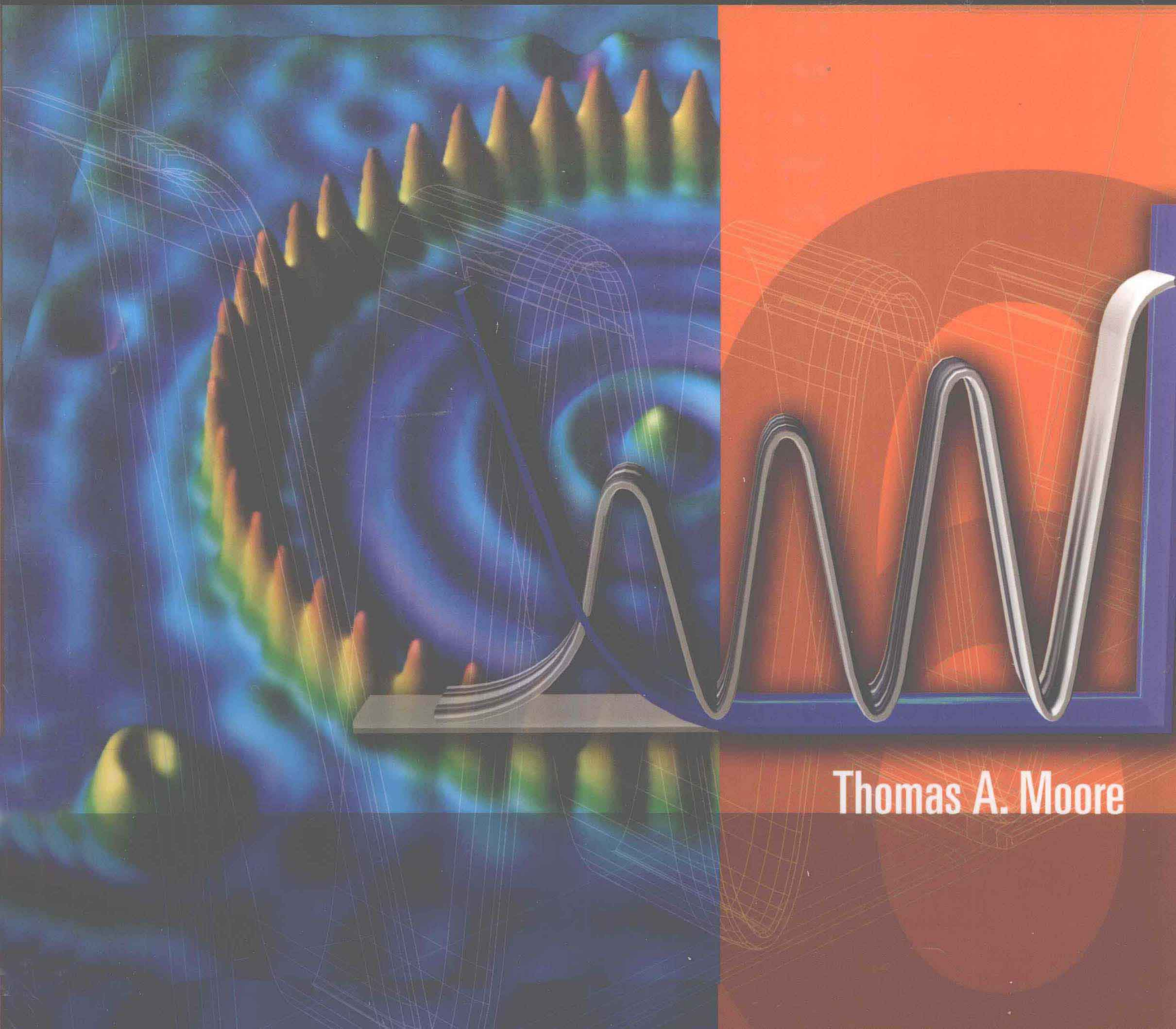
Six Ideas That Shaped Physics

Unit Q: Particles Behave Like Waves

Second Edition



Thomas A. Moore

McGraw-Hill Higher Education
A Division of The McGraw-Hill Companies

SIX IDEAS THAT SHAPED PHYSICS, UNIT Q: PARTICLES BEHAVE LIKE WAVES
SECOND EDITION

Published by McGraw-Hill, a business unit of The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY 10020.

