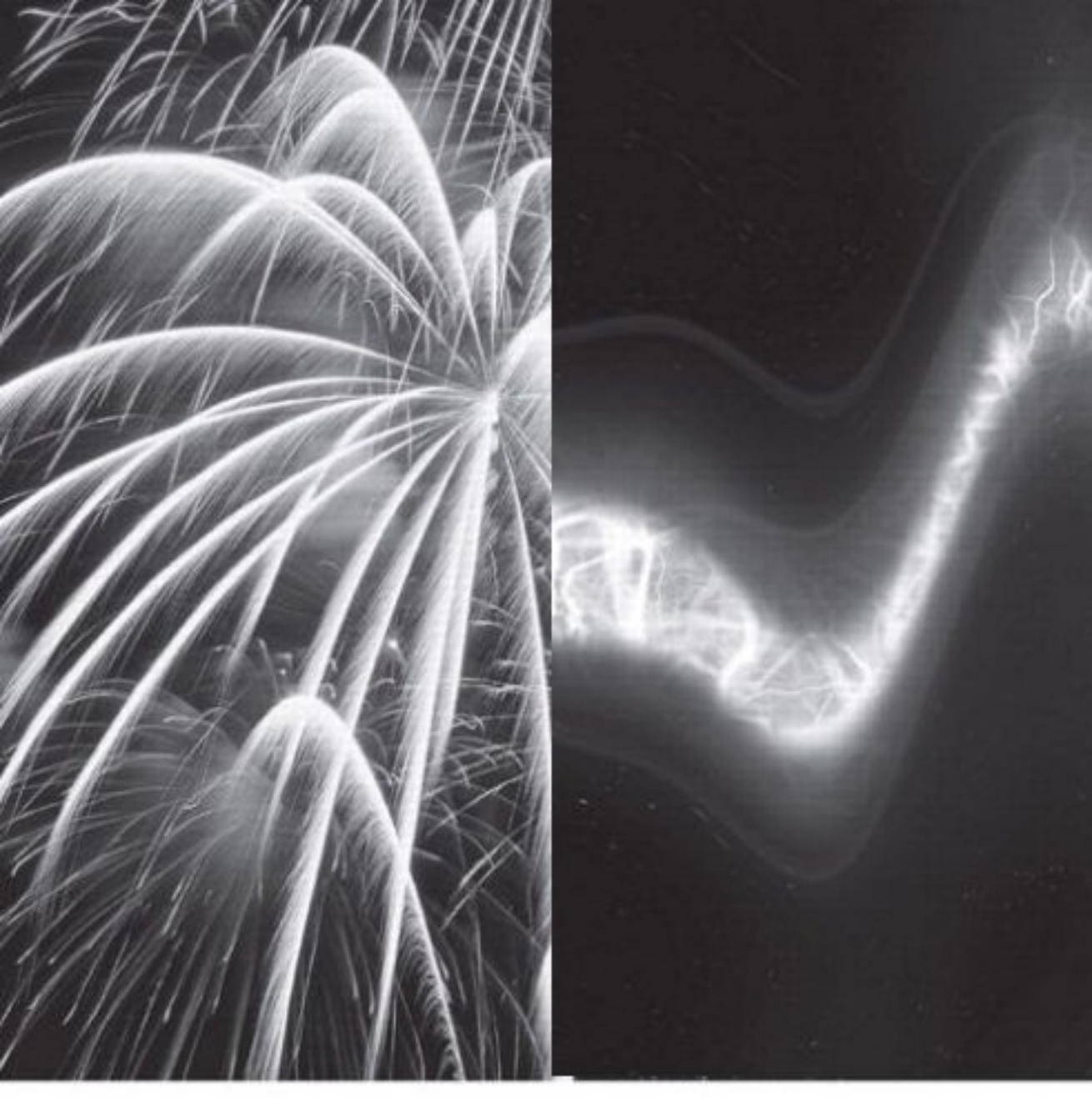


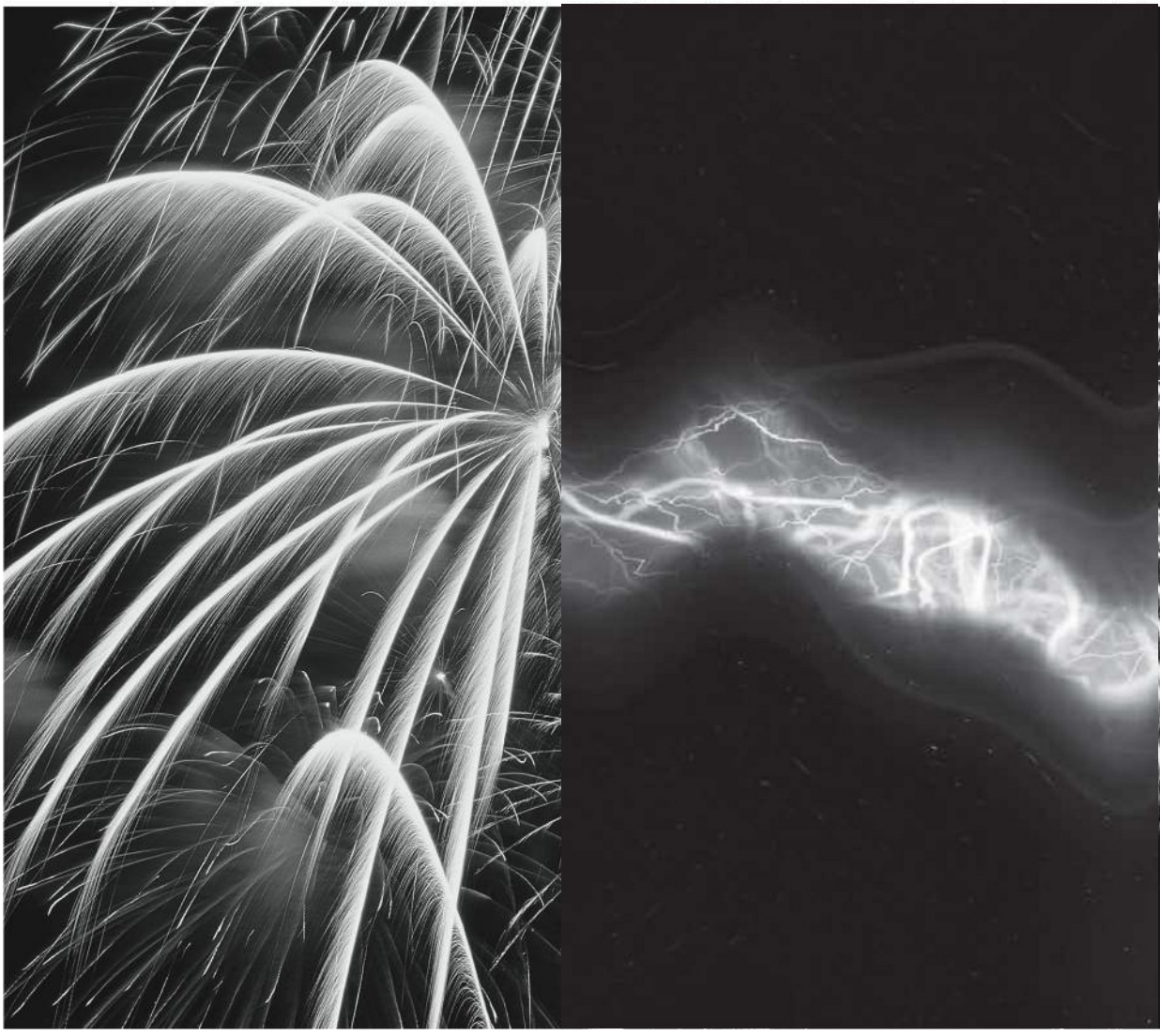
ESSENTIAL UNIVERSITY PHYSICS

THIRD EDITION

Richard Wolfson

ESSENTIAL UNIVERSITY PHYSICS

THIRD EDITION



Richard Wolfson
Middlebury College

PEARSON

Executive Editor: Nancy Whilton
Project Manager: Katie Conley
Development Editors: John Murdzek, Matt Walker
Editorial Assistant: Sarah Kaubisch
Development Manager: Cathy Murphy
Project Management Team Lead: Kristen Flathman
Compositor: Lumina Datamatics, Inc.
Design Manager: Marilyn Perry
Illustrators: Rolin Graphics
Rights & Permissions Management: Timothy Nicholls
Photo Researcher: Stephen Merland, Jen Simmons
Manufacturing Buyer: Maura Zaldivar-Garcia
Marketing Manager: Will Moore
Cover Photo Credit: 68/Ocean/Corbis

Copyright © 2016 Pearson Education, Inc. All Rights Reserved. Printed in the United States of America. This publication is protected by copyright, and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise. For information regarding permissions, request forms and the appropriate contacts within the Pearson Education Global Rights & Permissions department, please visit www.pearsoned.com/permissions/.

Acknowledgments of third party content appear on page C-1, which constitutes an extension of this copyright page.

PEARSON, ALWAYS LEARNING and MasteringPhysics are exclusive trademarks in the U.S. and/or other countries owned by Pearson Education, Inc. or its affiliates.

Unless otherwise indicated herein, any third-party trademarks that may appear in this work are the property of their respective owners and any references to third-party trademarks, logos or other trade dress are for demonstrative or descriptive purposes only. Such references are not intended to imply any sponsorship, endorsement, authorization, or promotion of Pearson's products by the owners of such marks, or any relationship between the owner and Pearson Education, Inc. or its affiliates, authors, licensees or distributors.

CIP data is on file with the Library of Congress.

1 2 3 4 5 6 7 8 9 10—V011—18 17 16 15 14

PEARSON www.pearsonhighered.com

ISBN 10: ~~0-321-99372-1~~; ISBN 13: ~~978-0-321-99372-4~~
0134202708 9780134202709

PhET Simulations

Available in the Pearson eText and in the Study Area of MasteringPhysics

Chapter	PhET	Page
1	Estimation	8
2	The Moving Man	16
3	Vector Addition	33
