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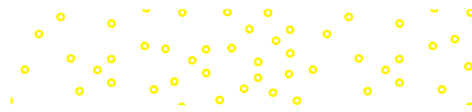
The PHYSICS of Everyday Phenomena

A Conceptual Introduction to Physics

Mc
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Hill

W. Thomas Griffith

Juliet W. Broising



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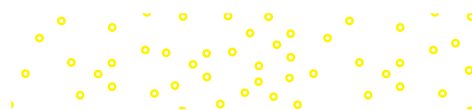
Pacific University

Juliet W. Broising

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THE PHYSICS OF EVERYDAY PHENOMENA: A CONCEPTUAL INTRODUCTION TO PHYSICS,
TENTH EDITION

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About the Authors

Tom Griffith is now Distinguished University Professor Emeritus at Pacific University in Forest Grove, Oregon, having retired after 36 years of teaching physics at Pacific. He still shows up on campus on occasion and might make a rare appearance with his guitar in a physics course. He now spends half of the year in Portland, Oregon, and his winters in Green Valley, Arizona. Over the years he has enjoyed hiking, bicycling, singing, and participating in musical comedies, and he still performs in a jam band in Arizona. During his years at Pacific, he served as Physics Department Chair, Natural Sciences Division Chair, Interim Dean of Enrollment Management, and Director of Institutional Research, among other things, but his primary focus was always teaching physics. He was active in the American Association of Physics Teachers (AAPT) and the Northwest Association for College Physics (PNACP). His wife of 42 years, Adelia, died of cancer in 2009. He married his wife Sally, an art photographer, in 2014 and they both enjoy exploring the western United States and more distant places.



The author, Tom Griffith, and his wife, Sally.
Courtesy of Tom Griffith

Juliet Brosing is now Distinguished University Professor Emeritus at Pacific University in Forest Grove, Oregon, where she taught physics for 30 years. Her research interests included nuclear physics, medical physics, and the application of teaching methods grounded in physics educational research. She has supported the importance of attracting young women into careers in science by helping to plan and run summer camps for seventh- and eighth-grade girls during the past 30 years. In 2012, she was named Oregon Professor of the Year by the Carnegie Foundation for the Advancement of Teaching and CASE (the Council for Advancement and Support of Education). She is the proud owner of three potato guns; parties with students at her house still involve projectiles, lots of noise, and fudge. Even though retired, Dr. Brosing retains contact with her many talented alumni. She now finds time for kayaking, gardening, and, of course, working on this book! Above all, Dr. Brosing is dedicated to helping faculty teach physics with a positive outlook and methods that encourage and benefit students, regardless of their chosen field of study.



The author, Juliet Brosing, and her husband, Keith LeComte, at the Oregon coast with their dog, Walter.
Karla Rumpf

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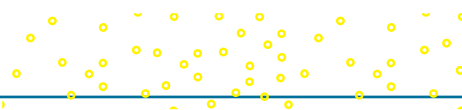
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Preface

The satisfaction of understanding how rainbows are formed, how ice skaters spin, or why ocean tides roll in and out—phenomena that we have all seen or experienced—is one of the best motivators available for building scientific literacy. This book attempts to make that sense of satisfaction accessible to non-science majors. Intended for use in a one-semester or two-quarter course in conceptual physics, this book is written in a narrative style, frequently using questions designed to draw the reader into a dialogue about the ideas of physics. This inclusive style allows the book to be used by anyone interested in exploring the nature of physics and explanations of everyday physical phenomena.

“The origin of the book came from an effort to write usable conceptual questions. The concepts are what we hope non-science majors will carry with them. Quantitative exercises have their place, but should be subordinate to the concepts.”

—W. Thomas Griffith, author

How This Book Is Organized

The organization of chapters is traditional, with some minor variations. The chapter on energy (chapter 6) appears prior to that on momentum (chapter 7), so that energy ideas can be used in the discussion of collisions. Wave motion is found in chapter 15, following electricity and magnetism and prior to chapters 16 and 17 on optics. The chapter on fluids (chapter 9) follows mechanics and leads into the chapters on thermodynamics. The first 17 chapters are designed to introduce students to the major ideas of classical physics and can be covered in a one-semester course with some judicious paring.

The complete 21 chapters could easily support a two-quarter course, and even a two-semester course in which the ideas are treated thoroughly and carefully. Chapters 18 and 19, on atomic and nuclear phenomena, are considered essential by many instructors, even in a one-semester course. If included in such a course, we recommend curtailing

coverage in other areas to avoid student overload. Sample syllabi for these different types of courses can be found on the instructor’s website.

Some instructors would prefer to put chapter 20 on relativity at the end of the mechanics section or just prior to the modern physics material. Relativity has little to do with everyday phenomena, of course, but is included because of the high interest that it generally holds for students. The final chapter (21) introduces a variety of topics in modern physics—including particle physics, cosmology, semiconductors, and superconductivity—that could be used to stimulate interest at various points in a course.

One plea to instructors, as well as to students using this book: Don’t try to cram too much material into too short a time! We have worked diligently to keep this book to a reasonable length while still covering the core concepts usually found in an introduction to physics. These ideas are most enjoyable when enough time is spent in lively discussion and in consideration of questions, so that a real understanding develops. Trying to cover material too quickly defeats the conceptual learning and leaves students in a dense haze of words and definitions. Less can be more if a good understanding results.

Mathematics in a Conceptual Physics Course

The use of mathematics in a physics course is a formidable block for many students, particularly non-science majors. Although there have been attempts to teach conceptual physics without any mathematics, these attempts miss an opportunity to help students gain confidence in using and manipulating simple quantitative relationships.

Clearly, mathematics is a powerful tool for expressing the quantitative relationships of physics. The use of mathematics can be carefully limited, however, and subordinated to the physical concepts being addressed. Many users of the first edition of this text felt that mathematical expressions appeared too frequently for the comfort of some students. In response, we substantially reduced the use of mathematics in the body of the text in the second edition. Most users have indicated that the current level is about right, so we have not changed the mathematics level in subsequent editions.

Logical coherence is a strong feature of this book. Formulas are introduced carefully after conceptual arguments are provided, and statements in words of these relationships generally accompany their introduction. We have continued to fine tune the example boxes that present sample exercises and questions. Most of these provide simple numerical illustrations of the ideas discussed. No mathematics prerequisite beyond high school algebra should be necessary. A discussion of the basic ideas of very simple algebra is found in appendix A, together with some practice exercises, for students who need help with these ideas.

New to This Edition

Building on the existing strengths of the *Physics of Everyday Phenomena* text, we have made additions to our offerings based on reviewer feedback. The most significant changes in this edition have come with the digital enhancements.

- We have added to our Connect® offerings by incorporating the concept videos, narrated by one of the authors, into the Connect question bank. These videos explain how physics is involved in everyday situations, so question content has likewise been authored and enhanced to showcase the everyday application of physics. The Instructor's Manual for each chapter also lists the specific section of the text each video corresponds to, and the videos are then hyperlinked in the eBook and noted in the print text with an icon. These additional guides will help faculty, should they wish to use the videos during class. Each video is no more than 5 minutes long.
- We have developed additional conceptual questions and exercises and made them available as Connect online homework.
- The Instructor's Manual, downloadable from the instructor resources in Connect, has also been improved and describes which PowerPoint slides and which clicker questions go with each section of the text, making it easier for an instructor to prepare for an engaged class period with a minimum of effort. Within the Instructor's Manual, instructors will also find suggestions for demonstrations and discussions.
- For maximum flexibility, the test bank is available in both the Connect question bank and Test Builder. Found in Connect under the Library Tab, Test Builder is a cloud-based tool that enables instructors to format tests that can be printed or administered within a Learning Management System.

In addition to the enhanced digital offerings, we have continued to improve upon the text with the 10th edition. As the book has evolved, we have tried to remain faithful to the principles that have guided the writing of the book from the outset. One of these has been to keep the book to a manageable length, in both the number of chapters and the overall content.