2 3 4 5 6 7 8 9 0 QPD/QPD 0 9 8 7 6

ISBN-13: 978-0-07-239713-0
ISBN-10: 0-07-239713-6

Publisher: *Kent A. Peterson*
Sponsoring editor: *Daryl Bruflodt*
Developmental editor: *Spencer J. Cotkin, Ph.D.*
Marketing manager: *Debra B. Hash*
Senior project manager: *Susan J. Brusch*
Senior production supervisor: *Sandy Ludovissy*
Media project manager: *Sandra M. Schnee*
Designer: *David W. Hash*
Cover/interior designer: *Rokusek Design*
Cover image: © *IBM Corporation, Research Division, Almaden Research Center*
Senior photo research coordinator: *Lori Hancock*
Photo research: *Chris Hammond/PhotoFind LLC*
Supplement producer: *Brenda A. Ernzen*
Compositor: *Interactive Composition Corporation*
Typeface: *10/12 Palatino*
Printer: *Quebecor World Dubuque, IA*

Credit List: **Chapter 1** Q1.10: Courtesy Pasco Scientific; Q1.14a, b: Photo Courtesy of Richard Pelland, Pelland Pipe Organ Company; Q1.15: © James L. Amos/Corbis; Q1.16: Corbis/R-F Website. **Chapter 2** Q2.1: © Richard Megna/Fundamental Photographs; Q2.4b: © Erich Schrempp/Photo Researchers; Q2.7c, Q2.10b: © Richard Megna/Fundamental Photographs; Q2.12: © Tom Pantages; Q2.14: © Springer-Verlag. **Chapter 3** Q3.1c, Q3.3b: © McGraw-Hill Companies, Inc./photo by Chris Hammond. **Chapter 4** Q4.1: Lawrence Berkeley Radiation Laboratory; Q4.4: © Zeitschrift fur Physik, Springer-Verlag; Q4.5: From O. Carnal and J. Mlyneck, Physical Review Letters, 66, 2691, 1991. Copyright © 1991 by the American Physical Society. Q4.6: M.R. Andrews, C.G. Townsend, H.J. Miesner, D.S. Durfee, D.M. Kurn, and W. Ketterle: Observation of interference between two Bose condensates. Science 275, 637-641 (1997). **Chapter 5** Q5.2b: P.G. Merli, G. F. Missiroli and G. Pozzi, Journal of American Physics, Vol. 44, No. 3, March 1976, Fig. 1, pg. 306. **Chapter 8** Q8.5c: © BAse de donnees Solaire Sol 2000, Solar Survey Archive; Q8.6: Courtesy of NRAO/AUI. **Chapter 11** Q11.7b: Courtesy LBL. **Chapter 15** Q15.1: © Roger Ressmeyer/Corbis Images; Q15.4b Q15.5: © Bettmann/Corbis; Q15.7a: Courtesy of Princeton Plasma Physics Laboratory; Q15.7b: © PhotoDisc/ Vol. 6.

Library of Congress Cataloging-in-Publication Data

Moore, Thomas A. (Thomas Andrew)
Six ideas that shaped physics. Unit Q: Particles behave like waves. / Thomas A. Moore. — 2nd ed.
p. cm.
Contents: [1] Unit C: Conservation laws constrain interactions — [2] Unit N: The laws of physics are universal — [3] Unit R: The laws of physics are frame-independent — [4] Unit E: Electric and magnetic fields are unified — [5] Unit Q: Particles behave like waves — [6] Unit T: Some processes are irreversible.
Includes bibliographical references and index.
ISBN 0-07-239713-6 (acid-free paper)
1. Physics—Study and teaching (Higher) 2. Physics—Problems, exercise, etc. I. Title: Particles behave like waves. II. Title.

QC32 .M647 2003
530—dc21

2002032552
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www.mhhe.com

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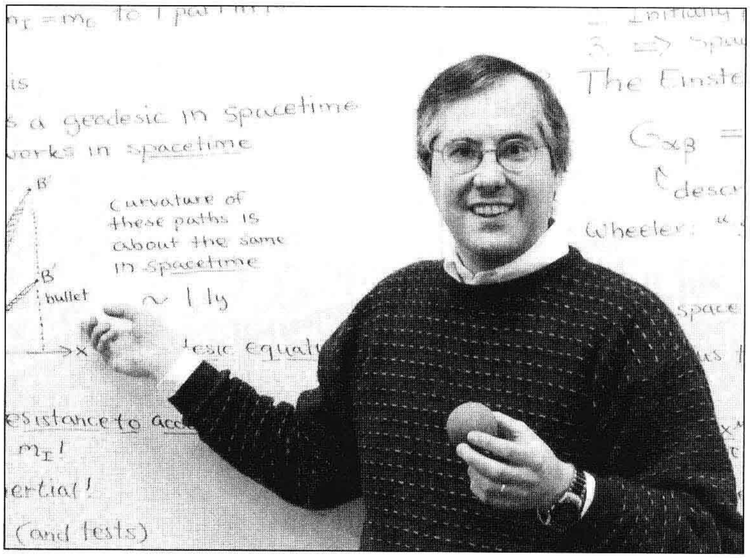


