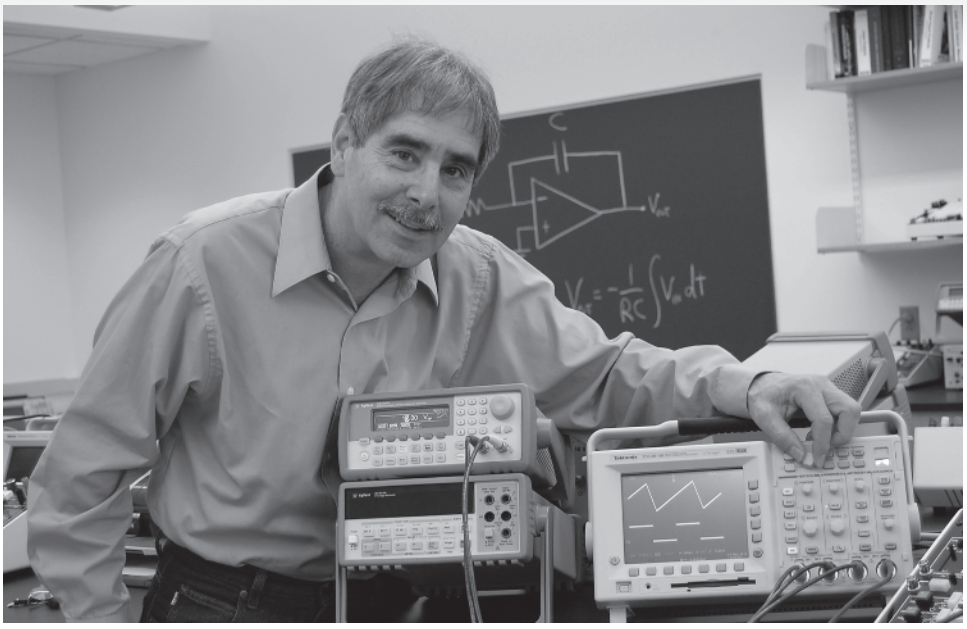
About the Author



Richard Wolfson

Richard Wolfson is the Benjamin F. Wissler Professor of Physics at Middlebury College, where he has taught since 1976. He did undergraduate work at MIT and Swarthmore College, and he holds an M.S. from the University of Michigan and a Ph.D. from Dartmouth. His ongoing research on the Sun's corona and climate change has taken him to sabbaticals at the National Center for Atmospheric Research in Boulder, Colorado; St. Andrews University in Scotland; and Stanford University.

Rich is a committed and passionate teacher. This is reflected in his many publications for students and the general public, including the video series *Einstein's Relativity and the Quantum Revolution: Modern Physics for Nonscientists* (The Teaching Company, 1999), *Physics in Your Life* (The Teaching Company, 2004), *Physics and Our Universe: How It All Works* (The Teaching Company, 2011), and *Understanding Modern Electronics* (The Teaching Company, 2014); books *Nuclear Choices: A Citizen's Guide to Nuclear Technology* (MIT Press, 1993), *Simply Einstein: Relativity Demystified* (W. W. Norton, 2003), and *Energy, Environment, and Climate* (W. W. Norton, third edition, 2018); and articles for *Scientific American* and the *World Book Encyclopedia.*

Outside of his research and teaching, Rich enjoys hiking, canoeing, gardening, cooking, and watercolor painting.

Preface to the Instructor

Introductory physics texts have grown ever larger, more massive, more encyclopedic, more colorful, and more expensive. *Essential University Physics* bucks that trend—without compromising coverage, pedagogy, or quality. The text benefits from the author's four decades of teaching introductory physics, seeing firsthand the difficulties and misconceptions that students face as well as the GOT IT? moments when big ideas become clear. It also builds on the author's honing multiple editions of a previous calculus-based textbook and on feedback from hundreds of instructors and students.

Goals of This Book

Physics is the fundamental science, at once fascinating, challenging, and subtle—and yet simple in a way that reflects the few basic principles that govern the physical universe. My goal is to bring this sense of physics alive for students in a range of academic disciplines who need a solid calculus-based physics course—whether they're engineers, physics majors, premeds, biologists, chemists, geologists, mathematicians, computer scientists, or other majors. My own courses are populated by just such a variety of students, and among my greatest joys as a teacher is having students who took a course only because it was required say afterward that they really enjoyed their exposure to the ideas of physics. More specifically, my goals include:

- Helping students build the analytical and quantitative skills and confidence needed to apply physics in problem solving for science and engineering.
- Addressing key misconceptions and helping students build a stronger conceptual understanding.
- Helping students see the relevance and excitement of the physics they're studying with contemporary applications in science, technology, and everyday life.
- Helping students develop an appreciation of the physical universe at its most fundamental level.
- Engaging students with an informal, conversational writing style that balances precision with approachability.

New to the Fourth Edition

The emphasis in this fourth-edition revision has been on pedagogical features, including substantial updates to the end-of-chapter problem sets, learning outcomes, annotated equations, and new, contemporary applications. In addition, I've responded—as I have in previous editions—to the many suggestions made by my colleagues, by instructors around the world, and by reviewers engaged to help make this the most student-friendly and pedagogically useful edition of *Essential University Physics*. And, as always, I've been on the lookout for new developments in physics and technology to incorporate into the text.

- Chapter opening pages have been redesigned to include explicit lists of **learning outcomes** associated with each chapter. Learning outcomes appear at the appropriate section headings and are also keyed with specific problems.
- End-of-chapter problem sets each have between 15% and 20% **new problems**. Many of the new problems are of intermediate difficulty, featuring multiple steps and requiring a clear understanding of problem-solving strategies. I've also increased the number of estimation problems and of problems involving symbolic rather than numerical answers. Still other new problems feature contemporary real-world situations.

- Among the most exciting of the new features—and one that gave me both great challenges and great professional satisfaction—are the **Example Variation (EV)** problems. These two sets of four related problems in each chapter, each set based on one of the chapter's worked examples, help the student make connections, enhance her understanding of physics, and build confidence in solving problems different from ones she's seen before. The first problem in each set is essentially the example problem but with different numbers. The second presents the same scenario as the example but asks a different question. The third and fourth problems repeat this pattern but with entirely different scenarios. Working these problems ensures first that the student understands the worked example and then gradually takes her out of her comfort zone to explore new physics, more challenging math, and more complex problem solving.
- Students should perceive a physics textbook as more than a list of equations to consult in solving assigned problems. *Essential University Physics* has always helped students avoid this unfortunate approach to physics. Earlier editions had a few instances where I felt an equation was so important that I developed a separate figure that was essentially an "anatomy" of the equation, with annotations pointing to and explaining the terms in the equation. The new edition extends this approach with **annotated key equations**, giving life to and understanding of all the most important and fundamental equations as statements about the physical universe rather than mere math into which numbers get plugged.
- A host of **new applications** connects physics concepts that students are learning with contemporary technological and biomedical innovations, as well as recent scientific discoveries. A sample of new applications includes the acceleration of striking rattlesnakes, gravitational wave detection and multimessenger astronomy, earthquake resonance effects, the *New Horizons* mission to Pluto, the audacious *Starshot* project, the graded-index lenses of squids' eyes, and environmental and energy issues.
- As with earlier revisions, I've incorporated new research results, new applications of physics principles, and findings from physics education research.
- Finally, this edition includes the 2019 revision of the SI—the international system of units—which represents the most significant change the SI has undergone in more than a century.

