HOW THINGS WORK

THE PHYSICS OF EVERYDAY LIFE

SIXTH EDITION

LOUIS A. BLOOMFIELD

WILEY

6TH EDITION

How Things Work

THE PHYSICS OF EVERYDAY LIFE

Louis A. Bloomfield

The University of Virginia

WILEY

To Karen for being such a wonderful friend and companion,

to Aaron, Elana, and Rich for being everything a father could want,

to Max and Rosie for being so cheerful and attentive,

and to the students of the University of Virginia for making teaching, research, and writing fun.

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This book was set in 10/12 Times Roman by Aptara Corporation. Book and cover were printed and bound by Quad Graphics/Versailles.

The book is printed on acid-free paper.

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Library of Congress Cataloging-in-Publication Data

Names: Bloomfield, Louis, author.
Title: How things work : the physics of everyday life / Louis A. Bloomfield,
The University of Virginia.
Description: Sixth edition. | Hoboken, NJ : John Wiley & Sons, Inc., [2015] |
?2016 | Includes index.
Identifiers: LCCN 2015033708| ISBN 9781119013846 (loose-leaf : alk. paper) |
ISBN 1119013844 (loose-leaf: alk. paper)
Subjects: LCSH: Physics—Textbooks.
Classification: LCC QC21.3 .B56 2015 | DDC 530—dc23 LC record available at http://lccn.loc.gov/2015033708

ISBN 978-1119-01384-6 (Binder Version)

The inside back cover will contain printing identification and country of origin if omitted from this page. In addition, if the ISBN on the back cover differs from the ISBN on this page, the one on the back cover is correct.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Foreword

In today's world we are surrounded by science and by the technology that has grown out of that science. For most of us, this is making the world increasingly mysterious and somewhat ominous as technology becomes ever more powerful. For instance, we are confronted by many global environmental questions such as the dangers of greenhouse gases and the best choices of energy sources. These are questions that are fundamentally technical in nature and there is a bewildering variety of claims and counterclaims as to what is "the truth" on these and similar important scientific issues. For many people, the reaction is to throw up their hands in hopeless frustration and accept that the modern world is impossible to understand and one can only huddle in helpless ignorance at the mercy of its mysterious and inexplicable behavior.

In fact, much of the world around us and the technology of our everyday lives is governed by a few basic physics principles, and once these principles are understood, the world and the vast array of technology in our lives become understandable and predictable. How does your microwave oven heat up food? Why is your radio reception bad in some places and not others? And why can birds happily land on a high-voltage electrical wire? The answers to questions like these are obvious once you know the relevant physics. Unfortunately, you are not likely to learn that from a standard physics course or physics textbook. There is a large body of research showing that, instead of providing this improved understanding of everyday life, most introductory physics courses are doing quite the opposite. In spite of the best intentions of the teachers, most students are "learning" that physics is abstract, uninteresting, and unrelated to the world around them.

How Things Work is a dramatic step toward changing that by presenting physics in a new way. Instead of starting out with abstract principles that leave the reader with the idea that physics is about artificial and uninteresting ideas, Lou Bloomfield starts out talking about real objects and devices that we encounter in our everyday lives. He then shows how these seemingly magical devices can be understood in terms of the basic physics principles that govern their behavior. This is much the way that most physics was discovered in the first place: people asked why the world around them behaved as it did and as a result discovered the principles that explained and predicted what they observed.

I have been using this book in my classes for several years, and I continue to be impressed with how Lou can take seemingly highly complex devices and strip away the complexity to show how at their heart are simple physics ideas. Once these ideas are understood, they can be used to understand the behavior of many devices we encounter in our daily lives, and often even fix things that before had seemed impossibly complex. In the process of teaching from this book, I have increased my own understanding of the physics behind much of the world around me. In fact, after consulting *How Things Work*, I have had the confidence to confront both plumbers and airconditioner repairmen to tell them (correctly as it turned out) that their diagnosis did not make sense and they needed to do something different to solve my plumbing and AC problems. Now I am regularly amused at the misconceptions some trained physicists have about some of the physics they encounter in their daily lives, such as how a microwave oven works and why it can be made out of metal walls, but putting aluminum foil in it is bad. It has convinced me that we need to take the approach used in this book in far more of our science texts.

Of course, the most important impact is on the students in my classes that use this book. These are typically nonscience students majoring in fields such as film studies, classics, English, business, etc. They often come to physics with considerable trepidation. It is inspiring to see many of them discover to their surprise that physics is very different from what they thought—that physics can actually be interesting and useful and makes the world a much less mysterious and more understandable place. I remember many examples of seeing this in action: the student who, after learning how both speakers and TVs work, was suddenly able to understand that it was not magic that putting his large speaker next to the TV distorted the picture but in fact it was just physics, and now he knew just how to fix it; the young woman scuba diver who, after learning about light and color, suddenly interrupted class to announce that now she understood why it was that you could tell how deep you were by seeing what color lobsters appeared; or the students who announced that suddenly it made sense that the showers on the first floor of the dorm worked better than those on the second floor. In addition, of course everyone is excited to learn how a microwave oven works and why there are these strange rules as to what you can and cannot put in it.

These examples are particularly inspiring to a teacher, because they tell you that the students are not just learning the material presented in class but they are then able to apply that understanding to new situations in a useful way, something that happens far too seldom in science courses.