We have revised and updated the end-of-chapter material in the text and added some new conceptual questions and exercises. All odd-numbered exercises have the answers in

appendix D in the hard copy of the text, as well as links to the answers in the e-book. Answers to about one-sixth of the conceptual questions are also included in appendix D. Answers to a different one-sixth of the conceptual questions are included as a Student Resource on the Connect instructor resources and may be provided to students at the instructor's discretion. We encourage users to adopt the digital homework system, Connect. The value of this is that parameters in the exercises have been randomized for students. Thus, students spend time discussing *how* to solve the problems, rather than simply focusing on the answer. We have found this to be very powerful pedagogically. We have worked hard to reword the conceptual questions as multiple choice offerings in Connect—a significant tool to enhance conceptual understanding.

The everyday phenomenon boxes have been praised by many users. We have updated several of these boxes, particularly those in chapters 10 and 18, and have added a new one in chapter 1 (on dealing with proportions). In addition to these specific changes, we have also revised the text in many places to enhance understanding of some of the more difficult concepts.

Building an Energy Emphasis. Although this book remains a basic conceptual physics text, we are working to make the book better serve instructors who want to teach a conceptual physics course with an energy emphasis. A syllabus for instructors wishing to teach a course with an energy emphasis can be found in the Connect instructor resources. We plan to continue building this emphasis in future editions.

Continued Refinements in Artwork and Textual Clarity. Although the textual clarity of this text has been extensively praised by many reviewers and users, it can always be improved. Reviewers continue to point out places where either the art or the text can be improved, and we have responded to many of these suggestions. To this end, we have made many changes, often subtle, to both the art and the text.

Digital Learning Tools

Connect

McGraw-Hill Connect® is a highly reliable, easy-to-use homework and learning management solution that utilizes learning science and award winning adaptive tools to improve student results.

Homework and Adaptive Learning

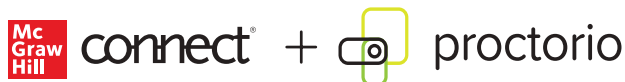
- Connect's assignments help students contextualize what they've learned through application, so they can better understand the material and think critically.
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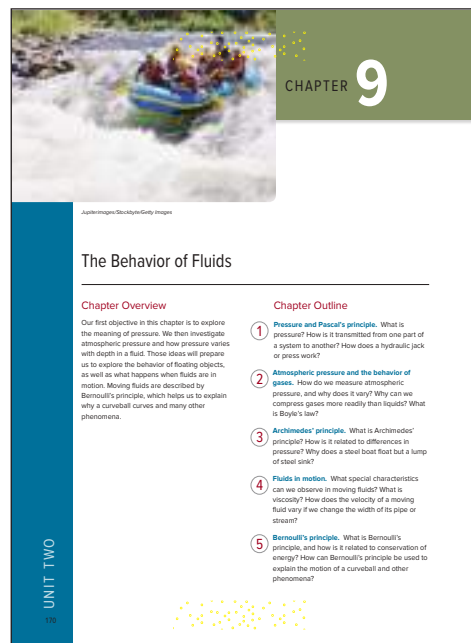
- Connect offers comprehensive service, support, and training throughout every phase of your implementation.
- If you're looking for some guidance on how to use Connect, or want to learn tips and tricks from super users, you can find tutorials as you work. Our Digital Faculty Consultants and Student Ambassadors offer insight into how to achieve the results you want with Connect.

Learning Aids

The overriding theme of this book is to introduce physical concepts by appealing to everyday phenomena whenever possible. To achieve this goal, this text includes a variety of features to make the study of *The Physics of Everyday Phenomena* more effective and enjoyable. A few key concepts form the basis for understanding physics, and the textual features described here reinforce this structure, so that the reader will not be lost in a flurry of definitions and formulas.

Chapter Openers

Each chapter begins with an illustration from everyday experience and then proceeds to use it as a theme for introducing relevant physical concepts. Physics can seem abstract to many students, but using everyday phenomena and concrete



examples reduces that abstractness. The chapter **overview** previews the chapter's contents and what students can expect to learn from reading the chapter. The overview introduces the concepts to be covered, facilitating the integration of topics and helping students to stay focused and organized while reading the chapter for the first time. The chapter **outline** includes all the major topic headings within the body of the chapter. It also contains questions that provide students with a guide of what they will be expected to know in order to comprehend the major concepts of the chapter. (These questions are then correlated to the end-of-chapter summaries.)

The chapter outlines, questions, and summaries provide a clear framework for the ideas discussed in each chapter. One of the difficulties that students have in learning physics (or any subject) is that they fail to construct the big picture of how things fit together. A consistent chapter framework can be a powerful tool in helping students see how ideas mesh.

Other Text Features

Running summary paragraphs are found at the end of each chapter section to supplement the more general summary at the end of the chapter.

Light rays are bent when they pass from one transparent substance to another, because the speed of light changes at the boundary between the two substances. The law of refraction describes how much bending occurs and whether the bending is toward or away from the surface normal. Because of this bending, the image of an underwater object appears to lie closer to the surface of the water than the actual position of the object. For light traveling initially inside glass or water, there is a critical angle of incidence beyond which the light is totally reflected rather than being refracted. The index of refraction varies with wavelength, producing the dispersion of colors we see when light passes through a prism.

Subsection headings are often cast in the form of questions to motivate the reader and pique curiosity.

What happens to the gas in a hot-air balloon?

When the gas is heated in a hot-air balloon (fig. 10.17), the pressure, not the temperature, remains constant. The pressure of the gas inside the balloon cannot be significantly larger than that of the surrounding atmosphere. When pressure remains constant in a process, it is called **isobaric** (*baric* refers to pressure). The internal energy increases as the gas is heated, and so does the temperature. The gas also expands in this process, however, which removes some internal energy.

The gas expands in the isobaric heating process because of another property of ideal gases discovered near the beginning of the nineteenth century. A series of experiments showed that

Everyday phenomenon boxes relate physical concepts discussed in the text to real-world topics, societal issues, and modern technology, underscoring the relevance of physics and how it relates to our day-to-day lives. The list of topics includes

The Case of the Malfunctioning Coffeemaker (chapter 1)
 Scaling a Recipe (chapter 1)
 Transitions in Traffic Flow (chapter 2)
 The 100-m Dash (chapter 2)
 Reaction Time (chapter 3)
 Shooting a Basketball (chapter 3)
 The Tablecloth Trick (chapter 4)
 Riding an Elevator (chapter 4)
 Seat Belts, Air Bags, and Accident Dynamics (chapter 5)
 Explaining the Tides (chapter 5)
 Conservation of Energy (chapter 6)
 Energy and the Pole Vault (chapter 6)
 The Egg Toss (chapter 7)
 An Automobile Collision (chapter 7)
 Achieving the State of Yo (chapter 8)
 Bicycle Gears (chapter 8)
 Measuring Blood Pressure (chapter 9)
 Throwing a Curveball (chapter 9)
 Heat Packs (chapter 10)
 Solar Collectors, Greenhouses, and Global Warming (chapter 10)
 Hybrid Automobile Engines (chapter 11)
 A Productive Pond (chapter 11)
 Cleaning Up the Smoke (chapter 12)
 Lightning (chapter 12)
 Electrical Impulses in Nerve Cells (chapter 13)
 The Hidden Switch in Your Toaster (chapter 13)
 Direct-Current Motors (chapter 14)
 Vehicle Sensors at Traffic Lights (chapter 14)
 Electric Power from Waves (chapter 15)

A Moving Car Horn and the Doppler Effect (chapter 15)
 Why Is the Sky Blue? (chapter 16)
 Antireflection Coatings on Eyeglasses (chapter 16)
 Rainbows (chapter 17)
 Laser Refractive Surgery (chapter 17)
 Fuel Cells and the Hydrogen Economy (chapter 18)
 Television Development (chapter 18)
 Smoke Detectors (chapter 19)
 What Happened at Fukushima? (chapter 19)
 The Twin Paradox (chapter 20)
 Holograms (chapter 21)

Everyday Phenomenon

Box 13.1

Electrical Impulses in Nerve Cells

The Situation. If you make a conscious decision to wiggle your big toe, the big toe will quickly wiggle. Somehow, a signal passes from your brain to the muscles in the toe, causing the muscles to contract. That process happens quickly—there is not much delay between the decision and the toe wiggle.

