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# Essential University Physics

## Volume 1

THIRD EDITION

Richard Wolfson

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# ESSENTIAL UNIVERSITY PHYSICS

VOLUME **1** CHAPTERS 1-19

THIRD EDITION

GLOBAL EDITION



Richard Wolfson  
*Middlebury College*

PEARSON

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# PhET Simulations

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



Chapter	PhET	Page	Chapter	PhET	Page
1	Estimation	26	24	Resistance in a Wire	519
2	The Moving Man	34	24	Ohm's Law	519
3	Vector Addition	51	25	Battery Resistor Circuit	530
3	Projectile Motion	57	25	Circuit Construction Kit (DC Only)	531, 536
3	Ladybug Motion 2D	61	25	Signal Circuit	531
3	Motion in 2D	61	26	Magnet and Compass	550
5	The Ramp	91	26	Magnets and Electromagnets	563
5	Forces in 1 Dimension	98	27	Farady's Law	578
5	Friction	98	27	Farady's Electromagnetic Lab	582
6	The Ramp	110, 114	27	Generator	586
7	Calculus Grapher	138	28	Circuit Construction Kit (AC + DC)	606, 610, 613
7	Energy Skate Park	138	29	Radio Waves and Electromagnetic Fields	636
8	Gravity Force Lab	149	29	Radiating Charge	636
8	My Solar System	150	29	Optical Tweezers and Applications	639
8	Gravity and Orbits	150	30	Bending Light (Intro)	649
9	Collisions (Introduction)	176	30	Bending Light (Prism Break)	652
9	Collisions (Advanced)	177	31	Geometric Optics	665
10	Ladybug Revolution	187	32	Wave Interference: Light	681
10	Torque (Torque)	191	34	Blackbody Spectrum	728
10	Torque (Moment of Inertia)	191	34	Photoelectric Effect	731
11	Simplified MRI	214	34	Neon Lights & Other Discharge Lamps	734
13	Masses and Springs	242	34	Quantum Wave Interference	739
13	Pendulum Lab	247	35	Quantum Bound State: One Well	751, 755
14	Wave on a String	265, 273	35	Quantum Tunneling and Wave Packets	757
14	Sound	269	36	Quantum Bound State: One Well: 3D Coulomb	765
14	Fourier: Making Waves	270	36	Build an Atom	773
14	Wave Interference	271	37	Quantum Bound States: Two Wells (Molecular Bonding)	783
15	Balloons and Buoyancy	287	37	Band Structure	789
16	Blackbody Spectrum	311	37	Semiconductors	792
16	The Greenhouse Effect	314	38	Rutherford Scattering	801
17	Gas Properties	321	38	Simplified MRI	804
17	States of Matter	325	38	Radioactive Dating Game	806
19	Reversible Reactions	362	38	Alpha Decay	809
20	Balloons and Static Electricity	436	38	Beta Decay	809
20	Charges and Fields	439, 442	38	Nuclear Fission: One Nucleus	814
20	Electricity Field Hockey	446	38	Nuclear Fission: Chain Reaction	815
22	Calculus Grapher	489	38	Nuclear Fission: Nuclear Reactor	816
22	Charges and Fields	489			
24	Conductivity	515			
24	Semiconductors	517			



