SECOND EDITION

# PRINCIPLES & PRACTICE OF PHYSICS

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Pearson

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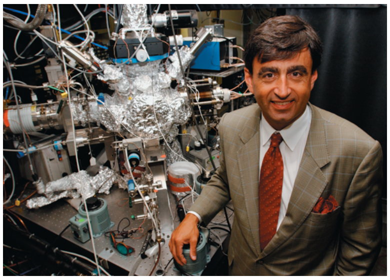
# Brief Contents

Volume 1 of *Principles & Practice of Physics* includes Chapters 1–21. Volume 2 of *Principles & Practice of Physics* includes Chapters 22–34.

# About the Author



Eric Mazur is the Balkanski Professor of Physics and Applied Physics at Harvard University, Area Chair of Applied Physics, and a member of the faculty of Education at the Harvard Graduate School of Education. Dr. Mazur is a renowned scientist and researcher in optical physics and in education research, and a sought-after author and speaker.

Dr. Mazur joined the faculty at Harvard shortly after obtaining his Ph.D. at the University of Leiden in the Netherlands. He was awarded Honorary Doctorates from the École Polytechnique and the University of Montreal, the Universidad Nacional Mayor de San Marcos in Lima, Peru, and the Katholieke Universiteit Leuven in Belgium. Dr. Mazur holds honorary professorships at the Institute of Semiconductor Physics of the Chinese Academy of Sciences in Beijing, the Institute of Laser Engineering at the Beijing University of Technology, the Beijing Normal University, Sichuan University, and Nanjing University of Science and Technology. He is a Member of the Royal Academy of Sciences of the Netherlands and a Member of the Royal Holland Society of Sciences and Humanities. In 2014, Dr. Mazur became the inaugural recipient of the Minerva Prize, and in 2018 he received the inaugural International Flipped Learning Award from the American Academy of Learning Arts and Sciences.

Dr. Mazur has held appointments as Visiting Professor or Distinguished Lecturer at Carnegie Mellon University, the Ohio State University, the Pennsylvania State University, Princeton University, Vanderbilt University, Hong Kong University, the University of Leuven in Belgium, and National Taiwan University in Taiwan, among others. From 2015–2017 Dr. Mazur served as Vice-President, President-Elect, and President of the Optical Society.

In addition to his work in optical physics, Dr. Mazur is interested in education, science policy, outreach, and the public perception of science. In 1990, he began developing Peer instruction, a method for teaching large lecture classes interactively. This teaching method has developed a large following, both nationally and internationally, and has been adopted across many science disciplines.

Dr. Mazur is author or co-author of over 300 scientific publications and holds three dozen patents. He has also written on education and is the author of *Peer Instruction: A User's Manual* (Pearson, 1997), a book that explains how to teach large lecture classes interactively. In 2006, he helped produce the award-winning DVD *Interactive Teaching*. He is the co-founder of Learning Catalytics, a platform for promoting interactive problem solving in the classroom, and of Perusall, the first truly AI-driven social learning platform.

# To the Student

Let me tell you a bit about myself.

I always knew exactly what I wanted to do. It just never worked out that way.

When I was seven years old, my grandfather gave me a book about astronomy. Growing up in the Netherlands I became fascinated by the structure of the solar system, the Milky Way, the universe. I remember struggling with the concept of infinite space and asking endless questions without getting satisfactory answers. I developed an early passion for space and space exploration. I knew I was going to be an astronomer. In high school I was good at physics, but when I entered university and had to choose a major, I chose astronomy.

It took only a few months for my romance with the heavens to unravel. Instead of teaching me about the mysteries and structure of the universe, astronomy had been reduced to a mind-numbing web of facts, from declinations and right ascensions to semi-major axes and eccentricities. Disillusioned about astronomy, I switched majors to physics. Physics initially turned out to be no better than astronomy, and I struggled to remain engaged. I managed to make it through my courses, often by rote memorization, but the beauty of science eluded me.

