Modern Physics

Modern Physics intertwines active learning pedagogy with the material typically covered in an introductory survey, from the basics of relativity and quantum mechanics through recent developments in particle physics and cosmology. The flexible approach taken by the authors allows instructors to easily incorporate as much or as little active learning into their teaching as they choose. Chapters are enhanced by “Discovery” and “Active Reading” exercises to guide students through key ideas before or during class, while “ConcepTests” check student understanding and stimulate classroom discussions. Each chapter also includes extensive assessment material, with a range of basic comprehension questions, drill and practice calculations, computer-based problems, and explorations of advanced applications. A test bank and interactive animations as well as other support for instructors and students are available online. Students are engaged by an accessible and lively writing style, thorough explanations, “Math Interludes” which account for varying levels of skill and experience, and advanced topics to further pique their interest in physics.

Gary N. Felder is Professor of Physics at Smith College, Massachusetts. His research has focused on inflationary cosmology, numerical simulations, and the development of computer and written tools for teaching physics concepts. In 2017 he received an SGA Faculty Teaching Award from Smith’s Student Government Association in recognition of his excellent teaching and positive impact on the student body. His paper “The Effects of Personality Type on Engineering Student Performance and Attitudes” received the American Society for Engineering Education 2003 “Best Paper of the Year” Award.

Kenny M. Felder has taught physics and mathematics at Raleigh Charter High School, North Carolina, for more than twenty years. He received his Bachelor’s degree in Physics with highest honors from the University of North Carolina at Chapel Hill. His book *Advanced Algebra II* pioneered much of the active learning pedagogy included in this textbook and was described by the Connexions project at Rice University as “a non-traditional approach to a very traditional subject” that makes “the world of second-year algebra come alive.”

Gary Felder and Kenny Felder also co-authored *Mathematical Methods in Engineering and Physics* (2016).

Modern Physics

Gary N. Felder
Smith College, Massachusetts

Kenny M. Felder
Raleigh Charter High School, North Carolina

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of
education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/highereducation/isbn/9781108842891
DOI: 10.1017/9781108913270

First published 2023

Printed in the United Kingdom by TJ Books Limited, Padstow, Cornwall, 2023

A catalogue record for this publication is available from the British Library.

ISBN 978-1-108-84289-1 Hardback

Additional resources for this publication at www.cambridge.org/felder-modernphysics

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-84289-1 — Modern Physics
Gary N. Felder , Kenny M. Felder
Frontmatter
More Information

Contents

Cambridge University Press & Assessment
978-1-108-84289-1 — Modern Physics
Gary N. Felder , Kenny M. Felder
Frontmatter
More Information

Preface

Notes to the Instructor

This textbook provides an introductory course in modern physics. Students are assumed to have already taken introductory courses in classical mechanics and electromagnetism, so this course might be the third in the physics sequence. Mathematically, the minimum prerequisite is a semester of calculus including both derivatives and integrals; more advanced mathematical topics are introduced or reviewed in the book as needed.

There are a good number of textbooks for such courses already on the market. So why did we feel the need to write a new one?

- We wanted to highlight the conceptual breakthroughs represented by relativity and quantum mechanics: how these breakthroughs build on classical physics, how they radically depart from our day-to-day physical intuition, and how the equations reflect those radical changes in physical paradigms. We felt that the existing books on the market did not do this well. Many existing texts seem to be written for professors more than for students, and can leave students solving equations with no clear idea of what those equations are telling them.
- We wanted questions that make sure students understand the material at a basic level, and also questions that push them into deeper exploration of the subtleties. We wanted lots of problems that provide drill and practice on core mathematical skills, and also problems that ensure students understand and can replicate key derivations. Existing texts generally don't provide enough in any of these categories.
- We wanted to review (or in some cases introduce) math topics that students might not have already mastered – topics such as standing and traveling waves, complex exponential functions, discrete and continuous probability distributions, partial derivatives, spherical coordinates, and of course partial differential equations – as they are needed for quantum mechanics.
- We wanted to make use of digital functionality to offer a suite of online materials to support both instructors and students. Later in this Preface we detail the resources available online, but just in case you don't read that far, we want to grab your attention now and urge you to browse and see what is available at www.cambridge.org/felder-modernphysics. We also recommend telling your students to bookmark this site at the beginning of the course, as they may need to refer back to it often.

