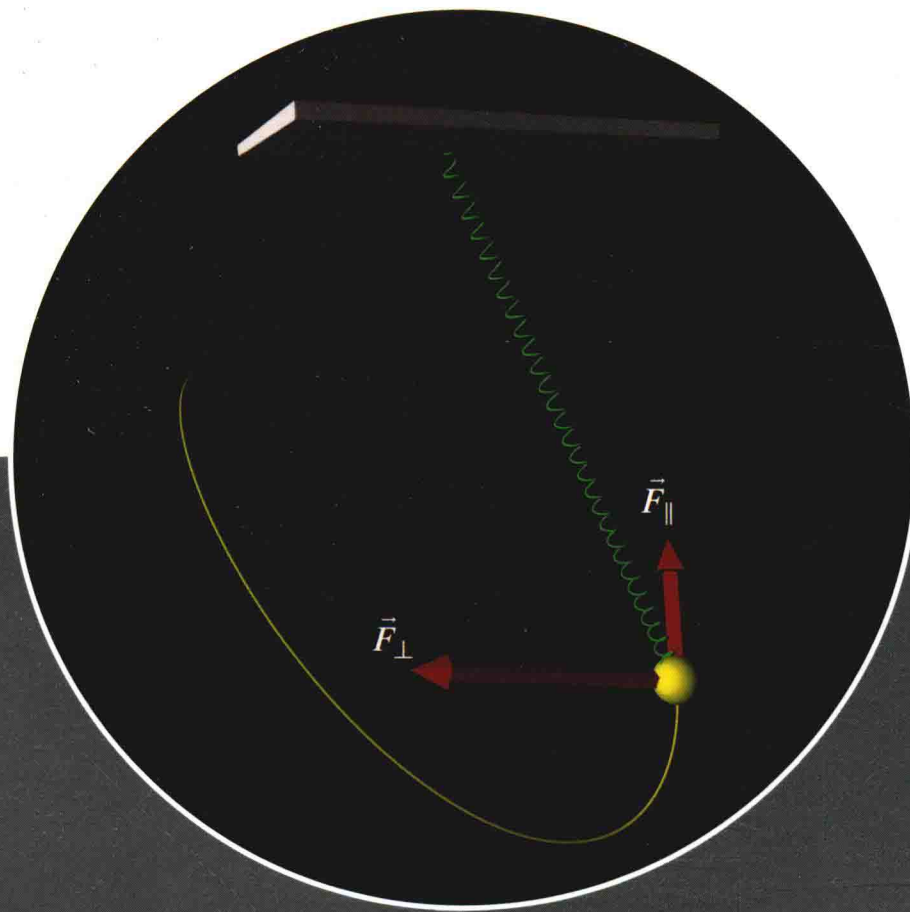


MATTER & INTERACTIONS

MODERN MECHANICS



FOURTH EDITION

CHABAY • SHERWOOD

VOLUME ONE

WILEY

FOURTH EDITION

Matter & Interactions

VOLUME I

Modern Mechanics

VOLUME II

Electric and Magnetic Interactions

RUTH W. CHABAY

BRUCE A. SHERWOOD

North Carolina State University

WILEY

VICE PRESIDENT & PUBLISHER Petra Recter
EXECUTIVE EDITOR Jessica Fiorillo
ASSOCIATE EDITOR Aly Rentrop
EDITORIAL ASSISTANT Amanda Rillo
SENIOR MARKETING MANAGER Kristy Ruff
MARKETING ASSISTANT Claudine Scrivanich
SENIOR CONTENT MANAGER Kevin Holm
SENIOR PRODUCTION EDITOR Elizabeth Swain
DESIGN DIRECTOR Harry Nolan
TEXT/COVER DESIGN Maureen Eide
COVER IMAGE Ruth Chabay

Cover Description: The cover image is a snapshot from a VPython program that models the motion of a mass-spring system in 3D (see Computational Problem P70 in Chapter 4).

This book was set in 10/12 Times Ten Roman in LaTeX by MPS and printed and bound by Quad Graphics. The cover was printed by Quad Graphics.

This book is printed on acid-free paper.

Copyright © 2015, 2011, 2007 John Wiley & Sons, Inc. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, website www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030-5774, (201)748-6011, fax (201)748-6008, website <http://www.wiley.com/go/permissions>.

Evaluation copies are provided to qualified academics and professionals for review purposes only, for use in their courses during the next academic year. These copies are licensed and may not be sold or transferred to a third party. Upon completion of the review period, please return the evaluation copy to Wiley. Return instructions and a free of charge return shipping label are available at www.wiley.com/go/returnlabel. Outside of the United States, please contact your local representative.

Complete text ISBN 978-1-118-87586-5

Complete text binder version ISBN 978-1-118-91451-9

Volume 1 ISBN 978-1-118-91449-6

Volume 1 Binder version ISBN 978-1-118-91452-6

Volume 2 ISBN 978-1-118-91450-2

Volume 2 Binder version ISBN 978-1-118-91453-3

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Preface

TO THE STUDENT

This textbook emphasizes a 20th-century perspective on introductory physics. Contemporary physicists build models of the natural world that are based on a small set of fundamental physics principles and on an understanding of the microscopic structure of matter, and they apply these models to explain and predict a very broad range of physical phenomena. In order to involve students of introductory physics in the contemporary physics enterprise, this textbook emphasizes:

- Reasoning directly from a small number of fundamental physics principles, rather than from a large set of special-case equations.
- Integrating contemporary insights, such as atomic models of matter, quantized energy, and relativistic dynamics, throughout the curriculum.
- Engaging in the full process of creating and refining physical models (idealizing, making approximations, explicitly stating assumptions, and estimating quantities).
- Reasoning iteratively about the time-evolution of system behavior, both on paper and through the construction and application of computational models.

Because the physical world is 3-dimensional, we work in 3D throughout the text. Many students find the approach to 3D vectors used in this book easier than standard treatments of 2D vectors.