Whether a curious layperson, a trained physicist, or a beginning physics student, most everyone will find this book an interesting and enlightening read and will go away comforted in that the world is not so strange and inexplicable after all.

Carl Wieman
Nobel Laureate in Physics 2001
CASE/Carnegie US University Professor

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Preface

Physics is a remarkably practical science. Not only does it explain how things work or why they don't, it also offers great insight into how to create, improve, and repair those things. Because of that fundamental relationship between physics and real objects, introductory physics books are essentially users' manuals for the world in which we live.

Like users' manuals, however, introductory physics books are most accessible when they're based on real-world examples. Both users' manuals and physics texts tend to go unread when they're written like reference works, organized by abstract technical issues, indifferent to relevance, and lacking in useful examples. For practical guidance, most readers turn to "how to" books and tutorials instead; they prefer the "case-study" approach.

How Things Work is an introduction to physics and science that starts with whole objects and looks inside them to see what makes them work. It follows the case-study method, exploring physics concepts on a need-to-know basis in the context of everyday objects. More than just an academic volume, this book is intended to be interesting, relevant, and useful to non-science students.

Most physics texts develop the principles of physics first and present real-life examples of these principles reluctantly if at all. That approach is abstract and inaccessible, providing few conceptual footholds for students as they struggle to understand unfamiliar principles. After all, the comforts of experience and intuition lie in the examples, not in the principles. While a methodical and logical development of scientific principles can be satisfying to the seasoned scientist, it's alien to someone who doesn't even recognize the language being used.

In contrast, *How Things Work* brings science to the reader rather than the reverse. It conveys an understanding and appreciation for physics by finding physics concepts and principles within the familiar objects of everyday experience. Because its structure is defined by real-life examples, this book necessarily discusses concepts as they're needed and then revisits them whenever they reappear in other objects. What better way is there to show the universality of the natural laws?

I wrote this book to be read, not merely referred to. It has always been for nonscientists and I designed it with them in mind. In the seventeen years I have been teaching *How Things Work*, many of my thousands of students have been surprised at their own interest in the physics of everyday life, have asked insightful questions, have experimented on their own, and have found themselves explaining to friends and family how things in their world work.

Changes in the Sixth Edition

Content Changes

- **Video figures.** If a picture is worth a thousand words, a video is worth a thousand pictures. That's particularly true for this book because so much of physics is about how things evolve with time. Most students consider themselves visual learners—they need to see what happens in order to understand it. Given that requirement, still images are so 20th century.

  In this edition, I have replaced many of the static figures with video figures, using the tools of modern 3D animation and video editing. In print, those video figures are distilled into motionless images but online, they move and talk. Whenever possible and practical, the video figures are quantitatively accurate in both time and space. They're not just cartoons; they're careful models of the real world.

- **Rewriting and editing.** Despite teaching How Things Work for almost 25 years, I am still learning how to explain the physics of everyday life. I continue to discover clearer approaches, better analogies, and more effective techniques for conveying understanding and avoiding misconceptions. For this edition, I have examined every word of the book, editing and rewriting it to make sure that it is doing the best job possible.

- **Improved discussions of many physics concepts.** No one book can or should cover all of physics, but whatever physics is included should be presented carefully enough to be worthwhile. In this edition, I have refined the discussions of many physics issues and added some new ones. Look for improved coverage of concepts such as orbits, magnetic induction, and antennas, to name just a few.

The Goals of This Book

As they read this book, students should:

1. Begin to see science in everyday life. Science is everywhere; we need only open our eyes to see it. We're surrounded by things that can be understood in terms of science, much of which is within a student's reach. Seeing science doesn't mean that when viewing an oil painting they should note only the selective reflection of incident light waves by organic and inorganic molecules. Rather, they should realize that there's a beauty to science that complements 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 increasing technological complexity of our world has instilled within most people a significant fear of science. As the gulf widens between those who create technology and those who use it, their ability to understand one another and communicate diminishes. The average person no longer tinkers with anything and many modern devices are simply disposable, being too complicated to modify or repair. To combat the anxiety that accompanies unfamiliarity, this book shows students that most objects can be examined and understood, and that the science behind them isn't scary after all. The more we understand how others think, the better off we'll all be.

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 is a field of study where logic reigns supreme. Having learned a handful of 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 essential in everyday life, but it ordinarily takes time and experience to acquire. This book aims to broaden a student's physical intuition to situations they normally avoidor have yet to encounter. That is, after all, one of the purposes of reading and scholarship: to learn from other people's experiences.

5. Learn how things work. As this book explores the objects of everyday life, it gradually uncovers most of the physical laws that govern the universe. It reveals those laws as they were originally discovered: while trying to understand real objects. As they read this book and learn these laws, students should begin to see the similarities between objects, shared mechanisms, and recurring themes that are reused by nature or by people. This book reminds 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 foundations of science is that effects have causes and don't simply occur willy-nilly. Whatever happens, we can look backward in time to find what caused it. We can also predict the future to some extent, based on insight acquired from the past and on knowledge of the present. And where predictability is limited, we can understand those limitations. 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 that perhaps the most magical aspect of our universe is that it is not magic; that it is orderly, structured, and understandable.

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 generally 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.

Visual Media

Because this book is about real things, its videos, illustrations, and photographs are about real things, too. Whenever possible, these visual materials are built around familiar objects so that the concepts they are 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 visuals, 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 rich visual media associated with 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 15 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 15 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 is sometimes 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 followed by answers and explanations. 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 followed by answers and explanations.
- **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.
- **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 color-coded mark such as ■.