3	Projectile Motion	39
3	Ladybug Motion 2D	43
3	Motion in 2D	43
5	The Ramp	73
5	Forces in 1 Dimension	80
5	Friction	80
6	The Ramp	92, 96
7	Calculus Grapher	120
7	Energy Skate Park	120
8	Gravity Force Lab	131
8	My Solar System	132
8	Gravity and Orbits	132
9	Collisions (Introduction)	158
9	Collisions (Advanced)	159
10	Ladybug Revolution	169
10	Torque (Torque)	173
10	Torque (Moment of Inertia)	173
11	Simplified MRI	196
13	Masses and Springs	224
13	Pendulum Lab	229
14	Wave on a String	247, 255
14	Sound	251
14	Fourier: Making Waves	252
14	Wave Interference	253
15	Balloons and Buoyancy	269
16	Blackbody Spectrum	293
16	The Greenhouse Effect	296
17	Gas Properties	303
17	States of Matter	307
19	Reversible Reactions	344
20	Balloons and Static Electricity	356
20	Charges and Fields	359, 362
20	Electricity Field Hockey	366
22	Calculus Grapher	409
22	Charges and Fields	409
24	Conductivity	435
24	Semiconductors	437
24	Resistance in a Wire	439
24	Ohm's Law	439
25	Battery Resistor Circuit	450
25	Circuit Construction Kit (DC Only)	451, 456
25	Signal Circuit	451
26	Magnet and Compass	470
26	Magnets and Electromagnets	483
27	Farady's Law	498
27	Farady's Electromagentic Lab	502
27	Generator	506
28	Circuit Construction Kit (AC + DC)	526, 530, 533
29	Radio Waves and Electromagnetic Fields	556
29	Radiating Charge	556
29	Optical Tweezers and Applications	559
30	Bending Light (Intro)	569
30	Bending Light (Prism Break)	572
31	Geometric Optics	585
32	Wave Interference: Light	601
34	Blackbody Spectrum	648
34	Photoelectric Effect	651
34	Neon Lights & Other Discharge Lamps	654
34	Quantum Wave Interference	659
35	Quantum Bound State: One Well	671, 675
35	Quantum Tunneling and Wave Packets	677
36	Quantum Bound State: One Well: 3D Coulomb	685
36	Build an Atom	693
37	Quantum Bound States: Two Wells (Molecular Bonding)	703
37	Band Structure	709
37	Semiconductors	712
38	Rutherford Scattering	721
38	Simplified MRI	724
38	Radioactive Dating Game	726
38	Alpha Decay	729
38	Beta Decay	729
38	Nuclear Fission: One Nucleus	734
38	Nuclear Fission: Chain Reaction	735
38	Nuclear Fission: Nuclear Reactor	736

Video Tutor Demonstrations

Video tutor demonstrations can be accessed by scanning the QR codes in the textbook using a smartphone. They are also available in the Study Area and Instructor's Resource Area on MasteringPhysics and in the eText.

