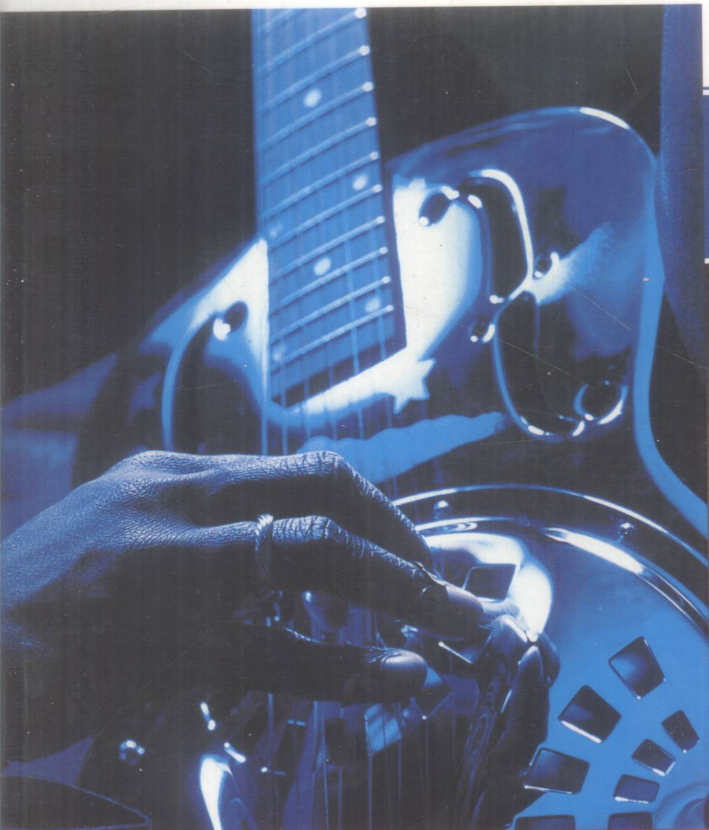
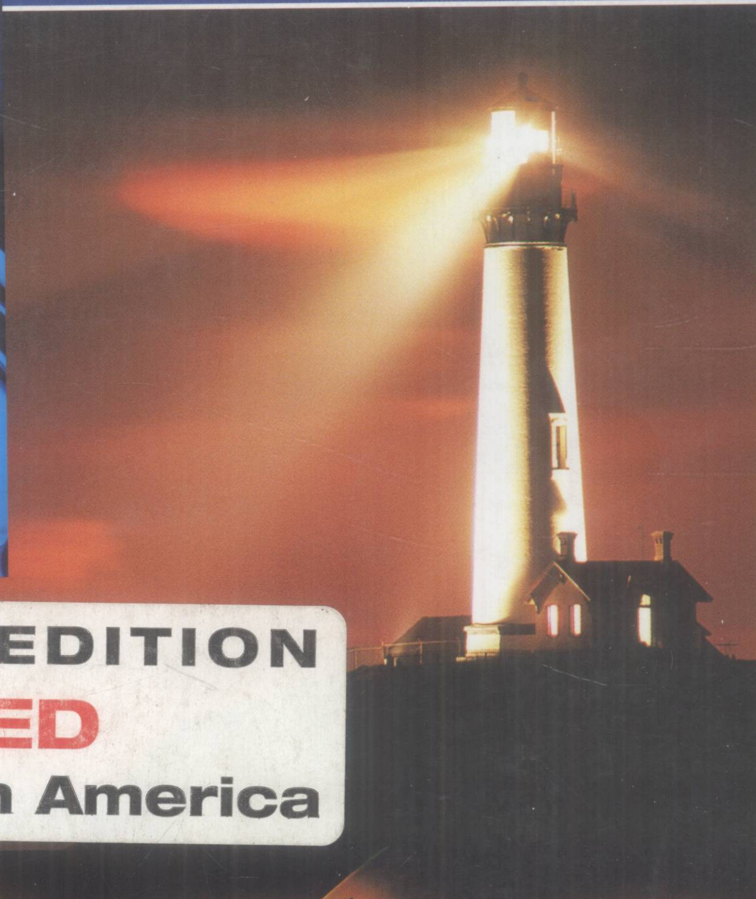
HOW THINGS WORK