Thomas A. Moore graduated from Carleton College (*magna cum laude* with Distinction in Physics) in 1976. He won a Danforth Fellowship that year that supported his graduate education at Yale University, where he earned a Ph.D. in 1981. He taught at Carleton College and Luther College before taking his current position at Pomona College in 1987, where he won a Wig Award for Distinguished Teaching in 1991. He served as an active member of the steering committee for the national Introductory University Physics Project (IUPP) from 1987 through 1995. This textbook grew out of a model curriculum that he developed for that project in 1989, which was one of only four selected for further development and testing by IUPP.

He has published a number of articles about astrophysical sources of gravitational waves, detection of gravitational waves, and new approaches to teaching physics, as well as a book on special relativity entitled *A Traveler's Guide to Spacetime* (McGraw-Hill, 1995). He has also served as a reviewer and an associate editor for *American Journal of Physics.* He currently lives in Claremont, California, with his wife, Joyce, and two college-age daughters, Brittany and Allison. When he is not teaching, doing research in relativistic astrophysics, or writing, he enjoys reading, hiking, scuba diving, teaching adult church-school classes on the Hebrew Bible, calling contradances, and playing traditional Irish fiddle music.

Preface

Introduction

Opening comments about *Six Ideas That Shaped Physics*

This volume is one of six that together comprise the text materials for *Six Ideas That Shaped Physics*, a fundamentally new approach to the two- or three-semester calculus-based introductory physics course. *Six Ideas That Shaped Physics* was created in response to a call for innovative curricula offered by the Introductory University Physics Project (IUPP), which subsequently supported its early development. In its present form, the course represents the culmination of more than a decade of development, testing, and evaluation at a number of colleges and universities nationwide.

This course is based on the premise that innovative approaches to the presentation of topics and to classroom activities can help students learn more effectively. I have completely rethought from the ground up the presentation of every topic, taking advantage of research into physics education wherever possible, and have done nothing just because "that is the way it has always been done." Recognizing that physics education research has consistently underlined the importance of active learning, I have provided tools supporting multiple opportunities for active learning both inside and outside the classroom. This text also strongly emphasizes the process of building and critiquing physical models and using them in realistic settings. Finally, I have sought to emphasize contemporary physics and view even classical topics from a thoroughly contemporary perspective.

I have not sought to "dumb down" the course to make it more accessible. Rather, my goal has been to help students become *smarter.* I intentionally set higher-than-usual standards for sophistication in physical thinking, and I have then used a range of innovative approaches and classroom structures to help even average students reach this standard. I don't believe that the mathematical level required by these books is significantly different from that in most university physics texts, but I do ask students to step beyond rote thinking patterns to develop flexible, powerful conceptual reasoning and model-building skills. My experience and that of other users are that normal students in a wide range of institutional settings can, with appropriate support and practice, meet these standards.

The six volumes of the *Six Ideas* text

The six volumes that comprise the complete *Six Ideas* course are

Unit C (**C**onservation Laws):	Conservation Laws Constrain Interactions
Unit N (**N**ewtonian Mechanics):	The Laws of Physics Are Universal
Unit R (**R**elativity):	The Laws of Physics Are Frame-Independent
Unit E (**E**lectricity and Magnetism):	Electric and Magnetic Fields Are Unified
Unit Q (**Q**uantum Physics):	Particles Behave Like Waves
Unit T (**T**hermal Physics):	Some Processes Are Irreversible

I have listed these units in the order that I recommend that they be taught, though other orderings are possible. At Pomona, we teach the first three units during the first semester and the last three during the second semester of a year-long course, but one can easily teach the six units in three quarters or even over three semesters if one wants a slower pace. The chapters of all these texts have been designed to correspond to what one might realistically discuss in a single 50-minute class session at the *highest possible pace:* while one might design a syllabus that covers chapters at a slower rate, one should *not* try to discuss more than one chapter in a 50-minute class.