Chapter	Video Tutor Demonstration	Page
2	Balls Take High and Low Tracks	16
3	Dropped and Thrown Balls	38
3	Ball Fired from Cart on Incline	39
3	Ball Fired Upward from Accelerating Cart	39
3	Range of a Gun at Two Firing Angles	43
4	Cart with Fan and Sail	53
4	Ball Leaves Circular Track	53
4	Suspended Balls: Which String Breaks?	54
4	Weighing a Hovering Magnet	63
5	Tension in String between Hanging Weights	76
7	Chin Basher?	118
9	Balancing a Meter Stick	146
9	Water Rocket	153
9	Happy/Sad Pendulums	154
10	Canned Food Race	182
11	Spinning Person Drops Weights	195
11	Off-Center Collision	195
12	Walking the Plank	207
13	Vibrating Rods	236
14	Out-of-Phase Speakers	251
15	Pressure in Water and Alcohol	268
15	Water Level in Pascal's Vases	268
15	Weighing Weights in Water	270
15	Air Jet Blows between Bowling Balls	274
16	Heating Water and Aluminum	288
16	Water Balloon Held over Candle Flame	288
16	Candle Chimneys	293
20	Charged Rod and Aluminum Can	369
21	Electroscope in Conducting Shell	391
22	Charged Conductor with Teardrop Shape	411
23	Discharge Speed for Series and Parallel Capacitors	423
24	Resistance in Copper and Nichrome	441
25	Bulbs Connected in Series and in Parallel	454
26	Magnet and Electron Beam	470
26	Current-Carrying Wire in Magnetic Field	475
27	Eddy Currents in Different Metals	507
29	Parallel-Wire Polarizer for Microwaves	553
29	Point of Equal Brightness between Two Light Sources	558
31	Partially Covering a Lens	587
36	Illuminating Sodium Vapor with Sodium and Mercury Lamps	696

Brief Contents

Chapter 1 Doing Physics 1

PART ONE

Mechanics 14

Chapter 2 Motion in a Straight Line 15

Chapter 3 Motion in Two and Three Dimensions 32

Chapter 4 Force and Motion 51

Chapter 5 Using Newton's Laws 71

Chapter 6 Energy, Work, and Power 90

Chapter 7 Conservation of Energy 109

Chapter 8 Gravity 129

Chapter 9 Systems of Particles 144

Chapter 10 Rotational Motion 168

Chapter 11 Rotational Vectors and Angular Momentum 189

Chapter 12 Static Equilibrium 204

PART TWO

Oscillations, Waves, and Fluids 221

Chapter 13 Oscillatory Motion 222

Chapter 14 Wave Motion 243

Chapter 15 Fluid Motion 265

PART THREE

Thermodynamics 284

Chapter 16 Temperature and Heat 285

Chapter 17 The Thermal Behavior of Matter 303

Chapter 18 Heat, Work, and the First Law of Thermodynamics 317

Chapter 19 The Second Law of Thermodynamics 334

PART FOUR

Electromagnetism 354

Chapter 20 Electric Charge, Force, and Field 355

Chapter 21 Gauss's Law 375

Chapter 22 Electric Potential 399

Chapter 23 Electrostatic Energy and Capacitors 418

Chapter 24 Electric Current 432

Chapter 25 Electric Circuits 449

Chapter 26 Magnetism: Force and Field 469

Chapter 27 Electromagnetic Induction 497

Chapter 28 Alternating-Current Circuits 525

Chapter 29 Maxwell's Equations and Electromagnetic Waves 543

PART FIVE

Optics 565

Chapter 30 Reflection and Refraction 566

Chapter 31 Images and Optical Instruments 579

Chapter 32 Interference and Diffraction 599

PART SIX

Modern Physics 621

Chapter 33 Relativity 622

Chapter 34 Particles and Waves 647

Chapter 35 Quantum Mechanics 667

Chapter 36 Atomic Physics 684

Chapter 37 Molecules and Solids 702

Chapter 38 Nuclear Physics 720

Chapter 39 From Quarks to the Cosmos 747

APPENDICES

Appendix A Mathematics A-1

Appendix B The International System of Units (SI) A-9

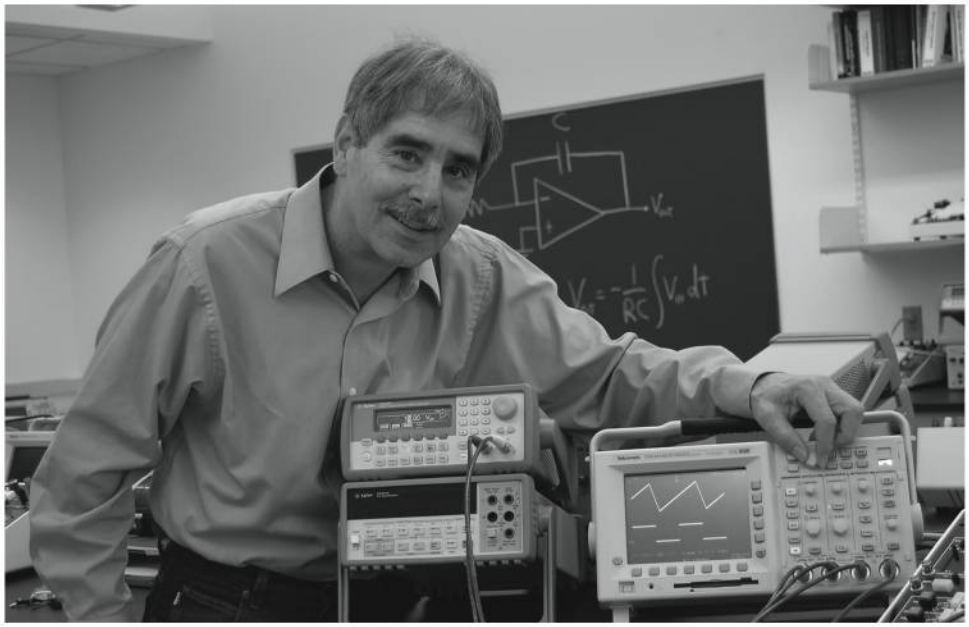
Appendix C Conversion Factors A-11

Appendix D The Elements A-13

Appendix E Astrophysical Data A-16

Answers to Odd-Numbered Problems A-17
Credits C-1
Index I-1

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. degree from the University of Michigan and 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, 2012); 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 three 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 Third Edition