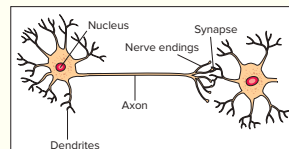
How does the wiggle command get from your brain to your toe? Does the signal travel over a biological wire or cable of some kind? Is a flow of electric charge involved similar to what happens in the wires of a landline telephone? We know that nerve cells are involved, but how do they work?

The Analysis. The study of electrical effects in nerve cells goes back to the work of Galvani and Volta on “animal electricity” that led to the invention of the battery. It was clear even then that an electrical process is involved. However, this process is much more complicated than the simple flow of charge in a wire.

The signal is transmitted through nerve cells (or *neurons*) like the one pictured in the first drawing. Like any biological cell, the main body of the neuron contains a nucleus and has a number of *dendrites* that can receive signals from other cells. Unlike most other cells, though, neurons have a long, tail-like segment called an *axon* that emerges from the main cell body. The axons can be as long as a meter or more, starting perhaps in the spinal cord and terminating in your foot or hand. At the end of the axon are a number of thinner filaments, or *nerve endings*, that may contact the dendrites of other cells in junctions called *synapses*.

Just as in a phone system, the signal that is transmitted involves a change in voltage. The change in voltage along the axon of a nerve cell is transmitted very differently than that in a metal wire, however. In fact, the primary flow of charge in a nerve cell occurs perpendicularly to the axon rather than along its length. To understand this, we need to take a closer look at the structure of the axon.

Any cell has a *membrane* that is essentially the outer covering of the cell that holds everything together. The membrane of an axon has some unusual properties. It maintains a balance between certain chemical ions (charged atoms) on the inside and outside surfaces of the membrane. In its normal (resting) state, positively charged sodium ions (Na^+) are excluded from the inside of the cell. There is a small excess of positively charged ions (mostly potassium, K^+) on the outside surface of the membrane and of negatively charged ions (mostly chloride, Cl^-) on the inside surface. This creates a voltage difference between the inside and outside surfaces of the axon. If we describe this difference as $\Delta V = V_{\text{inside}} - V_{\text{outside}}$, it is typically about -70 mV .



A neuron has a long extension called an axon, which is often much longer relative to the rest of the cell than shown here. The nerve endings may contact dendrites of other cells in synapses.

Study hints and **study suggestions** provide students with pointers on their use of the textbook, tips on applying the principles of physical concepts, and suggestions for home experiments.

Study Hint

If you have the materials handy, you should try the battery-and-bulb experiment before reading further. The delight of figuring out how to get the bulb to light is something not to be spoiled by reading on prematurely. Once you get it to light (without killing the battery), you may wish to experiment with other configurations and try to understand what distinguishes working arrangements from nonworking ones. Experimenting will help to make the concept of a circuit more vivid.

Example boxes are included within the chapter and contain one or more concrete, worked examples of a problem and its solution as it applies to the topic at hand. Through careful

study of these examples, students can better appreciate the many uses of problem solving in physics.

Example Box 2.4

Sample Exercise: Uniform Acceleration

A car traveling due east with an initial velocity of 10 m/s accelerates for 6 seconds at a constant rate of 4 m/s^2 .

- What is its velocity at the end of this time?
- How far does it travel during this time?

$$\begin{aligned} \text{a. } v_0 &= 10 \text{ m/s} & v &= v_0 + at \\ a &= 4 \text{ m/s}^2 & &= 10 \text{ m/s} + (4 \text{ m/s}^2)(6 \text{ s}) \\ t &= 6 \text{ s} & &= 10 \text{ m/s} + 24 \text{ m/s} \\ v &= ? & &= \mathbf{34 \text{ m/s}} \end{aligned}$$

$$v = 34 \text{ m/s due east}$$

$$\begin{aligned} \text{b. } d &= v_0 t + \frac{1}{2} at^2 \\ &= (10 \text{ m/s})(6 \text{ s}) + \frac{1}{2} (4 \text{ m/s}^2)(6 \text{ s})^2 \\ &= 60 \text{ m} + (2 \text{ m/s}^2)(36 \text{ s}^2) \\ &= 60 \text{ m} + 72 \text{ m} = \mathbf{132 \text{ m}} \end{aligned}$$

Debatable Issues provide open-ended, opinion questions on—but not limited to—energy and environmental issues to be used as class discussion, as writing assignments, and/or for Internet forums. Notes on discussion ideas and results are included in the instructor's manual.

Debatable Issue

France gets more than 75% of its power from nuclear energy and claims a substantial level of energy independence and almost the lowest-cost electricity in Europe. It also has an extremely low level of CO_2 emissions per capita from electricity generation. Why is nuclear power not used more extensively in other European countries or in the United States?

End-of-Chapter Features

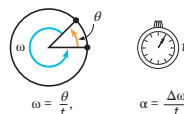
- The **summary** highlights the key elements of the chapter and correlates to the questions asked about the chapter's major concepts in the chapter opener.

Summary

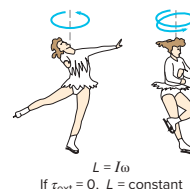
Summary

We have considered the rotational motion of a solid object and what causes changes in rotational motion. We have used an analogy between linear motion and rotational motion to develop many of the concepts. The key points are the following:

- What is rotational motion?** Rotational displacement is described by an angle. Rotational velocity is the rate of change of that angle with time. Rotational acceleration is the rate of change of rotational velocity with time.



- Conservation of angular momentum.** By analogy to linear momentum, angular momentum is defined as the rotational inertia times the rotational velocity. It is conserved when no net external torque acts on the system.



Key Terms

Rotational velocity, 146
Rotational displacement, 146
Radian, 146
Linear displacement, 146

Fulcrum, 149
Torque, 150
Lever arm, 150
Center of gravity, 151
Rotational inertia, 153

Moment of inertia, 153
Angular momentum, 156
Conservation of angular momentum, 156
Right-hand rule, 158

- Key terms** are page-referenced to where students can find the terms defined in context.

Key Terms

Conceptual Questions

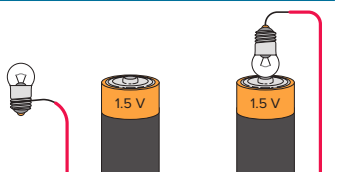
Conceptual Questions

* = more open-ended questions, requiring lengthier responses, suitable for group discussion

Q = sample responses are available in appendix D

Q = sample responses are available in Connect

- Q1. Two arrangements of a battery, bulb, and wire are shown in the diagram. Which of the two arrangements, if either, will light the bulb? Explain.



Exercises

For the exercises in this chapter (and subsequent chapters), use the more accurate value of $g = 9.8 \text{ m/s}^2$ for the acceleration due to gravity.

- E1. A single force of 42 N acts upon a 6-kg block. What is the magnitude of the acceleration of the block?

- E2. A heavy ball is suspended at a rate upon the

- E6. A 5-kg block being pushed across a table by an acceleration of 6.0 m/s^2 .

- What is the net force acting upon the block?
- If the magnitude of $\mathbf{P}$ is 38 N, what is the magnitude of the frictional force acting upon the block?

Synthesis Problems

- SP1. Two long, parallel wires carry currents of 8 A and 12 A in opposite directions, as shown in the diagram. The distance between the wires is 4 cm.

- What is the magnitude of the force per unit length exerted by one wire on the other?
- What are the directions of the forces on each wire?
- What is the total force exerted on a 30-cm length of the

- What is the direction of the magnetic field at the position shown?
- Will this force change the magnitude of the ball? Explain.
- From Newton's second law, what is the acceleration of the charged ball?
- Because centripetal acceleration is $a_c = v^2/r$, what is the radius of the path?