Organization

The 40 sections that make up this book are ordered so that they follow a familiar path through physics: mechanics, heat and thermodynamics, resonance and mechanical waves, electricity and magnetism, light, optics, and electronics, 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 1–9 and the second covering Chapters 1, 2, and 10–15. That two-course approach is the one I use myself. A detailed guide to shortcuts appears on the instructor's website.

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- **Online book with extensive video figures and annotation.** Although this book aims to be complete and self-contained, its pages can certainly benefit from additional explanations, answers to open questions, discussions of figures and equations, and real-life demonstrations of objects, ideas, and concepts. Using the web, I can provide all of those features. The online version of this book is annotated with hundreds, even thousands of short videos that bring it to life and enhance its ability to teach.
- **Computer simulations of the book's objects.** One of the best ways to learn how a violin or nuclear reactor works is to experiment with it, but that's not always practical or safe. Computer simulations are the next best thing and the student website includes many simulations of the book's objects. Associated with each simulation is a sequence of interactive questions that turn it into a virtual laboratory experiment. In keeping with the *How Things Work* concept, the student is then able to explore the concepts of physics in the context of everyday objects themselves.
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Acknowledgments

Many people have contributed to this book in one way or another and I am enormously grateful for their help. First among them are my editors, Jessica Fiorillo and Stuart Johnson, who together have guided this project and supported me for twenty years. Jennifer Yee has been amazingly generous with her time and attention in helping me develop this sixth edition, and Sandra Dumas and Jackie Henry have done a fantastic job of shepherding it through production. I'm delighted to have had Thomas Nery working on the graphic design, and Billy Ray working on the photographs. The online component that accompanies the print book would not have been possible or even conceivable without the help of John Duval and Mallory Fryc. And none of this could have happened without the support, guidance, and encouragement of Christine Kushner, Geraldine Osnato, and Petra Recter. To my numerous other friends and collaborators at John Wiley, many thanks.

I continue to enjoy tremendous assistance from colleagues here and elsewhere who have supported the How Things Work concept, discussed it with me, and often taught the course themselves. They are now too many to list, but I appreciate them all. I am particularly grateful, however, to my colleagues in AMO physics at Virginia, Tom Gallagher, Bob Jones, Olivier Pfister, and Cass Sackett, for more than making up for my reduced scientific accomplishments while working on this project, and to Carl Weiman for his vision of physics education as outlined in the foreword to this book. I must also thank our talented lecture-demonstration group, Al Tobias, Max Bychkov, Mike Timmins, Nikolay Sandev, and Roger Staton, for help to bring physics to life in my class and in the videos for this book.

Of course, the best way to discover how students learn science is to teach it. I am ever so grateful to the students of the University of Virginia for being such eager, enthusiastic, and interactive participants in this long educational experiment. It has been a delight and a privilege to get to know so many of them as individuals and their influence on this enterprise has been immeasurable.

Lastly, this book has benefited more than most from the constructive criticism of a number of talented reviewers. Their candid, insightful comments were sometimes painful to read or hear, but they invariably improved the book. Not only did their reviews help me to present the material more effectively, but they taught me some interesting physics as well. My deepest thanks to all of these fine people:

Brian DeMarco,
University of Illinois, Urbana Champaign

Dennis Duke,
Florida State University

Donald R. Francesschetti,
University of Memphis

Alejandro Garcia,
San Jose State University

Richard Gelderman,
Western Kentucky University

Robert B. Hallock,
University of Massachusetts, Amherst

Mark James,
Northern Arizona University

Tim Kidd,
University of Northern Iowa

Judah Levine,
University of Colorado, Boulder

Darryl J. Ozimek,
Duquesne University

Michael Roth,
University of Northern Iowa

Anna Solomey,
Wichita State University

Bonnie Wylo,
Eastern Michigan University

The real test of this book, and of any course taught from it, is its impact on students' lives long after their classroom days are done. Theirs' is a time both exciting and perilous; one in which physics will play an increasingly important and multifaceted role. It is my sincere hope that their encounter with this book will leave those students better prepared for what lies ahead and will help them make the world a better place in the years to come.

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1

The Laws of Motion

PART 1

The aim of this book is to broaden your perspectives on familiar objects and situations by helping you understand the science that makes them work. Instead of ignoring that science or taking it for granted, we'll seek it out in the world around us, in the objects we encounter every day. As we do so, we'll discover that seemingly "magical" objects and effects are quite understandable once we know a few of the physical concepts that make them possible. In short, we'll learn about *physics*—the study of the material world and the rules that govern its behavior.

To help us get started, this first pair of chapters will do two main things: introduce the language of physics, which we'll be using throughout the book, and present the basic laws of motion on which everything else will rest. In later chapters, we'll examine objects that are interesting and important, both in their own right and because of the scientific issues they raise. Most of these objects, as we'll see, involve many different aspects of physics and thus bring variety to each section and chapter. These first two chapters are special, though, because they must provide an orderly introduction to the discipline of physics itself.

ACTIVE LEARNING EXPERIMENTS

Removing a Tablecloth from a Table

One famous "magical" effect allows a tablecloth to be removed from a set table without breaking the dishes. The person performing this stunt pulls the tablecloth sideways in one lightning-fast motion. The smooth, slippery tablecloth slides out from under the dishes, leaving them behind and nearly unaffected.