Pedagogical Innovations

This book is *concise*, but it's also *progressive* in its embrace of proven techniques from physics education research and *strategic* in its approach to learning physics. Chapter 1 introduces the IDEA framework for problem solving, and every one of the book's subsequent **worked examples** employs this framework. IDEA—an acronym for Identify, Develop, Evaluate, Assess—is not a "cookbook" method for students to apply mindlessly, but rather a tool for organizing students' thinking and discouraging equation hunting. It begins with an interpretation of the problem and an identification of the key physics concepts involved; develops a plan for reaching the solution; carries out the mathematical evaluation; and assesses the solution to see that it makes sense, to compare the example with others, and to mine additional insights into physics. In nearly all of the text's worked examples, the Develop phase includes making a drawing, and most of these use a hand-drawn style to encourage students to make their own drawings—a step that research suggests they often skip. IDEA provides a common approach to all physics problem solving, an approach that emphasizes the conceptual unity of physics and helps break the typical student view of physics as a hodgepodge of equations and unrelated ideas. In addition to IDEA-based worked examples, other pedagogical features include:

- **Problem-Solving Strategy boxes** that follow the IDEA framework to provide detailed guidance for specific classes of physics problems, such as Newton's second law, conservation of energy, thermal-energy balance, Gauss's law, or multiloop circuits.
- **Tactics boxes** that reinforce specific essential skills such as differentiation, setting up integrals, vector products, drawing free-body diagrams, simplifying series and parallel circuits, or ray tracing.

- **QR** codes at the end of each chapter link to resources on Mastering Physics, including video tutorials. These "Pause and predict" videos of key physics concepts ask students to submit a prediction before they see the outcome. The videos are also available in the Study Area of Mastering and in the Pearson eText.
- **GOT IT? boxes** that provide quick checks for students to test their conceptual understanding. Many of these use a multiple-choice or quantitative ranking format to probe student misconceptions and facilitate their use with classroom-response systems.
- **Tips** that provide helpful problem-solving hints or warn against common pitfalls and misconceptions.
- **Chapter openers** that include a graphical indication of where the chapter lies in sequence as well as lists of the learning outcomes and of skills and knowledge needed for the chapter. Each chapter also includes an opening photo, captioned with a question whose answer should be evident after the student has completed the chapter.
- **Applications**, self-contained presentations typically shorter than half a page, provide interesting and contemporary instances of physics in the real world, such as bicycle stability; flywheel energy storage; laser vision correction; ultracapacitors; noise-cancelling headphones; wind energy; magnetic resonance imaging; smartphone gyroscopes; combined-cycle power generation; circuit models of the cell membrane; CD, DVD, and Blu-ray technologies; radiocarbon dating; and many, many more.
- **For Thought and Discussion** questions at the end of each chapter designed for peer learning or for self-study to enhance students' conceptual understanding of physics.
- **Annotated figures** that adopt the research-based approach of including simple "instructor's voice" commentary to help students read and interpret pictorial and graphical information.
- **Annotated equations**, new to the fourth edition, that feature a similar format to the annotated figures.
- **End-of-chapter** problems that begin with simpler exercises keyed to individual chapter sections and ramp up to more challenging and often multistep problems that synthesize chapter material. Context-rich problems focusing on real-world situations are interspersed throughout each problem set.
- **Chapter summaries** that combine text, art, and equations to provide a synthesized overview of each chapter. Each summary is hierarchical, beginning with the chapter's "big ideas," then focusing on key concepts and equations, and ending with a list of "applications"—specific instances or applications of the physics presented in the chapter.

Organization

This contemporary book is *concise*, *strategic*, and *progressive*, but it's *traditional* in its organization. Following the introductory Chapter 1, the book is divided into six parts. Part One (Chapters 2–12) develops the basic concepts of mechanics, including Newton's laws and conservation principles as applied to single particles and multiparticle systems. Part Two (Chapters 13–15) extends mechanics to oscillations, waves, and fluids. Part Three (Chapters 16–19) covers thermodynamics. Part Four (Chapters 20–29) deals with electricity and magnetism. Part Five (Chapters 30–32) treats optics, first in the geometrical optics approximation and then including wave phenomena. Part Six (Chapters 33–39) introduces relativity and quantum physics. Each part begins with a brief description of its coverage, and ends with a conceptual summary and a challenge problem that synthesizes ideas from several chapters.

Essential University Physics is available in two paperback volumes, so students can purchase only what they need—making the low-cost aspect of this text even more attractive. Volume 1 includes Parts One, Two, and Three, mechanics through thermodynamics. Volume 2 contains Parts Four, Five, and Six, electricity and magnetism along with optics and modern physics.

Instructor Supplements

Note: For convenience, all of the following instructor supplements can be downloaded from the Instructor's Resource Area of Mastering™ Physics (www.masteringphysics.com).

Name of Supplement	Instructor or Student Supplement	Description
Mastering™ Physics (www.masteringphysics.com) (9780135285848)	Supplement for Students and Instructors	Mastering Physics from Pearson is the most advanced physics homework and tutorial system available. This online homework and tutoring system guides students through the toughest topics in physics with self-paced tutorials that provide individualized coaching. These assignable, in-depth tutorials are designed to coach students with hints and feedback specific to their individual errors. Instructors can also assign end-of-chapter problems from every chapter, including multiple-choice questions, section-specific exercises, and general problems. Quantitative problems can be assigned with numerical answers and randomized values (with significant figure feedback) or solutions. The Mastering gradebook records scores for all automatically graded assignments in one place, while diagnostic tools give instructors access to rich data to assess student understanding and misconceptions. http://www.masteringphysics.com.
Pearson eText enhanced with media (9780135208120)	Supplement for Students and Instructors	The fourth edition of *Essential University Physics* features a Pearson eText enhanced with the media that were previously only accessible through Mastering. The Pearson eText offers students the power to create notes, highlight text in different colors, create bookmarks, zoom, launch videos as they read, and view single or multiple pages. Professors also have the ability to annotate the text for their course and hide chapters not covered in their syllabi.
Instructor Solutions Manual–Download Only (9780135191729)	Supplement for Instructors	Prepared by John Beetar, the Instructor Solutions Manual contains solutions to all end-of-chapter exercises and problems, written in the Interpret/Develop/Evaluate/Assess (IDEA) problem-solving framework. The solutions are provided in PDF and editable Microsoft® Word formats for Mac and PC, with equations in MathType.
Instructor Resources Materials–Download Only (9780135412510)	Supplement for Instructors	Includes all the art, photos, and tables from the book in JPEG format for use in classroom projection or when creating study materials and tests. Also available are downloadable files of the Instructor Solutions Manual and "Clicker Questions," including GOT IT? Clickers, for use with classroom-response systems. Each chapter also has a set of PowerPoint® lecture outlines. These resources are downloadable from the 'Instructor's Resources' area within Mastering Physics. They are also downloadable from the catalog page for Wolfson's *Essential University Physics*, 4th edition, at www.pearsonhighered.com.
TestGen Test Bank–Download Only (9780135412497)	Supplement for Instructors	The TestGen Test Bank contains more than 2000 multiple-choice, true-false, and conceptual questions in TestGen® and Microsoft® Word formats for Mac and PC users. More than half of the questions can be assigned with randomized numerical values.