- Conceptual Questions** are designed to challenge students to demonstrate their understanding of the key concepts. Selected answers are provided in appendix D to assist students with their study of more difficult concepts.

- Exercises and synthesis problems** are intended to help students test their grasp of problem solving. The odd-numbered exercises have answers in appendix D. By working through the odd-numbered exercises and checking the answers in appendix D, students can gain confidence in tackling

Exercises

Synthesis Problems

the even-numbered exercises and thus reinforce their problem-solving skills.

- Because many courses for non-science majors do not have a laboratory component, **home experiments and observations** are found at the end of each chapter. The spirit of these home experiments is to enable students to explore the behavior of physical phenomena using easily available rulers, string, paper clips, balls, toy cars, flashlight batteries, and so on. Many instructors have found them useful for putting students into the exploratory and observational frame of mind that is important to scientific thinking. This is certainly one of our objectives in developing scientific literacy.

“Students and faculty alike will find the home experiments engaging. Physics is not a spectator sport and participation is key.”

—Juliet W. Brosing, author

Supplements

Instructor Resources

In addition, instructor resources, accessed by the library tab in Connect, provide instructors with useful tools designed to help improve student understanding of the material presented in the text and class and other tools designed to help ease the time burdens of the course by providing valuable presentation and preparation tools.

Accessible PowerPoint Lectures
 Instructor’s Manual
 Sample Syllabi
 Clicker Questions
 PowerPoint and Image Files of Art and Photos from the Text
 Test Bank
 Formula Summaries
 Physics Interactives
 Concept Videos
 Practice Problems

For sharing with students:

- Author-narrated videos illustrating physics in everyday situations (noted in text with a video icon) ▶
- Student Solutions Manual
- Additional Solutions and Answers

Personal Response Systems

Personal Response Systems can bring interactivity into the classroom or lecture hall. Wireless response systems such as Poll Everywhere give the instructor and students immediate feedback from the entire class. Poll Everywhere allows

Home Experiments and Observations

Home Experiments and Observations

H111. The concept of half-life, and the associated exponential decay curve, can be made more vivid by using piles of pennies (or other stackable objects) to represent atoms.

- Collect as many pennies as you can find on desert raps and place them in one pile. This is one hundred percent of the original number of atoms.
- Divide your pile into two equal stacks, placed side by side. The left pile represents the original number of atoms.
- Divide the right pile in half. Place one of the resulting stacks next to the original left stack. This represents the number of atoms remaining after one half-life has elapsed.
- Continue this process, always dividing the remaining right stack in half and placing the stack obtained from

H112. The concept of a chain reaction can be made more vivid by using the same piles of pennies (or other objects) you used in H111. Gather about \$3.00 worth of pennies. Each pile will represent the number of neutrons produced in the chain reaction.

- Assume each fission creates 2 neutrons, as shown in figure 19.13. On the first pile, put one penny to indicate the neutron that initiated the fission.
- On the second pile, put 2 pennies, to indicate the 2 neutrons created in the fission.
- On the next pile, put 3 × 3, or 9, pennies, given that each of the 3 neutrons produced in the first reaction will create 3 more neutrons.
- How many pennies do you need in the next pile? And in subsequent piles?

students to use their computer, smartphone, tablet, or text message device to respond to questions. Instructors are able to motivate student preparation, interactivity, and active learning, receiving immediate feedback to gauge which concepts students understand. Questions covering the content of the *Physics of Everyday Phenomena* text are formatted in PowerPoint and are available on the Connect Instructor Resources for use with any personal response system.

Computerized Test Banks Online

For maximum flexibility, the test bank is available in both the Connect question bank and Test Builder. Found in Connect under the Library Tab, Test Builder is a cloud-based tool that enables instructors to format tests that can be printed or administered within a Learning Management System.

Acknowledgments

A large number of people have contributed to this 10th edition, either directly or indirectly. We extend particular thanks to those who participated in reviews of the previous editions. Their thoughtful suggestions have had a direct impact on the clarity and accuracy of this edition, even when it was not possible to fully incorporate all of their ideas due to space limitations or other constraints.

We also wish to acknowledge the contributions of the editorial staff and book team members at McGraw-Hill Higher Education. Their commitment of time and enthusiasm for this work has helped enormously in pushing this project forward. We also owe a huge debt of thanks to our colleagues at Pacific University for helpful suggestions as well as for their forbearance when this project limited our time for other activities. Our 10th edition accuracy checker, Michael Faux of SUNY Oneonta, also provided constructive criticisms and many suggestions for improvement.

Last, but certainly not least, we would both like to acknowledge the support of our families, friends, and colleagues. Their encouragement has been essential and has allowed us to enjoy the pleasure of this endeavor.



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- Jordan Cunningham,
Eastern Washington University



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Secrets to Success in Studying Physics

First of all, we should admit that there are no secrets. Conscientious work and follow-through with reading, problem assignments, and class participation will reap the rewards that students can expect from such efforts in other courses. Failing to do so will also lead to expected results.

There are some ways, however, in which studying physics is different from your studies in biology, history, or many other courses. Physics is not an area of study that can be mastered by memorizing discrete facts or by cramming before tests. Students sometimes bring study strategies to physics that have worked in other courses and are disappointed when they fail to work in their physics class. The suggestions that follow are sure-fire steps to getting the most out of your physics course and this textbook.

1. **Experiment.** Experiments play a key role in the development of physics but also in the growth of understanding for anyone approaching physics concepts. We often suggest in the text that you try simple experiments that might involve throwing a ball, walking across a room, or other very rudimentary activities. Do them right away as they arise in the text. Not only will you gain the benefit of increased blood flow to various parts of the body including the brain, but what follows in your reading will make more sense. Experience with everyday phenomena cannot be gained passively.
2. **Get the big picture.** Physics is a big-picture subject. Your understanding of Newton's laws of motion, for example, cannot be encapsulated by a formula or by memorizing the laws themselves. You need to see the entire context, understand the definitions, and work with how the laws are applied. The outlines and summaries provided at the beginning and end of each chapter can help to provide the context. They cannot stand alone, however. You need to place the examples and descriptions provided in the classroom and text in the framework provided by the outlines and summaries. If you grasp the big picture, the details will often follow.
3. **Explore questions.** The textbook provides a list of conceptual questions at the end of each chapter, but also raises questions in the body of the text. The greatest benefit is gained by attacking these questions first on your own and then by discussion with classmates. Write out answers to these questions using full sentences, not just short-answer phrases. Compare your answers with those provided at the back of the text for selected questions, but only after having a good crack at answering the questions yourself.
4. **Try the exercises.** The textbook also provides exercises and synthesis problems at the end of each chapter. Their purpose is to provide

practice with simple numerical applications of physics concepts. They are useful only if you do them yourself and write out the solution steps in such a way that you can follow your work. Copying answers and steps from classmates or other sources may gain points on the assignment but provides no benefit in understanding. As in sports and many other activities, success on physics exams will come to those who practice.

5. **Be there.** College students set their own priorities for use of time, and sometimes class attendance is not at the top of the list. In some classes, this may be justified by the nature of the benefit of class activities, but that is seldom the case in physics. The demonstrations, explanations, working of exercises, and class discussions that are usually part of what occurs during a physics class provide an invaluable aid to grasping the big picture and filling in holes in your understanding. The demonstrations alone are often worth the price of admission. (You do pay—it's called tuition.)
6. **Ask questions.** If the explanations of demonstrations or other issues are not clear, ask questions. If you are confused, chances are good that many other students are likewise befuddled. They will love you for raising the flag. Unless the instructor is unusually insecure, he or she will also love you for providing the opportunity to achieve better clarity. Physics instructors already know this stuff, so they sometimes have difficulty seeing where student hang-ups may lie. Questions provide the lubrication for moving things forward.
7. **Review understanding.** Preparing for tests should not be a matter of last-minute cramming and memorization. Instead, you should review your understanding of the big picture and question yourself on why we did what we did in answering questions and working exercises done previously. Memorization is usually pointless because many physics instructors provide or permit formula sheets that may include definitions and other information. Late-night cramming is counterproductive because it detracts from getting a good night's sleep. Sleep can be critical to having a clear head the next day to meet the challenges provided by the test.