Textbook and Supplemental Resources

Modern Mechanics (Volume 1, Chapters 1–12) focuses on the atomic structure of matter and interactions between material objects. It emphasizes the wide applicability and utility of a small number of fundamental principles: the Momentum Principle, the Energy Principle, and the Angular Momentum Principle, and the Fundamental Assumption of Statistical Mechanics. We study how to explain and predict the behavior of systems as different as elementary particles, molecules, solid metals, and galaxies.

Electric and Magnetic Interactions (Volume 2, Chapters 13–23) emphasizes the somewhat more abstract concepts of electric and magnetic fields and extends the study of the atomic structure of matter to include the role of electrons. The principles of electricity and magnetism are the foundation for much of today's technology, from cell phones to medical imaging.

Additional resources for students are freely available at this site:

www.wiley.com/college/chabay

The web resources include several supplements. A copy of Chapter 1 is provided for students who are currently using Volume 2 but whose previous physics course did not use Volume 1. This chapter introduces 3D vectors and vector algebra, and includes an introduction to computational modeling in VPython, which is used throughout the textbook.

Supplement S1 treats the kinetic theory of gases and heat engines, and can be used by students who have completed Chapter 12 on Entropy. Supplement S2 explains the basic principles of PN junctions in semiconductor devices, and can be used by students who have completed Chapter 21: Patterns of Field in Space. Supplement S3 includes a more mathematically sophisticated treatment of mechanical and electromagnetic waves and wave phenomena, and

can be used by students who have completed Chapter 23 on Electromagnetic Radiation.

Answers to odd-numbered problems may be found at the end of the book.

The new Student Solutions Manual is available for purchase as a printed supplement and contains fully worked solutions for a subset of end of chapter problems.

Prerequisites

This book is intended for introductory calculus-based college physics courses taken by science and engineering students. It requires a basic knowledge of derivatives and integrals, which can be obtained by studying calculus concurrently.

Modeling

Matter & Interactions places a major emphasis on constructing and using physical models. A central aspect of science is the modeling of complex real-world phenomena. A physical model is based on what we believe to be fundamental principles; its intent is to predict or explain the most important aspects of an actual situation. Modeling necessarily involves making approximations and simplifying assumptions that make it possible to analyze a system in detail.

Computational Modeling

Computational modeling is now as important as theory and experiment in contemporary science and engineering. We introduce you to serious computer modeling right away to help you build a strong foundation in the use of this important tool.

In this course you will construct simple computational models based on fundamental physics principles. You do not need any prior programming experience—this course will teach you the small number of computational concepts you will need. Using VPython, a computational environment based on the Python programming language, you will find that after less than an hour you can write a simple computational model that produces a navigable 3D animation as a side effect of your physics code.

Computational modeling allows us to analyze complex systems that would otherwise require very sophisticated mathematics or that could not be analyzed at all without a computer. Numerical calculations based on the Momentum Principle give us the opportunity to watch the dynamical evolution of the behavior of a system. Simple models frequently need to be refined and extended. This can be done straightforwardly with a computer model but is often impossible with a purely analytical (non-numerical) model.

VPython is free, and runs on Windows, MacOS, and Linux. Instructions in Chapter 1 tell you how to install it on your own computer, and how to find a set of instructional videos that will help you learn to use VPython.

Questions

As you read the text, you will frequently come to a question that looks like this:

QUESTION What should I do when I encounter a question in the text?














A question invites you to stop and think, to make a prediction, to carry out a step in a derivation or analysis, or to apply a principle. These questions are answered in the following paragraphs, but it is important that you make a serious effort to answer the questions on your own before reading further. Be honest in comparing your answers to those in the text. Paying attention to surprising or counterintuitive results can be a useful learning strategy.

Checkpoints

Checkpoints at the end of some sections ask you to apply new concepts or techniques. These may involve qualitative reasoning or simple calculations. You should complete these checkpoints when you come to them, before reading further. The goal of a checkpoint is to help you consolidate your understanding of the material you have just read, and to make sure you are ready to continue reading. Answers to checkpoints are found at the end of each chapter.

Conventions Used in Diagrams

The conventions most commonly used to represent vectors and scalars in diagrams in this text are shown in the margin. In equations and text, a vector will be written with an arrow above it: \vec{p} .

| | |
|---|-----------------------------|
|  | Force |
|  | Component of force |
|  | Velocity |
|  | Momentum |
|  | Electric field |
|  | Component of electric field |
|  | Magnetic field |
|  | Component of magnetic field |
|  | Position |
|  | Angular momentum |
|  | Torque |
|  | Distance |
|  | A path |

TO THE INSTRUCTOR

The approach to introductory physics in this textbook differs significantly from that in most textbooks. Key emphases of the approach include:

- Starting from fundamental principles rather than secondary formulas
- Atomic-level description and analysis
- Modeling the real world through idealizations and approximations
- Computational modeling of physical systems
- Unification of mechanics and thermal physics
- Unification of electrostatics and circuits
- The use of 3D vectors throughout

Web Resources for Instructors

Instructor resources are available at this web site:

www.wiley.com/college/chabay

Resources on this site include lecture-demo software, textbook figures, clicker questions, test questions, lab activities including experiments and computational modeling, a computational modeling guide, and a full solutions manual. Contact your Wiley representative for information about this site.

Electronic versions of the homework problems are available in WebAssign:

www.webassign.net

Some instructor resources are available through WebAssign as well.

Other information may be found on the authors' *Matter & Interactions* web site:

matterandinteractions.org

Also on the authors' website are reprints of published articles about *Matter & Interactions*, including these:

- Chabay, R. & Sherwood, B. (1999). Bringing atoms into first-year physics. *American Journal of Physics* 67, 1045–1050.
- Chabay, R. W. & Sherwood, B. (2004). Modern mechanics. *American Journal of Physics* 72, 439–445.
- Chabay, R. W. & Sherwood, B. (2006). Restructuring Introductory E&M. *American Journal of Physics* 74, 329–336.
- Chabay, R. & Sherwood, B. (2008) Computational physics in the introductory calculus-based course. *American Journal of Physics* 76(4&5), 307–313.
- Beichner, R., Chabay, R., & Sherwood, B. (2010) Labs for the Matter & Interactions curriculum. *American Journal of Physics* 78(5), 456–460.