With some practice, you too can do this stunt. Choose a slick, unhemmed tablecloth, one with no flaws that might catch on the dishes. A supple fabric such as silk helps because you can then pull the cloth slightly downward at the edge of the table. When you get up the nerve to try—with unbreakable dishes, of course—make sure that you pull suddenly and swiftly, so as to minimize the time it takes for the cloth to slide out from under the dishes. Leaving a little slack in the cloth at first helps you get your hands up to speed before the cloth snaps taut and begins to slide off the table. Don't make the mistake of starting slowly or you'll decorate the floor.

Courtesy Lou Bloomfield

Give the tablecloth a yank and watch what happens. With luck, the table will remain set. If it doesn't, try again, but this time go faster or change the types of dishes or the way you pull the cloth.

If you don't have a suitable tablecloth, or any dishes you care to risk, there are many similar experiments you can try. Put several coins on a sheet of paper and whisk that sheet out from under them. Or stack several books on a table and use a stiff ruler to knock out the bottom one. Especially impressive is balancing a short eraserless pencil on top of a wooden embroidery hoop that is itself balanced on the open mouth of a glass bottle. If you yank the ring away quickly enough, the pencil will be left behind and will drop right into the bottle.

The purpose of this experiment is addressed in a simple question: Why do the dishes stay put as you remove the tablecloth? We'll return to that question at the end of this chapter. In the meantime, we'll explore some of the physics concepts that allow us to answer it.

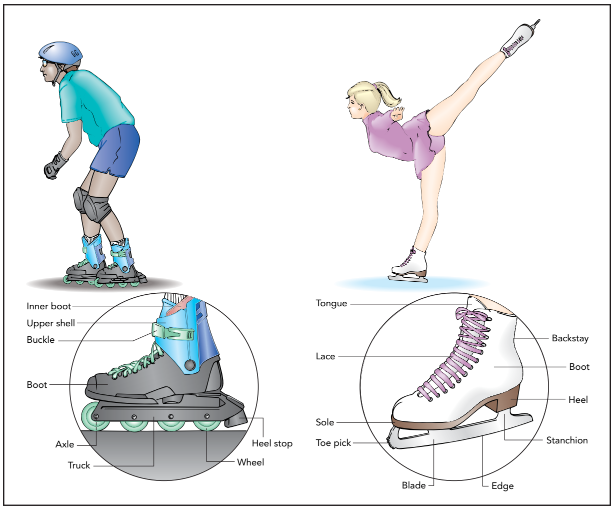
Chapter Itinerary

To examine these concepts, we'll look carefully at three kinds of everyday activities and objects: (1) *skating*, (2) *falling balls*, and (3) *ramps*. In Skating, we see how objects move when nothing pushes on them. In Falling Balls, we find out how that movement can be influenced by gravity. In Ramps, we explore mechanical advantage and how gradual inclines make it possible to lift heavy objects without pushing very hard. For a more complete preview of what we examine in this chapter, flip ahead to the Chapter Summary and Important Laws and Equations at the end of the chapter.

These activities may seem mundane, but understanding them in terms of basic physical laws requires considerable thought. These two introductory chapters will be like climbing up the edge of a high plateau: the ascent won't be easy, and our destination will be hidden from view. However, once we arrive at the top, with the language and basic concepts of physics in place, we'll be able to explain a broad variety of objects with only a small amount of additional effort. And so we begin the ascent.

SECTION 1.1

Skating



Like many sports, skating is trickier than it appears. If you're a first-time skater, you're likely to find yourself getting up repeatedly from the ground or ice, and it will take some practice before you can glide smoothly forward or come gracefully to a stop. But whether you're wearing ice skates or roller skates, the physics of your motion is surprisingly simple. When you're on a level surface with your skates pointing forward, you coast!

Coasting is one of the most basic concepts in physics and our starting point in this book. Joining it in this section will be starting, stopping, and turning, which together will help us understand the first few laws of motion. We'll leave sloping surfaces for the section on ramps and won't have time to teach you how to do spins or win a race. Nonetheless, our exploration of skating will get us well on the way to an understanding of the fundamental principles that govern all movement and thereby prepare us for many of the objects we'll examine in the rest of this book.

Questions to Think About: What do we mean by "movement"? What makes skaters move, and once they're moving, what keeps them in motion? What does it take to stop a moving skater or turn that skater in another direction?

Experiments to Do: A visit to the ice or roller rink would be ideal, but even a skateboard or a chair with wheels will suffice. Get yourself moving forward on a level surface and then let yourself coast. Why do you keep moving? Is anything pushing you forward? Does your direction ever reverse as you coast? How could you describe the details of your motion to someone on your cell phone? How would you measure your speed?

Before you run into a wall or tree, slow yourself to a stop. What was it that slowed you down? Were you still coasting as you stopped? Did anything push on you as you slowed yourself?

Get yourself moving again. What caused you to speed up? How quickly can you pick up speed, and what do you do differently to speed up quickly? Now turn to one side or the other. Did anything push on you as you turned? What happened to your speed? What happened to your direction of travel?

Gliding Forward: Inertia and Coasting

While you're putting on your skates, let's take a moment to think about what happens to a person who has nothing pushing on her at all. When she's completely free of outside influences (Fig. 1.1.1), free of pushes and pulls, does she stand still? Does she move? Does she speed up? Does she slow down? In short, what does she do?