Acknowledgments

A project of this magnitude isn't the work of its author alone. First and foremost among those I thank for their contributions are the now several thousand students I've taught in calculus-based introductory physics courses at Middlebury College. Over the years your questions have taught me how to convey physics ideas in many different ways appropriate to your diverse learning styles. You've helped identify the "sticking points" that challenge introductory physics students, and you've showed me ways to help you avoid and "unlearn" the misconceptions that many students bring to introductory physics.

Thanks also to the numerous instructors and students from around the world who have contributed valuable suggestions for improvement of this text. I've heard you, and you'll find many of your ideas implemented in this fourth edition of

Essential University Physics. And special thanks to my Middlebury physics colleagues who have taught from this text and who contribute valuable advice and insights on a regular basis: Jeff Dunham, Mike Durst, Angus Findlay, Eilat Glikman, Anne Goodsell, Noah Graham, Chris Herdmann, Paul Hess, Susan Watson, and especially Steve Ratcliff.

Experienced physics instructors thoroughly reviewed every chapter of this book, and reviewers' comments resulted in substantive changes—and sometimes in major rewrites—to the first drafts of the manuscript. We list these reviewers below. But first, special thanks are due to several individuals who made exceptional contributions to the quality and in some cases the very existence of this book. First is Professor Jay Pasachoff of Williams College, whose willingness more than three decades ago to take a chance on an inexperienced coauthor has made writing introductory physics a large part of my professional career. Dr. Adam Black, former physics editor at Pearson, had the vision to see promise in a new introductory text that would respond to the rising chorus of complaints about massive, encyclopedic, and expensive physics texts. Brad Patterson, developmental editor for the first edition, brought his graduate-level knowledge of physics to a role that made him a real collaborator. Brad is responsible for many of the book's innovative features, and it was a pleasure to work with him. John Murdzek continued Brad's excellent tradition of developmental editing on this fourth edition. We've gone to great lengths to make this book as error-free as possible, and much of the credit for that happy situation goes to John Beetar, who solved every new and revised end-of-chapter problem and updated the solutions manual, and to Edward Ginsberg, who blind-solved all the new problems and thus provided a third check on the answers.

I also wish to thank Nancy Whilton, Jeanne Zalesky, and Tiffany Mok at Pearson Education, and Kim Fletcher at Integra, for their highly professional efforts in shepherding this book through its vigorous production schedule. Finally, as always, I thank my family, my colleagues, and my students for the patience they showed during the intensive process of writing and revising this book.

Reviewers

John R. Albright, *Purdue University–Calumet*
Rama Bansil, *Boston University*
Richard Barber, *Santa Clara University*
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Rasheed Bashirov, *Albertson College of Idaho*
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Fredy Zypman, *Yeshiva University*

Preface to the Student

Welcome to physics! Maybe you're taking introductory physics because you're majoring in a field of science or engineering that requires a semester or two of physics. Maybe you're premed, and you know that medical schools are interested in seeing calculus-based physics on your transcript. Perhaps you're really gung-ho and plan to major in physics. Or maybe you want to study physics further as a minor associated with related fields like math, computer science, or chemistry or to complement a discipline like economics, environmental studies, or even music. Perhaps you had a great high-school physics course, and you're eager to continue. Maybe high-school physics was an academic disaster for you, and you're approaching this course with trepidation. Or perhaps this is your first experience with physics. Whatever your reason for taking introductory physics, welcome!

And whatever your reason, my goals for you are similar: I'd like to help you develop an understanding and appreciation of the physical universe at a deep and fundamental level; I'd like you to become aware of the broad range of natural and technological phenomena that physics can explain; and I'd like to help you strengthen your analytic and quantitative problem-solving skills. Even if you're studying physics only because it's a requirement, I want to help you engage the subject and come away with an appreciation for this fundamental science and its wide applicability. One of my greatest joys as a physics teacher is having students tell me after the course that they had taken it only because it was required, but found they really enjoyed their exposure to the ideas of physics.

Physics is fundamental. To understand physics is to understand how the world works, both in everyday life and on scales of time and space so small and so large as to defy intuition. For that reason I hope you'll find physics fascinating. But you'll also find it challenging. Learning physics will challenge you with the need for precise thinking and language; with subtle interpretations of even commonplace phenomena; and with the need for skillful application of mathematics. But there's also a simplicity to physics, a simplicity that results because there are in physics only a very few really basic principles to learn. Those succinct principles encompass a universe of natural phenomena and technological applications.

I've been teaching introductory physics for decades, and this book distills everything my students have taught me about the many different ways to approach physics; about the subtle misconceptions students often bring to physics; about the ideas and types of problems that present the greatest challenges; and about ways to make physics engaging, exciting, and relevant to your life and interests.

I have some specific advice for you that grows out of my long experience teaching introductory physics. Keeping this advice in mind will make physics easier (but not necessarily easy!), more interesting, and, I hope, more fun:

- *Read* each chapter thoroughly and carefully before you attempt to work any problem assignments. I've written this text with an informal, conversational style to make it engaging. It's not a reference work to be left alone until you need some specific piece of information; rather, it's an unfolding "story" of physics—its big ideas and their applications in quantitative problem solving. You may think physics is hard because it's mathematical, but in my long experience I've found that failure to *read* thoroughly is the biggest single reason for difficulties in introductory physics.
- *Look for the big ideas.* Physics isn't a hodgepodge of different phenomena, laws, and equations to memorize. Rather, it's a few big ideas from which flow myriad applications, examples, and special cases. In particular, don't think of physics as a jumble of equations that you choose among when solving a problem. Rather, identify those few big ideas and the equations that represent them, and try to see how seemingly distinct examples and special cases relate to the big ideas.
- *When working problems, re-read* the appropriate sections of the text, paying particular attention to the worked examples. Follow the IDEA strategy described in Chapter 1 and used in every subsequent worked example. Don't skimp on the final Assess step. Always ask: Does this answer make sense? How can I understand my answer in relation to the big principles of physics? How was this problem like others I've worked, or like examples in the text?
- *Don't confuse physics with math.* Mathematics is a tool, not an end in itself. Equations in physics aren't abstract math, but statements about the physical world. Be sure you understand each equation for what it says about physics, not just as an equality between mathematical terms.
- *Work with others.* Getting together informally in a room with a blackboard is a great way to explore physics, to clarify your ideas and help others clarify theirs, and to learn from your peers. I urge you to discuss physics problems together with your classmates, to contemplate together the "For Thought and Discussion" questions at the end of each chapter, and to engage one another in lively dialog as you grow your understanding of physics, the fundamental science.

Video Tutor Demonstrations

Video tutor demonstrations can be accessed by scanning the QR code at the end of each chapter in the textbook using a smartphone. They are also available in the Study Area and Instructor's Resource Area on Mastering Physics and in the eText. Practice Exams and Dynamic Study Modules, which can be used to prepare for exams, are also available in Mastering Physics.