Computational Homework Problems

Some important homework problems require the student to write a simple computer program. The textbook and associated instructional videos teach VPython, which is based on the Python programming language, and which generates real-time 3D animations as a side effect of simple physics code written by students. Such animations provide powerfully motivating and instructive visualizations of fields and motions. VPython supports true vector computations, which encourages students to begin thinking about vectors as much more than mere components. VPython can be obtained at no cost for Windows, Macintosh, and Linux at vpython.org.

In the instructor resources section of matterandinteractions.org is “A Brief Guide to Computational Modeling in Matter & Interactions” which explains how to incorporate computation into the curriculum in a way that is easy for instructors to manage and which is entirely accessible to students with no prior programming experience. There you will also find a growing list of advanced computational physics textbooks that use VPython, which means that introducing students to Python and VPython in the introductory physics course can be of direct utility in later courses. Python itself is now widely used in technical fields.

Desktop Experiment Kit for Volume 2

On the authors’ web site mentioned above is information about a desktop experiment kit for E&M that is distributed by PASCO. The simple equipment in this kit allows students to make key observations of electrostatic, circuit, and magnetic phenomena, tightly integrated with the theory (www.pasco.com, search for EM-8675). Several chapters contain optional experiments that can be done with this kit. This does not preclude having other, more complex laboratory experiences associated with the curriculum. For example, one such lab that we use deals with Faraday’s law and requires signal generators, large coils, and oscilloscopes. You may have lab experiments already in place that will go well with this textbook.

What’s New in the 4th Edition

The 4th edition of this text includes the following major new features:

- Increased support for computational modeling throughout, including sample code.
- Discussion throughout the text contrasting iterative and analytical problem solutions.
- Many new computational modeling problems (small and large).
- Improved discussion throughout the text of the contrast between models of a system as a point particle and as an extended system.
- An improved discussion of the Momentum Principle throughout Volume 1, emphasizing that the future momentum depends on two elements: the momentum now, and the impulse applied.
- Improved treatment of polarization surface charge in electrostatics (Chapter 14) and circuits (Chapter 18) based on the results of detailed 3D computational models.
- A more extensive set of problems at the end of each chapter, with improved indication of difficulty level.

In order to reduce cost and weight, some materials that have seen little use by instructors have been moved to the Wiley web site (www.wiley.com/college/chabay) where they are freely available. These materials include Supplement S1 (Chapter 13 in the 3rd Edition: kinetic theory of gases, thermal processes, and heat engines), Supplement S2 on PN

junctions (formerly an optional section in Chapter 22 in the 3rd Edition), and Supplement S3 (a significantly extended version of Chapter 25 in the 3rd Edition: electromagnetic interference and diffraction, wave-particle duality, and a new section on mechanical waves and the wave equation).

Additional changes in the 4th Edition include:

- In Chapter 5, improved treatment of curving motion and an added section on the dynamics of multiobject systems.
- An improved sequence of topics in Chapter 6, with an explicit discussion of the role of energy in computational models, and an improved treatment of path independence, highlighting its limitation to point particles.
- A new section in Chapter 7 on the effect of the choice of reference frame on the form of the Energy Principle, and explicit instruction on how to model several kinds of friction in a computational model.
- In Chapter 8, discussion of the lifetime of excited states and on the probabilistic nature of energy transitions.
- In Chapter 9, now renamed “Translational, Rotational, and Vibrational Energy,” improved treatment of the energetics of deformable systems.
- In Chapter 11, analysis of a physical pendulum.
- A detailed discussion in Chapter 16 of how to calculate potential difference by numerical path integration.
- An improved treatment of motional emf in the case of a bar dragged along rails (Chapter 20).

Suggestions for Condensed Courses

In a large course for engineering and science students with three 50-minute lectures and one 110-minute small-group studio lab per week, or in a studio format with five 50-minute sessions per week, it is possible to complete most but not all of the mechanics and E&M material in two 15-week semesters. In an honors course, or a course for physics majors, it is possible to do almost everything. You may be able to go further or deeper if your course has a weekly recitation session in addition to lecture and lab.

What can be omitted if there is not enough time to do everything? In mechanics, the one thing we feel should not be omitted is the introduction to entropy in terms of the statistical mechanics of the Einstein solid (Chapter 12). This is a climax of the integration of mechanics and thermal physics. One approach to deciding what mechanics topics can be omitted is to be guided by what foundation is required for Chapter 12. See other detailed suggestions below.

In E&M, one should not omit electromagnetic radiation and its effects on matter (Chapter 23). This is the climax of the whole E&M enterprise. One way to decide what E&M topics can be omitted is to be guided by what foundation is required for Chapter 23. See other detailed suggestions below.

Any starred section (*) can safely be omitted. Material in these sections is not referenced in later work. In addition, the following sections may be omitted:

Chapter 3 (The Fundamental Interactions): The section on determinism may be omitted.

Chapter 4 (Contact Interactions): Buoyancy and pressure may be omitted (one can return to these topics by using Supplement S1 on gases).

Chapter 7 (Internal Energy): If you are pressed for time, you might choose to omit the second half of the chapter on energy dissipation, beginning with Section 7.10.

Chapter 9 (Translational, Rotational, and Vibrational Energy): The formalism of finding the center of mass may be skipped, because the important

applications have obvious locations of the center of mass. Although they are very instructive, it is possible to omit the sections contrasting point-particle with extended system models; you may also omit the analysis of sliding friction.

Chapter 10 (Collisions): A good candidate for omission is the analysis of collisions in the center-of-mass frame. Since there is a basic introduction to collisions in Chapter 3 (before energy is introduced), one could omit all of Chapter 10. On the other hand, the combined use of the Momentum Principle and the Energy Principle can illuminate both fundamental principles.