For more information than I can include in this short preface about the goals of the *Six Ideas* course, its organizational structure (and the rationale behind that structure), the evidence for its success, and information about how to cut and/or rearrange material, as well as many other resources for both teachers and students, please visit the *Six Ideas* website (see the next section).

Important Resources

Instructions about how to use this text

I have summarized important information about how to read and use this text in an Introduction for Students immediately preceding the first chapter. Please look this over, particularly if you have not seen other volumes of this text.

The *Six Ideas* website

The *Six Ideas* website contains a wealth of up-to-date information about the course that I think both instructors and students will find very useful. The URL is

www.physics.pomona.edu/sixideas/

Essential computer programs

One of the most important resources available at this site are a number of computer applets that illustrate important concepts and aid in difficult calculations. In several places, this unit draws on some of these programs, and past experience indicates that students learn the ideas much more effectively when these programs are used both in the classroom and for homework. These applets are freeware and are available for both the Mac (Classic) and Windows operating systems.

Some Notes Specifically About Unit Q

The goal of this unit

This unit presents a basic introduction to the concepts of quantum physics and its application, most particularly to nuclear physics. This unit is structured to give the instructor a lot of flexibility in adjusting its length.

Chapters Q1 through Q8 are the irreducible core of the unit, discussing the basic behavior of waves, interference and diffraction experiments involving light, experiments that display the quantum nature of reality, the rules of quantum mechanics, and the basic concept of the wavefunction, the particle-in-a-box and Bohr models and energy quantization, and finally how spectra are connected with these models (but *not* the Schrödinger equation). This part of the unit depends on previous units as follows: in addition to basic mechanics, students need to know a few things about waves (discussed near the end of unit E), a bit about how electric fields are related to potential differences, and Coulomb's law. There is a part of chapter Q4 that refers to relativistic energy, but one can skip over this if necessary.

New in this edition is a discussion of complex numbers and the formal rules of quantum mechanics expressed in terms of vectors, using spin as an example. I recommend that instructors visit the website for more information about my goals for chapters Q5 and Q6; but in summary, I found by experience that tiptoeing around these issues (as I did in the last edition) was, I think, ultimately more confusing and less satisfying than confronting them head on.

Chapter Q9 discusses some general principles of atomic structure in a fairly superficial manner. I spend only a small amount of time on these topics because atomic physics, though important, is genuinely difficult, and I have not found treatments of atomic physics at this level to be either theoretically satisfactory or illuminating to students. I have tried to extract a few useful insights to give students some qualitative understanding of how atoms work without going too far into the details. This chapter can be omitted without loss of continuity.

By contrast, students can understand a *lot* of interesting things about nuclear structure (and do some decent physics) without knowing much more about quantum mechanics than the Pauli exclusion principle and the particle-in-a-box model. Nuclear physics also provides an excellent opportunity to apply ideas from other units in the course. Finally, nuclear physics has so many important social and historical implications that well-educated students ought to know something about it. Chapters Q12 through Q15 therefore provide a fairly detailed exploration of nuclear structure, nuclear stability, radioactivity, and nuclear technology. In addition to basic mechanics, this part of the unit draws on the Pauli exclusion principle from chapter Q8; the concepts of energy quantization and energy levels from chapters Q7 and Q8; the concept of relativistic energy and how it is related to mass from unit R; and electrostatic potential energy, potential energy diagrams, and concepts concerning bonds from unit C. This part of the unit, while I think it is fascinating and socially important, can be completely omitted if necessary.

Chapters Q10 and Q11 also constitute an independent set of chapters that discuss the one-dimensional time-independent Schrödinger equation and its solutions. These chapters deemphasize finding mathematical solutions to the Schrödinger equation and instead focus more on helping students see how this equation is a generalization of the de Broglie relation and on helping them develop an *intuitive* understanding of its solutions and their implications. This part culminates in a discussion of the covalent bond, which students can understand by applying carefully developed but qualitative wavefunction-sketching skills. This part draws on the core material presented in chapters Q1 through Q8 and basic mechanics (especially potential energy diagrams). It may be omitted, as no other material depends on it. It also can be discussed anytime after chapter Q7 (and doing it before chapter Q9 could make the material about the radial wavefunctions in that chapter more plausible).