- Most importantly, we wanted the kinds of tools that are available in many introductory mechanics and electricity and magnetism physics books, but are generally not available for higher-level courses. If you don't use active learning techniques in the classroom, we hope you will still see in our book all the advantages we list above. But if you have used active learning or are interested in trying it, you will find tools in this book that make it easy to experiment without sacrificing content. Much of this Preface is devoted to explaining how we envision those tools being used (and how we use them ourselves).

For both of us, at different times and in different schools, our introductions to modern physics came as life-changing revelations. Fast-moving objects do *what?* Individual photons do *what?* You're saying this stuff *really happens?*

We want to share that stunned feeling with students. We want them to gather around a conference table with Einstein, Bohr, and Schrödinger, and try to craft a coherent theoretical model to explain the startling experimental evidence. We want them to become comfortable with the mathematical processes involved, and simultaneously to see how the underlying physics defies their intuition.

One of our working titles for this book was "Childlike Wonder and Differential Equations." We want students to see all that in their introduction to special relativity and quantum mechanics. In the later chapters we want them to see how those theories helped answer some of the most daunting scientific problems of the twentieth and twenty-first centuries. And we also want to share with them the questions that are still open in 2022 – questions that they themselves may help to answer some day.

Topics and Organization

Broadly speaking, this book comprises three parts: special relativity (Chapters 1 and 2), quantum mechanics (Chapters 3–6), and advanced topics (Chapters 7–14). You could cover the entire book in two semesters. But in most institutions this course is only given one semester, forcing you to pick which sections to cover.

If your course does not include relativity, skip Chapters 1 and 2. If you do cover relativity, you could stop at any point from Section 1.2 (for a one- to two-day introduction) through the end of Chapter 2 (for two to three weeks). Relativity comes up occasionally in later chapters, most often in problems involving the formula $E^2 = p^2c^2 + m^2c^4$, so if you don't get that far in relativity you should avoid assigning those problems.

The first three sections of Chapter 3 – the mathematics of interference, the classical Young double-slit experiment, and then the same experiment repeated one photon at a time – are our introduction to quantum mechanics. Students should be given the chance to convince themselves that many counterintuitive aspects of the theory are *required* in order to explain these experimental results. The rest of the chapter presents blackbody radiation, the photoelectric effect, Compton scattering, and other results that led early twentieth-century physicists to propose and accept the quantum hypothesis; you can cover as many or as few of these as you like, but they are not essential for later chapters.

Chapters 4, 5, and 6 give the theory and the mathematics of quantum mechanics, at this introductory level. This material forms the largest part of a typical modern physics course. There are parts that can be omitted without loss of continuity, however.

- You could skip Section 6.3 (Momentum Eigenstates) and/or Section 6.4 (Phase Velocity and Group Velocity), although you should cover the former if you plan to do the latter.
- Section 6.6 introduces the time-dependent Schrödinger equation, and uses it to derive the rule for the time evolution of energy eigenstates that was introduced earlier. This section is more mathematically advanced than most, and can be omitted.

You could skip Sections 4.1 (Atomic Spectra and the Bohr Model) and 4.2 (Matter Waves), but we believe they provide important motivation for Schrödinger's wave mechanics and we recommend against skipping them. Section 5.1 is a review of concepts about force and potential energy that your students should have learned in introductory physics. This can be a quick review, but unless you are very confident that your students have mastered this information, you skip this section at your peril (or more to the point at theirs).

After Chapter 6, the book showcases applications of quantum mechanics. These later chapters are mostly independent of each other. Occasionally one section depends on an earlier section in another chapter, and such dependencies are noted at the beginning of the appropriate section. The only major inter-chapter dependency is that Chapter 9 (Molecules) depends on Chapter 8 (Atoms), which in turn depends on Chapter 7 (The Hydrogen Atom).