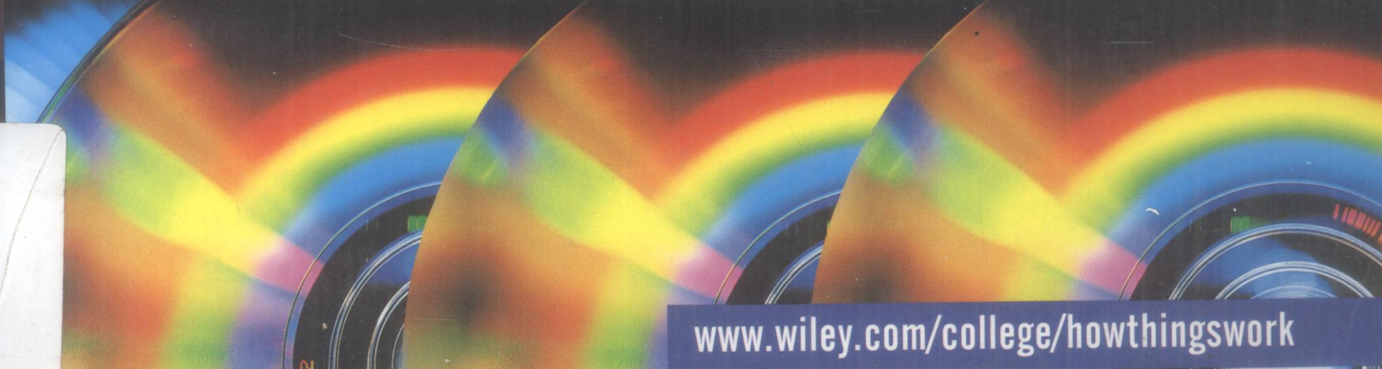
THE PHYSICS OF EVERYDAY LIFE



SECOND EDITION

LOUIS A. BLOOMFIELD





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how things work

THE PHYSICS OF EVERYDAY LIFE

SECOND EDITION

Louis A. Bloomfield

THE UNIVERSITY OF VIRGINIA

WILEY

John Wiley & Sons, Inc.

NEW YORK CHICHESTER WEINHEIM BRISBANE SINGAPORE TORONTO

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This book was set in Times Roman by PRD Group, Inc. and printed and bound by Von Hoffmann Press. The cover was printed by Von Hoffmann Press.

This book is printed on acid free paper. ∞

Library of Congress Cataloging in Publication Data

Bloomfield, Louis.

How things work: the physics of everyday life / Louis A. Bloomfield.—2nd ed.

p. cm.

Includes index.

ISBN 0-471-38151-9 (pbk. : alk. paper)

1. Physics. I. Title.

QC21.2.B59 2001

530—dc21 00-064917

ISBN 0-471-38151-9

Printed in the United States of America

10 9 8 7 5 4 3 2

how things work

To Karen, my dearest companion, whose wisdom, compassion, and love have sustained me in this adventure.

To our children, Elana and Aaron, who are growing up to be such wonderful people and such good friends.

And to the students of the University of Virginia, whose curiosity and enthusiasm make teaching fun.

Preface

This book offers a nonconventional view of physics and science that starts with whole objects and looks inside them to see what makes them work. It's written for liberal arts students who are seeking a connection between science and the world in which they live. While these students may be reluctant to study science as an intellectual exercise, they show remarkable enthusiasm for it when it appears in a useful context. Many of the 5000 students I've taught during the past nine years have been surprised at their own interest in the course, looking forward to classes, asking questions, experimenting on their own, and explaining to friends and family how things they use, and care about, work.

How Things Work brings science to the students rather than the reverse. Like the course on which it's based, this book has always been for nonscientists and is written with their interests in mind. Nonetheless, it has attracted students from the sciences, engineering, architecture, and other technical fields who wish to put familiar scientific concepts into context.

Most physics texts choose to develop the principles of physics first and to delay real-life examples of these principles until later. That teaching method provides few conceptual footholds for the students as they struggle to understand the principles. After all, the comforts of experience and intuition lie in the examples, not the principles. While a methodical and logical development of scientific principles can be satisfying to the seasoned physicist, it's alien to an individual who isn't even familiar with the language being used.

This book conveys an understanding and appreciation for physics by finding its concepts and principles within objects of everyday experience. Because its structure is defined by real-life examples, this book necessarily discusses various physical concepts as they're needed. These concepts are often revisited later on in other objects, thereby showing the universality of the natural laws.