The overall theme for this third-edition revision is to present a more unified view of physics, emphasizing "big ideas" and the connections among different topics covered throughout the book. We've also updated material and features based on feedback from instructors, students, and reviewers. A modest growth, averaging about one page per chapter, allows for expanded coverage of topics where additional elaboration seemed warranted. Several chapters have had major rewrites of key physics topics. We've also made a number of additions and modifications aimed at improving students' understanding, increasing relevancy, and offering expanded problem-solving opportunities.

- Chapter opening pages have been redesigned to include explicit connections, both textual and graphic, with preceding and subsequent chapters.
- The presentation of **energy and work** in Chapters 6 and 7 has been extensively rewritten with a clearer invocation of **systems concepts**. Internal energy is introduced much earlier in the book, and potential energy is carefully presented as a property not of objects but of systems. Two new sections in Chapter 7 emphasize the universality of energy conservation, including the role of internal energy in systems subject to dissipative forces. Forward references tie this material to the chapters on thermodynamics, electromagnetism, and relativity. The updated treatment of energy also allows the text to make a closer connection between the conservation laws for energy and momentum.

- The presentation of **magnetic flux and Faraday's law** in Chapter 27 has been recast so as to distinguish motional emf from emfs induced by changing magnetic fields—including Einstein's observation about induction, which is presented as a forward-looking connection to Chapter 33.
- There is more emphasis on calculus in earlier chapters, allowing instructors who wish to do so to use calculus approaches to topics that are usually introduced algebraically. We've also added more calculus-based problems. However, we continue to emphasize the standard approach in the main text for those who teach the course with a calculus corequisite or otherwise want to go slowly with more challenging math.
- A host of **new applications** connects the physics concepts that students are learning with contemporary technological and biomedical innovations, as well as recent scientific discoveries. A sample of new applications includes Inertial Guidance Systems, Vehicle Stability Control, Climate Modeling, Electrophoresis, MEMS (Microelectromechanical Systems), The Taser, Uninterruptible Power Supplies, Geomagnetic Storms, PET Scans, Noise-Cancelling Headphones, Femtosecond Chemistry, Windows on the Universe, and many more.
- Additional **worked examples** have been added in areas where students show the need for more practice in problem solving. Many of these are not just artificial textbook problems but are based on contemporary science and technology, such as the Mars *Curiosity* rover landing, the Fukushima accident, and the Chelyabinsk meteor. Following user requests, we've added an example of a collision in the center-of-mass reference frame.
- New GOT IT? boxes, now in nearly every section of every chapter, provide quick checks on students' conceptual understanding. Many of the GOT IT? questions have been formatted as Clicker questions, available on the Instructor's Resource DVD and in the Instructor's Resource Area in Mastering.
- End-of chapter problem sets have been extensively revised:
  - Each EOC problem set has at least 10 percent new or substantially revised problems.
  - More "For Thought and Discussion Questions" have been added.
  - Nearly every chapter has more intermediate-level problems.
  - More calculus-based problems have been added.
  - Every chapter now has at least one data problem, designed to help students develop strong quantitative reasoning skills. These problems present a data table and require students to determine appropriate functions of the data to plot in order to achieve a linear relationship and from that to find values of physical quantities involved in the experiment from which the data were taken.
  - New tags have been added to label appropriate problems. These include CH (challenge), ENV (environmental), and DATA, and they join the previous BIO and COMP (computer) problem tags.
- QR codes in margins allow students to use smartphones or other devices for immediate access to video tutor demonstrations that illustrate selected concepts while challenging students to interact with the video by predicting outcomes of simple experiments.
- References to PhET simulations appear in the margins where appropriate.
- As with earlier revisions, we've incorporated new research results, new applications of physics principles, and findings from physics education research.

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** in the textbook allow students to link to video tutor demonstrations as they read, using their smartphones. 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. Many new GOT IT? boxes have been added in the third edition, and now nearly every section of every chapter has at least one GOT IT? box.
- **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 three columns of points that help make connections with other material throughout the book. These include a backward-looking "What You Know," "What You're Learning" for the present chapter, and a forward-looking "How You'll Use It." 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.
- **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 (except the Instructor's Resource DVD) can be downloaded from the Instructor's Resource Area of MasteringPhysics® (www.masteringphysics.com) as well as from the Instructor's Resource Center on www.pearsonhighered.com/irc.

- The **Instructor's Solutions Manual** (ISBN 0-133-85713-1) 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.
- The **Instructor's Resource DVD** (ISBN 0-133-85714-X) provides all the figures, photos, and tables from the text in JPEG format. All the problem-solving strategies, Tactics Boxes, key equations, and chapter summaries are provided in PDF and editable Microsoft® Word formats with equations in MathType. Each chapter also has a set of PowerPoint® lecture outlines and questions including the new GOT IT! Clickers. A comprehensive library of more than 220 applets from **ActivPhysics OnLine™**, a suite of over 70 PhET simulations, and 40 video tutor demonstrations are also included. Also, the complete Instructor's Solutions Manual is provided in both Word and PDF formats.
- **MasteringPhysics®** (www.masteringphysics.com) 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 sig fig feedback) or solutions. This third edition includes nearly 400 new problems written by the author explictly for use with MasteringPhysics.
- **Learning Catalytics** is a "bring your own device" student engagement, assessment, and classroom intelligence system that is based on cutting-edge research, innovation, and implementation of interactive teaching and peer instruction. With Learning Catalytics pre-lecture questions, you can see what students do and don't understand and adjust lectures accordingly.
- **Pearson eText** is available either automatically when MasteringPhysics® is packaged with new books or as a purchased upgrade online. Users can search for words or phrases, create notes, highlight text, bookmark sections, click on definitions to key terms, and launch PhET simulations and video tutor demonstrations as they read. Professors also have the ability to annotate the text for their course and hide chapters not covered in their syllabi.
- The **Test Bank** (ISBN 0-133-85715-8) 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.