Although there is an element of common sense in most of these suggestions, you will probably not be surprised to learn that many students do not approach things following these guidelines. Old habits are hard to break and peer pressure can also be a negative influence at times. Students fall into patterns that they know are ineffective, but are unable to climb out of the rut. We have done our duty in disclosing these secrets. You are on your own if you choose a different path. Let us know if it works.



CHAPTER 2

Describing Motion

Chapter Overview

The main purpose of this chapter is to provide clear definitions and illustrations of the terms used in physics to describe motion, such as the motion of the car described in this chapter's opening example. Speed, velocity, and acceleration are crucial concepts for the analysis of motion in later chapters. Precise description is the first step to understanding. Without it, we remain awash in vague ideas that are not defined well enough to test our explanations.

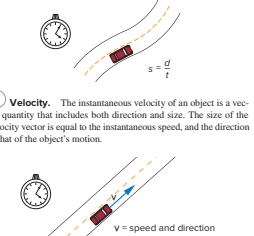
Each numbered topic in this chapter builds on the previous section, so it is important to obtain a clear understanding of each topic before going on. The distinctions between speed and velocity and velocity and acceleration are particularly important.

Key Terms 33

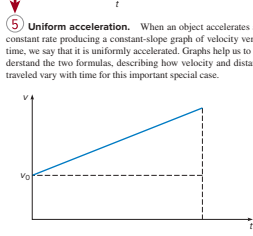
Summary

The main purpose of this chapter is to introduce concepts that are crucial to a precise description of motion. To understand acceleration, you must first grasp the concept of velocity, which in turn builds on the idea of speed. The distinctions between speed and velocity, and between velocity and acceleration, are particularly important.

- 1 **Average and instantaneous speed.** Average speed is defined as the distance traveled divided by the time. It is the average rate at which distance is covered. Instantaneous speed is the rate at which distance is being covered at a given instant in time and requires that we use very short time intervals for computation.
- 2 **Velocity.** The instantaneous velocity of an object is a vector quantity that includes both direction and size. The size of the velocity vector is equal to the instantaneous speed, and the direction is that of the object's motion.
- 3 **Acceleration.** Acceleration is defined as the time rate of change of velocity and is found by dividing the change in velocity by the time. Acceleration is also a vector quantity. It can be computed as either an average or an instantaneous value. A change in the direction of the velocity can be as important as a change in magnitude. Both involve acceleration.
- 4 **Graphing motion.** Graphs of distance, speed, velocity, and acceleration plotted against time can illustrate relationships between these quantities. Instantaneous velocity is equal to the slope of the distance-time graph. Instantaneous acceleration is equal to the slope of the velocity-time graph. The distance traveled is equal to the area under the velocity-time graph.
- 5 **Uniform acceleration.** When an object accelerates at a constant rate producing a constant-slope graph of velocity versus time, we say that it is uniformly accelerated. Graphs help us to understand the two formulas, describing how velocity and distance traveled vary with time for this important special case.



$v = \text{speed and direction}$



$v = v_0 + at$
 $d = v_0t + \frac{1}{2}at^2$

The concepts of velocity and acceleration discussed in this chapter are often difficult to understand, particularly because we use the same terms in everyday life but often with different meanings. There are mastery quizzes and other helpful resources in Connect that will help you clarify your understanding of these ideas. We encourage you to try them.

Key Terms

Speed, 19	Magnitude, 23	Average acceleration, 25
Average speed, 19	Vector, 23	Instantaneous acceleration, 25
Rate, 20	Vector quantity, 24	Slope, 28
Instantaneous speed, 21	Instantaneous velocity, 24	Uniform acceleration, 31
Velocity, 23	Acceleration, 24	

The chapter outline and chapter summary provide related frameworks for organizing concepts.

study hint:

How to Use the Features of This Book

This book has a number of features designed to make it easier for you to organize and grasp the concepts that we will explore. These features include the chapter overview and outline at the beginning of each chapter and the summary at the end of each chapter, as well as the structure of individual sections of the chapters. The questions, exercises, and synthesis problems at the end of each chapter also play an important role. How can these features be used to the best advantage?

Chapter outlines and summaries

Knowing where you are heading before you set out on a journey can be the key to the success of your mission. Students get a better grasp of concepts if they have some structure or framework to help them to organize the ideas. Both the chapter overview and outline at the beginning of each chapter and the summary at the end are designed to provide such a framework. Having a clear idea of what you are trying to accomplish before you invest time in reading a chapter will make your reading more effective and enjoyable.

The list of topics and questions in the chapter outline can be used as a checklist for measuring your progress as you read. Each numbered topic in the outline, with its associated questions, pertains to a section of the chapter. The outline is designed to stimulate your curiosity by providing some blanks (unanswered questions) to be filled in by your reading. Without the blanks, your mind has no organizational structure to store the information. Without structure, recall is more difficult. You can use the questions in the outline to check the effectiveness of your reading. Can you answer all of the questions when you are done? Each section of a chapter also begins with questions, and the section subheadings are likewise often cast as questions. At the end of each section there is also an indented summary paragraph designed to help you tie the ideas in that section together.

The end-of-chapter summary gives a short description of the key ideas in each section, often cast in the form of answers to the questions raised in the outline (see diagram). Summaries provide a quick review, but they are no substitute for a careful reading of the main text. By following the same organizational structure as the outline, the summary reminds you where to find a more complete discussion of these ideas. The purpose of both the outlines and the summaries is to make your reading more organized and effective.

Studying any new discipline requires forming new patterns of thought that can take time to gel. The summaries at the end of each section, as well as at the end of the chapter, can help this gelling to take place. A structure is often built layer by layer, and the later layers will be shaky if the base is unstable.

How should the questions and exercises be used?

At the end of each chapter you will find a group of questions, followed by a group of exercises, and, finally, by a small number of synthesis problems. Your grasp of the chapter will improve if you write out answers to the questions and exercises, either as assigned by your instructor or in independent study. The ideas contained in each chapter cannot be thoroughly mastered without this kind of practice.

The questions are crucial to helping you fix the important concepts and distinctions in your mind. Most of the questions call for a short answer as well as an explanation. A few of the questions, marked with asterisks, are more open-ended and call for lengthier responses. It is a good idea to write out the explanations in clear sentences when you answer these questions, because it is only through reinforcement that ideas become a part of you. Also, if you can explain something clearly to someone else, you understand it. A sample question and answer appears in example box 1.1.

The exercises are designed to give you practice in using the ideas and the related formulas to do simple computations. The exercises also help to solidify your understanding of concepts by giving you a sense of the units and the sizes of the quantities involved. Even though many of the exercises are straightforward enough to work in your head without writing much down, we recommend writing out the information given, the information sought, and the solution in the manner shown in example boxes 1.2 and 1.3 in section 1.3. This develops careful work habits that will help you avoid careless mistakes. Most students find the exercises easier than the questions. The sample exercises scattered through each chapter can help you get started.

The synthesis problems are more wide-ranging than the questions or exercises. They often involve features of both. Although not necessarily harder than the questions or exercises, they do take more time and are sometimes used to extend ideas beyond what was discussed in the chapter. Doing one or two of these in each chapter should build your confidence. They are

particularly recommended for those students who have worked the exercises and want to explore the topic in more depth.

Answers to the odd-numbered exercises, odd-numbered synthesis problems, and selected questions are found in the back of the book in appendix D. Looking up the answer before attempting the problem is self-defeating. It deprives you of practice in thinking things through on your own. Checking answers *after* you have worked an exercise can be a confidence builder. Answers should be used only to confirm or improve your own thinking.

Home experiments and everyday phenomenon boxes

Reading or talking about physical ideas is useful, but there is no substitute for hands-on experience with the phenomena. You already have a wealth of experience with many of these phenomena, but you probably have not related it to the physical concepts you will be learning. Seeing things in new ways will make you a more astute observer.