# 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.

<b>Chapter</b>	<b>Video Tutor Demonstration</b>	<b>Page</b>	<b>Chapter</b>	<b>Video Tutor Demonstration</b>	<b>Page</b>
2	Balls Take High and Low Tracks	34	15	Weighing Weights in Water	288
3	Dropped and Thrown Balls	56	15	Air Jet Blows between Bowling Balls	292
3	Ball Fired from Cart on Incline	57	16	Heating Water and Aluminum	306
3	Ball Fired Upward from Accelerating Cart	57	16	Water Balloon Held over Candle Flame	306
3	Range of a Gun at Two Firing Angles	61	16	Candle Chimneys	311
4	Cart with Fan and Sail	71	20	Charged Rod and Aluminum Can	449
4	Ball Leaves Circular Track	71	21	Electroscope in Conducting Shell	471
4	Suspended Balls: Which String Breaks?	72	22	Charged Conductor with Teardrop Shape	491
4	Weighing a Hovering Magnet	81	23	Discharge Speed for Series and Parallel Capacitors	503
5	Tension in String between Hanging Weights	94	24	Resistance in Copper and Nichrome	521
7	Chin Basher?	136	25	Bulbs Connected in Series and in Parallel	534
9	Balancing a Meter Stick	164	26	Magnet and Electron Beam	550
9	Water Rocket	171	26	Current-Carrying Wire in Magnetic Field	555
9	Happy/Sad Pendulums	172	27	Eddy Currents in Different Metals	587
10	Canned Food Race	200	29	Parallel-Wire Polarizer for Microwaves	633
11	Spinning Person Drops Weights	213	29	Point of Equal Brightness between Two Light Sources	638
11	Off-Center Collision	213	31	Partially Covering a Lens	667
12	Walking the Plank	225	36	Illuminating Sodium Vapor with Sodium and Mercury Lamps	776
13	Vibrating Rods	254			
14	Out-of-Phase Speakers	269			
15	Pressure in Water and Alcohol	286			
15	Water Level in Pascal's Vases	286			