It might be fun to pick one or two of those chapters and explore them in depth. (Gary recommends Chapter 14, Cosmology!) On the other hand, you may want to give your students a taste of many different topics. To facilitate that latter option, we've organized many of these chapters so that the first section or two can be presented as standalone overviews. Consider doing only the first section of Chapter 7 (The Hydrogen Atom), the first two sections of Chapter 10 (Statistical Mechanics), the first two sections of Chapter 11 (Solids), the first section or two of Chapter 12 (The Atomic Nucleus), the first two sections of Chapter 13 (Particle Physics), and/or the first section or two of Chapter 14 (Cosmology). (For Chapter 7, you could also do the introduction in the first section and then jump to the discussion of spin in Sections 7.5 and 7.6.)

Active Learning

As we observed above, we believe that our book offers many advantages over the existing textbooks on this subject. If you have no interest in active learning, we hope that you will judge for yourself whether our Explanation sections are clearer, and our Questions and Problems more thorough and probing, than other texts you are considering.

But we are unabashed proponents of active learning, because all the research says that it works: students learn better, understand in greater depth, and retain longer when active learning techniques are applied properly.[1]

1 See, for example, Freeman, S., Eddy, S. L., McDonough, M., et al., Active learning increases student performance in science, engineering, and mathematics, *Proceedings of the National Academy of Sciences of the United States of America*, **111**(23), 8410–15, 2014.

At the same time, we are very aware of the challenges. How do you incorporate active, challenging moments into your already packed class time without sacrificing content? And even if you want to, how do you come up with the right activities to get students constructively engaged? This book makes it easy to experiment with active learning in small ways that take very little extra time, in or out of class. If you find that these experiments are genuinely fast, easy, and (most importantly) effective in increasing student understanding and retention, you may feel emboldened to try a few more.

So here is a guide to the elements of our book that are designed for that purpose.

Discovery Exercises

A "Discovery Exercise" is a self-guided tutorial meant to take 5–20 minutes *before* a lecture. It can be assigned as homework due on the day of the lecture, done in class at the start of the topic, or done in class at the end of the previous topic to prime them for the next class. The students work through some of the math and physics of a topic on their own. If they are able to solve it all, they start the lecture well prepared. If they get stuck, they come into the lecture with a clearer sense of what the topic is, and of exactly what they are confused about, and they are ready to learn.

We should emphasize that we are not urging you to use all the exercises in this book. We ourselves don't use all of them when we teach! The book gives you a lot of exercises so that you can pick and choose.

Active Reading Exercises

The following box appears in our section on scattering. We've already shown students how to solve for the energy eigenstates of a particle incident on a barrier whose height is greater than the particle's energy. Now we consider a barrier whose energy is less than the particle's energy. Having seen the earlier case, they should easily be able to write down the solutions mathematically, but we want to lead them to understand that in this case those solutions show us that some part of the wave will be transmitted.

Active Reading Exercise: A Potential Step with $E > U_0$

1. Write the energy eigenstate at $x \geq 0$ for a particle with $E > U_0$.
2. Your answer to Part 1 includes two pieces. What does each of the two pieces represent about our particle?
3. Neither of these two pieces blows up as $x \rightarrow \infty$, but one of them has to equal zero anyway. Can you guess which one, on physical grounds?

For motivated students reading the text before class, pausing to try these exercises before moving on will greatly improve their understanding and retention of the material. But many students will not do that (if they read the book at all), and their first introduction to the material will be in your lectures.

So we would love you to try, just with one or two of these, pausing your lecture at that point. Put a slide up with those questions. (We provide all the slides online.) Give the students one minute to think about these questions on their own, and then another minute to compare and discuss answers with their neighbors. Research shows that one or two such interruptions, lasting no more than 1–2 minutes each, vastly improve student retention of a 50-minute lecture.

What then? In some cases (such as the one above), we answer the Active Reading Exercise immediately in the text. In such cases the answer is vital to the next steps in the lecture. So you might pick up your lecture by polling the students about their responses and then discussing the right answer. In other cases, the answer to the Active Reading Exercise is online; you can choose to discuss it in class, or tell students that they can find it later.