Chapter	Video Tutor Demonstration
2	Balls Take High and Low Tracks
3	Dropped and Thrown Balls
3	Ball Fired from Cart on Incline
3	Ball Fired Upward from Accelerating Cart
3	Range of a Gun at Two Firing Angles
3	Independent Horizontal and Vertical Motion
4	Cart with Fan and Sail
4	Ball Leaves Circular Track
4	Suspended Balls: Which String Breaks?
4	Weighing a Hovering Magnet
5	Tension in String between Hanging Weights
5	Rotational Motion—Loop the Loop
6	Work and Kinetic Energy
7	Chin Basher?
9	Balancing a Meter Stick
9	Water Rocket
9	Happy/Sad Pendulums
9	Conservation of Linear Momentum
10	Canned Food Race
11	Spinning Person Drops Weights
11	Off-Center Collision
11	Conservation of Vector Angular Momentum
11	Conservation of Angular Momentum
12	Walking the Plank
13	Vibrating Rods
13	Resonance of Everyday Items
14	Out-of-Phase Speakers
15	Pressure in Water and Alcohol
15	Water Level in Pascal's Vases
15	Weighing Weights in Water
15	Air Jet Blows between Bowling Balls
15	Bernoulli's Principle—Venturi Tubes
16	Heating Water and Aluminum
16	Water Balloon Held over Candle Flame
16	Candle Chimneys
20	Charged Rod and Aluminum Can
21	Electroscope in Conducting Shell
22	Charged Conductor with Teardrop Shape
23	Discharge Speed for Series and Parallel Capacitors
24	Resistance in Copper and Nichrome
25	Bulbs Connected in Series and in Parallel
26	Magnet and Electron Beam
26	Current-Carrying Wire in Magnetic Field
27	Eddy Currents in Different Metals
29	Parallel-Wire Polarizer for Microwaves
29	Point of Equal Brightness between Two Light Sources
31	Partially Covering a Lens
36	Illuminating Sodium Vapor with Sodium and Mercury Lamps

Essential University Physics

Doing Physics

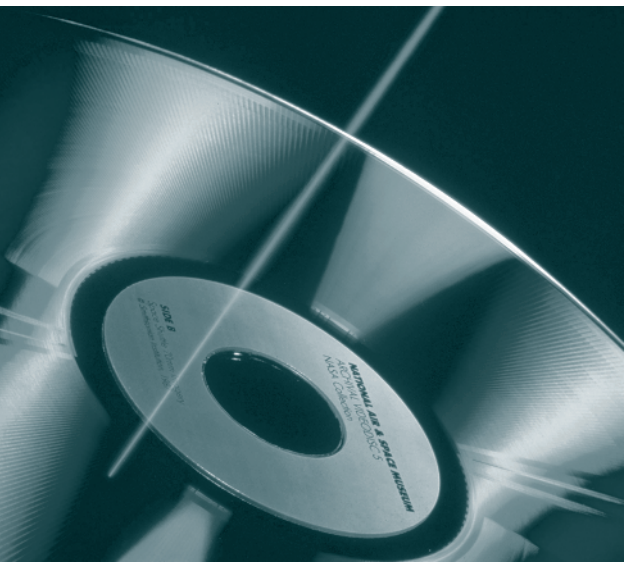
Skills & Knowledge You'll Need

- Your high school algebra and geometry
- Later, trigonometry and beginning calculus

Learning Outcomes

After finishing this chapter you should be able to:

LO 1.1 Describe the scope and realms of physics.
LO 1.2 List the base units of the International System of Units (SI).
LO 1.3 Convert units to and from other unit systems.
LO 1.4 Express numbers using scientific notation or SI prefixes.
LO 1.5 Do calculations with attention to significant figures.
LO 1.6 Make order-of-magnitude estimates.
LO 1.7 Plot data and extract information using best-fit lines.



Which realms of physics are involved in the workings of your DVD player?

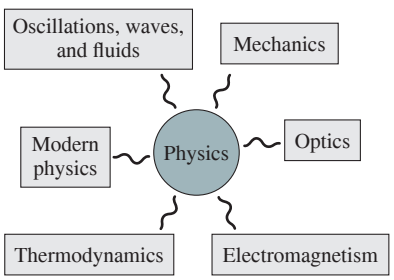


FIGURE 1.1 Realms of physics.

You slip a DVD into your player and settle in to watch a movie. The DVD spins, and a precisely focused laser beam "reads" its content. Electronic circuitry processes the information, sending it to your video display and to loudspeakers that turn electrical signals into sound waves. Every step of the way, principles of physics govern the delivery of the movie from DVD to you.

1.1 Realms of Physics

LO 1.1 *Describe the scope and realms of physics.*

That DVD player is a metaphor for all of **physics**—the science that describes the fundamental workings of physical reality. Physics explains natural phenomena ranging from the behavior of atoms and molecules to thunderstorms and rainbows and on to the evolution of stars, galaxies, and the universe itself. Technological applications of physics are the basis for everything from microelectronics to medical imaging to cars, airplanes, and space flight.

At its most fundamental, physics provides a nearly unified description of all physical phenomena. However, it's convenient to divide physics into distinct realms (Fig. 1.1). Your DVD player encompasses essentially all those realms. **Mechanics**, the branch of physics that deals with motion, describes the spinning disc. Mechanics also explains the motion of a car, the orbits of the planets, and the stability of a skyscraper. Part 1 of this book deals with the basic ideas of mechanics.

Those sound waves coming from your loudspeakers represent **wave motion**. Other examples include the ocean waves that pound Earth's coastlines, the wave of standing spectators that sweeps through a football stadium, and the undulations of Earth's crust that spread the energy of an earthquake. Part 2 of this book covers wave motion and other phenomena involving the motion of fluids like air and water.

When you burn your own DVD, the high temperature produced by an intensely focused laser beam alters the material properties of a writable DVD, thus storing video or computer information. That's an example of **thermodynamics**—the study of heat and its effects on matter. Thermodynamics also describes the delicate balance of energy-transfer processes that keeps our planet at a habitable temperature and puts serious constraints on our ability to meet the burgeoning energy demands of modern society. Part 3 comprises four chapters on thermodynamics.

An electric motor spins your DVD, converting electrical energy to the energy of motion. Electric motors are ubiquitous in modern society, running everything from subway trains and electric cars, to elevators and washing machines, to insulin pumps and artificial hearts. Conversely, electric generators convert the energy of motion to electricity, providing virtually all of our electrical energy. Motors and generators are two applications of **electromagnetism** in modern technology. Others include computers, audiovisual electronics, microwave ovens, digital watches, and even the humble lightbulb; without these electromagnetic technologies our lives would be very different. Equally electromagnetic are all the wireless technologies that enable modern communications, from satellite TV to cell phones to wireless computer networks, mice, and keyboards. And even light itself is an electromagnetic phenomenon. Part 4 presents the principles of electromagnetism and their many applications.

The precise focusing of laser light in your DVD player allows hours of video to fit on a small plastic disc. The details and limitations of that focusing are governed by the principles of **optics**, the study of light and its behavior. Applications of optics range from simple magnifiers to contact lenses to sophisticated instruments such as microscopes, telescopes, and spectrometers. Optical fibers carry your e-mail, web pages, and music downloads over the global Internet. Natural optical systems include your eye and the raindrops that deflect sunlight to form rainbows. Part 5 of the book explores optical principles and their applications.