# Brief Contents

**Chapter 1** Doing Physics 19

## **PART ONE**

### Mechanics 32

**Chapter 2** Motion in a Straight Line 33

**Chapter 3** Motion in Two and Three Dimensions 50

**Chapter 4** Force and Motion 69

**Chapter 5** Using Newton's Laws 89

**Chapter 6** Energy, Work, and Power 108

**Chapter 7** Conservation of Energy 127

**Chapter 8** Gravity 147

**Chapter 9** Systems of Particles 162

**Chapter 10** Rotational Motion 186

**Chapter 11** Rotational Vectors and Angular Momentum 207

**Chapter 12** Static Equilibrium 222

## **PART TWO**

### Oscillations, Waves, and Fluids 239

**Chapter 13** Oscillatory Motion 240

**Chapter 14** Wave Motion 261

**Chapter 15** Fluid Motion 283

## **PART THREE**

### Thermodynamics 302

**Chapter 16** Temperature and Heat 303

**Chapter 17** The Thermal Behavior of Matter 321

**Chapter 18** Heat, Work, and the First Law of Thermodynamics 335

**Chapter 19** The Second Law of Thermodynamics 352

## **APPENDICES**

**Appendix A** Mathematics 373

**Appendix B** The International System of Units (SI) 381

**Appendix C** Conversion Factors 383

**Appendix D** The Elements 385

**Appendix E** Astrophysical Data 388

Answers to Odd-Numbered Problems 389

Credits 398

Index 401

## **PART FOUR**

### Electromagnetism 434

**Chapter 20** Electric Charge, Force, and Field 435

**Chapter 21** Gauss's Law 455

**Chapter 22** Electric Potential 479

**Chapter 23** Electrostatic Energy and Capacitors 498

**Chapter 24** Electric Current 512

**Chapter 25** Electric Circuits 529

**Chapter 26** Magnetism: Force and Field 549

**Chapter 27** Electromagnetic Induction 577

**Chapter 28** Alternating-Current Circuits 605

**Chapter 29** Maxwell's Equations and Electromagnetic Waves 623

## **PART FIVE**

### Optics 645

**Chapter 30** Reflection and Refraction 646

**Chapter 31** Images and Optical Instruments 659

**Chapter 32** Interference and Diffraction 679

## **PART SIX**

### Modern Physics 701

**Chapter 33** Relativity 702

**Chapter 34** Particles and Waves 727

**Chapter 35** Quantum Mechanics 747

**Chapter 36** Atomic Physics 764

**Chapter 37** Molecules and Solids 782

**Chapter 38** Nuclear Physics 800

**Chapter 39** From Quarks to the Cosmos 827

## **APPENDICES**

**Appendix A** Mathematics 847

**Appendix B** The International System of Units (SI) 855

**Appendix C** Conversion Factors 857

**Appendix D** The Elements 859

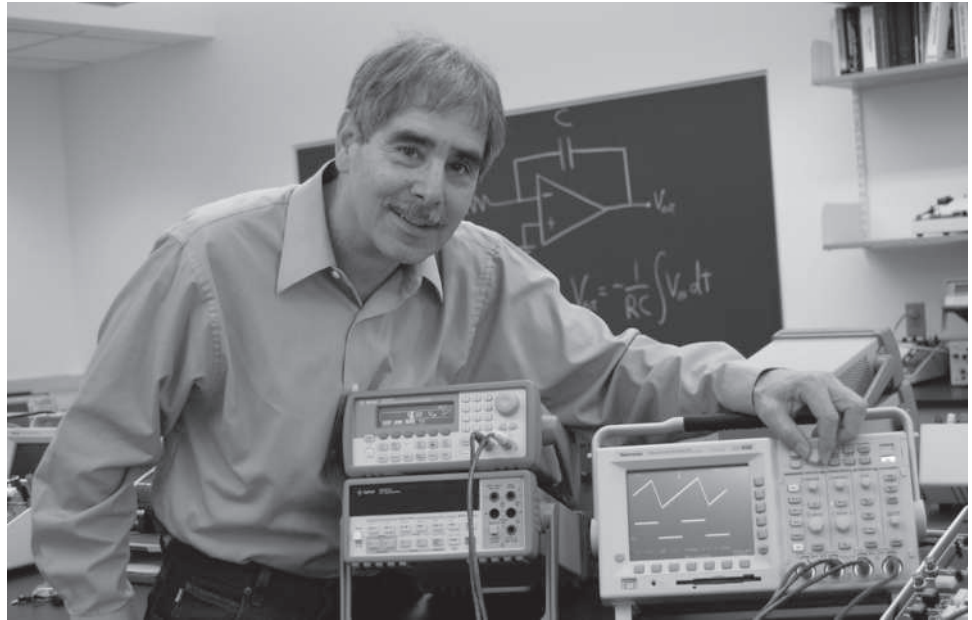
**Appendix E** Astrophysical Data 862

Answers to Odd-Numbered Problems 863

Credits 872

Index 875

# 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 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 can be downloaded from the Instructor's Resource Area of MasteringPhysics® ([www.masteringphysics.com](http://www.masteringphysics.com)) as well as from the Instructor's Resource Center on [www.pearsonglobaleditions.com/Wolfson](http://www.pearsonglobaleditions.com/Wolfson).

- The **Instructor's 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.
-  **MasteringPhysics®** ([www.masteringphysics.com](http://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 explicitly 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 through MasteringPhysics®. 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** 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](http://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®. 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.

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# 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.

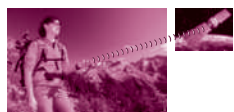
# Detailed Contents

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

## Chapter 1 Doing Physics 19

- 1.1 Realms of Physics 19
- 1.2 Measurements and Units 21
- 1.3 Working with Numbers 23
- 1.4 Strategies for Learning Physics 27

## PART ONE



## Mechanics 32

### Chapter 2 Motion in a Straight Line 33

- 2.1 Average Motion 33
- 2.2 Instantaneous Velocity 35
- 2.3 Acceleration 37
- 2.4 Constant Acceleration 39
- 2.5 The Acceleration of Gravity 42
- 2.6 When Acceleration Isn't Constant 44

### Chapter 3 Motion in Two and Three Dimensions 50

- 3.1 Vectors 50
- 3.2 Velocity and Acceleration Vectors 53
- 3.3 Relative Motion 54
- 3.4 Constant Acceleration 55
- 3.5 Projectile Motion 57
- 3.6 Uniform Circular Motion 61