Quick Checks and ConcepTests

Among the online resources that accompany the book is a bank of multiple-choice questions designed for use in class. One common active learning technique is to ask students to vote on such a question with clicker systems, with smartphone apps, or just by holding up pieces of paper. If almost all students get the answer right, you simply note the correct answer and move on. If many of them don't, you can ask them to discuss it in pairs and then come back and talk about it.

These questions are divided into two categories.

- A "Quick Check" is a simple factual question. ("Which of the following defines a reference frame as 'inertial'?") Quick Checks are intended to quickly make sure the class is following the basic material. They are only offered online, not in the printed book.
- A "ConcepTest," a term coined by Harvard physicist Eric Mazur, is a subtler test of understanding. A ConcepTest will often garner as many wrong answers as correct ones. But if you give students a minute to answer on their own, and then another minute to confer with their neighbors, scores should be significantly higher after the second minute – and a lot of learning takes place in those two minutes. ConcepTests can also be used as parts of homework sets. All of our ConcepTests are offered online, but some are also included in the book as "Conceptual Questions" (described below).

As with the Exercises, we provide a large number of multiple-choice questions so that you can pick and choose, not to urge you to use all of them!

Other Key Features of the Book

In addition to the Exercises and Questions designed to explicitly support active learning, our book includes several other features that can help students learn and retain the material.

Math Interludes

How much math have the students in a modern physics class been exposed to? How much have they comfortably mastered? The answers vary tremendously from school to school. It is likely that most students at this level are comfortable with basic trigonometry and introductory calculus. They are probably less familiar with multivariate functions (a traveling wave $y = A\sin(kx - \omega t)$, for instance), even if they have seen them. They may not have seen complex numbers since high school. They may not have worked with partial derivatives, spherical coordinates, or partial differential equations. If you assume that students have mastered all these topics, or will pick them up as they go, the result may be frustration and superficial understanding. So we devote sections to these topics at the points where they are needed for the continued development of the physics.

For math topics that are not prerequisite to your course, you might want to spend class time covering these sections. For math topics that are prerequisite to your course, consider assigning a few homework problems from these sections to alert students to topics they might need to review.

Questions

After the Explanation in each section you'll find an extensive list of Questions and Problems.

Our questions are divided into "Conceptual Questions and ConcepTests" and "For Deeper Discussion." Unlike Problems, these questions require little or no calculation. A student who understands the topic presented in a section should be able to answer most of the Conceptual Questions, perhaps after some work and discussion, so these questions are appropriate for regular homework assignments and/or in-class discussions. But that same student may still struggle with the For Deeper Discussion questions. This struggle can be valuable, especially if it leads to discussion and debate! These questions make great extra credit problems, topics for longer class discussions, or extra challenges for highly motivated students. We recommend bracketing these with a caveat like "I don't necessarily expect you to get the right answer, but I do expect you to show me some real thought."

Problems

The last part of each section is Problems, which in many ways look like the problems you would see in any other textbook. The first difference you may notice is that we have many more of them. (In our experience, professors almost always want more problems than they have been given.) The problems marked as "Explorations" push deeper into real-world applications or advanced concepts, and might be appropriate for extra credit or as group projects.

Many derivations that are traditionally done in Explanations are done entirely or in part in our Problems. Our goal is to provide enough scaffolding to guide the students successfully through the derivations. For the derivations you really want your students to learn, we strongly believe the students will understand and retain them better if they do them (or at least attempt them) on their own before they see them from you.

When a problem explores a particular topic such as single-slit diffraction or pair annihilation, we mark it with a boldface problem title.

Because departments differ on whether they require multivariate calculus as a prerequisite for modern physics, problems that require multiple integrals are marked so that professors can skip those if their students haven't learned that skill yet.

Some problems are also marked as dependent on previous problems. If in some section you see "15. [*This problem depends on Problem 14.*]" that means you can assign just Problem 14 or both Problems 14 and 15, but you shouldn't assign Problem 15 without Problem 14.