That laser light in your DVD player is an example of an electromagnetic wave, but an atomic-level look at the light's interaction with matter reveals particle-like "bundles" of electromagnetic energy. This is the realm of **quantum physics**, which deals with the often counterintuitive behavior of matter and energy at the atomic level. Quantum phenomena also explain how that DVD laser works and, more profoundly, the structure of atoms and the periodic arrangement of the elements that is the basis of all chemistry. Quantum physics is one of the two great developments of **modern physics**. The other is Einstein's **theory of relativity**. Relativity and quantum physics arose during the 20th century, and together they've radically altered our commonsense notions of time, space, and causality. Part 6 of the book surveys the ideas of modern physics, ending with what we do—and don't—know about the history, future, and composition of the entire universe.

CONCEPTUAL EXAMPLE 1.1 Car Physics

Name some systems in your car that exemplify the different realms of physics.

EVALUATE *Mechanics* is easy; the car is fundamentally a mechanical system whose purpose is motion. Details include starting, stopping, cornering, as well as a host of other motions within mechanical subsystems. Your car's springs and shock absorbers constitute an *oscillatory* system engineered to give a comfortable ride. The car's engine is a prime example of a *thermodynamic* system, converting the energy of burning gasoline into the car's motion. *Electromagnetic* systems range from the starter motor and spark plugs to sophisticated electronic devices that monitor and optimize engine performance. *Optical* principles govern rear- and side-view mirrors and headlights. Increasingly, optical fibers transmit information to critical safety systems. *Modern physics* is less obvious in your car, but ultimately, everything from the chemical reactions of burning gasoline to the atomic-scale operation of automotive electronics is governed by its principles.

1.2 Measurements and Units

LO 1.2 *List the base units of the International System of Units (SI).*

LO 1.3 *Convert units to and from other unit systems.*

"A long way" means different things to a sedentary person, a marathon runner, a pilot, and an astronaut. We need to quantify our measurements. Science uses the **metric system**, with

fundamental quantities length, mass, and time measured in meters, kilograms, and seconds, respectively. The modern version of the metric system is **SI**, for *Système International d'Unités* (International System of Units), which incorporates scientifically precise definitions of the fundamental quantities.

The three fundamental quantities were originally defined in reference to nature: the meter in terms of Earth's size, the kilogram as an amount of water, and the second by the length of the day. For length and mass, these were later replaced by specific artifacts— a bar whose length was defined as 1 meter and a cylinder whose mass defined the kilogram. But natural standards like the day's length can change, as can the properties of artifacts. So early SI definitions gave way to **operational definitions**, which are measurement standards based on laboratory procedures. Such standards have the advantage that scientists anywhere can reproduce them. By the late 20th century, two of the three fundamental units—the meter and the second—had operational definitions, but the kilogram did not.

A special type of operational definition involves giving an exact value to a particular constant of nature—a quantity formerly subject to experimental determination and with a stated uncertainty in its value. As described below, the meter was the first such unit to be defined in this way. By the early 21st century, it was clear that defining units in terms of fundamental, invariant physical constants was the best way to ensure long-term stability of the SI unit system. Laboratories around the world sought the most reliable measurement techniques and collaborated in narrowing uncertainties in fundamental constants. Then, in 2019, the International Bureau of Weights and Measures approved a sweeping revision of the SI system that redefined the kilogram and other so-called base units in terms of fundamental constants that are now given exact values. These so-called **explicit-constant** definitions also make clear how some definitions depend on others—for example, the definition of the meter requires the definition of the second.

APPLICATION

Units Matter: A Bad Day on Mars

In September 1999, the *Mars Climate Orbiter* was destroyed when the spacecraft passed through Mars's atmosphere and experienced stresses and heating it was not designed to tolerate. Why did this $125-million craft enter the Martian atmosphere when it was supposed to remain in the vacuum of space? NASA identified the root cause as a failure to convert the English units one team used to specify rocket thrust to the SI units another team expected. Units matter!

Time

The **second** used to be defined by Earth's rotation, but that's not constant, so it was later redefined as a specific fraction of the year 1900. An operational definition followed in 1967, associating the second with the radiation emitted by a particular atomic process. The new definition keeps the essence of that operational definition but rewords it in the explicit-constant style:

> The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the cesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the cesium-133 atom, to be 9,192,631,770 when expressed in the unit Hz, which is equal to s^{-1}.

The device that implements this definition—which will seem less obscure once you've studied some atomic physics—is called an *atomic clock*. Here the phrase "in the unit Hz" introduces the unit hertz (Hz) for frequency—the number of cycles of a repeating process that occur each second.

Length

The **meter** was first defined as one ten-millionth of the distance from Earth's equator to the North Pole. In 1889 a standard meter was fabricated to replace the Earth-based unit, and in 1960 that gave way to a standard based on the wavelength of light. By the 1970s, the speed of light had become one of the most precisely determined quantities. As a result, the meter was redefined in 1983 as the distance light travels in vacuum in 1/299,792,458 of a second. The effect of this definition is to make the speed of light a defined quantity: 299,792,458 m/s. Thus, the meter became the first SI unit to be based on a defined value for a fundamental constant. The new SI definition preserves the 1983 definition, but rewords it in the form of an explicit-constant definition and also links it to the definition of the second:

> The meter, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299,792,458 when expressed in the unit $m \cdot s^{-1}$, where the second is defined in terms of the cesium frequency $\Delta\nu_{Cs}$.

Mass

From 1889 to 2019, the kilogram was defined as the mass of a single artifact—the international prototype kilogram, a platinum–iridium cylinder kept in a vault at the International Bureau of Weights and Measures in Sèvres, France. Not only was this artifact-based standard awkward to access, but comparison measurements revealed tiny yet growing mass discrepancies between the international prototype kilogram and secondary mass standards based on it.

In the 2019 SI revision, the kilogram became the last unit to get an explicit-constant definition. The kilogram's new definition is tied to the value of *Planck's constant*, h, a fundamental constant related to the "graininess" of physical quantities that's evident at the atomic and subatomic levels. It also depends on the definitions of the second and the meter:

> The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\,070\,040 \times 10^{-34}$ when expressed in the unit $\mathrm{J \cdot s}$, which is equal to $\mathrm{kg \cdot m^2 \cdot s^{-1}}$, where the meter and the second are defined in terms of c and Δv_{Cs}.

One technique that implements this definition uses the *watt balance* or *Kibble balance* (after its inventor). This instrument balances an unknown force against electrical forces whose magnitude can be related to Planck's constant. Another approach uses X rays to probe a sphere of crystalline silicon, effectively counting the atoms and yielding the mass of the sphere. Either way, the new kilogram definition provides a standard that can be reproduced in laboratories around the world. Note that the new definition also depends explicitly on the definitions of both the second and the meter.

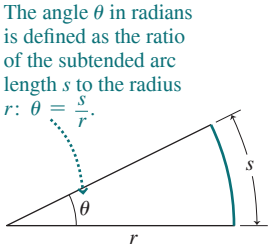


FIGURE 1.2 The radian is the SI unit of angle.