Chapter 11 (Angular Momentum): The main content of this chapter should not be omitted, as it introduces the third fundamental principle of mechanics, the Angular Momentum Principle. One might choose to omit most applications involving nonzero torque.

Chapter 12 (Entropy: Limits on the Possible): The second half of this chapter, on the Boltzmann distribution, may be omitted if necessary.

Chapter 15 (Electric Field of Distributed Charges): It is important that students acquire a good working knowledge of the patterns of electric field around some standard charged objects (rod, ring, disk, capacitor, sphere). If however they themselves are to acquire significant expertise in setting up physical integrals, they need extensive practice, and you might decide that the amount of time necessary for acquiring this expertise is not an appropriate use of the available course time.

Chapter 16 (Electric Potential): The section on dielectric constant can be omitted if necessary.

Chapter 17 (Magnetic Field): In the sections on the atomic structure of magnets, you might choose to discuss only the first part, in which one finds that the magnetic moment of a bar magnet is consistent with an atomic model. Omitting the remaining sections on spin and domains will not cause significant difficulties later.

Chapter 19 (Circuit Elements): The sections on series and parallel resistors and on internal resistance, meters, quantitative analysis of RC circuits, and multiloop circuits can be omitted. Physics and engineering students who need to analyze complex multiloop circuits will later take specialized courses on the topic; in the introductory physics course the emphasis should be on giving all students a good grounding in the fundamental mechanisms underlying circuit behavior.

Chapter 20 (Magnetic Force): We recommend discussing Alice and Bob and Einstein, but it is safe to omit the sections on relativistic field transformations. However, students often express high interest in the relationship between electric fields and magnetic fields, and here is an opportunity to satisfy some aspects of their curiosity. Motors and generators may be omitted or downplayed. The case study on sparks in air can be omitted, because nothing later depends critically on this topic, though it provides an introductory-level example of a phenomenon where an intuitively appealing model fails utterly, while a different model predicts several key features of the phenomenon. Another possibility is to discuss sparks near the end of the course, because it can be a useful review of many aspects of E&M.

Chapter 22 (Faraday's Law): Though it can safely be omitted, we recommend retaining the section on superconductors, because students are curious about this topic. The section on inductance may be omitted.

Chapter 23 (Electromagnetic Radiation): The treatment of geometrical optics may be omitted.

Acknowledgments

We owe much to the unusual working environment provided by the Department of Physics and the former Center for Innovation in Learning at Carnegie Mellon, which made it possible during the 1990s to carry out the

research and development leading to the first edition of this textbook in 2002. We are grateful for the open-minded attitude of our colleagues in the Carnegie Mellon physics department toward curriculum innovations.

We are grateful to the support of our colleagues Robert Beichner and John Risley in the Physics Education Research and Development group at North Carolina State University, and to other colleagues in the NCSU physics department.

We thank Fred Reif for emphasizing the role of the three fundamental principles of mechanics, and for his view on the reciprocity of electric and gravitational forces. We thank Robert Bauman, Gregg Franklin, and Curtis Meyer for helping us think deeply about energy.

Much of Chapter 12 on quantum statistical mechanics is based on an article by Thomas A. Moore and Daniel V. Schroeder, "A different approach to introducing statistical mechanics," *American Journal of Physics*, vol. 65, pp. 26–36 (January 1997). We have benefited from many stimulating conversations with Thomas Moore, author of another introductory textbook that takes a contemporary view of physics, *Six Ideas that Shaped Physics*. Michael Weissman and Robert Swendsen provided particularly helpful critiques on some aspects of our implementation of Chapter 12.

We thank Hermann Haertel for opening our eyes to the fundamental mechanisms of electric circuits. Robert Morse, Priscilla Laws, and Mel Steinberg stimulated our thinking about desktop experiments. Bat-Sheva Eylon offered important guidance at an early stage. Ray Sorensen provided deep analytical critiques that influenced our thinking in several important areas. Randall Feenstra taught us about semiconductor junctions. Thomas Moore showed us a useful way to present the differential form of Maxwell's equations. Fred Reif helped us devise an assessment of student learning of basic E&M concepts. Uri Ganiel suggested the high-voltage circuit used to demonstrate the reality of surface charge. The unusual light bulb circuits at the end of Chapter 22 are based on an article by P. C. Peters, "The role of induced emf's in simple circuits," *American Journal of Physics* 52, 1984, 208–211. Thomas Ferguson gave us unusually detailed and useful feedback on the E&M chapters. Discussions with John Jewett about energy transfers were helpful. We thank Seth Chabay for help with Latin.

We thank David Andersen, David Scherer, and Jonathan Brandmeyer for the development of tools that enabled us and our students to write associated software.

The research of Matthew Kohlmyer, Sean Weatherford, and Brandon Lunk on student engagement with computational modeling has made major contributions to our instruction on computational modeling. Lin Ding developed an energy assessment instrument congruent with the goals of this curriculum.

We thank our colleagues David Brown, Krishna Chowdary, Laura Clarke, John Denker, Norman Derby, Ernst-Ludwig Florin, Thomas Foster, Jon D.H. Gaffney, Chris Gould, Mark Haugan, Joe Heafner, Robert Hilborn, Eric Hill, Andrew Hirsch, Leonardo Hsu, Barry Luokkala, Sara Majetich, Jonathan Mitschele, Arjendu Pattanayak, Jeff Polak, Prabha Ramakrishnan, Vidhya Ramachandran, Richard Roth, Michael Schatz, Robert Swendsen, Aaron Titus, Michael Weissman, and Hugh Young.

We thank a group of reviewers assembled by the publisher, who gave us useful critiques on the second edition of this textbook: Kelvin Chu, Michael Dubson, Tom Furtak, David Goldberg, Javed Iqbal, Shawn Jackson, Craig Ogilvie, Michael Politano, Norris Preyer, Rex Ramsier, Tycho Sleator, Robert Swendsen, Larry Weinstein, and Michael Weissman. We also thank the group who offered useful critiques on the third edition: Alex Small, Bereket Behane, Craig Wiegert, Galen Pickett, Ian Affleck, Jeffrey Bindel, Jeremy King, Paula Heron, and Surenda Singh.