Computer Problems

Using computers to solve problems is a crucial skill for physics students, but over-reliance on computers can prevent students from learning crucial skills. Our goal is not to dictate the right balance, but to support you wherever you find it. Scattered throughout our problem sections are problems marked with an icon (💻) indicating that they require use of a computer. (We don't mark problems that simply require a graphing calculator.) You could have the students do these problems with Wolfram Alpha®, Wolfram Mathematica, Matlab®, Excel, or any other program. If you don't want computation in your course, don't assign these problems.

Online Resources

The online resources at www.cambridge.org/felder-modernphysics that accompany our book are designed to make teaching this course as easy as possible, and taking the course as productive as possible.

Some of these resources involve the active learning tools discussed above.

Discovery Exercises

All Discovery Exercises are in the printed book, so you can assign them by saying "Do Exercise 1.1." But they are also available in printable form on the website, including blank space for student work, so you can hand them to students to work on in class.

Active Reading Exercises

The Active Reading Exercises are also available in two forms: in the printed book, and on the website as slides that you can easily flash up in the middle of class.

Solutions to *Some* Active Reading Exercises

If the solution to an Active Reading Exercise is essential in order to continue to the lecture, the solution is provided in the textbook immediately under the Exercise. The assumption is that you will present the Exercise, discuss it, and then make sure the solution is clear before proceeding further. So the solutions that are online, where students can refer to them later, are the ones that are *not* necessary for the rest of the lecture.

Quick Checks and ConcepTests

All our multiple-choice questions are available on PowerPoint and PDF slides, formatted for easy use as in-class polls. Some, but not all, of the ConcepTests are also included with the Conceptual Questions in the printed book.

We have also created other resources that will support more traditional courses which don't use active learning tools.

Homework Sets

We have emphasized that our textbook gives professors more problems, and a greater variety of problems, than others. But that strength can become a weakness, if putting together homework assignments becomes too time-consuming. For each section we've selected a small sample of Questions and Problems that cover the key ideas from the section. If you assign daily homeworks, you can simply use that set. If you assign weekly homeworks, you can paste together the sets from whichever sections you've covered.

Animations

At a number of points in the book we have a link to an online animation, usually interactive, that illustrates an idea better than a static picture can. For example, the book shows images of a wave packet approaching a barrier and being partially reflected and partially transmitted. The online animation allows the student to watch the wave packet hit the barrier, penetrate in, and then create reflected and transmitted waves. Then the student can adjust the barrier height and rerun to see what changes. These animations can be shown in class, used as hands-on activities, or assigned as part of the reading.

Supplemental Sections

The book also includes links to several sections on topics that supplement the coverage in the book. These topics include, for example, antimatter, interpretations of quantum mechanics, and open questions in cosmology. These can be assigned as extra credit, or simply made available to interested students.

One Final Thought

We leave you with a few words about the amazing enterprise that is science.

> *We are physical machinery – puppets that strut and talk and laugh and die as the hand of time pulls the strings beneath. But there is one elementary inescapable answer. We are that which asks the question.*
>
> – Sir Arthur Stanley Eddington

Cambridge University Press & Assessment
978-1-108-84289-1 — Modern Physics
Gary N. Felder , Kenny M. Felder
Frontmatter
More Information

Acknowledgments and Figure Credits

On the front cover of this book you see two names, Gary N. Felder and Kenny M. Felder. But this book would not have been possible without the contributions of a lot more people.

Vince Higgs and Melissa Shivers, our editors at Cambridge University Press, have walked this path with us from the beginning. Both of them immediately saw that we were trying to do something different from most other Cambridge textbooks (or *"different to* other Cambridge textbooks," as they said with the English accents that never lost their charm to our American ears). Our unusual approach didn't scare them; they were supportive of it, even excited by it, and they worked with us every step of the way to make our initially vague vision into a tangible reality. They got our book to dozens of early reviewers, whose feedback made every part of the book better. They pointed out aspects of the book that were non-standard in ways we hadn't intended, and gave us advice on how to fix them. (We're still not sure how Melissa found every instance of "stacked heads" without reading the entire book cover to cover. But they're all gone now.) Melissa and Vince, we sincerely want you to know that the two of us had conversations behind your backs about how thoroughly supported we always felt by both of you, and how much we appreciated it.