There is a computer program (called *SchroSolver*) that helps make the ideas in this part of the course clearer. This program solves the Schrödinger equation for a variety of potential energy functions and is discussed explicitly in chapter Q10. Since it can generate a solution for any arbitrary energy, it vividly illustrates why energy must be quantized by showing how unrealistic solutions are for energies other than the quantized values. You can download this program from the *Six Ideas* website.

Here is a table summarizing how one might adjust the length of this unit:

Class days	Chapters	Comments
8	Q1–Q8	Just the basics
9	Q1–Q9	The basics + atomic physics
10	Q1–Q8, Q10–Q11	The basics + the Schrödinger equation
11	Q1–Q11	The above + atomic physics
12	Q1–Q8, Q12–Q15	The basics + nuclear physics
13	Q1–Q9, Q12–Q15	The basics + atomic and nuclear physics
14	Q1–Q8, Q10–Q15	Everything but atomic physics
15	Q1–Q15	Everything

One should also budget a day to talk about waves if unit E does not precede this unit.

Please see the Instructor's Manual for more detailed comments about this unit and suggestions about how to teach it effectively.

Appreciation

Thanks!

A project of this magnitude cannot be accomplished alone. I would first like to thank the others who served on the IUPP development team for this project: Edwin Taylor, Dan Schroeder, Randy Knight, John Mallinckrodt, Alma Zook, Bob Hilborn, and Don Holcomb. I'd like to thank John Rigden and other members of the IUPP steering committee for their support of the project in its early stages, which came ultimately from an NSF grant and the special efforts of Duncan McBride. Users of the texts, especially Bill Titus, Richard Noer, Woods Halley, Paul Ellis, Doreen Weinberger, Nalini Easwar, Brian Watson, Jon Eggert, Catherine Mader, Paul De Young, Alma Zook, Dan Schroeder, David Tanenbaum, Alfred Kwok, and Dave Dobson, have offered invaluable feedback and encouragement. I'd also like to thank Alan Macdonald, Roseanne Di Stefano, Ruth Chabay, Bruce Sherwood, and Tony French for ideas, support, and useful suggestions. Thanks also to Robs Muir for helping with several of the indexes. My editors Jim Smith, Denise Schanck, Jack Shira, Karen Allanson, Lloyd Black, J. P. Lenney, and Daryl Bruflodt as well as Spencer Cotkin, Donata Dettbarn, David Dietz, Larry Goldberg, Sheila Frank, Jonathan Alpert, Zanae Roderigo, Mary Haas, Janice Hancock, Lisa Gottschalk, Debra Hash, David Hash, Patti Scott, Chris Hammond, Rick Hecker, and Susan Brusch have all worked very hard to make this text happen, and I deeply appreciate their efforts. I'd like to thank all the reviewers, including Edwin Carlson, David Dobson, Irene Nunes, Miles Dressler, O. Romulo Ochoa, Qichang Su, Brian Watson, and Laurent Hodges, for taking the time to do a careful reading of various units and offering valuable suggestions.

I also wish to thank the following panel of reviewers for providing careful and insightful comments on the second edition of this unit:

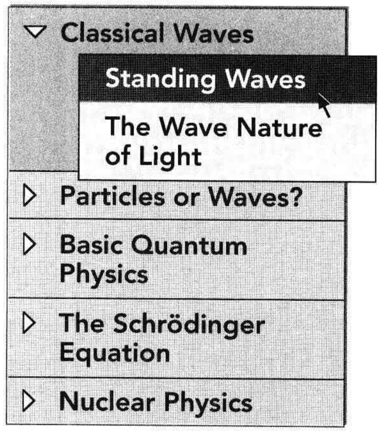
Amy Bug, *Swarthmore College*
Shane Burns, *Colorado College*
Zhigang Chen, *San Francisco State University*
Richard Gelderman, *Western Kentucky University*
Keith Honey, *West Virginia Institute of Technology*
Michael Jackson, *University of Wisconsin—La Crosse*
Renee James, *San Houston State University*
Elizabeth McCormack, *Bryn Mawr College*
Ann Schmiedekamp, *Pennsylvania State University—Abingdon*
Brian Raichle, *Appalachian State University*
Bill Titus, *Carleton College*
John Walkup, *California State University—San Luis Obispo*
Brock Weiss, *Sonoma State University*

Thanks to Connie Wilson, Hilda Dinolfo, Connie Inman, and special student assistants Michael Wanke, Paul Feng, Mara Harrell, Jennifer Lauer, Tony Galuhn, Eric Pan, and all the Physics 51 mentors for supporting (in various ways) the development and teaching of this course at Pomona College. Thanks also to my Physics 51 students, and especially Win Yin, Peter Leth, Eddie Abarca, Boyer Naito, Arvin Tseng, Rebecca Washenfelder, Mary Donovan, Austin Ferris, Laura Siegfried, and Miriam Krause, who have offered many suggestions and have together found many hundreds of typos and other errors. Eric and Brian Daub, Nate Smith, and Ryan McLaughlin were indispensable in helping me put this edition together. Finally, very special thanks to my wife, Joyce, and to my daughters, Brittany and Allison, who contributed with their support and patience during this long and demanding project. Heartfelt thanks to all!