It wasn't until doing research in graduate school that I rediscovered the beauty of science. I knew one thing for sure, though: I was never going to be an academic. I was going to do something useful in my life. Just before obtaining my doctorate, I lined up my dream job working on the development of the compact disc, but I decided to spend one year doing postdoctoral research first.

It was a long year. After my postdoc, I accepted a junior faculty position and started teaching. That's when I discovered that the combination of doing research—uncovering the mysteries of the universe—and teaching—helping others to see the beauty of the universe—is a wonderful combination.

When I started teaching, I did what all teachers did at the time: lecture. It took almost a decade to discover that my award-winning lecturing did for my students exactly what the courses I took in college had done for me: It turned the subject that I was teaching into a collection of facts that my students memorized by rote. Instead of transmitting the beauty of my field, I was essentially regurgitating facts to my students.

When I discovered that my students were not mastering even the most basic principles, I decided to completely change my approach to teaching. Instead of lecturing, I asked students to read my lecture notes at home, and then, in class, I taught by questioning—by asking my students to reflect on concepts, discuss in pairs, and experience their own "aha!" moments.

Over the course of more than twenty years, the lecture notes have evolved into this book. Consider this book to be my best possible "lecturing" to you. But instead of listening to me without having the opportunity to reflect and think, this book will permit you to pause and think; to hopefully experience many "aha!" moments on your own.

I hope this book will help you develop the thinking skills that will make you successful in your career. And remember: your future may be—and likely will be—very different from what you imagine.

I welcome any feedback you have. Feel free to send me email or tweets.

I wrote this book for you.

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# To the Instructor

As you may recall from the first edition of this book, the idea of using conservation principles derived from a conversation with a dear friend and colleague, Albert Altman, professor at the University of Massachusetts, Lowell, who asked me if I was familiar with the approach to physics taken by Ernst Mach.

Mach treats conservation of momentum before discussing the laws of motion. It involves direct experimental observation, which appealed to me. His formulation of mechanics had a profound influence on Einstein. Most physicists never use the concept of force because it relates only to mechanics. It has no role in quantum physics, for example. The conservation principles, however, hold throughout all of physics. In that sense they are much more fundamental than Newton's laws. Furthermore, conservation principles involve only algebra, whereas Newton's second law is a differential equation.

Physics education research has shown that the concept of force, where most physics books begin, is fraught with pitfalls. What's more, after tediously deriving many results using kinematics and dynamics, most physics textbooks show that you can derive the same results from conservation principles in just one or two lines. Why not do the easy way first?

In this edition Principles and Practice of Physics, I start with conservation of both momentum and energy, and later bring in the concept of force. The approach is more unified and modern—the conservation principles are the theme that runs throughout this entire book.

Additional motives for writing this text came from my own teaching. Most textbooks focus on the acquisition of information and on the development of procedural knowledge. This focus comes at the expense of conceptual understanding or the ability to transfer knowledge to a new context. As explained below, I have structured this text to redress that balance. I also have drawn deeply on the results of physics education research, including that of my own research group.

## Organization of this book

As I considered the best way to convey the conceptual framework of mechanics, it became clear that the standard curriculum needed rethinking. For example, standard texts are forced to redefine certain concepts more than once—a strategy that we know befuddles students. (Examples are work, the standard definition of which is incompatible with the first law of thermodynamics, and energy, which is redefined when modern physics is discussed.)

Another point that has always bothered me is the arbitrary division between "modern" and "classical" physics. In most texts, the first thirty-odd chapters present physics essentially as it was known at the end of the 19th century; "modern physics" gets tacked on at the end. There's no need for this separation. Our goal should be to explain physics in the way that works best for students, using our full contemporary understanding. All physics is modern!

That is why my table of contents departs from the "standard organization" in the following specific ways.