We have benefited greatly from the support and advice of Stuart Johnson and Jessica Fiorillo of John Wiley & Sons. Elizabeth Swain of John Wiley & Sons was exceptionally skilled in managing the project. Helen Walden did a superb job of copyediting; any remaining errors are ours.

This project was supported, in part, by the National Science Foundation (grants MDR-8953367, USE-9156105, DUE-9554843, DUE-9972420, DUE-0320608, DUE-0237132, and DUE-0618504). We are grateful to the National Science Foundation and its reviewers for their long-term support of this challenging project. Opinions expressed are those of the authors, and not necessarily those of the Foundation.

How the Figures Were Made

Almost all of the figures in this book were produced by us (for the third edition the Aptara studio created the figures that show human figures, and the studio added full color to our two-color versions from the second edition). Our main tool was Adobe Illustrator. The many 3D computer-generated images were made using VPython, with optional processing in POV-Ray using a module written by Ruth Chabay to generate a POV-Ray scene description file corresponding to a VPython scene, followed by editing in Adobe Photoshop before exporting to Illustrator. We used TeXstudio for editing LaTeX, with a package due in part to the work of Aptara. All the computer work was done on Windows computers.

Ruth Chabay and Bruce Sherwood
Santa Fe, New Mexico, July 2014

Biographical Background

Ruth Chabay earned a Ph.D in physical chemistry from the University of Illinois at Urbana-Champaign; her undergraduate degree was in chemistry from the University of Chicago. She is Professor Emerita in the Department of Physics at North Carolina State University and was Weston Visiting Professor, Department of Science Teaching, at the Weizmann Institute of Science in Rehovot, Israel. She has also taught at the University of Illinois at Urbana-Champaign and Carnegie Mellon University. She is a Fellow of the American Physical Society.

Bruce Sherwood's Ph.D is in experimental particle physics from the University of Chicago; his undergraduate degree was in engineering science from Purdue University, after which he studied physics for one year at the University of Padua, Italy. He is Professor Emeritus in the Department of Physics at North Carolina State University. He has also taught at Caltech, the University of Illinois at Urbana-Champaign, and Carnegie Mellon University. He is a Fellow of the American Physical Society and of the American Association for the Advancement of Science.

Chabay and Sherwood have been joint recipients of several educational awards. At Carnegie Mellon University they received the Ashkin Award for Teaching in the Mellon College of Science in 1999 and the Teaching Award of the National Society of Collegiate Scholars in 2001. At North Carolina State University they received the Margaret Cox Award for excellence in teaching and learning with technology in 2005. In 2014 the American Association of Physics Teachers presented them with the David Halliday and Robert Resnick Award for Excellence in Undergraduate Physics Teaching.

Brief Contents

VOLUME I Modern Mechanics

- 1 *Interactions and Motion* 1
- 2 *The Momentum Principle* 45
- 3 *The Fundamental Interactions* 88
- 4 *Contact Interactions* 130
- 5 *Determining Forces from Motion* 173
- 6 *The Energy Principle* 215
- 7 *Internal Energy* 284
- 8 *Energy Quantization* 323
- 9 *Translational, Rotational, and Vibrational Energy* 349
- 10 *Collisions* 383
- 11 *Angular Momentum* 416
- 12 *Entropy: Limits on the Possible* 472

VOLUME II Electric and Magnetic Interactions

- 13 *Electric Field* 513
- 14 *Electric Fields and Matter* 546
- 15 *Electric Field of Distributed Charges* 588
- 16 *Electric Potential* 626
- 17 *Magnetic Field* 673
- 18 *Electric Field and Circuits* 716
- 19 *Circuit Elements* 765
- 20 *Magnetic Force* 805
- 21 *Patterns of Field in Space* 867
- 22 *Faraday's Law* 902
- 23 *Electromagnetic Radiation* 939

The Supplements can be found at the web site, www.wiley.com/college/chabay

- Supplement S1** *Gases and Heat Engines* S1-1
Supplement S2 *Semiconductor Devices* S2-1
Supplement S3 *Waves* S3-1

Contents

VOLUME I Modern Mechanics

CHAPTER 1 *Interactions and Motion* 1

- 1.1 Kinds of Matter 1
- 1.2 Detecting Interactions 4
- 1.3 Newton's First Law of Motion 6
- 1.4 Describing the 3D World: Vectors 8
- 1.5 SI Units 17
- 1.6 Speed and Velocity 18
- 1.7 Predicting a New Position 20
- 1.8 Momentum 24
- 1.9 Using Momentum to Update Position 27
- 1.10 Momentum at High Speeds 28
- 1.11 Computational Modeling 31
- 1.12 *The Principle of Relativity 33
- 1.13 *Updating Position at High Speed 36

Summary 37

Questions 38

Problems 39

Computational Problems 42

Answers to Checkpoints 44

CHAPTER 2 *The Momentum Principle* 45

- 2.1 The Momentum Principle 45
- 2.2 Large Forces and Short Times 50
- 2.3 Predicting the Future 55
- 2.4 Iterative Prediction: Constant Net Force 57
- 2.5 Analytical Prediction: Constant Net Force 60
- 2.6 Iterative Prediction: Varying Net Force 65
- 2.7 Iterative Calculations on a Computer 72
- 2.8 *Derivation: Special-Case Average Velocity 75
- 2.9 *Relativistic Motion 77
- 2.10 *Measurements and Units 79