Thomas A. Moore
Claremont, California

Introduction for Students

How to Read and Use This Text Effectively



Introduction

Welcome to *Six Ideas That Shaped Physics!* This text has been designed using insights from recent research into physics learning to help you learn physics as effectively as possible. It thus has many features that may be different from those in science texts you have probably encountered. This section discusses these features and how to use them effectively.

Why Is This Text Different?

Research consistently shows that people learn physics most effectively if they participate in *activities* that help them *practice* applying physical reasoning in realistic situations. This is so because physics is not a collection of facts to absorb, but rather is a set of *thinking skills* requiring practice to master. You cannot learn such skills by going to factual lectures any more than you can learn to play the piano by going to concerts!

This text is designed, therefore, to support *active learning* both inside and outside the classroom by providing (1) resources for various kinds of learning activities, (2) features that encourage active reading, and (3) features that make it easier for the text (as opposed to lectures) to serve as the primary source of information, so that more class time is available for active learning.

The Text as Primary Source

Features that help the text serve as the primary source of information

To serve the last goal, I have adopted a conversational style that I hope will be easy to read, and I tried to be concise without being so terse that you need a lecture to fill in the gaps. There are also many text features designed to help you keep track of the big picture. The unit's **central idea** is summarized on the front cover where you can see it daily. Each chapter is designed to correspond to one 50-minute class session, so that each session is a logically complete unit. The two-page **chapter overview** beginning each chapter provides a compact summary of that chapter's contents to consider before you are submerged by the details (it also provides a useful summary when you review for exams). An accompanying **chapter location diagram** uses a computer menu metaphor to display how the current chapter fits into the unit (see the example at the upper right). Major unit subdivisions appear as gray boxes, with the current subdivision highlighted in color. Chapters in the current subdivision appear in a submenu with the current chapter highlighted in black and indicated by an arrow.

All technical terms are highlighted using a **bold** type when they first appear, and a **Glossary** at the end of the text summarizes their definitions. Please also note the tables of useful information, including definitions of common symbols, that appear inside the front cover.

A physics *formula* is both a mathematical equation and a *context* that gives the equation meaning. Every important formula in this text appears in a **formula box.** Each contains the equation, a **purpose** (describing the formula's meaning and utility), a definition of the **symbols** used in the equation, a description of any **limitations** on the formula's applicability, and possibly some other useful **notes.** Treat everything in such a box as an *indivisible unit* to be remembered and used together.

Active Reading

What it means to be an *active reader*

Like passively listening to a lecture, passively scanning a text does not really help you learn. *Active* reading is a crucial study skill for effectively learning from this text (and other types of technical literature as well). An active reader stops frequently to pose internal questions such as these: *Does this make sense? Is this consistent with my experience? Am I following the logic here? Do I see how I might use this idea in realistic situations?* This text provides two important tools to make this easier.

Tools to help you become an active reader

Use the **wide margins** to (1) record *questions* that occur to you as you read (so that you can remember to get them answered), (2) record *answers* when you receive them, (3) flag important passages, (4) fill in missing mathematics steps, and (5) record insights. Doing these things helps keep you actively engaged as you read, and your marginal comments are also generally helpful as you review. Note that I have provided some marginal notes in the form of *sidebars* that summarize the points of crucial paragraphs and help you find things quickly.

The single most important thing you can do

The **in-text exercises** help you develop the habits of (1) filling in missing mathematics steps and (2) posing questions that help you *practice* using the chapter's ideas. Also, although this text has many examples of worked problems similar to homework or exam problems, *some* of these appear in the form of in-text exercises (as you are more likely to *learn* from an example if you work on it some yourself instead of just scanning someone else's solution). Answers to *all* exercises appear at the end of each chapter, so you can get immediate feedback on how you are doing. Doing at least some of the exercises as you read is probably the *single most important thing you can do* to become an active reader.