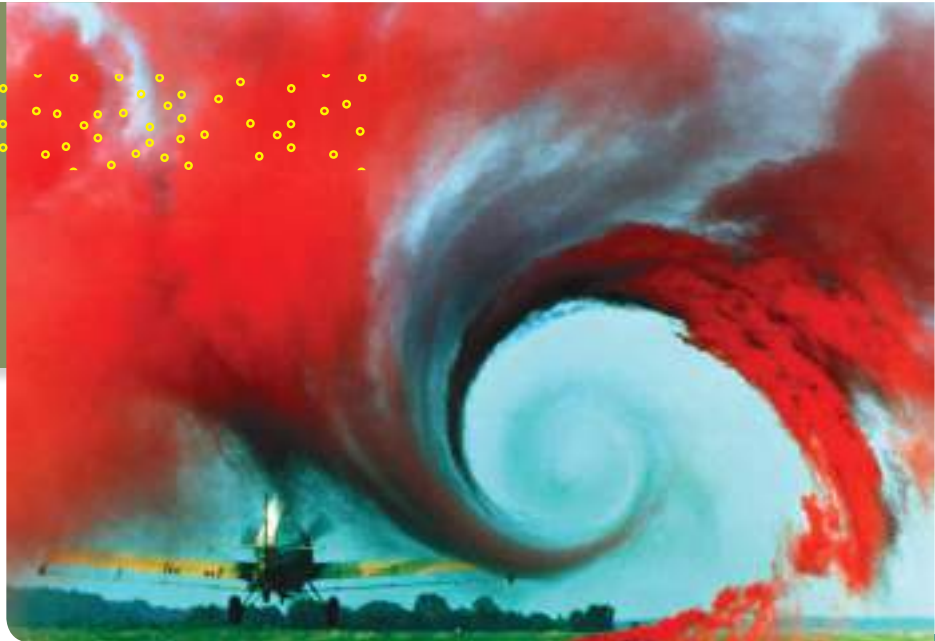
In addition to the home experiments at the end of each chapter, we often suggest some simple experiments in the main text or in the study hints. We strongly recommend making these observations and doing the experiments. Lecture demonstrations can help, but doing something yourself imprints it vividly on your mind. There is excitement in discovering things yourself and seeing them in a new light.

The boxes that discuss everyday phenomena also give you practice in applying physical concepts. Most of the phenomena discussed in these boxes are familiar. The boxes allow us to explore these examples more thoroughly. Participating in these investigations of everyday phenomena can help bring the ideas home.

Connect has many features that will help you be successful in the course. The study hints given for each chapter often give a concise and thorough summary of the chapter. Read them to check if you have understood the key points of each chapter. There are both mastery quizzes and practice problems provided. Mastery quizzes test your conceptual understanding of the material. Many of the your exam questions may be worded similar to these quizzes. Practice problems allow you to practice problems similar to the exercises at the end of each chapter in the text. Complete solutions are provided for these and you can check them after trying the problems.

CHAPTER

1



Source: NASA/Langley Research Center (NASA-LaRC)

Physics, the Fundamental Science

Chapter Overview

The main objective of this chapter is to help you understand what physics is and where it fits in the broader scheme of the sciences. A secondary purpose is to acquaint you with the metric system of units and the advantages of the use of simple mathematics.

Chapter Outline

- 1 What about energy?** What do concerns about global warming and climate change have to do with energy? How is physics involved in these discussions?
- 2 The scientific enterprise.** What is the scientific method? How do scientific explanations differ from other types of explanation?
- 3 The scope of physics.** What is physics? How is it related to the other sciences and to technology? What are the major subfields of physics?
- 4 The role of measurement and mathematics in physics.** Why are measurements so important? Why is mathematics so extensively used in science? What are the advantages of the metric system of units?
- 5 Physics and everyday phenomena.** How is physics related to everyday experience and common sense? What are the advantages of using physics to understand common experience?

Imagine that you are riding your bike on a country road on an Indian-summer afternoon. The sun has come out after a brief shower, and as the rain clouds move on, a rainbow appears in the east (fig. 1.1). A leaf flutters to the ground, and an acorn, shaken loose by a squirrel, misses your head by only a few inches. The sun is warm on your back, and you are at peace with the world around you.

No knowledge of physics is needed to savor the moment, but your curiosity may bring some questions to mind. Why does the rainbow appear in the east rather than in the west, where it may also be raining? What causes the colors to appear? Why does the acorn fall more rapidly than the leaf? Why is it easier to keep your bicycle upright while you are moving than when you are standing still?

Your curiosity about questions like these is similar to what motivates scientists. Learning to devise and apply theories or models that can be used to understand, explain, and predict such phenomena can be a rewarding intellectual game. Crafting an explanation and testing it with simple experiments or

observations is fun. That enjoyment is often missed when the focus of a science course is on accumulating facts.

This book can enhance your ability to enjoy the phenomena that are part of everyday experience. Learning to produce your own explanations and to perform simple experimental tests can be gratifying. The questions posed here lie in the realm of physics, but the spirit of inquiry and explanation is found throughout science and in many other areas of human activity. The greatest rewards of scientific study are the fun and excitement that come from understanding something that has not been understood before. This is true whether we are talking about a physicist making a major scientific breakthrough or about a bike rider understanding how rainbows are formed. There are also benefits to understanding the physics concepts that underlie issues arising in political and policy debates. The next section introduces questions in the very important areas of energy use and climate change. These involve everyday phenomena of a more pressing nature than rainbows.



Figure 1.1 Rainbows appear to the east in late afternoon. How can this phenomenon be explained? (See everyday phenomenon box 17.1.) *Courtesy of Sally Cantrell Griffith*

Study Hint

If you have a clear idea of what you want to accomplish before you begin to read a chapter, your reading will be more effective. The questions in the chapter outline—as well as those in the subheadings of each section—can serve as a checklist for measuring your progress as you read. A clear picture of what questions are going to be addressed and where the answers will be found forms a mental road map to guide you through the chapter. Take a few minutes to study the outline and fix this road map in your mind. It will be time well spent.

1.1 What about Energy?

Suppose that you have just emerged from a heated argument with a friend about global warming and energy. Your friend has a different political bent than your own and you suspect that his or her opinions on global warming are simply a matter of political bias. However, since you may know very little about the details of energy issues, you are really not in a position to counter the arguments. Where do you go from there?

All of us find ourselves in this position from time to time. Energy issues lie at the heart of the political debate on global

warming and climate change. Understanding the basics of these issues is important to politicians, policymakers, and ordinary citizens who discuss these issues and vote for or against ballot measures and candidates.

What is energy and how is it used? Which energy sources are renewable and which are not? What can you do to understand and coherently discuss energy issues?

How is energy involved in the global warming debate?

Much of our use of energy involves the burning of fossil fuels. The carbon that is released in this process was locked up millions of years ago in coal, oil, and natural gas. Therefore, this carbon has not been a part of ongoing processes that absorb and release carbon dioxide. From the perspective of geological time frames, this burning of fossil fuels is happening on a very short timescale. It is a geologic flash in the pan. (See fig. 1.2.)

What are the natural ongoing processes involving carbon? Trees and other green plants absorb carbon dioxide from the atmosphere—it is essential to their growth. When the plants die, they decay, releasing some carbon dioxide back to the atmosphere. Forest or brush fires release carbon dioxide to the atmosphere more quickly. A small portion of the carbon in plants may get buried and may ultimately, over a period of many millions of years, be converted to a fossil fuel. When we burn wood as a fuel, we release carbon dioxide, but this has no long-term effect on greenhouse gases, because the carbon dioxide released was absorbed from the atmosphere not too long ago. Wood burning does emit particles of ash and other pollutants that can have undesirable effects.