Student Supplements

- **MasteringPhysics®** (www.masteringphysics.com) is the most advanced physics homework and tutorial system available. This online homework and tutoring system guides students through the most important 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 sig fig feedback) or solutions.
- **Pearson eText** is available through MasteringPhysics®, either automatically when MasteringPhysics® is packaged with new books or as a purchased upgrade online. Allowing students access to the text wherever they have access to the Internet, Pearson eText comprises the full text with additional interactive features. Users can search for words or phrases, create notes, highlight text, bookmark sections, click on definitions to key terms, and launch PhET simulations and video tutor demonstrations as they read.

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 third 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, Anne Goodsell, Noah Graham, Steve Ratcliff, and Susan Watson.

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 all 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 and Matt Walker continued with Brad's excellent tradition of developmental editing on this third 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 Sen-Ben Liao, who solved every new and revised homework problem and updated the solutions manual.

I also wish to thank Nancy Whilton and Katie Conley at Pearson Education, and Haylee Schwenk at Lumina Datamatics, 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*
Linda S. Barton, *Rochester Institute of Technology*
Rasheed Bashirov, *Albertson College of Idaho*
Chris Berven, *University of Idaho*
David Bixler, *Angelo State University*
Ben Bromley, *University of Utah*
Charles Burkhardt, *St. Louis Community College*
Susan Cable, *Central Florida Community College*
George T. Carlson, Jr., *West Virginia Institute of Technology–West Virginia University*
Catherine Check, *Rock Valley College*
Norbert Chencinski, *College of Staten Island*
Carl Covatto, *Arizona State University*
David Donnelly, *Texas State University–San Marcos*
David G. Ellis, *University of Toledo*
Tim Farris, *Volunteer State Community College*
Paula Fekete, *Hunter College of The City University of New York*

Idan Ginsburg, *Harvard University*
James Goff, *Pima Community College*
Austin Hedeman, *University of California–Berkeley*
Andrew Hirsch, *Purdue University*
Mark Hollabaugh, *Normandale Community College*
Eric Hudson, *Pennsylvania State University*
Rex W. Joyner, *Indiana Institute of Technology*
Nikos Kalogeropoulos, *Borough of Manhattan Community College–The City University of New York*
Viken Kiledjian, *East Los Angeles College*
Kevin T. Kilty, *Laramie County Community College*
Duane Larson, *Bevill State Community College*
Kenneth W. McLaughlin, *Loras College*
Tom Marvin, *Southern Oregon University*
Perry S. Mason, *Lubbock Christian University*
Mark Masters, *Indiana University–Purdue University Fort Wayne*
Jonathan Mitschele, *Saint Joseph's College*
Gregor Novak, *United States Air Force Academy*
Richard Olenick, *University of Dallas*
Robert Philbin, *Trinidad State Junior College*
Russell Poch, *Howard Community College*
Steven Pollock, *Colorado University–Boulder*
Richard Price, *University of Texas at Brownsville*
James Rabchuk, *Western Illinois University*
George Schmiedeshoff, *Occidental College*
Natalia Semushkina, *Shippensburg University of Pennsylvania*
Anwar Shiekh, *Dine College*
David Slimmer, *Lander University*
Chris Sorensen, *Kansas State University*
Ronald G. Tabak, *Youngstown State University*
Gajendra Tulsian, *Daytona Beach Community College*
Brigita Urbanc, *Drexel University*
Henry Weigel, *Arapahoe Community College*
Arthur W. Wiggins, *Oakland Community College*
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 increasingly 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 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.

Detailed Contents

Volume 1 contains Chapters 1–19
Volume 2 contains Chapters 20–39

Chapter 1 Doing Physics 1
- 1.1 Realms of Physics 1
- 1.2 Measurements and Units 3
- 1.3 Working with Numbers 5
- 1.4 Strategies for Learning Physics 9

PART ONE

Mechanics 14

Chapter 2 Motion in a Straight Line 15
- 2.1 Average Motion 15
- 2.2 Instantaneous Velocity 17
- 2.3 Acceleration 19
- 2.4 Constant Acceleration 21
- 2.5 The Acceleration of Gravity 24
- 2.6 When Acceleration Isn't Constant 26

Chapter 3 Motion in Two and Three Dimensions 32
- 3.1 Vectors 32
- 3.2 Velocity and Acceleration Vectors 35
- 3.3 Relative Motion 36
- 3.4 Constant Acceleration 37
- 3.5 Projectile Motion 39
- 3.6 Uniform Circular Motion 43

Chapter 4 Force and Motion 51
- 4.1 The Wrong Question 51
- 4.2 Newton's First and Second Laws 52
- 4.3 Forces 55
- 4.4 The Force of Gravity 56
- 4.5 Using Newton's Second Law 58
- 4.6 Newton's Third Law 60

Chapter 5 Using Newton's Laws 71
- 5.1 Using Newton's Second Law 71
- 5.2 Multiple Objects 74
- 5.3 Circular Motion 76
- 5.4 Friction 80
- 5.5 Drag Forces 84

Chapter 6 Energy, Work, and Power 90
- 6.1 Energy 91
- 6.2 Work 92
- 6.3 Forces That Vary 96
- 6.4 Kinetic Energy 99
- 6.5 Power 101

Chapter 7 Conservation of Energy 109
- 7.1 Conservative and Nonconservative Forces 110
- 7.2 Potential Energy 111
- 7.3 Conservation of Mechanical Energy 115
- 7.4 Nonconservative Forces 118
- 7.5 Conservation of Energy 119
- 7.6 Potential-Energy Curves 120