**Emphasis on conservation laws.** As mentioned earlier, this book introduces the conservation laws early and treats them the way they should be: as the backbone of physics. The advantages of this shift are many. First, it avoids many of the standard pitfalls related to the concept of force, and it leads naturally to the two-body character of forces and the laws of motion. Second, the conservation laws enable students to solve a wide variety of problems without any calculus. Indeed, for complex systems, the conservation laws are often the natural (or only) way to solve problems. Third, the book deduces the conservation laws from experimental observations, helping to make clear their connection with the world around us. I and several other instructors have tested this approach extensively in our classes and found markedly improved performance on problems involving momentum and energy, with large gains on assessment instruments like the Force Concept Inventory.

**Early emphasis on the concept of system.** Fundamental to most physical models is the separation of a system from its environment. This separation is so basic that physicists tend to carry it out unconsciously, and traditional texts largely gloss over it. This text introduces the concept in the context of conservation principles and uses it consistently.

**Postponement of vectors.** Most introductory physics concerns phenomena that take place along one dimension. Problems that involve more than one dimension can be broken down into one-dimensional problems using vectorial notation. So, a solid understanding of physics in one dimension is of fundamental importance. However, by introducing vectors in more than one dimension from the start, standard texts distract the student from the basic concepts of kinematics.

In this book, I develop the complete framework of mechanics for motions and interactions in one dimension. I introduce the second dimension when it is needed, starting with rotational motion. Hence, students can focus on the actual physics early on.

**Table 1** Scheduling matrix

| Topic | Chapters | Can be inserted after chapter . . . | Chapters that can be omitted without affecting continuity |
|---|---|---|---|
| Mechanics | 1–14 | | 6, 13–14 |
| Waves | 15–17 | 12 | 16–17 |
| Fluids | 18 | 9 | |
| Thermal Physics | 19–21 | 10 | 21 |
| Electricity & Magnetism | 22–30 | 12 (but 17 is needed for 29–30) | 29–30 |
| Circuits | 31–32 | 26 (but 30 is needed for 32) | 32 |
| Optics | 33–34 | 17 | 34 |

**Just-in-time introduction of concepts.** Wherever possible, I introduce concepts only when they are necessary. This approach allows students to put ideas into immediate practice, leading to better assimilation.

**Integration of modern physics.** A survey of syllabi shows that less than half the calculus-based courses in the United States cover modern physics. I have therefore integrated selected "modern" topics throughout the text. For example, special relativity is covered in Chapter 14, at the end of mechanics. Chapter 32, Electronics, includes sections on semiconductors and semiconductor devices. Chapter 34, Wave and Particle Optics, contains sections on quantization and photons.

**Modularity.** I have written the book in a modular fashion so it can accommodate a variety of curricula (See Table 1, "Scheduling matrix").

The book contains two major parts, Mechanics and Electricity and Magnetism, plus five shorter parts. The two major parts by themselves can support an in-depth two-semester or three-quarter course that presents a complete picture of physics embodying the fundamental ideas of modern physics. Additional parts can be added for a longer or faster-paced course. The five shorter parts are more or less self-contained, although they do build on previous material, so their placement is flexible. Within each part or chapter, more advanced or difficult material is placed at the end.

## Pedagogy

This text draws on many models and techniques derived from my own teaching and from physics education research. The following are major themes that I have incorporated throughout.

**Separation of conceptual and mathematical frameworks.** Each chapter is divided into two parts: Concepts and Quantitative Tools. The first part, Concepts, develops the full conceptual framework of the topic and addresses many of the common questions students have. It concentrates on the underlying ideas and paints the big picture, whenever possible without equations. The second part of the chapter, Quantitative Tools, then develops the mathematical framework.

**Deductive approach; focus on ideas before names and equations.** To the extent possible, this text develops arguments deductively, starting from observations, rather than stating principles and then "deriving" them. This approach makes the material easier to assimilate for students. In the same vein, this text introduces and explains each idea before giving it a formal name or mathematical definition.