The reduction of forest cover to create cities, highways, and the like therefore also affects the balance of carbon dioxide in the atmosphere. But it is the burning of fossil fuels that has the greatest impact, and that is where the focus must be if we are to change the rate at which greenhouse gases are increasing. This, then, gets us into the familiar debates on how we produce energy, how we use energy, and what can be done to change these patterns.

But what is energy? Although the term is bandied about all the time and we all think we have some sense of what it means, it turns out that providing a satisfactory definition is

not a trivial matter. Many of the misunderstandings involved in the global-warming debate result from poor understanding of what energy is. For example, is hydrogen a source of energy or merely a means of transporting energy, and what is the difference (see everyday phenomenon box 18.1)? Much of the political hoopla regarding the hydrogen economy failed to address this basic question.

In this book, we will define energy initially in chapter 6, titled “Energy and Oscillations.” The prior chapters on mechanics provide the underpinnings for the introduction of the energy concept. In fact, it is difficult to understand how energy is defined without having some knowledge of mechanics. Following the introduction in chapter 6, energy ideas appear and are expanded in all of the chapters that follow. These ideas are central to all of physics.

Physics and energy

Understanding the definition of energy is obviously a good starting point for discussions of energy policies. The meaning of energy and the nature of energy transformations are firmly within the realm of physics. How we convert one form of energy to another, how we can use energy efficiently, and what it means to conserve energy are all topics that will come up in this book and in the study of physics more generally.

Many other topics within the realm of physics also play important roles in addressing energy issues. For example, transportation is a major area of energy use in our society. Cars, trucks, airplanes, boats, and trains are all part of the mix. They all utilize energy in some manner, but their basic physics can be understood from ideas in mechanics that are discussed in the early chapters of this book before energy ideas are introduced.

In the short term, one of our best options for reducing our use of fossil fuels involves energy conservation. Changes can be made in this realm more quickly than in the development of alternative energy resources. The rising costs of gasoline, diesel fuel, and fuel oil for heating have already been shown to significantly affect our energy consumption. Strictly speaking, we do not really consume energy—we simply convert it to less usable forms (see chapter 6 and chapter 11). The study of the mechanics of transportation (chapters 2–4) and the thermodynamics of engines (chapters 9–11) play important roles in energy conservation.

Questions regarding choices on how to generate usable forms of energy all involve physics concepts. Is it better to use natural gas than nuclear power (fig. 1.3), for example? Nuclear power has been a particularly contentious issue for many years and has suffered somewhat from the whims of political fashion. What is nuclear energy, and should we be rushing into a new commitment to its use, or should we be afraid of going there? Natural gas releases less carbon dioxide per unit of energy generated than does coal or oil, and it is a relatively clean fuel. It is, however, an emitter of greenhouse gases, and its long-term supply is questionable.

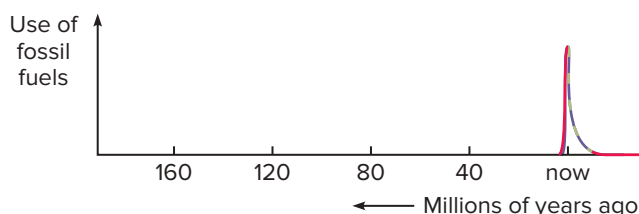


Figure 1.2 A schematic sketch of our use of fossil fuels on a geologic timescale. Coal, oil, and natural gas were produced from 40 million to 200 million years ago.



Figure 1.3 Are nuclear power plants our salvation or relics of the past? Steve Allen/Brand X Pictures/Alamy Stock Photo

Nuclear power does not involve the burning of a carbon-based fuel, so it does not release carbon dioxide into the atmosphere. For this reason, it is now receiving renewed attention as a possible resource for reducing our “carbon footprint.” Nuclear power does involve the mining of a limited resource, uranium, and has serious environmental issues associated with mining, possible accidents, and waste disposal. However, the utilization of any energy resource has environmental consequences, so the weighing of such issues must be an important aspect of our decision making.

We will not provide a definitive answer to the questions we have just raised. What we will do is discuss some of the basic physics underlying nuclear power, natural-gas power plants, and other resources used in electric power generation. Fossil-fuel power plants are discussed in chapter 11, and nuclear power is addressed in chapter 19. Many other means of generating energy will also be discussed, and some of the pros and cons of their use will be indicated in many sections of the book.

After studying these issues, will you win your argument with your friend? Perhaps not, but you will be in a much better position to debate the questions. Both of you may come to a better understanding of the real issues involved.

Political debates on climate change and energy utilization are important features of current events. The two topics are intimately related, because the burning of fossil fuels for energy generation is the primary cause of release into the atmosphere of the greenhouse gas carbon dioxide. Physics is the science of energy and is therefore heavily involved in decisions on energy conversion and utilization. Thus, the study of physics provides a basis for understanding some of the fundamental issues in these debates.

1.2 The Scientific Enterprise

How do scientists go about explaining something like the temperature change of the Earth or the rainbow described in the introduction? How do scientific explanations differ from other types of explanations? Can we count on the scientific method to explain almost anything? It is important to understand what science can and cannot do.

Philosophers have devoted countless hours and pages to questions about the nature of knowledge, and of scientific knowledge in particular. Many issues are still being refined and debated. Science grew rapidly during the twentieth century and has had a tremendous impact on our lives. Innovations in medicine, communications, transportation, and computer technology all have resulted from advances in science. What is it about science that explains its impressive advances and steady expansion?

Science and rainbows

Let’s consider a specific example of how a scientific explanation comes to be. Where would you turn for an explanation of how rainbows are formed? If you return from your bike ride with that question on your mind, you might look up *rainbow* in a textbook on physics or on the Internet and read the explanation found there. Are you behaving like a scientist?

The answer is both yes and no. Many scientists would do the same if they were unfamiliar with the explanation. When we do this, we appeal to the authority of the textbook author and to those who preceded the author in inventing the explanation. Appeal to authority is one way of gaining knowledge, but you are at the mercy of your source for the validity of your explanation. You are also hoping that someone has already raised the same question and done the work to create and test an explanation.

Suppose you go back three hundred years or more and try the same approach. One book might tell you that a rainbow is a painting of the angels. Another might speculate on the nature of light and its interactions with raindrops but be quite tentative in its conclusions. Either of these books might have seemed authoritative in its day. Where, then, do you turn? Which explanation will you accept?

If you are behaving like a scientist, you might begin by reading the ideas of other scientists about light and then test these ideas against your own observations of rainbows. You would carefully note the conditions when rainbows appear, the position of the sun relative to you and the rainbow, and the position of the rain shower. What is the order of the colors in the rainbow? Have you observed that order in other phenomena?

You would then invent an explanation, or **hypothesis**, using current ideas on light and your own guess about what happens as light passes through a raindrop. You could devise



Figure 1.4 French physicist and chemist Marie Curie (1867–1937) gives a lecture to an audience of men and women at the Conservatory of Arts and Crafts, Paris, 1925. Curie won Nobel prizes for both Physics (1903) and Chemistry (1911). Jacques Boyer/Roger Viollet/Getty Images

experiments with water drops or glass beads to test your hypothesis. (See chapter 17 for a modern view of how rainbows are formed.)

If your explanation is consistent with your observations and experiments, you could report it by giving a paper or talk to scientific colleagues. They may critique your explanation, suggest modifications, and perform their own experiments to confirm or refute your claims. If others confirm your results, your explanation will gain support and eventually become part of a broader **theory*** about phenomena involving light. The experiments you and others do may also lead to the discovery of new phenomena, which will call for refined explanations and theories.

What is critical to the process just described? First is the importance of careful observation. Another aspect is the idea of testability. An acceptable scientific explanation should suggest some means to test its predictions by observations or experiment. Saying that rainbows are the paintings of angels may be poetic, but it certainly is not testable by mere humans. It is not a scientific explanation.

Another important part of the process is a social one, the communication of your theory and experiments to colleagues (fig. 1.4). Submitting your ideas to the criticism (at times blunt) of your peers is crucial to the advancement of science. Communication is also important

in assuring your own care in performing the experiments and interpreting the results. A scathing attack by someone who has found an important error or omission in your work is a strong incentive for being more careful in the future. One person working alone cannot hope to think of all the possible ramifications, alternative explanations, or potential mistakes in an argument or theory. The explosive growth of science has depended heavily on cooperation and communication.