Chapter 8 Gravity 129
- 8.1 Toward a Law of Gravity 129
- 8.2 Universal Gravitation 130
- 8.3 Orbital Motion 132
- 8.4 Gravitational Energy 135
- 8.5 The Gravitational Field 138

Chapter 9 Systems of Particles 144
- 9.1 Center of Mass 144
- 9.2 Momentum 149
- 9.3 Kinetic Energy of a System 153
- 9.4 Collisions 153
- 9.5 Totally Inelastic Collisions 154
- 9.6 Elastic Collisions 156

Chapter 10 Rotational Motion 168
- 10.1 Angular Velocity and Acceleration 168
- 10.2 Torque 171
- 10.3 Rotational Inertia and the Analog of Newton's Law 173
- 10.4 Rotational Energy 178
- 10.5 Rolling Motion 180

Chapter 11 Rotational Vectors and Angular Momentum 189
11.1 Angular Velocity and Acceleration Vectors 189
11.2 Torque and the Vector Cross Product 190
11.3 Angular Momentum 192
11.4 Conservation of Angular Momentum 194
11.5 Gyroscopes and Precession 196

Chapter 12 Static Equilibrium 204
12.1 Conditions for Equilibrium 204
12.2 Center of Gravity 206
12.3 Examples of Static Equilibrium 207
12.4 Stability 209

PART TWO

Oscillations, Waves, and Fluids 221

Chapter 13 Oscillatory Motion 222
13.1 Describing Oscillatory Motion 223
13.2 Simple Harmonic Motion 224
13.3 Applications of Simple Harmonic Motion 227
13.4 Circular Motion and Harmonic Motion 231
13.5 Energy in Simple Harmonic Motion 232
13.6 Damped Harmonic Motion 233
13.7 Driven Oscillations and Resonance 235

Chapter 14 Wave Motion 243
14.1 Waves and Their Properties 244
14.2 Wave Math 245
14.3 Waves on a String 247
14.4 Sound Waves 250
14.5 Interference 251
14.6 Reflection and Refraction 254
14.7 Standing Waves 255
14.8 The Doppler Effect and Shock Waves 258

Chapter 15 Fluid Motion 265
15.1 Density and Pressure 265
15.2 Hydrostatic Equilibrium 266
15.3 Archimedes' Principle and Buoyancy 269
15.4 Fluid Dynamics 271
15.5 Applications of Fluid Dynamics 273
15.6 Viscosity and Turbulence 277

PART THREE

Thermodynamics 284

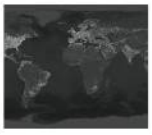
Chapter 16 Temperature and Heat 285
16.1 Heat, Temperature, and Thermodynamic Equilibrium 285
16.2 Heat Capacity and Specific Heat 287
16.3 Heat Transfer 289
16.4 Thermal-Energy Balance 294

Chapter 17 The Thermal Behavior of Matter 303
17.1 Gases 303
17.2 Phase Changes 307
17.3 Thermal Expansion 310

Chapter 18 Heat, Work, and the First Law of Thermodynamics 317
18.1 The First Law of Thermodynamics 317
18.2 Thermodynamic Processes 319
18.3 Specific Heats of an Ideal Gas 326

Chapter 19 The Second Law of Thermodynamics 334
19.1 Reversibility and Irreversibility 334
19.2 The Second Law of Thermodynamics 335
19.3 Applications of the Second Law 339
19.4 Entropy and Energy Quality 342

PART FOUR



Electromagnetism 354

Chapter 20 Electric Charge, Force, and Field 355
20.1 Electric Charge 355
20.2 Coulomb's Law 356
20.3 The Electric Field 359
20.4 Fields of Charge Distributions 362
20.5 Matter in Electric Fields 366

Chapter 21 Gauss's Law 375
21.1 Electric Field Lines 375
21.2 Electric Field and Electric Flux 377
21.3 Gauss's Law 380

21.4 Using Gauss's Law 382
21.5 Fields of Arbitrary Charge Distributions 388
21.6 Gauss's Law and Conductors 390

Chapter 22 Electric Potential 399
22.1 Electric Potential Difference 400
22.2 Calculating Potential Difference 403
22.3 Potential Difference and the Electric Field 408
22.4 Charged Conductors 410

Chapter 23 Electrostatic Energy and Capacitors 418
23.1 Electrostatic Energy 418
23.2 Capacitors 419
23.3 Using Capacitors 421
23.4 Energy in the Electric Field 425

Chapter 24 Electric Current 432
24.1 Electric Current 433
24.2 Conduction Mechanisms 435
24.3 Resistance and Ohm's Law 439
24.4 Electric Power 441
24.5 Electrical Safety 442

Chapter 25 Electric Circuits 449
25.1 Circuits, Symbols, and Electromotive Force 449
25.2 Series and Parallel Resistors 450
25.3 Kirchhoff's Laws and Multiloop Circuits 456
25.4 Electrical Measurements 458
25.5 Capacitors in Circuits 459

Chapter 26 Magnetism: Force and Field 469
26.1 What Is Magnetism? 470
26.2 Magnetic Force and Field 470
26.3 Charged Particles in Magnetic Fields 472
26.4 The Magnetic Force on a Current 475
26.5 Origin of the Magnetic Field 476
26.6 Magnetic Dipoles 479
26.7 Magnetic Matter 483
26.8 Ampère's Law 484

Chapter 27 Electromagnetic Induction 497
27.1 Induced Currents 498
27.2 Faraday's Law 499
27.3 Induction and Energy 503
27.4 Inductance 509
27.5 Magnetic Energy 514
27.6 Induced Electric Fields 517

Chapter 28 Alternating-Current Circuits 525
28.1 Alternating Current 525
28.2 Circuit Elements in AC Circuits 526
28.3 *LC* Circuits 530
28.4 Driven *RLC* Circuits and Resonance 533
28.5 Power in AC Circuits 536
28.6 Transformers and Power Supplies 537

