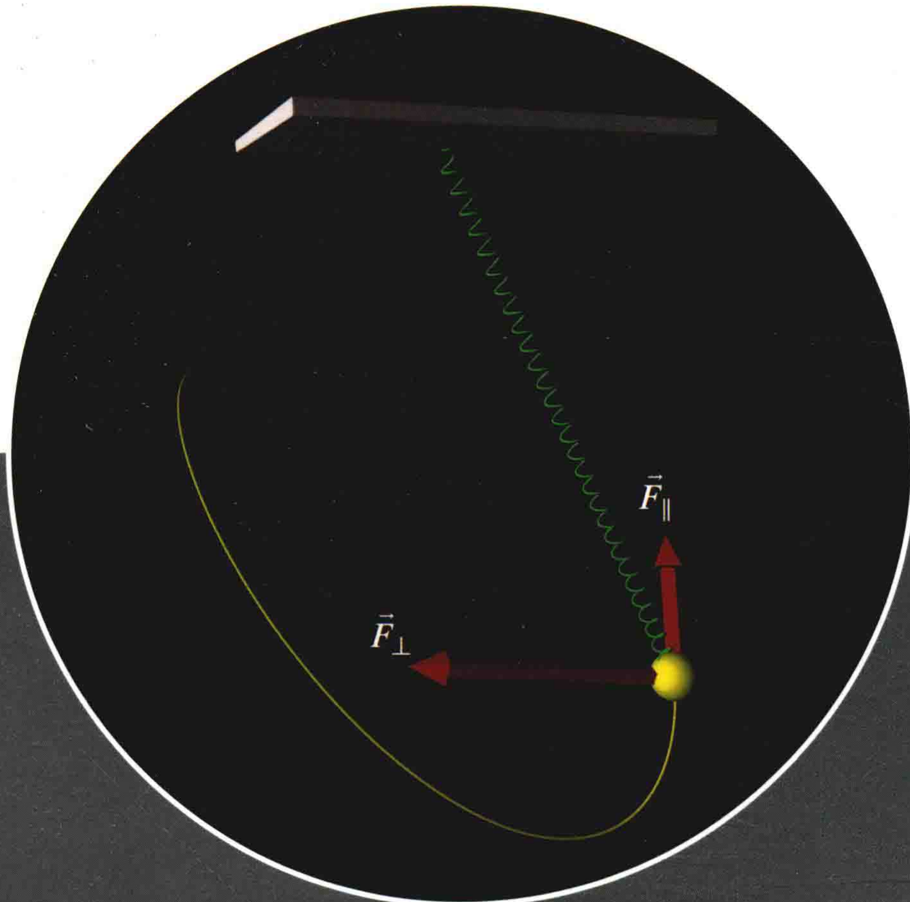
MATTER & INTERACTIONS

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.

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:

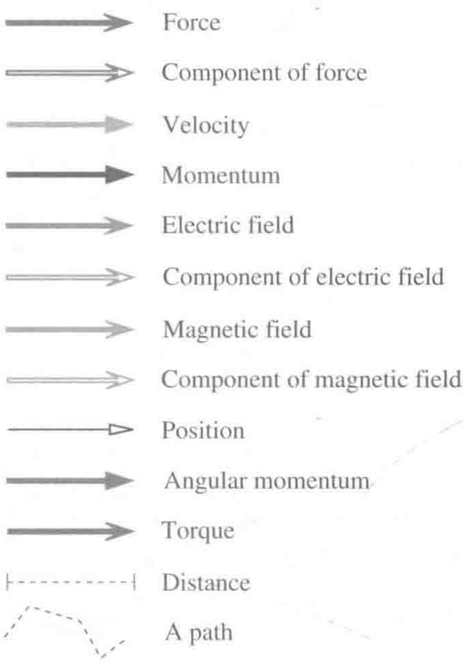
> **QUESTION** What should I do when I encounter a question in the text?

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: $\vec{p}$.

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. Č. 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

VOLUME II Electric and Magnetic Interactions

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

Contents

VOLUME I
Modern Mechanics

CHAPTER 1 *Interactions and Motion* 1

CHAPTER 2 *The Momentum Principle* 45

CHAPTER 3 *The Fundamental Interactions* 88

CHAPTER 4 *Contact Interactions* 130

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