### Chapter 4 Force and Motion 69

- 4.1 The Wrong Question 69
- 4.2 Newton's First and Second Laws 70
- 4.3 Forces 73
- 4.4 The Force of Gravity 74
- 4.5 Using Newton's Second Law 76
- 4.6 Newton's Third Law 78

### Chapter 5 Using Newton's Laws 89

- 5.1 Using Newton's Second Law 89
- 5.2 Multiple Objects 92

- 5.3 Circular Motion 94

- 5.4 Friction 98

- 5.5 Drag Forces 102

### Chapter 6 Energy, Work, and Power 108

- 6.1 Energy 109
- 6.2 Work 110
- 6.3 Forces That Vary 114
- 6.4 Kinetic Energy 117
- 6.5 Power 119

### Chapter 7 Conservation of Energy 127

- 7.1 Conservative and Nonconservative Forces 128
- 7.2 Potential Energy 129
- 7.3 Conservation of Mechanical Energy 133
- 7.4 Nonconservative Forces 136
- 7.5 Conservation of Energy 137
- 7.6 Potential-Energy Curves 138

### Chapter 8 Gravity 147

- 8.1 Toward a Law of Gravity 147
- 8.2 Universal Gravitation 148
- 8.3 Orbital Motion 150
- 8.4 Gravitational Energy 153
- 8.5 The Gravitational Field 156

### Chapter 9 Systems of Particles 162

- 9.1 Center of Mass 162
- 9.2 Momentum 167
- 9.3 Kinetic Energy of a System 171
- 9.4 Collisions 171
- 9.5 Totally Inelastic Collisions 172
- 9.6 Elastic Collisions 174

### Chapter 10 Rotational Motion 186

- 10.1 Angular Velocity and Acceleration 186
- 10.2 Torque 189
- 10.3 Rotational Inertia and the Analog of Newton's Law 191
- 10.4 Rotational Energy 196
- 10.5 Rolling Motion 198

**Chapter 11** Rotational Vectors and Angular Momentum 207

- 11.1 Angular Velocity and Acceleration Vectors 207
- 11.2 Torque and the Vector Cross Product 208
- 11.3 Angular Momentum 210
- 11.4 Conservation of Angular Momentum 212
- 11.5 Gyroscopes and Precession 214

**Chapter 12** Static Equilibrium 222

- 12.1 Conditions for Equilibrium 222
- 12.2 Center of Gravity 224
- 12.3 Examples of Static Equilibrium 225
- 12.4 Stability 227

**PART TWO****Oscillations, Waves, and Fluids 239****Chapter 13** Oscillatory Motion 240

- 13.1 Describing Oscillatory Motion 241
- 13.2 Simple Harmonic Motion 242
- 13.3 Applications of Simple Harmonic Motion 245
- 13.4 Circular Motion and Harmonic Motion 249
- 13.5 Energy in Simple Harmonic Motion 250
- 13.6 Damped Harmonic Motion 251
- 13.7 Driven Oscillations and Resonance 253

**Chapter 14** Wave Motion 261

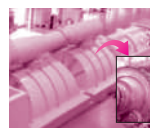
- 14.1 Waves and Their Properties 262
- 14.2 Wave Math 263
- 14.3 Waves on a String 265
- 14.4 Sound Waves 268
- 14.5 Interference 269
- 14.6 Reflection and Refraction 272
- 14.7 Standing Waves 273
- 14.8 The Doppler Effect and Shock Waves 276

**Chapter 15** Fluid Motion 283

- 15.1 Density and Pressure 283
- 15.2 Hydrostatic Equilibrium 284
- 15.3 Archimedes' Principle and Buoyancy 287
- 15.4 Fluid Dynamics 289

## 15.5 Applications of Fluid Dynamics 291

## 15.6 Viscosity and Turbulence 295

**PART THREE****Thermodynamics 302****Chapter 16** Temperature and Heat 303

- 16.1 Heat, Temperature, and Thermodynamic Equilibrium 303
- 16.2 Heat Capacity and Specific Heat 305
- 16.3 Heat Transfer 307
- 16.4 Thermal-Energy Balance 312