Summary 81

Questions 81

Problems 82

Computational Problems 86

Answers to Checkpoints 87

CHAPTER 3 *The Fundamental Interactions* 88

- 3.1 The Fundamental Interactions 88
- 3.2 The Gravitational Force 89
- 3.3 Approximate Gravitational Force Near the Earth's Surface 93
- 3.4 Reciprocity 95
- 3.5 Predicting Motion of Gravitationally Interacting Objects 96
- 3.6 Gravitational Force in Computational Models 100
- 3.7 The Electric Force 102
- 3.8 The Strong Interaction 104
- 3.9 The Weak Interaction 106
- 3.10 Conservation of Momentum 107
- 3.11 The Multiparticle Momentum Principle 110
- 3.12 Collisions: Negligible External Forces 113
- 3.13 Newton and Einstein 116
- 3.14 Predicting the Future of Complex Systems 117
- 3.15 Determinism 119
- 3.16 Points and Spheres 121
- 3.17 Measuring the Gravitational Constant G 122

Summary 122

Questions 123

Problems 123

Computational Problems 128

Answers to Checkpoints 129

CHAPTER 4 *Contact Interactions* 130

- 4.1 Beyond Point Particles 130
- 4.2 The Ball-Spring Model of a Solid 131
- 4.3 Tension Forces 132
- 4.4 Length of an Interatomic Bond 133
- 4.5 The Stiffness of an Interatomic Bond 135
- 4.6 Stress, Strain, and Young's Modulus 138
- 4.7 Compression (Normal) Forces 141
- 4.8 Friction 141
- 4.9 Speed of Sound in a Solid and Interatomic Bond Stiffness 144
- 4.10 Derivative Form of the Momentum Principle 146
- 4.11 Analytical Solution: Spring-Mass System 148
- 4.12 Analytical vs. Iterative Solutions 152
- 4.13 Analytical Expression for Speed of Sound 154
- 4.14 Contact Forces Due to Gases 156
- 4.15 *Acceleration 160
- 4.16 *A Vertical Spring-Mass System 161
- 4.17 *General Solution for the Mass-Spring System 161

Summary 163
Questions 164
Problems 166
Computational Problems 170
Answers to Checkpoints 172

CHAPTER 5 *Determining Forces from Motion* 173

5.1 Unknown Forces 173
5.2 Identifying all Forces 173
5.3 Determining Unknown Forces 174
5.4 Uniform Motion 176
5.5 Changing Momentum 184
5.6 Force and Curving Motion 185
5.7 $d\vec{p}/dt$ for Curving Motion 190
5.8 Unknown Forces: Curving Motion 195
5.9 Kinesthetic Sensations 200
5.10 More Complex Problems 202

Summary 205
Questions 206
Problems 206
Computational Problems 213
Answers to Checkpoints 214

CHAPTER 6 *The Energy Principle* 215

6.1 The Energy Principle 215
6.2 Energy of a Single Particle 216
6.3 Work: Mechanical Energy Transfer 221
6.4 Work and Energy 227
6.5 Change of Rest Energy 231
6.6 Proof of the Energy Principle for a Particle 234
6.7 Potential Energy in Multiparticle Systems 235
6.8 Gravitational Potential Energy 240
6.9 Electric Potential Energy 249
6.10 Plotting Energy vs. Separation 250
6.11 General Properties of Potential Energy 255
6.12 The Mass of a Multiparticle System 258
6.13 Reflection: Why Energy? 263
6.14 Identifying Initial and Final States 264
6.15 Energy in Computational Models 268
6.16 *A Puzzle 269
6.17 *Gradient of Potential Energy 270
6.18 *Integrals and Antiderivatives 271
6.19 *Approximation for Kinetic Energy 272
6.20 *Finding the Expression for Particle Energy 273
6.21 *Finding an Angle from the Dot Product 274

Summary 274
Questions 275
Problems 276
Computational Problems 282
Answers to Checkpoints 283

CHAPTER 7 *Internal Energy* 284

7.1 Extended Objects 284
7.2 Potential Energy of Macroscopic Springs 284
7.3 Potential Energy of a Pair of Neutral Atoms 290
7.4 Internal Energy 292

7.5 Energy Transfer Due to a Temperature Difference 297
7.6 Power: Energy per Unit Time 300
7.7 Open and Closed Systems 300
7.8 The Choice of System Affects Energy Accounting 302
7.9 The Choice of Reference Frame Affects Energy Accounting 304
7.10 Energy Dissipation 306
7.11 Energy Dissipation in Computational Models 312
7.12 *Resonance 314

Summary 315
Questions 316
Problems 317
Computational Problems 320
Answers to Checkpoints 321

CHAPTER 8 *Energy Quantization* 323

8.1 Photons 323
8.2 Electronic Energy Levels 324
8.3 The Effect of Temperature 334
8.4 Vibrational Energy Levels 335
8.5 Rotational Energy Levels 338
8.6 Other Energy Levels 339
8.7 Comparison of Energy-Level Spacings 339
8.8 *Random Emission Time 340
8.9 *Case Study: How a Laser Works 340
8.10 *Wavelength of Light 342

Summary 343
Questions 343
Problems 344
Computational Problems 346
Answers to Checkpoints 348

CHAPTER 9 *Translational, Rotational, and Vibrational Energy* 349

9.1 Separation of Multiparticle System Energy 349
9.2 Rotational Kinetic Energy 353
9.3 Comparing Two Models of a System 359
9.4 Modeling Friction in Detail 368
9.5 *Derivation: Kinetic Energy of a Multiparticle System 373
9.6 *Derivation: The Point Particle Energy Equation 374

Summary 376
Questions 376
Problems 377
Answers to Checkpoints 382

CHAPTER 10 *Collisions* 383

10.1 Collisions 383
10.2 Elastic and Inelastic Collisions 384
10.3 A Head-on Collision of Equal Masses 386
10.4 Head-on Collisions Between Unequal Masses 389
10.5 Frame of Reference 391
10.6 Scattering: Collisions in 2D and 3D 392
10.7 Discovering the Nucleus Inside Atoms 395
10.8 Distribution of Scattering Angles 398
10.9 Computational and Analytical Approaches 400
10.10 Relativistic Momentum and Energy 401

| | |
|---|-----|
| 10.11 Inelastic Collisions and Quantized Energy | 403 |
| 10.12 Collisions in Other Reference Frames | 405 |
| Summary | 410 |
| Questions | 410 |
| Problems | 411 |
| Computational Problems | 414 |
| Answers to Checkpoints | 415 |