Cambridge assigned two different people, at two very different stages of the book's development, to copy-edit and proofread the entire text. First John King, and later Susan Parkinson, read through every Explanation, every Exercise, every Question and every Problem. And in both cases, we were stunned by the quality of their feedback. Some of it was detail-oriented ("this diagram is subtly wrong"). Some of it required content expertise ("that isn't actually a magnetic effect"). They caught mistakes that we had missed after dozens of re-readings, and they suggested improvements that we would never have thought of. It was clear from beginning to end that they were not just doing what was required; they cared about making this book the best it could possibly be. At one point we commented to each other that whatever Cambridge pays these people, it isn't enough. Toward the end of the project, much of the leadership of the process came from Rachel Norridge at Cambridge. Rachel continually made sure we understood where things stood, and why, and did her best to accommodate our (sometimes unorthodox) requests about how to handle the proofing process. She made smooth a process that could otherwise have felt very rocky.

We also received invaluable advice from early readers that we found on our own. Listing some of the most important (in alphabetical order): Richard Felder, Jessica Jiang, Chitose Maruko, Travis Norsen, Hyo Jung (Catherine) Park, and Barbara Soloman all read many first drafts and pointed out places where we were unclear, places where we needed fewer words and more

pictures, new ways in which we could explain things, and just plain mistakes. Every part of the book has been touched by their expertise and care.

Jessica Jiang and Chitose Maruko (yes, the same ones from the previous paragraph) – both Gary's students at Smith College, by the way – are responsible for all of the wonderful animations on our website. We would say something like "It would be nice to have something that illustrates different eigenfunctions of the infinite square well combining," and one of them would say "OK, I'll do that." (Or surprisingly often, "Oh yeah, I wrote something like that last week.") They designed them, coded them, debugged them, and gave them to us fully ready to post. Jessica and Chitose, you are both amazing.

Hugh Churchill, Jerome Fung, and Will Williams taught entire semester-long modern physics courses from our book, occasionally getting PDFs the day before they needed them. The feedback from them and their students improved the book in many ways. Using an unfinished book involves hassles and logistical problems for both teachers and students, and we appreciate the faith they showed in us and the help they gave us.

This book benefited from discussions with subject experts on many topics. We particularly want to acknowledge Andrew Berke for advising us on atomic and molecular chemistry, Nat Fortune for helping us understand crystal structure, and Doreen Weinberger for making our optics discussion clearer.

Our highest and fondest gratitude goes always to our wives, Rosemary McNaughton and Joyce Felder. It goes without saying that they put up with a lot, and put in a lot of extra work, for years. (The same is true of our children: Mary, Benjamin, Jack, Shannon, James, and Cecelia Felder.) But Rosemary and Joyce are also both expert teachers who listened and gave us feedback throughout the process. The book you are holding would be a much inferior product without their contributions.

Figure Credits

4.0 (https://creativecommons.org/licenses/by/4.0)]. Access for free at https://openstax.org/books/university-physics-volume-3/pages/1-introduction; **Figure 12.5** OpenStax [CC BY 4.0 (https://creativecommons.org/licenses/by/4.0)]. Access for free at https://openstax.org/books/chemistry-2e/pages/1-introduction; **Figure 12.7** This figure is a part of the Nobel Prize lecture of Robert Hofstadter. Copyright © The Nobel Foundation 1961; **Figure 12.9** J.J. Thomson, 1913. Public Domain; **Figure 13.6** Reprinted with permission from: Carl D. Anderson, Physical Review, 43, 491-494, 1933. Copyright 1933 by the American Physical Society; **Figure 13.7** © 1970-2022 CERN (License: CC-BY-4.0); **Figure 13.8** © The Regents of the University of California, Lawrence Berkeley National Laboratory; **Figure 14.3** Henrietta S. Leavitt and Edward C. Pickering, 1912. Public Domain; **Figure 14.10** Mario De Leo [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)]; **Figure 14.15** © ESA and the Planck Collaboration.