Other SI Units

The SI includes seven independent base units: In addition to the meter, second, and kilogram, there are the ampere (A) for electric current, the kelvin (K) for temperature, the mole (mol) for the amount of a substance, and the candela (cd) for luminosity. We'll introduce these units later, as needed. The SI revision gives these new, explicit-constant definitions; for all but the candela, this involves fixing the values of fundamental physical constants. In addition to the seven physical base units, two supplementary units define geometrical measures of angle: the radian (rad) for ordinary angles (Fig. 1.2) and the steradian (sr) for solid angles. Units for all other physical quantities are derived from the base units.

SI Prefixes

You could specify the length of a bacterium (e.g., 0.00001 m) or the distance to the next city (e.g., 58,000 m) in meters, but the results are unwieldy—too small in the first case and too large in the latter. So we use prefixes to indicate multiples of the SI base units. For example, the prefix k (for "kilo") means 1000; 1 km is 1000 m, and the distance to the next city is 58 km. Similarly, the prefix μ (the lowercase Greek "mu") means "micro," or 10^{-6}. So our bacterium is 10 μm long. The SI prefixes are listed in Table 1.1, which is repeated inside the front cover. We'll use the prefixes routinely in examples and problems, and we'll often express answers using SI prefixes, without doing an explicit unit conversion.

When two units are used together, a hyphen appears between them—for example, newton-meter. Each unit has a symbol, such as m for meter or N for newton (the SI unit of force). Symbols are ordinarily lowercase, but those named after people are uppercase. Thus "newton" is written with a small "n," but its symbol is a capital N. The exception is the unit of volume, the liter; since the lowercase "l" is easily confused with the number 1, the symbol for liter is a capital L. When two units are multiplied, their symbols are separated by a centered dot: $\mathrm{N \cdot m}$ for newton-meter. Division of units is expressed by using the slash (/) or writing with the denominator unit raised to the −1 power. Thus the SI unit of speed is the meter per second, written m/s or $\mathrm{m \cdot s^{-1}}$.

Table 1.1 SI Prefixes

Prefix	Symbol	Power
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10^{1}
—	—	10^{0}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

EXAMPLE 1.1 **Changing Units: Speed Limits**
Worked Example with Variation Problems

Express a 65 mi/h speed limit in meters per second.

EVALUATE According to Appendix C, 1 mi = 1609 m, so we can multiply miles by the ratio 1609 m/mi to get meters. Similarly, we use the conversion factor 3600 s/h to convert hours to seconds. Combining these two conversions gives

$$65 \text{ mi/h} = \left(\frac{65 \cancel{\text{mi}}}{\cancel{\text{h}}}\right)\left(\frac{1609 \text{ m}}{\cancel{\text{mi}}}\right)\left(\frac{1 \cancel{\text{h}}}{3600 \text{ s}}\right) = 29 \text{ m/s}$$

Other Unit Systems

The inches, feet, yards, miles, and pounds of the so-called English system still dominate measurement in the United States. Other non-SI units such as the hour are often mixed with English or SI units, as with speed limits in miles per hour or kilometers per hour. In some areas of physics there are good reasons for using non-SI units. We'll discuss these as the need arises and will occasionally use non-SI units in examples and problems. We'll also often find it convenient to use degrees rather than radians for angles. The vast majority of examples and problems in this book, however, use strictly SI units.

Changing Units

Sometimes we need to change from one unit system to another—for example, from English to SI. Appendix C contains tables for converting among unit systems; you should familiarize yourself with this and the other appendices and refer to them often.

For example, Appendix C shows that 1 ft = 0.3048 m. Since 1 ft and 0.3048 m represent the same physical distance, multiplying any distance by their ratio will change the units but not the actual physical distance. Thus the height of Dubai's Burj Khalifa (Fig. 1.3)—the world's tallest structure—is 2722 ft or

$$(2722 \text{ ft})\left(\frac{0.3048 \text{ m}}{1 \text{ ft}}\right) = 829.7 \text{ m}$$

Often you'll need to change several units in the same expression. Keeping track of the units through a chain of multiplications helps prevent you from carelessly inverting any of the conversion factors. A numerical answer cannot be correct unless it has the right units!

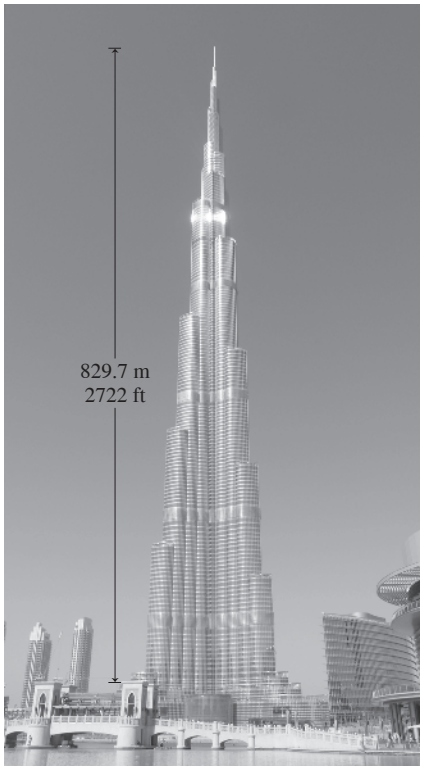


FIGURE 1.3 Dubai's Burj Khalifa is the world's tallest structure.

GOT IT?

1.1 A Canadian speed limit of 50 km/h is closest to which U.S. limit expressed in miles per hour? (a) 60 mi/h; (b) 45 mi/h; (c) 30 mi/h

1.3 Working with Numbers

LO 1.4 *Express numbers using scientific notation or SI prefixes.*

LO 1.5 *Do calculations with attention to significant figures.*

LO 1.6 *Make order-of-magnitude estimates.*

LO 1.7 *Plot data and extract information using best-fit lines.*

Scientific Notation

The range of measured quantities in the universe is enormous; lengths alone go from about 1/1,000,000,000,000,000 m for the radius of a proton to 1,000,000,000,000,000,000,000 m for the size of a galaxy; our telescopes see 100,000 times farther still. Therefore, we frequently express numbers in **scientific notation**, where a reasonable-sized number is multiplied by a power of 10. For example, 4185 is 4.185×10^3 and 0.00012 is 1.2×10^{-4}. Table 1.2 suggests the vast range of measurements for the fundamental quantities of length, time, and mass. Take a minute (about 10^2 heartbeats, or 3×10^{-8} of a typical human lifespan) to peruse this table along with Fig. 1.4.

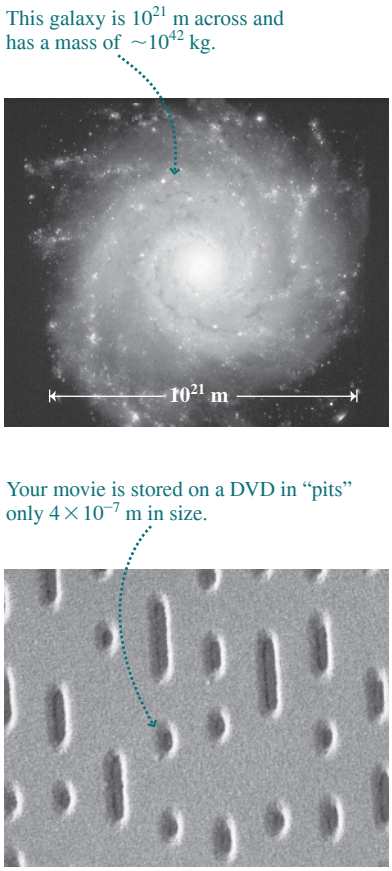


FIGURE 1.4 Large and small.