CHAPTER 11 *Angular Momentum* 416

| | |
|--|-----|
| 11.1 Translational Angular Momentum | 416 |
| 11.2 Rotational Angular Momentum | 422 |
| 11.3 Total Angular Momentum | 425 |
| 11.4 Torque | 426 |
| 11.5 The Angular Momentum Principle | 428 |
| 11.6 Multiparticle Systems | 430 |
| 11.7 Systems with Zero Torque | 432 |
| 11.8 Systems with Nonzero Torques | 441 |
| 11.9 Predicting Positions When There is Rotation | 443 |
| 11.10 Computation and Angular Momentum | 445 |
| 11.11 Angular Momentum Quantization | 445 |
| 11.12 *Gyroscopes | 450 |
| 11.13 *More on Moment of Inertia | 455 |
| Summary | 457 |
| Questions | 458 |
| Problems | 459 |
| Computational Problems | 469 |
| Answers to Checkpoints | 471 |

CHAPTER 12 *Entropy: Limits on the Possible* 472

| | |
|---|-----|
| 12.1 Irreversibility | 472 |
| 12.2 The Einstein Model of a Solid | 473 |
| 12.3 Thermal Equilibrium of Blocks in Contact | 480 |
| 12.4 The Second Law of Thermodynamics | 484 |
| 12.5 What is Temperature? | 485 |
| 12.6 Specific Heat of a Solid | 488 |
| 12.7 Computational Models | 493 |
| 12.8 The Boltzmann Distribution | 494 |
| 12.9 The Boltzmann Distribution in a Gas | 498 |
| Summary | 506 |
| Questions | 507 |
| Problems | 508 |
| Computational Problems | 511 |
| Answers to Checkpoints | 512 |

VOLUME II

Electric and Magnetic Interactions

CHAPTER 13 *Electric Field* 513

| | |
|--------------------------------|-----|
| 13.1 New Concepts | 513 |
| 13.2 Electric Charge and Force | 513 |

| | |
|--|-----|
| 13.3 The Concept of "Electric Field" | 515 |
| 13.4 The Electric Field of a Point Charge | 519 |
| 13.5 Superposition of Electric Fields | 522 |
| 13.6 The Electric Field of a Dipole | 524 |
| 13.7 Choice of System | 532 |
| 13.8 Is Electric Field Real? | 533 |
| 13.9 Computational Modeling of Electric Fields | 535 |
| Summary | 538 |
| Questions | 539 |
| Problems | 540 |
| Computational Problems | 544 |
| Answers to Checkpoints | 545 |

CHAPTER 14 *Electric Fields and Matter* 546

| | |
|---|-----|
| 14.1 Charged Particles in Matter | 546 |
| 14.2 How Objects Become Charged | 548 |
| 14.3 Polarization of Atoms | 551 |
| 14.4 Polarization of Insulators | 557 |
| 14.5 Polarization of Conductors | 558 |
| 14.6 Charge Motion in Metals | 561 |
| 14.7 Charge Transfer | 568 |
| 14.8 Practical Issues in Measuring Electric Field | 570 |
| Summary | 571 |
| Experiments | 572 |
| Questions | 578 |
| Problems | 580 |
| Answers to Checkpoints | 586 |

CHAPTER 15 *Electric Field of Distributed Charges* 588

| | |
|---|-----|
| 15.1 A Uniformly Charged Thin Rod | 588 |
| 15.2 Procedure for Calculating Electric Field | 595 |
| 15.3 A Uniformly Charged Thin Ring | 597 |
| 15.4 A Uniformly Charged Disk | 599 |
| 15.5 Two Uniformly Charged Disks: A Capacitor | 603 |
| 15.6 A Spherical Shell of Charge | 606 |
| 15.7 A Solid Sphere Charged Throughout its Volume | 608 |
| 15.8 Infinitesimals and Integrals in Science | 609 |
| 15.9 3D Numerical Integration with a Computer | 610 |
| 15.10 *Integrating the Spherical Shell | 613 |
| Summary | 614 |
| Questions | 616 |
| Problems | 617 |
| Computational Problems | 624 |
| Answers to Checkpoints | 625 |

CHAPTER 16 *Electric Potential* 626

| | |
|---|-----|
| 16.1 A Review of Potential Energy | 626 |
| 16.2 Systems of Charged Objects | 629 |
| 16.3 Potential Difference in a Uniform Field | 632 |
| 16.4 Sign of Potential Difference | 635 |
| 16.5 Potential Difference in a Nonuniform Field | 637 |
| 16.6 Path Independence | 644 |
| 16.7 The Potential at One Location | 648 |
| 16.8 Computing Potential Differences | 652 |
| 16.9 Potential Difference in an Insulator | 653 |

- 16.10 Energy Density and Electric Field 656
- 16.11 *Potential of Distributed Charges 658
- 16.12 *Integrating the Spherical Shell 658
- 16.13 *Numerical Integration Along a Path 660

Summary 661
 Questions 661
 Problems 663
 Computational Problems 672
 Answers to Checkpoints 672

CHAPTER 17 *Magnetic Field* 673

- 17.1 Electron Current 673
- 17.2 Detecting Magnetic Fields 674
- 17.3 Biot–Savart Law: Single Moving Charge 676
- 17.4 Relativistic Effects 678
- 17.5 Electron Current and Conventional Current 679
- 17.6 The Biot–Savart Law for Currents 682
- 17.7 The Magnetic Field of Current Distributions 683
- 17.8 A Circular Loop of Wire 686
- 17.9 Computation and 3D Visualization 689
- 17.10 Magnetic Dipole Moment 690
- 17.11 The Magnetic Field of a Bar Magnet 691
- 17.12 The Atomic Structure of Magnets 693
- 17.13 *Estimate of Orbital Angular Momentum of an Electron in an Atom 699
- 17.14 *Magnetic Field of a Solenoid 700