**Stronger connection to experiment and experience.** Physics stems from observations, and this text is structured so that it can do the same. As much as possible, I develop the material from experimental observations (and preferably those that students can make) rather than assertions. Most chapters use actual data in developing ideas, and new notions are always introduced by going from the specific to the general—whenever possible by interpreting everyday examples.

By contrast, standard texts often introduce laws in their most general form and then show that these laws are consistent with specific (and often highly idealized) cases. Consequently, the world of physics and the "real" world remain two different things in the minds of students.

**Addressing physical complications.** I also strongly oppose presenting unnatural situations; real life complications must always be confronted head-on. For example, the use of unphysical words like frictionless or massless sends a message to the students that physics is unrealistic or, worse, that the world of physics and the real world are unrelated entities. This can easily be avoided by pointing out that friction or mass may be neglected under certain circumstances and pointing out why this may be done.

**Engaging the student.** Education is more than just transfer of information. Engaging the student's mind so the information can be assimilated is essential. To this end, the text is written as a dialog between author and reader (often invoking the reader—you—in examples) and is punctuated by Checkpoints—questions that require the reader to stop and think. The text following a Checkpoint often refers directly to its conclusions. Students will find complete solutions to all the Checkpoints at the back of the book; these solutions are written to emphasize physical reasoning and discovery.

**Visualization.** Visual representations are central to physics, so I developed each chapter by designing the figures before writing the text. Many figures use multiple representations to help students make connections (for example, a sketch may be combined with a graph and a bar diagram). Also, in accordance with research, the illustration style is spare and simple, putting the emphasis on the ideas and relationships rather than on irrelevant details. The figures do not use perspective unless it is needed, for instance.

## Physics for today's student

This new edition focuses on today's physics student who not only learns in the physical classroom but gleans knowledge in a digital environment. The content format is modified for students to actively engage with online content first. The second edition optimizes the delivery of the content by combining both volumes of the first edition (Principles volume and Practice volume) and providing it as one single volume via etext and Mastering Physics.

Best practices reflect the idea that by engaging with the material before coming to class better prepares students to learn. The new edition provides new prelecture videos by both Eric Mazur and his Harvard colleague Greg Kestin (researcher and consultant for NOVA) to help students come to class ready to participate, encourage the understanding of real-world application of physics, and support instructors in building active and relevant classes.

As pointed out earlier, each chapter is divided into two parts. The first part (Concepts) develops the conceptual framework in an accessible way, relying primarily on qualitative descriptions and illustrations. In addition to including Checkpoints, each Concepts section ends with a one-page Self-quiz consisting of qualitative questions. The second part of each chapter (Quantitative Tools) formalizes the ideas developed in the first part in mathematical terms. While concise, it is relatively traditional in nature—teachers should be able to continue to use material developed for earlier courses. To avoid creating the impression that equations are more important than the concepts behind them, no equations are highlighted or boxed. Both parts of the chapters contain worked examples to help students develop problem-solving skills.

At the end of each chapter is a Chapter Summary and a Questions and Problems section. The problems 1) offer a range of levels; 2) include problems relating to client disciplines (life sciences, engineering, chemistry, astronomy, etc.); 3) use the second person as much as possible to draw in the student; and 4) do not spoonfeed the students with information and unnecessary diagrams. The problems are classified into three levels as follows: (•) application of single concept; numerical plug-and-chug; (••) nonobvious application of single concept or application of multiple concepts from current chapter; straightforward numerical or algebraic computation; (•••) application of multiple concepts, possibly spanning multiple chapters. Context-rich problems are designated CR.