The correct answer to that apparently simple question eluded people for thousands of years; even Aristotle, perhaps the most learned philosopher of the classical world, was mistaken about it (see 1). What makes this question so tricky is that objects on Earth are never truly free of outside influences; instead, they all push on, rub against, or interact with one another in some way.

As a result, it took the remarkable Italian astronomer, mathematician, and physicist Galileo Galilei many years of careful observation and logical analysis to answer that question 2. The solution he came up with, like the question itself, is simple: if the person is stationary, she will remain stationary; if she is moving in some particular direction, she will continue moving in that direction at a steady pace, following a straight-line path. This property of steady motion in the absence of any outside influence is called **inertia** (Fig 1.1.2).

INERTIA

A body in motion tends to remain in motion; a body at rest tends to remain at rest.

The main reason that Aristotle failed to discover inertia, and why we often overlook inertia ourselves, is friction. When you slide across the floor in your shoes, friction quickly slows you to a stop and masks your inertia. To make inertia more obvious, we must get rid of friction. That's why you're wearing skates.

Skates almost completely eliminate friction, at least in one direction, so that you can glide effortlessly across the ice or roller rink and experience your own inertia. For simplicity, imagine that your skates are perfect and experience no friction at all as you glide. Also, for this and the next couple of sections, let's forget not only about friction but also about air resistance. Since the air is calm and you're not moving too fast, air resistance isn't all that important to skating anyway.

Now that you're ready to skate, we'll begin to examine five important physical quantities relating to motion and look at their relationships to one another. These quantities are position, velocity, mass, acceleration, and force.

Let's start by describing where you are. At any particular moment, you're located at a **position**—that is, at a specific point in space. Whenever we report your position, it's always as a **distance** and **direction** from some reference point, how many meters north of the refreshment stand or how many kilometers west of Cleveland. For our discussion of skating, we'll choose as our reference point the bench you used while putting on your skates.

Position is an example of a vector quantity. A **vector quantity** consists of both a magnitude and a direction; the **magnitude** tells you how much of the quantity there is, while the direction tells you which way the quantity is pointing. Vector quantities are common in nature. When you encounter one, pay attention to the direction part; if you're looking for buried treasure 30 paces from the old tree but forget that it's due east of that tree, you'll have a lot of digging ahead of you.

You're on your feet and beginning to skate. Once you're moving, your position is changing, which brings us to our second vector quantity—velocity. **Velocity** measures the

Courtesy of Lou Bloomfield

Fig. 1.1.1 This skater glides without any horizontal influences. If she's stationary, she'll tend to remain stationary; if she's moving, she'll tend to continue moving.

1 Aristotle (Greek philosopher, 384–322 BC) theorized that objects' velocities were proportional to the forces exerted on them. While this theory correctly predicted the behavior of a sliding object, it incorrectly predicted that heavier objects should fall faster than lighter objects. Nonetheless, Aristotle's theory was respected for a long time, in part because finding the simpler and more complete theory was hard and in part because the scientific method of relating theory and observation took time to develop.

2 While a professor in Pisa, Galileo Galilei (Italian scientist, 1564–1642) was obliged to teach the natural philosophy of Aristotle. Troubled with the conflict between Aristotle's theory and observations of the world around him, Galileo devised experiments that measured the speeds at which objects fall and determined that all falling objects fall at the same rate.

rate at which your position is changing with time. Its magnitude is your **speed**, the distance you travel in a certain amount of time,

$$\text{speed} = \frac{\text{distance}}{\text{time}},$$

and its direction is the direction in which you're heading.

For example, if you move 2 meters (6.6 feet) west in 1 second, then your velocity is 2 meters per second (6.6 feet per second) toward the west. If you maintain that velocity, your position moves 20 meters west in 10 seconds, 200 meters west in 100 seconds, and so on. Even when you're motionless, you still have a velocity—zero. A velocity of zero is special, however, because it has no direction.

When you're gliding freely, however, with nothing pushing you horizontally, your velocity is particularly easy to describe. Since you travel at a steady speed along a straight-line path, your velocity is constant—it never changes. In a word, you **coast**. And if you happen to be at rest with nothing pushing you horizontally, you remain at rest. Your velocity is constantly zero.

Thanks to your skates, we can now restate the previous description of inertia in terms of velocity: an object that is not subject to any outside influences moves at a constant velocity, covering equal distances in equal times along a straight-line path. This statement is frequently identified as **Newton's first law of motion**, after its discoverer, the English mathematician and physicist Sir Isaac Newton [3]. The outside influences referred to in this law are called **forces**, a technical term for pushes and pulls. An object that moves in accordance with Newton's first law is said to be **inertial**.

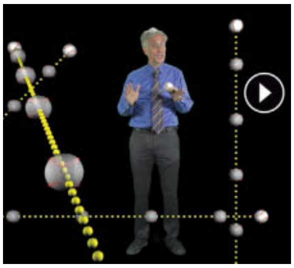


Fig. 1.1.2 These baseballs are in deep space and free from outside influences. Each ball moves according to inertia alone, following a straight-line path at a steady pace.

[3] In 1664, while Sir Isaac Newton (English scientist and mathematician, 1642–1727) was a student at Cambridge University, the university was forced to close for 18 months because of the plague. Newton retreated to the country, where he discovered the laws of motion and gravitation and invented the mathematical basis of calculus. These discoveries, along with his observation that celestial objects such as the moon obey the same simple physical laws as terrestrial objects such as an apple (a new idea for the time), are recorded in his *Philosophiæ Naturalis Principia Mathematica*, first published in 1687. This book is perhaps the most important and influential scientific and mathematical work of all time.