Table 1.2 Distances, Times, and Masses (rounded to one significant figure)

Radius of observable universe	1×10^{26} m
Earth's radius	6×10^{6} m
Tallest mountain	9×10^{3} m
Height of person	2 m
Diameter of red blood cell	1×10^{-5} m
Size of proton	1×10^{-15} m
Age of universe	4×10^{17} s
Earth's orbital period (1 year)	3×10^{7} s
Human heartbeat	1 s
Wave period, microwave oven	5×10^{-10} s
Time for light to cross a proton	3×10^{-24} s
Mass of Milky Way galaxy	1×10^{42} kg
Mass of mountain	1×10^{18} kg
Mass of human	70 kg
Mass of red blood cell	1×10^{-13} kg
Mass of uranium atom	4×10^{-25} kg
Mass of electron	1×10^{-30} kg

Scientific calculators handle numbers in scientific notation. But straightforward rules allow you to manipulate scientific notation if you don't have such a calculator handy.

Tactics 1.1 USING SCIENTIFIC NOTATION

Addition/Subtraction

To add (or subtract) numbers in scientific notation, first give them the same exponent and then add (or subtract):

$$3.75\times10^{6} + 5.2\times10^{5} = 3.75\times10^{6} + 0.52\times10^{6} = 4.27\times10^{6}$$

Multiplication/Division

To multiply (or divide) numbers in scientific notation, multiply (or divide) the digits and add (or subtract) the exponents:

$$(3.0\times10^{8}\ \text{m/s})(2.1\times10^{-10}\ \text{s}) = (3.0)(2.1)\times10^{8+(-10)}\ \text{m} = 6.3\times10^{-2}\ \text{m}$$

Powers/Roots

To raise numbers in scientific notation to any power, raise the digits to the given power and multiply the exponent by the power:

$$\sqrt{(3.61\times10^{4})^{3}} = \sqrt{3.61^{3}\times10^{(4)(3)}} = (47.04\times10^{12})^{1/2}$$
$$= \sqrt{47.04}\times10^{(12)(1/2)} = 6.86\times10^{6}$$

EXAMPLE 1.2 Scientific Notation: Tsunami Warnings

Earthquake-generated tsunamis are so devastating because the entire ocean, from surface to bottom, participates in the wave motion. The speed of such waves is given by $v = \sqrt{gh}$, where $g = 9.8\ \text{m/s}^2$ is the gravitational acceleration and h is the depth in meters. Determine a tsunami's speed in 3.0-km-deep water.

EVALUATE That 3.0-km depth is 3.0×10^{3} m, so we have

$$v = \sqrt{gh} = [(9.8\ \text{m/s}^2)(3.0\times10^{3}\ \text{m})]^{1/2} = (29.4\times10^{3}\ \text{m}^2/\text{s}^2)^{1/2}$$
$$= (2.94\times10^{4}\ \text{m}^2/\text{s}^2)^{1/2} = \sqrt{2.94}\times10^{2}\ \text{m/s} = 1.7\times10^{2}\ \text{m/s}$$

where we wrote $29.4\times10^{3}\ \text{m}^2/\text{s}^2$ as $2.94\times10^{4}\ \text{m}^2/\text{s}^2$ in the second line in order to calculate the square root more easily. Converting the speed to km/h gives

$$1.7\times10^{2}\ \text{m/s} = \left(\frac{1.7\times10^{2}\ \cancel{\text{m}}}{\cancel{\text{s}}}\right)\left(\frac{1\ \text{km}}{1.0\times10^{3}\ \cancel{\text{m}}}\right)\left(\frac{3.6\times10^{3}\ \cancel{\text{s}}}{\text{h}}\right)$$
$$= 6.1\times10^{2}\ \text{km/h}$$

This speed—about 600 km/h—shows why even distant coastlines have little time to prepare for the arrival of a tsunami.

Significant Figures

How precise is that 1.7×10^2 m/s we calculated in Example 1.2? The two **significant figures** in this number imply that the value is closer to 1.7 than to 1.6 or 1.8. The fewer significant figures, the less precisely we can claim to know a given quantity.

In Example 1.2 we were, in fact, given two significant figures for both quantities. The mere act of calculating can't add precision, so we rounded our answer to two significant figures as well. Calculators and computers often give numbers with many figures, but most of those are usually meaningless.

What's Earth's circumference? It's $2\pi R_E$, and π is approximately 3.14159. . . . But if you only know Earth's radius as 6.37×10^6 m, knowing π to more significant figures doesn't mean you can claim to know the circumference any more precisely. This example suggests a rule for handling calculations involving numbers with different precisions:

> In multiplication and division, the answer should have the same number of significant figures as the least precise of the quantities entering the calculation.

You're engineering an access ramp to a bridge whose main span is 1.248 km long. The ramp will be 65.4 m long. What will be the overall length? A simple calculation gives 1.248 km + 0.0654 km = 1.3134 km. How should you round this? You know the bridge length to ± 0.001 km, so an addition this small is significant. Therefore, your answer should have three digits to the right of the decimal point, giving 1.313 km. Thus:

> In addition and subtraction, the answer should have the same number of digits to the right of the decimal point as the term in the sum or difference that has the smallest number of digits to the right of the decimal point.

In subtraction, this rule can quickly lead to loss of precision, as Example 1.3 illustrates.

EXAMPLE 1.3 Significant Figures: Nuclear Fuel

Worked Example with Variation Problems

A uranium fuel rod is 3.241 m long before it's inserted in a nuclear reactor. After insertion, heat from the nuclear reaction has increased its length to 3.249 m. What's the increase in its length?

EVALUATE Subtraction gives 3.249 m − 3.241 m = 0.008 m or 8 mm. Should this be 8 mm or 8.000 mm? Just 8 mm. Subtraction affected only the last digit of the four-significant-figure lengths, leaving only one significant figure in the answer.

INTERMEDIATE RESULTS Although it's important that your final answer reflect the precision of the numbers that went into it, any intermediate results should have at least one extra significant figure. Otherwise, rounding of intermediate results could alter your answer. If you use a calculator or software when working problems, you'll automatically be carrying many more significant figures in intermediate calculations. We do that in many of the examples and solutions for this book, and therefore you may sometimes find discrepancies in the last digit between your results and the book's.

GOT IT?

1.2 Rank the numbers according to (1) their size and (2) the number of significant figures. Some may be of equal rank. 0.0008, 3.14×10^7, 2.998×10^{-9}, 55×10^6, 0.041×10^9

What about whole numbers ending in zero, like 60, 300, or 410? How many significant figures do they have? Strictly speaking, 60 and 300 have only one significant figure, while 410 has two. If you want to express the number 60 to two significant figures, you should write 6.0×10^1; similarly, 300 to three significant figures would be 3.00×10^2, and 410 to three significant figures would be 4.10×10^2.