Active reading does take effort. *Scanning* the 5200 words of a typical chapter might take 45 minutes, but active reading could take twice as long. I personally tend to "blow a fuse" in my head after about 20 minutes of active reading, so I take short breaks to do something else to keep alert. Pausing to fill in missing mathematics also helps me to stay focused longer.

Class Activities and Homework

End-of-chapter problems support active learning

The problems at the end of each chapter are organized into categories that reflect somewhat different active-learning purposes. **Two-minute problems** are short, concept-oriented, multiple-choice problems that are primarily meant to be used *in* class as a way of practicing the ideas and/or exposing conceptual problems for further discussion. (The letters on the back cover make it possible to display responses to your instructor.) The other types of problems are primarily meant for use as homework *outside* class. **Basic** problems are simple drill-type problems that help you practice in straightforward applications of a single formula or technique. **Synthetic** problems are more challenging and realistic questions that require you to bring together multiple formulas and/or techniques (maybe from different chapters) and to think carefully about physical principles. These problems define the level of sophistication that you should strive to achieve. **Rich-context** problems are yet more challenging problems that are often written in a narrative format and ask you to answer a practical, real-life question rather than explicitly asking for a numerical result. Like situations you will encounter in real life, many provide too little information and/or too much information, requiring you to make estimates and/or discard irrelevant data (this is true of a some *synthetic* problems as well). Rich-context problems are generally too difficult for most students to solve alone; they are designed for *group* problem-solving sessions. **Advanced** problems are very sophisticated problems that provide supplemental discussion of subtle or advanced issues related to the material discussed in the chapter. These problems are for instructors and truly exceptional students.

Read the Text *Before* Class!

You will be able to participate in the kinds of activities that promote real learning *only* if you come to each class having already read and thought about the assigned chapter. This is likely to be *much* more important in a class using this text than in science courses you may have taken before! Class time can also (*if* you are prepared) provide a great opportunity to get your *particular* questions about the material answered.

Class time works best if you are prepared

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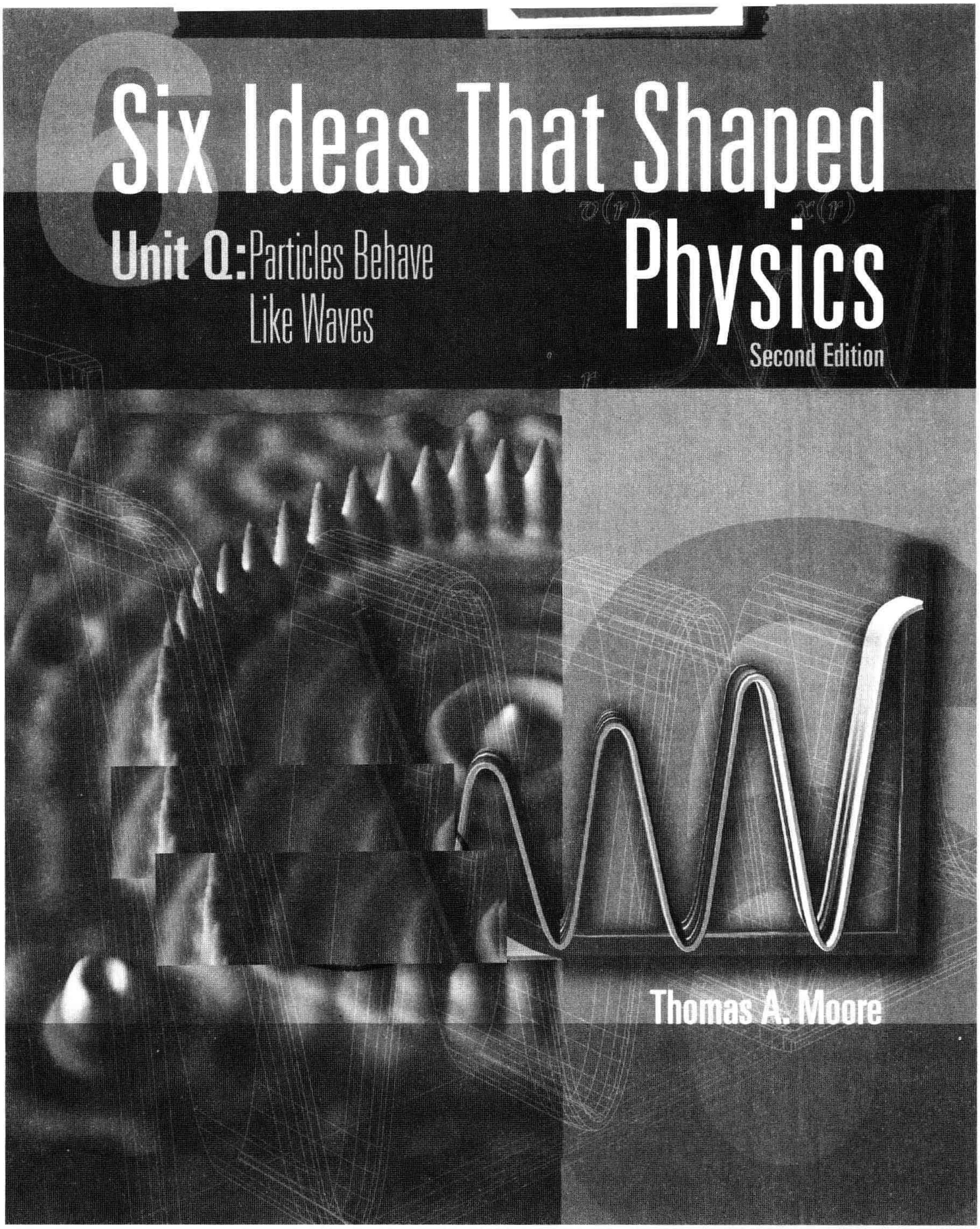