NEWTON'S FIRST LAW OF MOTION

An object that is not subject to any outside forces moves at a constant velocity, covering equal distances in equal times along a straight-line path.

INTUITION ALERT: Coasting

Intuition says that when nothing pushes on an object, that object slows to a stop; you must push it to keep it going.

Physics says that when nothing pushes on an object, that object coasts at constant velocity.

Resolution: Objects usually experience hidden forces, such as friction or air resistance, that tend to slow them down. Eliminating those hidden forces is difficult, so that you rarely see the full coasting behavior of force-free objects.

Check Your Understanding #1: **A Puck on Ice**

Why does a moving hockey puck continue to slide across an ice rink even though no one is pushing on it?

Answer: The puck coasts across the ice because it has inertia.

Why: A hockey puck resting on the surface of wet ice is almost completely free of horizontal influences. If someone pushes on the puck, so that it begins to travel with a horizontal velocity across the ice, inertia will ensure that the puck continues to slide at constant velocity.

The Alternative to Coasting: Acceleration

As you glide forward with nothing pushing you horizontally, what prevents your speed and direction from changing? The answer is your mass. **Mass** is the measure of your inertia, your resistance to changes in velocity. Almost everything in the universe has mass. Mass has no direction, so it's not a vector quantity. It is a **scalar quantity**—that is, a quantity that has only an amount.

Because you have mass, your velocity will change only if something pushes on you—that is, only if you experience a force. You'll keep moving steadily in a straight path until something exerts a force on you to stop you or send you in another direction. *Force* is our third vector quantity, having both a magnitude and a direction. After all, a push to the right is different from a push to the left.

When something pushes on you, your velocity changes; in other words, you accelerate. **Acceleration**, our fourth vector quantity, measures the rate at which your velocity is changing with time (Fig. 1.1.3). *Any* change in your velocity is acceleration, whether you're speeding up, slowing down, or turning. If either your speed or direction of travel is changing, you're accelerating!

Like any vector quantity, acceleration has a magnitude and a direction. To see how these two parts of acceleration work, imagine that you're at the starting line of a speed-skating race, waiting for it to begin. The starting buzzer sounds, and you're off! You dig your skates into the surface beneath you and begin to accelerate—your speed increases and you cover ground more and more quickly. The magnitude of your acceleration depends on how hard the skating surface pushes you forward. If it's a long race and you're not in a hurry, you take your time getting up to full speed. The surface pushes you forward gently and the magnitude of your acceleration is small. Your velocity changes slowly. However, if the race is a sprint and you need to reach top speed as quickly as possible, you spring forward hard and the surface exerts an enormous forward force on you. The magnitude of your acceleration is large, and your velocity changes rapidly. In this case, you can actually feel your inertia opposing your efforts to pick up speed.

Acceleration has more than just a magnitude, though. When you start the race, you also select a direction for your acceleration—the direction toward which your velocity is shifting with time. This acceleration is in the same direction as the force causing it. If you obtain a forward force from the surface, you'll accelerate forward—your velocity will shift more and more forward. If you obtain a sideways force from the surface, the other racers will have to jump out of your way as you careen into the wall. They'll laugh all the way to the finish line at your failure to recognize the importance of direction in the definitions of force and acceleration.

Once you're going fast enough, you can stop fighting inertia and begin to glide. You coast forward at a constant velocity. Now inertia is helping you; it keeps you moving

Fig. 1.1.3 A rightward force is causing this baseball to accelerate toward the right. Its velocity is increasing toward the right so that it travels farther with each passing second.

steadily along even though nothing is pushing you forward. (Recall that we're neglecting friction and air resistance. In reality, those effects push you backward and gradually slow you down as you glide.)

Even when you're not trying to speed up or slow down, you can still accelerate. As you steer your skates or go over a bump, you experience sideways or up–down forces that change your *direction of travel* and thus cause you to accelerate.

Finally the race is over, and you skid to a stop. You're accelerating again, but this time in the backward direction—opposite your forward velocity. Although we often call this process *deceleration*, it's just a special type of acceleration. Your forward velocity gradually diminishes until you come to rest.

To help you recognize acceleration, here are some accelerating objects:

1. A runner who's leaping forward at the start of a race—the runner's velocity is changing from zero to forward, so the runner is accelerating *forward*.
2. A bicycle that's stopping at a crosswalk—its velocity is changing from forward to zero, so it's accelerating *backward* (that is, it's decelerating).
3. An elevator that's just starting upward from the first floor to the fifth floor—its velocity is changing from zero to upward, so it's accelerating *upward*.
4. An elevator that's stopping at the fifth floor after coming from the first floor—its velocity is changing from upward to zero, so it's accelerating *downward*.
5. A car that's beginning to shift left to pass another car—its velocity is changing from forward to left-forward, so it's accelerating mostly *leftward*.
6. An airplane that's just beginning its descent—its velocity is changing from level-forward to descending-forward, so it's accelerating almost directly *downward*.
7. Children riding a carousel around in a circle—while their speeds are constant, their directions of travel are always changing. We'll discuss the directions in which they're accelerating in Section 3.3.

Here are some objects that are *not* accelerating:

1. A parked car—its velocity is always zero.
2. A car traveling straight forward on a level road at a steady speed—there is no change in its speed or direction of travel.
3. A bicycle that's climbing up a smooth, straight hill at a steady speed—there is no change in its speed or direction of travel.
4. An elevator that's moving straight upward at a steady pace, halfway between the first floor and the fifth floor—there is no change in its speed or direction of travel.