Working with Data

In physics, in other sciences, and even in nonscience fields, you'll find yourself working with data—numbers that come from real-world measurements. One important use of

data in the sciences is to confirm hypotheses about relations between physical quantities. Scientific hypotheses can generally be described quantitatively using equations, which often give or can be manipulated to give a linear relationship between quantities. Plotting such data and fitting a line through the data points—using procedures such as regression analysis, least-squares fitting, or even "eyeballing" a best-fit line—can confirm the hypothesis and give useful information about the phenomena under study. You'll probably have opportunities to do such data fitting in your physics lab and in other science courses. Because it's so important in experimental science, we've included at least one data problem with each chapter. Example 1.4 shows a typical example of fitting data to a straight line.

Estimation

Some problems in physics and engineering call for precise numerical answers. We need to know exactly how long to fire a rocket to put a space probe on course toward a distant planet, or exactly what size to cut the tiny quartz crystal whose vibrations set the pulse of a digital watch. But for many other purposes, we need only a rough idea of the size of a physical effect. And rough estimates help check whether the results of more difficult calculations make sense.

EXAMPLE 1.4 Data Analysis: A Falling Ball

As you'll see in Chapter 2, the distance fallen by an object dropped from rest should increase in proportion to the square of the time since it was dropped; the proportionality should be half the acceleration due to gravity. The table shows actual data from measurements on a falling ball. Determine a quantity such that, when you plot fall distance y against it, you should get a straight line. Make the plot, fit a straight line, and from its slope determine an approximate value for the gravitational acceleration.

Time (s)	0.500	1.00	1.50	2.00	2.50	3.00
Distance (m)	1.12	5.30	12.2	18.5	34.1	43.6

Time Squared (s^2)	0.250	1.00	2.25	4.00	6.25	9.00

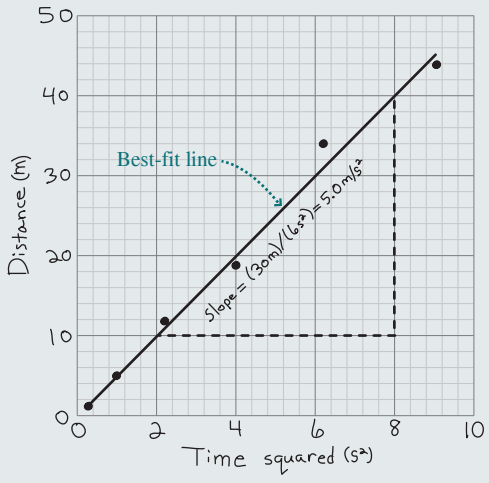


FIGURE 1.5 Our graph for Example 1.4. We "eyeballed" the best-fit line using a ruler; note that it doesn't go through particular points but tries to capture the average trend of all the data points.

EVALUATE We're told that the fall distance y should be proportional to the square of the time; thus we choose to plot y versus t^2. So we've added a row to the table, listing the values of t^2. Figure 1.5 is our plot. Although we did this one by hand, on graph paper, you could use a spreadsheet or other program to make your plot. A spreadsheet program would offer the option to draw a best-fit line and give its slope, but a hand-drawn line, "eyeballed" to catch the general trend of the data points, works surprisingly well. We've indicated such a line, and the figure shows that its slope is very nearly 5.0 m/s^2.

ASSESS The fact that our data points lie very nearly on a straight line confirms the hypothesis that fall distance should be proportional to time squared. Real data almost never lie exactly on a theoretically predicted line or curve. A more sophisticated analysis would show error bars, indicating the measurement uncertainty in each data point. Because our line's measured slope is supposed to be half the gravitational acceleration, our analysis suggests a gravitational acceleration of about 10 m/s^2. This is close to the commonly used value of 9.8 m/s^2.

1.4 Strategies for Learning Physics

You can learn *about* physics, and you can learn to *do* physics. This book emphasizes both. Learning about physics will help you appreciate the role of this fundamental science in explaining both natural and technological phenomena. Learning to do physics will make you adept at solving quantitative problems—finding answers to questions about how the natural world works and about how we forge the technologies at the heart of modern society.

EXAMPLE 1.5 Estimation: Counting Brain Cells

Estimate the mass of your brain and the number of cells it contains.

EVALUATE My head is about 6 in. or 15 cm wide, but there's a lot of skull bone in there, so maybe my brain is about 10 cm or 0.1 m across. I don't know its exact shape, but for estimating, I'll take it to be a cube. Then its volume is $(10\,\text{cm})^3 = 1000\,\text{cm}^3$, or $10^{-3}\,\text{m}^3$. I'm mostly water, and water's density is 1 gram per cubic centimeter ($1\,\text{g/cm}^3$), so my 1000-cm^3 brain has a mass of about 1 kg.

How big is a brain cell? I don't know, but Table 1.2 lists the diameter of a red blood cell as about 10^{-5} m. If brain cells are roughly the same size, then each cell has a volume of approximately $(10^{-5}\,\text{m})^3 = 10^{-15}\,\text{m}^3$. Then the number of cells in my 10^{-3}-m^3 brain is roughly

$$N = \frac{10^{-3}\,\text{m}^3/\text{brain}}{10^{-15}\,\text{m}^3/\text{cell}} = 10^{12}\,\text{cells/brain}$$

Crude though they are, these estimates aren't bad. The average adult brain's mass is about 1.3 kg, and it contains at least 10^{11} cells (Fig. 1.6).

FIGURE 1.6 The average human brain contains more than 10^{11} cells.

Physics: Challenge and Simplicity

Physics problems can be challenging, calling for clever insight and mathematical agility. That challenge is what gives physics a reputation as a difficult subject. But underlying all of physics is only a handful of basic principles. Because physics is so fundamental, it's also inherently simple. There are only a few basic ideas to learn; if you really understand those, you can apply them in a wide variety of situations. These ideas and their applications are all connected, and we'll emphasize those connections and the underlying simplicity of physics by reminding you how the many examples, applications, and problems are manifestations of the same few basic principles. If you approach physics as a hodgepodge of unrelated laws and equations, you'll miss the point and make things difficult. But if you look for the basic principles, for connections among seemingly unrelated phenomena and problems, then you'll discover the underlying simplicity that reflects the scope and power of physics—the fundamental science.

Problem Solving: The IDEA Strategy

Solving a quantitative physics problem always starts with basic principles or concepts and ends with a precise answer expressed as either a numerical quantity or an algebraic expression. Whatever the principle, whatever the realm of physics, and whatever the specific situation, the path from principle to answer follows four simple steps—steps that make up a comprehensive strategy for approaching all problems in physics. Their acronym, IDEA, will help you remember these steps, and they'll be reinforced as we apply them over and over again in worked examples throughout the book. We'll generally write all four steps separately, although the examples in this chapter cut right to the EVALUATE phase. And in some chapters we'll introduce versions of this strategy tailored to specific material. Although the IDEA acronym is tailored to *Essential University Physics*, our four-step approach derives from a 1945 book, *How to Solve It*, by George Polya—intended for mathematics students but readily adapted for physics.

The IDEA strategy isn't a "cookbook" formula for working physics problems. Rather, it's a tool for organizing your thoughts, clarifying your conceptual understanding, developing and executing plans for solving problems, and assessing your answers. The big IDEA is summarized in Problem-Solving Strategy 1.1 on the next page.