Changes in the Second Edition

Design Changes

- **Color.** The transition to color gives this edition a much richer look and a more relaxed feel and makes the book's artwork far more clear and meaningful. In particular, the color of each vector in the line art indicates its type (e.g., a force, velocity, or acceleration), and pressures in the calculated drawings of fluid flow are indicated dramatically by color. Color also helps to clarify the book's structure and highlights its support features.
- **More open format.** The previous edition had large pages that were densely packed with text and illustrations. This edition follows a smaller and more open design, making the book easier to read and less imposing to the reader. Illustrations have been enlarged when necessary to make them clearer.
- **Linkage to the web.** Icons now direct the reader to the extensive supplementary materials available on the book's website.

Content Changes

- **Fewer, more focused presentations.** Like many texts, the previous edition tried to cover too much material and often overwhelmed both the students and the instructor. To alleviate this problem, a number of sections have been shifted to the web and the remaining sections have been carefully streamlined to make them more accessible to the reader. That streamlining was done with a scalpel, not an ax, and many of the sections were extensively rewritten in the process of giving them a sharper focus. Off-topic diversions have been reduced to a minimum, and the central theme of each section shines through more clearly than before.
- **Two opening chapters instead of one.** The previous edition packed too much into the four sections of the opening chapter. That material is now spread over six sections in two opening chapters, one primarily on translational motion and the other primarily on rotational method. In the process, two new topics have entered the book—skating and bumper cars.
- **Regrouping of sections.** With the streamlining of the book and the transfer of some topics to the web came the need to rethink the overall organization of the sections and their associated objects. In this edition, all of the sophisticated mechanical objects are grouped together in Chapter 3, thermal objects are in Chapter 6, objects involving resonance or mechanical waves are in Chapter 7, and objects involving modern physics are in Chapter 14.
- **Newtonian view of fluid flow.** The sections on fluid flow now treat the changes in pressure in a flowing fluid as the consequences of acceleration and flow deflection rather than the other way around (the Bernoullian view). This shift in emphasis makes the origins of lift and drag much more transparent and provides a stronger and more intuitive connection between fluid-based objects and the mechanical ones that precede them in the text.
- **Improved development of solid-state physics.** This edition consistently uses a theater analogy to aid the student's understanding of metals, insulators, semiconductors, and semiconductor devices.
- **Keeping up with new technology.** While physics at the introductory level changes fairly slowly, the objects that use physics change almost daily. This edition reflects those developments, particularly in the sections on television and optical recording and communication.
- **Fixes to conceptual flaws.** Trying to understand exactly how such a wide range of objects work is a daunting task, and I made a number of embarrassing mistakes in the previous edition. In the intervening four years, many readers have helped me learn what I did not know, and this book reflects my improved understanding of the objects and their physics.

Feature Changes

- **Rearrangement of support features.** To reduce the book's encyclopedic feel, all of the section ending features of the previous edition have been moved to the ends of chapters or to the web. This change allows the exercises and problems to be ordered by physics concept rather than by the section in which they appear. Moving the review questions and physics concept list to the web allows them to become interactive tools to help students assess their understanding and prepare for examinations.

- **Single glossary.** The glossary has been brought together at the end of the book, where it serves as a convenient reference for students who are struggling with the language of physics.

The Goals of This Book

As they read this book, students should:

1. **Begin to see science in everyday life.** This goal is the central focus of the book. Science is all around us; we only need to keep our eyes open to see it. We're surrounded by things that can be understood at various levels and it's within a student's reach to see science in each of those things. That doesn't mean that they should look at an oil painting and see only preferential absorption of incident light by organic and inorganic molecules. Rather, they should realize that there's a beauty to science that can supplement aesthetic beauty. They can learn to look at a glorious red sunset and appreciate both its appearance *and* why it exists.
2. **Learn that science isn't frightening.** The increased technological complexity of our world has done more than just stop people from looking for science in their environment. It has instilled within them a significant fear of science. One of the unintended consequences of modern technology is that few people tinker with anything anymore. Many devices are just disposable, being too complicated to modify or repair, and the resulting unfamiliarity breeds anxiety. To combat that anxiety, this book shows students that most objects can be examined and understood, and that the science behind them isn't so scary.
3. **Learn to think logically in order to solve problems.** Because the universe obeys a system of well-defined rules, it permits a logical understanding of its behaviors. Like mathematics and computer science, physics offers a field of study where logic reigns supreme. Having learned two or three simple rules, students can combine them logically to obtain more complicated rules and be certain that those new rules are true. So the study of physical systems is a good place to practice logical thinking.
4. **Develop and expand their physical intuition.** When you're exiting from a highway, you don't have to consider velocity, acceleration, and inertia to know that you should brake gradually—you already have physical intuition that tells you the consequences of doing otherwise. Such physical intuition is wonderfully useful in everyday life, but it takes time and experience to acquire. This book is intended to broaden a student's physical intuition to situations normally avoided and to ones never even encountered. That is, after all, one of the purposes of reading books and studying other people's scholarship: to learn from other people's experiences.
5. **Learn how things work.** This book is about objects from everyday life. Its sections deal with specific objects and with the mechanisms that permit those objects to work. As it explores the objects, it exposes bits and pieces of the overall physical laws that govern the universe. It approaches those laws as they were originally discovered: while trying to understand real objects. Although each of the objects in this book may only touch on one or two physical concepts, as a whole, this book presents many or most of the laws of

physics. Students should begin to see the similarities between objects, shared mechanisms, and recurring themes that are reused by nature or by people. This book tries to remind students of these connections and is ordered so that later objects build on their understanding of concepts encountered earlier.

6. **Begin to understand that the universe is predictable rather than magical.** One of the most fundamental principles of science, not described by equations or complex diagrams, is the notion that every effect has its cause. Things don't just occur willy-nilly. Whatever happens, we can look backward in time to find its real causes. We can also predict the future to some extent, based on insight acquired from the past and a knowledge of the present. What distinguishes the physical sciences and mathematics from other fields is that there are often absolute answers, free from inconsistency, contraindication, or paradox. Once students understand how the physical laws govern the universe, they can start to appreciate how orderly it is. They can replace a sense of magic at seeing a certain behavior with a sense of structure and understanding.
7. **Obtain a perspective on the history of science and technology.** None of the objects that this book examines appeared suddenly and spontaneously in the workshop of a single individual who was oblivious to what had been done before. These objects were developed in the context of history by people who were fairly aware of what they were doing and usually familiar with any similar objects that already existed. Nearly everything is discovered or developed when related activities make their discoveries or developments inevitable and timely. To establish that historical context, this book describes some of the history behind the objects it discusses.

Artwork

Because this book is about real things, its illustrations and photographs are about real things, too. Whenever possible, artwork is built around familiar objects so that the concepts the artwork is meant to convey become associated with objects students already know. Many students are visual learners—if they see it, they can learn it. By superimposing the abstract concepts of physics onto simple realistic artwork, this book attempts to connect physics with everyday life. That idea is particularly evident at the opening of each section, where the object examined in that section appears in a carefully rendered drawing. This drawing provides students with something concrete to keep in mind as they encounter the more abstract physical concepts that appear in that section. By lowering the boundaries between what the students see in the book and what they see in their environment, the artwork of this book makes science a part of their world.

Features

This printed book contains 40 sections, each of which discusses how something works. The sections are grouped together in 14 chapters according to the major physical themes developed. In addition to the discussion itself, the sections and chapters include a number of features intended to strengthen the educational value of this book. Among these features are:

- **Chapter introductions, experiments, and itineraries.** Each of the 14 chapters begins with a brief introduction to the principal theme underlying that chapter. It then presents an experiment that students can do with household items to observe firsthand some of the issues associated with that physical theme. Lastly, it presents a general itinerary for the chapter, identifying some of the physical issues that will come up as the objects in the chapter are discussed.
- **Section introductions, questions, and experiments**. Each of the 40 sections explains how something works. Often that something is a specific object or group of objects, but it can be more general. A section begins by introducing the object and then asks a number of questions about it, questions that might occur to students as they think about the object and that are answered by the section. Lastly, it suggests some simple experiments that students can do to observe some of the physical concepts that are involved in the object.
- **Check your understanding and check your figures.** Sections are divided into a number of brief segments, each of which ends with a "Check Your Understanding" question. These questions apply the physics of the preceding segment to new situations and are answered and explained in the summary material at the end of this chapter. Segments that introduce important equations also end with a "Check Your Figures" question. These questions show how the equations can be applied and are also answered and explained in the summary material.
- **Chapter epilogue and explanation of experiment.** Each chapter ends with an epilogue that reminds the students of how the objects they studied in that chapter fit within the chapter's physical theme. Following the epilogue is a brief explanation of the experiment suggested at the beginning of the chapter, using physical concepts that were developed in the intervening sections.
- **Chapter summary and laws and equations.** The sections covered in each chapter are summarized briefly at the end of the chapter, with an emphasis on how the objects work. These summaries are followed by a restatement of the important physical laws and equations encountered within the chapter.
- **Chapter exercises and problems.** Following the chapter summary material is a collection of questions dealing with the physics concepts in that chapter. Exercises ask the students to apply those concepts to new situations. Problems ask the students to apply the equations in that chapter and to obtain quantitative results.
- **Chapter cases.** The final items in each chapter are cases, extended exercises that apply the physical concepts from that chapter and sometimes previous chapters to new circumstances. Each case asks a series of questions and leads the students through an examination of the physical principles involved in a new object or situation. Quantitative questions are marked with an asterisk (*). In addition to tying the chapters together, these cases introduce many interesting objects, worthy of sections of their own. By studying these cases, students learn to explain how new objects work.
- **Three-way approach to the equation of physics.** The laws and equations of physics are the groundwork on which everything else is built. But because each student responds differently to the equations, this book presents them carefully and in context. Rather than making one size fit all, these equations are presented in three different forms. The first is a word equation, identifying each physical quantity by name to avoid any ambiguities. The second is a symbolic equation, using the standard format and notation. The third is a sentence that conveys the meaning of the equation in simple terms and often by example. Each student is likely to find one of these three forms more comfortable, meaningful, and memorable than the others.

- **Glossary.** The key physics terms are assembled into a glossary at the end of the book. Each glossary term is also marked in bold in the text when it first appears together with its contextual definition.
- **Historical, technical, and biographical asides.** To show how issues discussed in this book fit into the real world of people, places, and things, a number of brief asides have been placed in the margins of the text. An appropriate time at which to read a particular aside is marked in the text by a ❑.

Organization

The 40 sections that make up this book are ordered so that they follow a familiar path through physics: mechanics, heat, resonance and waves, electricity and magnetism, light and optics, and modern physics. Because there are too many topics here to cover in a single semester, the book is designed to allow shortcuts through the material. In general, the final sections in each chapter and the final chapters in each of the main groups mentioned above can be omitted without serious impact on the material that follows. The only exceptions to that rule are the first two chapters, which should be covered in their entirety as the introduction to any course taught from this book. The book also divides neatly in half so that it can be used for two independent one-semester courses—the first covering Chapters 1–7 and the second covering Chapters 1, 2, and 8–14. A detailed guide to shortcuts appears in the Instructor's Manual.

Student Website

This book is supported by an ever-increasing array of web-based student supplements. Starting from the book's student entry URL,

www.wiley.com/college/howthingswork

a student has free access to resources that include:

- **Review questions and physics concept summaries.** Tied to each of the book's 40 sections are a collection of review questions and a list of the important physical and scientific concepts covered in those sections. Answers are available for the review questions so that students can see if they understand the material.
- **Additional material for each section.** Many of the subjects discussed in this book have so many interesting facets that they could serve as the bases for hundred-page dissertations. However, to keep the printed sections at a reasonable length, some of their content has been placed on the web. When the icon appears next to a paragraph, additional discussion of the current topic can be found on the web. When the appears at the end of a section, additional topics associated with that section are available on the web. Simply go to the student web page and enter the keyword or phrase accompanying the icon.
- **Additional exercises, problems, and cases.** These questions provide alternatives to those that appear in the printed book.
- **Additional sections and chapters.** More than 20 complete sections are available online to supplement the 40 that appear in this book. These include several special opening sections that can be used to get the course off to an exciting start.
- **Links to related websites for each section.**

Instructor Website and Instructor's Manual

The instructor's website, located at URL

www.wiley.com/college/ howthingswork/instructor

provides everything described above, plus access to:

- **Additional homework questions and solutions**
- **Test questions and solutions**
- **Organizational ideas for designing a course**
- **Demonstration ideas for each section**
- **Lecture slides for each section**
- **Artwork to use in presentations**
- **Resource lists**

Many of these items also appear in printed form in the Instructor's Manual.