Additional material can be found online in Mastering Physics:

1. *Review Questions.* The goal of this section is to allow students to quickly review the corresponding chapter. The questions are straightforward one-liners starting with "what" and "how" (rather than "why" or "what if"). These questions are in Mastering Physics and interactive etext.
2. *Developing a Feel.* The goals of this section are to develop a quantitative feel for the quantities introduced in the chapter; to connect the subject of the chapter to the real world; to train students in making estimates and assumptions; to bolster students' confidence in dealing with unfamiliar material. It can be used for self-study or for a homework or recitation assignment. This section, which has no equivalent in existing books, combines a number of ideas (specifically, Fermi problems and tutoring in the style of the *Princeton Learning Guide*). The idea is to start with simple estimation problems and then build up to Fermi problems (in early chapters Fermi problems are hard to compose because few concepts have been introduced). Because students initially find these questions hard, the section provides many hints, which take the form of guiding questions. A key then provides answers to these "hints." These Developing a Feel questions are now included in Mastering Physics, as well as in the interactive etext.
3. *Worked and Guided Problems.* This section contains worked examples whose primary goal is to teach problem solving. The Worked Problems are fully solved; the Guided Problems have a list of guiding questions and suggestions to help the student think about how to solve the problem. Typically, each Worked Problem is followed by a related Guided Problem. Both are available in Mastering Physics and the interactive etext.

## Instructor supplements

Downloadable ***Instructor Resources*** (ISBN 013561113X/ 9780135611135) includes an Image Library, the Procedure and special topic boxes from *Principles and Practice of Physics*, and a library PhET simulations and PhET Clicker Questions. **Lecture Outlines** with embedded **Clicker Questions in PowerPoint®** are provided, as well as the ***Instructor's Guide*** and ***Instructor's Solutions Manual***.

The ***Instructor's Guide*** (ISBN 0135611091/ 9780135611098) provides chapter-by-chapter ideas for lesson planning using *Principles & Practice of Physics* in class, including strategies for addressing common student difficulties.

The ***Instructor's Solutions Manual*** (ISBN 0135610893/ 9780135610893) is a comprehensive solutions manual containing complete answers and solutions to Questions and Problems found at the end of each chapter, as well as all Developing a Feel questions and Guided Problems found in Mastering Physics. The solutions to the Guided Problems use the book's four-step problem-solving strategy (Getting Started, Devise Plan, Execute Plan, Evaluate Result).

**Mastering Physics®** is the leading online homework, tutorial, and assessment product designed to improve results by helping students quickly master concepts. Students benefit from self-paced tutorials that feature specific wrong-answer feedback, hints, and a wide variety of educationally effective content to keep them engaged and on track. Robust diagnostics and unrivalled gradebook reporting allow instructors to pinpoint the weaknesses and misconceptions of a student or class to provide timely intervention.

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**Learning Catalytics™** is a "bring your own device" student engagement, assessment, and classroom intelligence system available within Mastering Physics. With Learning Catalytics you can:

- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical-thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

The **Test Bank** (ISBN 0135610729/9780135610725) contains more than 2000 high-quality problems, with a range of multiple-choice, true-false, short-answer, and conceptual questions correlated to *Principles & Practice of Physics* chapters. Test files are provided in both TestGen® and Microsoft® Word for Mac and PC.

Instructor supplements are available in the Instructor Resource area of Mastering Physics (www.masteringphysics.com).

## Student supplements

**Mastering Physics** (www.masteringphysics.com) is designed to provide students with customized coaching and individualized feedback to help improve problem-solving skills. Students complete homework efficiently and effectively with tutorials that provide targeted help. By combining trusted author content with digital tools developed to engage students and emulate the office-hour experience, Mastering personalizes learning and improves results for each student. Built for, and directly tied to the text, Mastering Physics gives students a platform to practice, learn, and apply knowledge outside of the classroom.

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This book would not exist without the contributions from many people. It was Tim Bozik, currently the President of Global Product at Pearson, who first approached me about writing a physics textbook. If it wasn't for his persuasion and his belief in me, I don't think I would have ever undertaken the writing of a textbook. Tim's suggestion to develop the art electronically also had a major impact on my approach to the development of the visual part of this book.

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## Reviewers of *Principles & Practice of Physics*

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