**Chapter 17** The Thermal Behavior of Matter 321

- 17.1 Gases 321
- 17.2 Phase Changes 325
- 17.3 Thermal Expansion 328

**Chapter 18** Heat, Work, and the First Law of Thermodynamics 335

- 18.1 The First Law of Thermodynamics 335
- 18.2 Thermodynamic Processes 337
- 18.3 Specific Heats of an Ideal Gas 344

**Chapter 19** The Second Law of Thermodynamics 352

- 19.1 Reversibility and Irreversibility 352
- 19.2 The Second Law of Thermodynamics 353
- 19.3 Applications of the Second Law 357
- 19.4 Entropy and Energy Quality 360

**APPENDICES****Appendix A** Mathematics 373**Appendix B** The International System of Units (SI) 381**Appendix C** Conversion Factors 383**Appendix D** The Elements 385**Appendix E** Astrophysical Data 388

## Answers to Odd-Numbered Problems 389

## Credits 398

## Index 401

**PART FOUR****Electromagnetism 434****Chapter 20** Electric Charge, Force, and Field 435

- 20.1 Electric Charge 435
- 20.2 Coulomb's Law 436
- 20.3 The Electric Field 439
- 20.4 Fields of Charge Distributions 442
- 20.5 Matter in Electric Fields 446

**Chapter 21** Gauss's Law 455

- 21.1 Electric Field Lines 455
- 21.2 Electric Field and Electric Flux 457
- 21.3 Gauss's Law 460
- 21.4 Using Gauss's Law 462
- 21.5 Fields of Arbitrary Charge Distributions 468
- 21.6 Gauss's Law and Conductors 470

**Chapter 22** Electric Potential 479

- 22.1 Electric Potential Difference 480
- 22.2 Calculating Potential Difference 483
- 22.3 Potential Difference and the Electric Field 488
- 22.4 Charged Conductors 490

**Chapter 23** Electrostatic Energy and Capacitors 498

- 23.1 Electrostatic Energy 498
- 23.2 Capacitors 499
- 23.3 Using Capacitors 501
- 23.4 Energy in the Electric Field 505

**Chapter 24** Electric Current 512

- 24.1 Electric Current 513
- 24.2 Conduction Mechanisms 515
- 24.3 Resistance and Ohm's Law 519
- 24.4 Electric Power 521
- 24.5 Electrical Safety 522

**Chapter 25** Electric Circuits 529

- 25.1 Circuits, Symbols, and Electromotive Force 529
- 25.2 Series and Parallel Resistors 530

## 25.3 Kirchhoff's Laws and Multiloop Circuits 536

## 25.4 Electrical Measurements 538

## 25.5 Capacitors in Circuits 539

**Chapter 26** Magnetism: Force and Field 549

- 26.1 What Is Magnetism? 550
- 26.2 Magnetic Force and Field 550
- 26.3 Charged Particles in Magnetic Fields 552
- 26.4 The Magnetic Force on a Current 555
- 26.5 Origin of the Magnetic Field 556
- 26.6 Magnetic Dipoles 559
- 26.7 Magnetic Matter 563
- 26.8 Ampère's Law 564

**Chapter 27** Electromagnetic Induction 577

- 27.1 Induced Currents 578
- 27.2 Faraday's Law 579
- 27.3 Induction and Energy 583
- 27.4 Inductance 589
- 27.5 Magnetic Energy 594
- 27.6 Induced Electric Fields 597

**Chapter 28** Alternating-Current Circuits 605

- 28.1 Alternating Current 605
- 28.2 Circuit Elements in AC Circuits 606
- 28.3 LC Circuits 610
- 28.4 Driven RLC Circuits and Resonance 613
- 28.5 Power in AC Circuits 616
- 28.6 Transformers and Power Supplies 617