Chapter 29 Maxwell's Equations and Electromagnetic Waves 543
29.1 The Four Laws of Electromagnetism 544
29.2 Ambiguity in Ampère's Law 544
29.3 Maxwell's Equations 546
29.4 Electromagnetic Waves 547
29.5 Properties of Electromagnetic Waves 551
29.6 The Electromagnetic Spectrum 554
29.7 Producing Electromagnetic Waves 555
29.8 Energy and Momentum in Electromagnetic Waves 556

PART FIVE

Optics 565

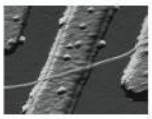
Chapter 30 Reflection and Refraction 566
30.1 Reflection 567
30.2 Refraction 568
30.3 Total Internal Reflection 571
30.4 Dispersion 572

Chapter 31 Images and Optical Instruments 579
31.1 Images with Mirrors 580
31.2 Images with Lenses 585
31.3 Refraction in Lenses: The Details 588
31.4 Optical Instruments 591

Chapter 32 Interference and Diffraction 599
32.1 Coherence and Interference 599
32.2 Double-Slit Interference 601
32.3 Multiple-Slit Interference and Diffraction Gratings 604

32.4 Interferometry 607
32.5 Huygens' Principle and Diffraction 610
32.6 The Diffraction Limit 613

PART SIX



Modern Physics 621

Chapter 33 Relativity 622
33.1 Speed *c* Relative to What? 623
33.2 Matter, Motion, and the Ether 623
33.3 Special Relativity 625
33.4 Space and Time in Relativity 626
33.5 Simultaneity Is Relative 632
33.6 The Lorentz Transformations 633
33.7 Energy and Momentum in Relativity 637
33.8 Electromagnetism and Relativity 640
33.9 General Relativity 641

Chapter 34 Particles and Waves 647
34.1 Toward Quantum Theory 648
34.2 Blackbody Radiation 648
34.3 Photons 650
34.4 Atomic Spectra and the Bohr Atom 654
34.5 Matter Waves 657
34.6 The Uncertainty Principle 659
34.7 Complementarity 661

Chapter 35 Quantum Mechanics 667
35.1 Particles, Waves, and Probability 668
35.2 The Schrödinger Equation 669
35.3 Particles and Potentials 671
35.4 Quantum Mechanics in Three Dimensions 678
35.5 Relativistic Quantum Mechanics 679

Chapter 36 Atomic Physics 684
36.1 The Hydrogen Atom 684
36.2 Electron Spin 688
36.3 The Exclusion Principle 691
36.4 Multielectron Atoms and the Periodic Table 692
36.5 Transitions and Atomic Spectra 696

Chapter 37 Molecules and Solids 702
37.1 Molecular Bonding 702
37.2 Molecular Energy Levels 704
37.3 Solids 707
37.4 Superconductivity 713

Chapter 38 Nuclear Physics 720
38.1 Elements, Isotopes, and Nuclear Structure 721
38.2 Radioactivity 726
38.3 Binding Energy and Nucleosynthesis 731
38.4 Nuclear Fission 733
38.5 Nuclear Fusion 739

Chapter 39 From Quarks to the Cosmos 747
39.1 Particles and Forces 748
39.2 Particles and More Particles 749
39.3 Quarks and the Standard Model 752
39.4 Unification 755
39.5 The Evolving Universe 757

APPENDICES

Appendix A Mathematics A-1
Appendix B The International System of Units (SI) A-9
Appendix C Conversion Factors A-11
Appendix D The Elements A-13
Appendix E Astrophysical Data A-16

Answers to Odd-Numbered Problems A-17
Credits C-1
Index I-1

Doing Physics

What You Know

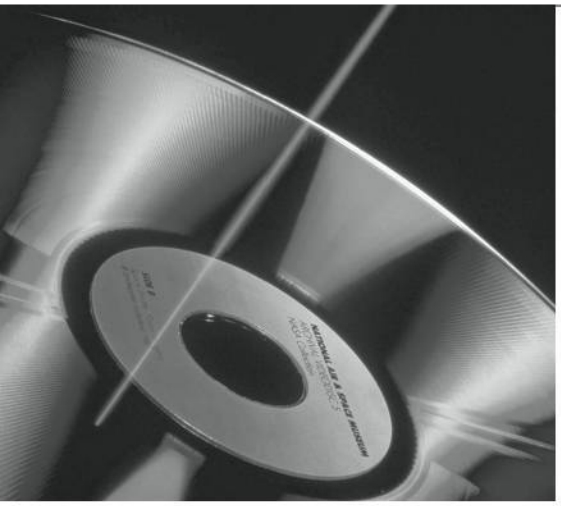
- You're coming to this course with a solid background in algebra, geometry, and trigonometry.
- You may have had calculus, or you'll be starting it concurrently.
- You don't need to have taken physics to get a full understanding from this book.

What You're Learning

- This chapter gives you an overview of physics and its subfields, which together describe the entire physical universe.
- You'll learn the basis of the SI system of measurement units.
- You'll learn to express and manipulate numbers used in quantitative science.
- You'll learn to deal with precision and uncertainty.
- You'll develop a skill for making quick estimates.
- You'll learn how to extract information from experimental data.
- You'll see a strategy for solving physics problems.

How You'll Use It

- Skills and knowledge that you develop in this chapter will serve you throughout your study of physics.
- You'll be able to express quantitative answers to physics problems in scientific notation, with the correct units and the appropriate uncertainty expressed through significant figures.
- Being able to make quick estimates will help you gauge the sizes of physical effects and will help you recognize whether your quantitative answers make sense.
- The problem-solving strategy you'll learn here will serve you in the many physics problems that you'll work in order to really learn physics.



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

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

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.

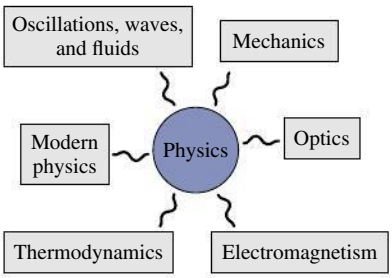


FIGURE 1.1 Realms of physics.

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 hybrid 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

"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. Currently, SI is undergoing a sweeping revision, which will result in redefining the kilogram and three of the four remaining so-called base units with definitions that lock in exact values of fundamental constants. These so-called **explicit-constant** definitions will have similar wording, making explicit that the unit in question follows from the defined value of the particular physical constant.

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!