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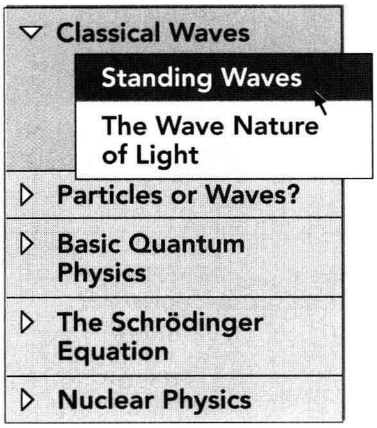
Q1 Standing Waves



Chapter Overview

Section Q1.1: Introduction to the Unit

This unit is focused on *quantum mechanics*, the revolutionary theory of microscopic systems that lies at the foundation of most of 20th-century physics. This theory grew out of the observation that in certain circumstances, *matter behaves like waves.* Each of the unit subdivisions shown in the menu to the left explores a crucial aspect of this great idea. See the section for a more detailed description of each of the five subunits.

Section Q1.2: Tension and Sound Waves

In this chapter, we will focus primarily on one-dimensional waves that we can describe with a disturbance function $f(x,t)$ of position and time alone. **Tension waves** on a stretched string and **sound waves** in a tube are common and accessible examples of one-dimensional classical waves. A sound wave involves disturbances of the pressure and density of a gas away from the ambient atmospheric pressure and density.

Section Q1.3: The Superposition Principle

The **superposition principle** for waves states that

> If two traveling waves are moving through a given medium, the disturbance function $f(x,t)$ for the combined wave at any time t and any position x is simply the algebraic sum of the functions $f_1(x,t)$ and $f_2(x,t)$ that describe the individual waves: $f(x,t) = f_1(x,t) + f_2(x,t)$.

This is not always strictly true, but for almost all small-amplitude mechanical waves, it is an excellent approximation.

Section Q1.4: Reflection

When a medium's characteristics change significantly and suddenly at a certain **boundary,** waves will at least be partially reflected by that boundary. Waves are *completely* reflected at boundaries where their disturbance values are either *fixed* (for example, a string whose end is attached to a fixed point) or *free* (for example, a string whose end is allowed to move freely up and down). The wave reflected from a fixed boundary is *inverted,* but the wave reflected from a free end is *upright.* For sound waves in a tube, an opening in the tube acts as a fixed end on a string (because the air pressure at the opening is constrained to be the same as atmospheric pressure), while a closed end acts as the free end of a string does.

Section Q1.5: Standing Waves

Sinusoidal waves reflected from a boundary will interfere with incoming waves in such a way as to create a standing wave described by the disturbance function

$$f(x,t) = 2A \sin kx \cos \omega t \qquad \text{(Q1.9)}$$

Such a wave does not move, but amounts to a fixed sinusoidal disturbance $\sin kx$ whose overall amplitude oscillates with time. The disturbance is always zero at points where $\sin kx = 0$; we call such points **nodes** of the standing wave. The disturbance oscillates maximally at positions where $\sin kx = \pm 1$; we call such points **antinodes** of the standing wave.