**Chapter 29** Maxwell's Equations and Electromagnetic Waves 623

- 29.1 The Four Laws of Electromagnetism 624
- 29.2 Ambiguity in Ampère's Law 624
- 29.3 Maxwell's Equations 626
- 29.4 Electromagnetic Waves 627
- 29.5 Properties of Electromagnetic Waves 631
- 29.6 The Electromagnetic Spectrum 634
- 29.7 Producing Electromagnetic Waves 635
- 29.8 Energy and Momentum in Electromagnetic Waves 636

**PART FIVE****Optics 645****Chapter 30** Reflection and Refraction 646

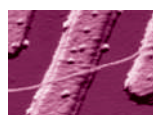
- 30.1 Reflection 647
- 30.2 Refraction 648
- 30.3 Total Internal Reflection 651
- 30.4 Dispersion 652

**Chapter 31** Images and Optical Instruments 659

- 31.1 Images with Mirrors 660
- 31.2 Images with Lenses 665
- 31.3 Refraction in Lenses: The Details 668
- 31.4 Optical Instruments 671

**Chapter 32** Interference and Diffraction 679

- 32.1 Coherence and Interference 679
- 32.2 Double-Slit Interference 681
- 32.3 Multiple-Slit Interference and Diffraction Gratings 684
- 32.4 Interferometry 687
- 32.5 Huygens' Principle and Diffraction 690
- 32.6 The Diffraction Limit 693

**PART SIX****Modern Physics 701****Chapter 33** Relativity 702

- 33.1 Speed  $c$  Relative to What? 703
- 33.2 Matter, Motion, and the Ether 703
- 33.3 Special Relativity 705
- 33.4 Space and Time in Relativity 706
- 33.5 Simultaneity Is Relative 712
- 33.6 The Lorentz Transformations 713
- 33.7 Energy and Momentum in Relativity 717
- 33.8 Electromagnetism and Relativity 720
- 33.9 General Relativity 721

**Chapter 34** Particles and Waves 727

- 34.1 Toward Quantum Theory 728
- 34.2 Blackbody Radiation 728
- 34.3 Photons 730
- 34.4 Atomic Spectra and the Bohr Atom 734

34.5 Matter Waves 737

34.6 The Uncertainty Principle 739

34.7 Complementarity 741

**Chapter 35** Quantum Mechanics 747

- 35.1 Particles, Waves, and Probability 748
- 35.2 The Schrödinger Equation 749
- 35.3 Particles and Potentials 751
- 35.4 Quantum Mechanics in Three Dimensions 758
- 35.5 Relativistic Quantum Mechanics 759

**Chapter 36** Atomic Physics 764

- 36.1 The Hydrogen Atom 764
- 36.2 Electron Spin 768
- 36.3 The Exclusion Principle 771
- 36.4 Multielectron Atoms and the Periodic Table 772
- 36.5 Transitions and Atomic Spectra 776

**Chapter 37** Molecules and Solids 782

- 37.1 Molecular Bonding 782
- 37.2 Molecular Energy Levels 784
- 37.3 Solids 787
- 37.4 Superconductivity 793

**Chapter 38** Nuclear Physics 800

- 38.1 Elements, Isotopes, and Nuclear Structure 801
- 38.2 Radioactivity 806
- 38.3 Binding Energy and Nucleosynthesis 811
- 38.4 Nuclear Fission 813
- 38.5 Nuclear Fusion 819

**Chapter 39** From Quarks to the Cosmos 827

- 39.1 Particles and Forces 828
- 39.2 Particles and More Particles 829
- 39.3 Quarks and the Standard Model 832
- 39.4 Unification 835
- 39.5 The Evolving Universe 837

**APPENDICES****Appendix A** Mathematics 847**Appendix B** The International System of Units (SI) 855**Appendix C** Conversion Factors 857**Appendix D** The Elements 859**Appendix E** Astrophysical Data 862

Answers to Odd-Numbered Problems 863

Credits 872

Index 875



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## 1

2

Motion in a  
Straight Line

3

Motion in Two and  
Three Dimensions

# 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?

**Y**ou 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.