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 definitions won't change the meter but will reword its definition to make it of the explicit-constant type:

> The meter, symbol m, is the unit of length; its magnitude is set by fixing the numerical value of the speed of light in vacuum to be equal to exactly 299,792,458 when it is expressed in the SI unit m/s.

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 will keep the essence of that operational definition but reworded in the explicit-constant style:

> The second, symbol s, is the unit of time; its magnitude is set by fixing the numerical value of the ground-state hyperfine splitting frequency of the cesium-133 atom, at rest and at a temperature of 0 K, to be exactly 9,192,631,770 when it is expressed in the SI unit s^{-1}, which is equal to Hz.

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 "equal to Hz" introduces the unit hertz (Hz) for frequency—the number of cycles of a repeating process that occur each second.

Mass

Since 1889, the kilogram has been 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 is this artifact-based standard awkward to access, but comparison measurements have revealed tiny yet growing mass discrepancies between the international prototype kilogram and secondary mass standards based on it.

In the current SI revision, the kilogram will become the last of the SI base units to be defined operationally, with a new explicit-constant definition resulting from fixing the value of *Planck's constant*, h, a fundamental constant of nature related to the "graininess" of physical quantities at the atomic and subatomic levels. The units of Planck's constant involve seconds, meters, and kilograms, and giving h an exact value actually sets the value of 1 $s^{-1} \cdot m^2 \cdot kg$. But with the meter and second already defined, fixing the unit $s^{-1} \cdot m^2 \cdot kg$ then determines the kilogram. A device that implements this definition is the *watt balance*, which balances an unknown mass against forces resulting from electrical effects whose magnitude, in turn, can be related to Planck's constant. The new formal definition of the kilogram will be similar to the explicit-constant definitions of the meter and second, but the exact value of Planck's constant is yet to be established.

The angle θ in radians is defined as the ratio of the subtended arc length s to the radius r: $\theta = \frac{s}{r}$.

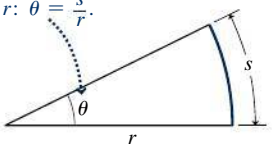


FIGURE 1.2 The radian is the SI unit of angle.

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. In the ongoing SI revision these will be given 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: $N \cdot m$ 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 $m \cdot s^{-1}$.

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

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

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

■

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 2717 ft or

$$(2717 \text{ ft})\left(\frac{0.3048 \text{ m}}{1 \text{ ft}}\right) = 828.1 \text{ m}$$

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!

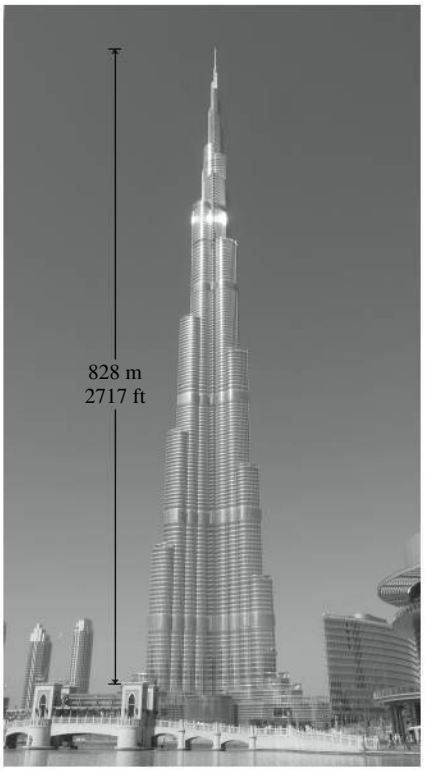


FIGURE 1.3 Dubai's Burj Khalifa is the world's tallest structure.

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 mph; (b) 45 mph; (c) 30 mph

1.3 Working with Numbers

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-size 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.

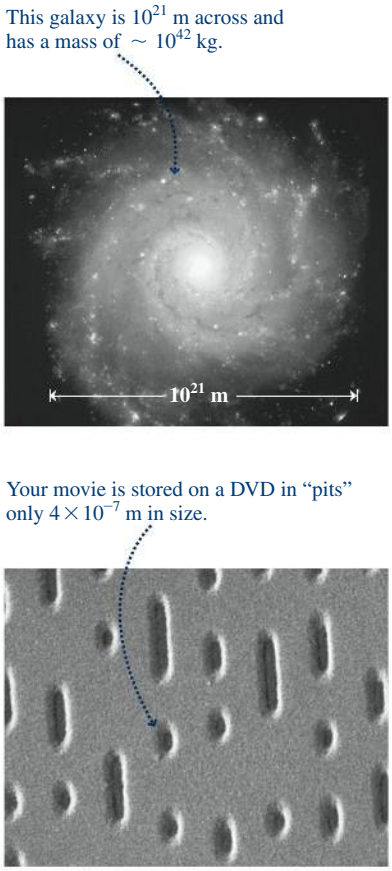


FIGURE 1.4 Large and small.

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

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. ■

✓TIP 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.

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.

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.

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.

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

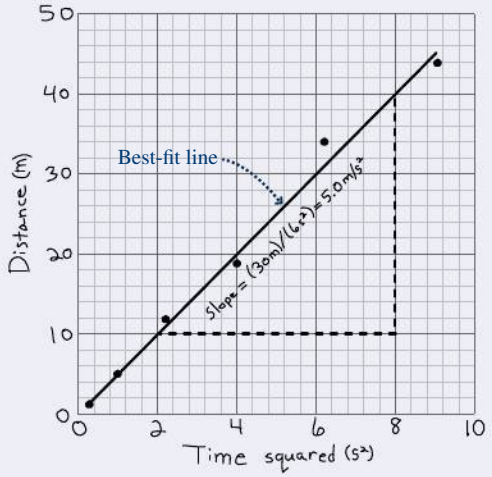


FIGURE 1.5 Our graph for Example 1.4. We "eyeballed" the best-fit line using a ruler; note that it doesn't go through particular points but tries to capture the average trend of all the data points.

■

MP

PhET: Estimation

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 1.5 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.

■

1.4 Strategies for Learning Physics

You can learn *about* physics, and you can learn to *do* physics. This book is for science and engineering students, so it 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.

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