Summary 702
 Experiments 703
 Questions 707
 Problems 708
 Computational Problems 713
 Answers to Checkpoints 715

CHAPTER 18 *Electric Field and Circuits* 716

- 18.1 A Circuit Is Not in Equilibrium 716
- 18.2 Current in Different Parts of a Circuit 717
- 18.3 Electric Field and Current 720
- 18.4 What Charges Make the Electric Field Inside the Wires? 722
- 18.5 Surface Charge Distributions 726
- 18.6 Connecting a Circuit: The Initial Transient 732
- 18.7 Feedback 734
- 18.8 Surface Charge and Resistors 735
- 18.9 Energy in a Circuit 738
- 18.10 Applications of the Theory 742
- 18.11 Detecting Surface Charge 747
- 18.12 *Computational Model of a Circuit 749

Summary 751
 Experiments 752
 Questions 755
 Problems 757
 Answers to Checkpoints 763

CHAPTER 19 *Circuit Elements* 765

- 19.1 Capacitors 765
- 19.2 Resistors 771

- 19.3 Conventional Symbols and Terms 776
- 19.4 Work and Power in a Circuit 777
- 19.5 Batteries 779
- 19.6 Ammeters, Voltmeters, and Ohmmeters 781
- 19.7 Quantitative Analysis of an RC Circuit 783
- 19.8 Reflection: The Macro-Micro Connection 786
- 19.9 *What Are AC and DC? 787
- 19.10 *Electrons in Metals 789
- 19.11 *A Complicated Resistive Circuit 789

Summary 792
 Experiments 792
 Questions 794
 Problems 797
 Answers to Checkpoints 803

CHAPTER 20 *Magnetic Force* 805

- 20.1 Magnetic Force on a Moving Charge 805
- 20.2 Magnetic Force on a Current-Carrying Wire 810
- 20.3 Combining Electric and Magnetic Forces 812
- 20.4 The Hall Effect 814
- 20.5 Motional Emf 819
- 20.6 Magnetic Force in a Moving Reference Frame 824
- 20.7 Magnetic Torque 828
- 20.8 Potential Energy for a Magnetic Dipole 829
- 20.9 Motors and Generators 834
- 20.10 *Case Study: Sparks in Air 836
- 20.11 *Relativistic Field Transformations 846

Summary 850
 Experiments 851
 Questions 851
 Problems 854
 Computational Problems 864
 Answers to Checkpoints 866

CHAPTER 21 *Patterns of Field in Space* 867

- 21.1 Patterns of Electric Field: Gauss's Law 867
- 21.2 Definition of "Electric Flux" 869
- 21.3 Gauss's Law 871
- 21.4 Reasoning from Gauss's Law 877
- 21.5 Gauss's Law for Magnetism 882
- 21.6 Patterns of Magnetic Field: Ampere's Law 883
- 21.7 Maxwell's Equations 889
- 21.8 Semiconductor Devices 889
- 21.9 *The Differential Form of Gauss's Law 889
- 21.10 *The Differential Form of Ampere's Law 895

Summary 896
 Questions 897
 Problems 897
 Computational Problem 901
 Answers to Checkpoints 901

CHAPTER 22 *Faraday's Law* 902

- 22.1 Curly Electric Fields 902
- 22.2 Faraday's Law 905
- 22.3 Faraday's Law and Motional Emf 912

- 22.4 Maxwell's Equations 915
- 22.5 Superconductors 916
- 22.6 Inductance 918
- 22.7 *Inductor Circuits 922
- 22.8 *Some Peculiar Circuits 926
- 22.9 *The Differential Form of Faraday's Law 928
- 22.10 *Lenz's Rule 929

Summary 930
Questions 931
Problems 932
Answers to Checkpoints 938

CHAPTER 23 *Electromagnetic Radiation* 939

- 23.1 Maxwell's Equations 939
- 23.2 Fields Traveling Through Space 942
- 23.3 Accelerated Charges Produce Radiation 947

- 23.4 Sinusoidal Electromagnetic Radiation 951
- 23.5 Energy and Momentum in Radiation 955
- 23.6 Effects of Radiation on Matter 959
- 23.7 Light Propagation Through a Medium 964
- 23.8 Refraction: Bending of Light 966
- 23.9 Lenses 969
- 23.10 Image Formation 972
- 23.11 *The Field of an Accelerated Charge 983
- 23.12 *Differential Form of Maxwell's Equations 985

Summary 986
Questions 986
Problems 988
Computational Problems 991
Answers to Checkpoints 992

Answers to Odd-Numbered Problems A-1
Index I-1

The Supplements can be found at the web site, www.wiley.com/college/chabay

SUPPLEMENT S1 *Gases and Heat Engines*

- S1.1 Gases, Solids, and Liquids S1-1
- S1.2 Gas Leaks Through a Hole S1-2
- S1.3 Mean Free Path S1-5
- S1.4 Pressure and Temperature S1-6
- S1.5 Energy Transfers S1-13
- S1.6 Fundamental Limitations on Efficiency S1-21
- S1.7 A Maximally Efficient Process S1-23
- S1.8 *Why Don't We Attain the Theoretical Efficiency? S1-31
- S1.9 *Application: A Random Walk S1-33

SUPPLEMENT S2 *Semiconductor Devices*

- S2.1 Semiconductor Devices S2-1

SUPPLEMENT S3 *Waves*

- S3.1 Wave Phenomena S3-1
- S3.2 Multisource Interference: Diffraction S3-8
- S3.3 Angular Resolution S3-17
- S3.4 Mechanical Waves S3-21
- S3.5 Standing Waves S3-31
- S3.6 Wave and Particle Models of Light S3-37
- S3.7 *Fourier Analysis S3-44
- S3.8 *Derivation: Two Slits are Like Two Sources S3-45
- S3.9 *The Wave Equation for Light S3-46