Seeing acceleration isn't as easy as seeing position or velocity. You can determine a skater's position in a single glance and her velocity by comparing her positions in two separate glances. To observe her acceleration, however, you need at least three glances because you are looking for how her velocity is changing with time. If her speed isn't steady or her path isn't straight, then she's accelerating.

Check Your Understanding #2: **Changing Trains**

Trains spend much of their time coasting along at constant velocity. When does a train accelerate forward? backward? leftward? downward?

Answer: The train accelerates forward when it starts out from a station, backward when it arrives at the next station, to the left when it turns left, and downward when it begins its descent out of the mountains.

Why: Whenever the train changes its speed or its direction of travel, it is accelerating. When it speeds up on leaving a station, it is accelerating forward (more forward-directed speed). When it slows down at the next station, it is accelerating backward (more backward-directed speed or, equivalently, less forward-directed speed). When it turns left, it is accelerating to the left (more leftward-directed speed). When it begins to descend, it is accelerating downward (more downward-directed speed).

How Forces Affect Skaters

Your friends skate over to congratulate you after the race, patting you on the back and giving you high-fives. They're exerting forces on you, so you accelerate—but how much do you accelerate and in which direction?

First, although each of your friends is exerting a separate force on you, you can't accelerate in response to each force individually. After all, you have only one acceleration. Instead, you accelerate in response to the **net force** you experience—the sum of all the individual forces being exerted on you. Drawing this distinction between individual forces and net force is important whenever an object is experiencing several forces at once. For simplicity now, however, let's wait until you have only one friend left on the ice. When that friend finally pats you on the back, you experience only that one force, so it is the net force on you and it causes you to accelerate.

Your acceleration depends on the strength of that net force: the stronger the net force, the more you accelerate. However, your acceleration also depends on your mass: the more massive you are, the less you accelerate. For example, it's easier to change your velocity before you eat Thanksgiving dinner than afterward.

There is a simple relationship among the net force exerted on you, your mass, and your acceleration. Your acceleration is equal to the net force exerted on you divided by your mass or, as a word equation,

$$\text{acceleration} = \frac{\text{net force}}{\text{mass}}. \qquad (1.1.1)$$

Your acceleration, as we've seen, is in the same direction as the net force on you.

This relationship was deduced by Newton from his observations of motion and is referred to as **Newton's second law of motion**. Structuring the relationship this way sensibly distinguishes the causes (net force and mass) from their effect (acceleration). However, it has become customary to rearrange this equation to eliminate the division. The relationship then takes its traditional form, which can be written in a word equation:

$$\text{net force} = \text{mass} \cdot \text{acceleration} \qquad (1.1.2)$$

in symbols:

$$\mathbf{F}_{\text{net}} = m \cdot \mathbf{a},$$

and in everyday language:

Throwing a baseball is much easier than throwing a bowling ball (Fig. 1.1.4).

Remember that in Eq. 1.1.2 the direction of the acceleration is the same as the direction of the net force.

NEWTON'S SECOND LAW OF MOTION

The net force exerted on an object is equal to that object's mass times its acceleration. The acceleration is in the same direction as the net force.

Because it's an equation, the two sides of Eq. 1.1.1 are equal. Your acceleration equals the net force on you divided by your mass. Since your mass is constant unless you visit the snack bar, Eq. 1.1.1 indicates that an increase in the net force on you is accompanied by a

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Fig. 1.1.4 A baseball accelerates easily because of its small mass. A bowling ball has a large mass and is harder to accelerate.

corresponding increase in your acceleration. That way, as the right side of the equation increases, the left side increases to keep the two sides equal. Thus the harder your friend pushes on you, the more rapidly your velocity changes in the direction of that push.

We can also compare the effects of equal forces on two different masses, for example, you and the former sumo wrestler to your left. I'll assume, for the sake of argument, that you're the less massive of the two. Equation 1.1.1 indicates that an increase in mass must be accompanied by a corresponding decrease in acceleration. Sure enough, your velocity changes more rapidly than the velocity of the sumo wrestler when the two of you are subjected to identical forces (Fig. 1.1.5).

So far we've explored five principles:

1. Your position indicates exactly where you're located.
2. Your velocity measures the rate at which your position is changing with time.
3. Your acceleration measures the rate at which your velocity is changing with time.
4. To accelerate, you must experience a net force.
5. The greater your mass, the less acceleration you experience for a given net force.

We've also encountered five important physical quantities—mass, force, acceleration, velocity, and position—as well as some of the rules that relate them to one another. Much of the groundwork of physics rests on these five quantities and on their interrelationships.

Skating certainly depends on these quantities. We can now see that, in the absence of any horizontal forces, you either remain stationary or coast along at a constant velocity. To start, stop, or turn, something must push you horizontally and that something is the ice or pavement. We haven't talked about how you obtain horizontal forces from the ice or pavement, and we'll leave that problem for later sections. As you skate, however, you should be aware of these forces and notice how they change your speed, direction of travel, or both. Learn to watch yourself accelerate.

Check Your Understanding #3: **Hard to Stop**

It's much easier to stop a bicycle traveling toward you at 5 kilometers per hour (3 miles per hour) than an automobile traveling toward you at the same velocity. What accounts for this difference?