Acknowledgments

There are a great many people who have contributed to this second edition and to whom I am enormously grateful. First among them is my editor, Stuart Johnson, whose enthusiasm for this project has kept things moving forward all these years. It has also been a pleasure working with Anne Smith, Deanna Campbell, and Tom Hempsted during the development process and with Barbara Russiello during production. Harry Nolan has orchestrated a beautiful design for the book, Hilary Newman has been wonderful at finding interesting photographs, Sigmund Malinowski has done a terrific job coordinating the development of the line art, Geraldine Osnato has been very helpful at finding existing line art, and Christina della Bartolomea has done a spectacular job of line editing the manuscript. Thanks to Bob Smith and Sue Lyons for helping learn what instructors and students want from this book and to Mark Gerber for helping plan the website for this book. I also appreciate the continued interest and support from *How Things Work* veterans Barbara Heaney and Maddy Lesure.

I continue to enjoy tremendous assistance from colleagues here and elsewhere who have supported the *How Things Work* concept and have often taught the course themselves. These people include Rob Watkins, Mike Noel, Bascom Deaver, Vittorio Celli, and Michael Fowler at the University of Virginia, John Krupczak at Hope College, Laura Lising at NIST, William McNairy at Duke University, Martin Mason at College of the Desert, Robert Reynolds at Reed College, Maarten Rutgers at Ohio State University, Richard Superfine at the University of North Carolina at Chapel Hill, and Robert Welsh at College of William and Mary.

Because this book is about real objects, the course I teach from it is enriched by countless demonstrations. I couldn't have done those demonstrations, nor taken many of the photographs for this book, without the vast experience and enormous enthusiasm of Mike Timmins, John Malone, and Roger Staton. Together with several talented student assistants, they make as fine a lecture-demonstration group as one could ever want.

I am also extremely grateful to the students of the University of Virginia for being so eager and interested, and also so tolerant of my endless experimenting with the content and delivery of the course. Many students have contributed directly or indirectly to the book itself and are now too numerous to name individually. To all of you who have talked to me or written to me about the course, voiced your concerns, ideas, and observations, and urged me onward, my sincerest thanks.

Thanks also to my family, Karen, Elana, and Aaron Bloomfield, for helping me with everything from editing sections of text to photographing whirling wineglasses.

Lastly, this book has benefited more than most from the constructive criticism of a number of talented reviewers. In addition to getting a better sense of how to present the material in this book, I have learned a great deal of physics from their reviews. My deepest thanks to all of these fine people:

Charles Ardary
Edmonds Community College

Ali Badakhshan
University of Northern Iowa

Keith Bonin
Wak Forest University

Edward R. Borchardt
Mankato State University

Robert Boughton
Bowling Green State University

Arthur J. Braundmeier
Southern Illinois University

David Buckley
East Stroudsburg University

Neal Cason
University of Notre Dame

Joshua Cohn
University of Miami

James J. Donaghy
Washington & Lee University

Gordon Donaldson
University of Strathclyde, Scotland

Sherman Frye
Northern Virginia Community College

Bob Hallock
University of Massachusetts—Amherst

Glenn M. Julian
Miami University

Mary Lu Larsen
Towson State University

David Markowitz
University of Connecticut

Martin Mason
College of the Desert

David C. McKenna
Rensselaer Polytechnic Institute

William McNairy
Virginia Military Institute

Jon Nadler
Richland Community College

Adam Niculescu
Virginia Commonwealth University

David Raffaelle
Glendale Community College

John C. Raich
Colorado State University

Paul Schuyler
Spokane Community College

Romeo A. Segnan
American University

Peter Sheldon
Randolph-Macon Woman's College

Stanley J. Sobolewski
Indiana University of Pennsylvania

Robert Tremblay
Southern Connecticut State University

Tim Usher
California State University—San Bernardino

Terrance Vacha
Cuyahoga Community College

David Wagner
Edinboro University of Pennsylvania

Bob Welsh
The College of William and Mary

John Yelton
University of Florida

I have always felt that the real test of this book, and of any course taught from it, is its impact on students' lives long after final grades have been recorded. It is my sincere hope that many of these students will find themselves looking at objects in the world around them years later with understanding and insight that they would not have had were it not for their encounter with this book.

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Contents

*All entries in blue are found on the web, www.wiley.com/college/howthingswork, and are accessed by entering the key words at right.