Answer: An automobile has a much greater mass than a bicycle.

Why: To stop a moving vehicle, you must exert a force on it in the direction opposite its velocity. The vehicle will then accelerate backward so that it eventually comes to rest. If the vehicle is heading toward you, you must push it away from you. The more mass the vehicle has, the less it will accelerate in response to a certain force and the longer you will have to push on it to stop it completely. Although it's easy to stop a bicycle by hand, stopping even a slowly moving automobile by hand requires a large force exerted for a substantial amount of time.

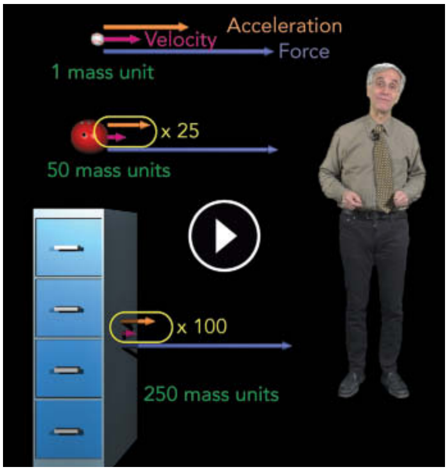

Fig. 1.1.5 A baseball, bowling ball, and file cabinet have different masses and accelerate quite differently in response to equal rightward forces. Arrows representing the accelerations and velocities of the bowling ball and file cabinet are magnified to make them visible.

Check Your Figures #1: **At the Bowling Alley**

Bowling balls come in various masses. Suppose that you try bowling with two different balls, one with twice the mass of the other. If you push on them with equal forces, which one will accelerate faster and how much faster?

Answer: The less massive ball will accelerate twice as rapidly.

Why: Equation 1.1.1 shows that an object's acceleration is inversely proportional to its mass:

$$\text{acceleration} = \frac{\text{force}}{\text{mass}}.$$

If you push on both bowling balls with equal forces, then their accelerations will depend only on their masses. Doubling the mass on the right side of this equation halves the acceleration on the left side. That means that the more massive ball will accelerate only half as quickly as the other ball.

Several Skaters: Frames of Reference

While skating alone is peaceful, it's usually more fun with other skaters around. That way, you have people to talk to and an audience for your athleticism and artistry.

However, with several skaters coasting on the ice at once, there's a question of perspective. As you glide steadily past a friend, the two of you see the world somewhat differently. From your perspective, you are motionless and your friend is moving. From your friend's perspective, though, your friend is motionless and you are moving. Who is right?

It turns out that you're both right and that physics has a way of accommodating this apparent paradox. Each of you is observing the world from a different **inertial frame of reference**, the viewpoint of an *inertial* object—an object that is not accelerating and that moves according to Newton's first law. One of the remarkable discoveries of Galileo and Newton is that the laws of physics work perfectly in any inertial frame of reference (Fig. 1.1.6). From an inertial frame, everything you see in the world around you obeys the laws of motion that we're in the process of exploring. Although you may find it odd to think of scenery as moving, your inertial frame of reference is as good as any and in your frame you are at rest amid the moving landscape.

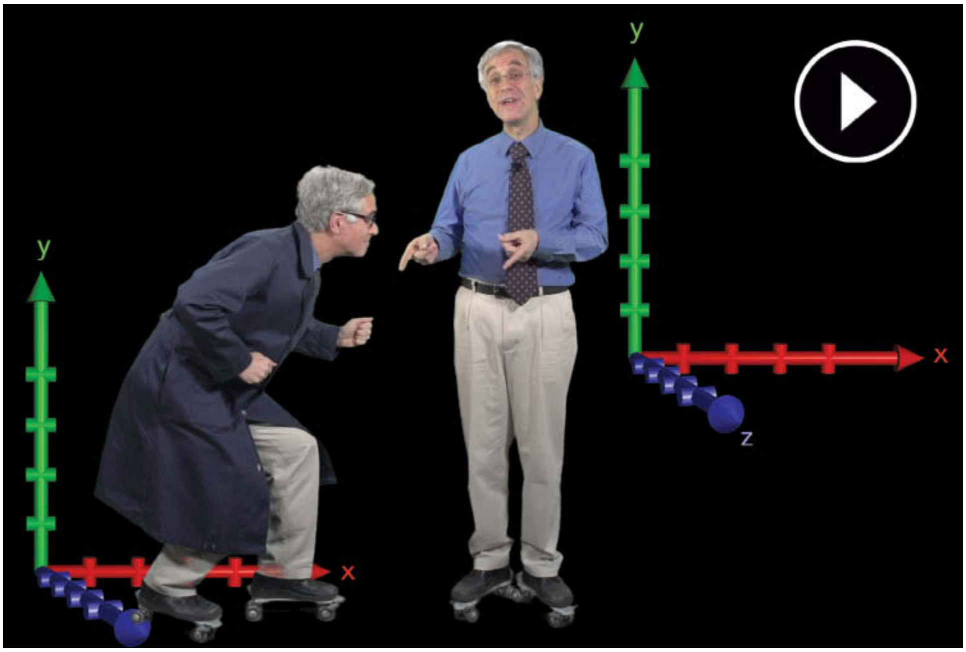

Fig. 1.1.6 Two skaters who are moving relative to one another, but not accelerating, have different inertial frames of reference. Although each skater will have a different coordinate system in which to measure physical quantities, the laws of physics will correctly describe what that skater observes from his own inertial frame of reference.