What is the scientific method?

Is there something we can call the **scientific method** within this description, and if so, what is it? The process just described is a sketch of how the scientific method works. Although there are variations on the theme, this method is often described as shown in table 1.1.

The steps in table 1.1 are all involved in our description of how to develop an explanation of rainbows. Careful observation may lead to **empirical laws** for when and where rainbows appear. An empirical law is a generalization derived from experiments or observations. An example of an empirical law is the statement that we see rainbows with the sun at our backs as we look at the rainbow. This is an important clue for developing our hypothesis, which must be consistent with this rule. The hypothesis, in turn, suggests ways of producing rainbows artificially that could lead to experimental tests and, eventually, to a broader theory.

This description of the scientific method is not bad, although it ignores the critical process of communication. Few scientists are engaged in the full cycle that these steps suggest. Theoretical physicists, for example, may spend all of their time with step 3. Although they have some interest in experimental results, they may never do any experimental work themselves. Today, little science is done by simple observation, as step 1 may seem to imply. Most observations are designed to test a hypothesis or existing theory and often involve carefully controlled

Table 1.1

Steps in the Scientific Method

1. Careful observation of natural phenomena.
2. Formulation of rules or empirical laws based on generalizations from these observations and experiments.
3. Development of hypotheses to explain the observations and empirical laws, and the refinement of hypotheses into theories.
4. Testing of the hypotheses or theories by further experiment or observation.

*The concept of a theory, as used in science, is often misunderstood. It is much more than a simple hypothesis. A theory consists of a set of basic principles from which many predictions can be deduced. The basic principles involved in the theory are often widely accepted by scientists working in the field.

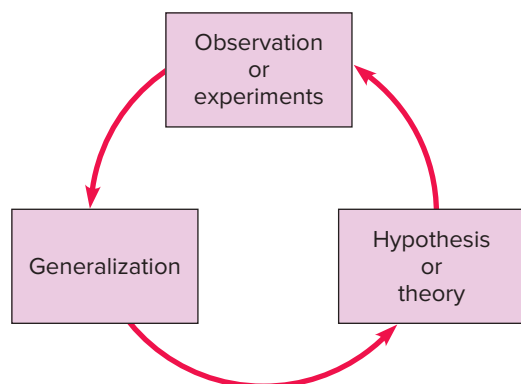


Figure 1.5 The scientific method cycles back to observations or experiments as we seek to test our hypotheses or theories. Communication with peers is involved in all stages of the process.

experiments. Although the scientific method is presented here as a stepwise process, in reality these steps often happen simultaneously with much cycling back and forth between steps (fig. 1.5).

The scientific method is a way of testing and refining ideas. Note that the method applies only when experimental tests or other consistent observations of phenomena are feasible. Testing is crucial for weeding out unproductive hypotheses; without tests, rival theories may compete endlessly for acceptance. Example box 1.1 provides a sample question and response illustrating these ideas.

How should science be presented?

Traditional science courses focus on presenting the results of the scientific process rather than the story of how scientists arrived at these results. This is why the general public often sees science as a collection of facts and established theories. To some extent, that charge could be made

Example Box 1.1

Sample Question: How Reliable Is Astrology?

Question: Astrologers claim that many events in our lives are determined by the positions of the planets relative to the stars. Is this a testable hypothesis?

Answer: Yes, it could be tested if astrologers were willing to make explicit predictions about future events that could be verified by independent observers. In fact, astrologers usually carefully avoid doing this, preferring to cast their predictions as vague statements subject to broad interpretation. This prevents clean tests. Astrology is not a science!

against this book, because it describes theories that have resulted from the work of others without giving the full picture of their development. Building on the work of others, without needing to repeat their mistakes and unproductive approaches, is a necessary condition for human and scientific progress.

This book attempts to engage you in the process of making your own observations and developing and testing your own explanations of everyday phenomena. By doing home experiments or observations, constructing explanations of the results, and debating your interpretations with your friends, you will appreciate the give-and-take that is the essence of science.

Whether or not we are aware of it, we all use the scientific method in our everyday activities. The case of the malfunctioning coffeemaker described in everyday phenomenon box 1.1 provides an example of scientific reasoning applied to ordinary troubleshooting.

The process of science begins with, and returns to, observations of or experiments on natural phenomena. Observations may suggest empirical laws, and these generalizations may be incorporated into a more comprehensive hypothesis. The hypothesis is then tested against more observations or by controlled experiments to form a theory. Working scientists are engaged in one or more of these activities, and we all use the scientific method on everyday problems.

Debatable Issue

We are often told that there is a strong consensus among climate scientists that global warming and climate change are being caused by human activity that is producing growing amounts of greenhouse gases, particularly carbon dioxide, in the atmosphere. Does a strong consensus among scientists imply that this idea is correct? Why or why not?

1.3 The Scope of Physics

Where does physics fit within the sciences? Since this book is about physics, rather than biology, chemistry, geology, or some other science, it is reasonable to ask where we draw the lines between the disciplines. It is not possible, however, to make sharp distinctions among the disciplines or to provide a definition of physics that will satisfy everyone. The easiest way to give a sense of what physics is and does is by example—that is, by listing some of its subfields and exploring their content. First, let's consider a definition, however incomplete.

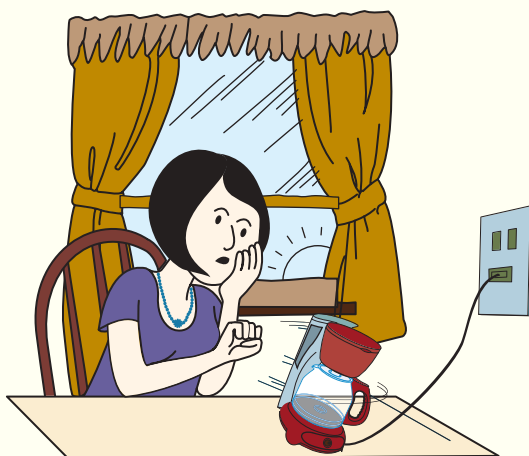
Everyday Phenomenon

Box 1.1

The Case of the Malfunctioning Coffeemaker

The Situation. It is Monday morning and you are, as usual, only half-awake and feeling at odds with the world. You are looking forward to reviving yourself with a freshly brewed cup of coffee when you discover that your coffeemaker refuses to function. Which of these alternatives is most likely to work?

1. Pound on the appliance with the heel of your hand.
2. Search desperately for the instruction manual, which you probably threw away two years ago.
3. Call a friend who knows about these things.
4. Apply the scientific method to troubleshoot the problem.



Fixing a malfunctioning coffee pot—alternative 1.

The Analysis. All of these alternatives have some chance of success. The sometimes positive response of electrical or mechanical appliances to physical abuse is well documented. The second two alternatives are both forms of appeal to authority that could produce results. The fourth alternative, however, may be the most productive and quickest, barring success with alternative 1.

How would we apply the scientific method as outlined in table 1.1 to this problem? Step 1 involves calmly observing the symptoms of the malfunction. Suppose that the coffeemaker simply refuses to heat up. When the switch is turned on, no

sounds of warming water are heard. You notice that no matter how many times you turn the switch on or off, no heat results. This is the kind of simple generalization called for in step 2.

We can now generate some hypotheses about the cause of the malfunction, as suggested in step 3. Here are some candidates:

- a. The coffeemaker is not plugged in.
- b. The external circuit breaker or fuse has tripped.
- c. The power is off in the entire house or neighborhood.
- d. An internal fuse in the coffeemaker has blown.
- e. A wire has become loose or burned through inside the coffeemaker.
- f. The internal thermostat of the coffeemaker is broken.

No detailed knowledge of electrical circuits is needed to check these possibilities, although the last three call for more sophistication (and are more trouble to check) than the first three. The first three possibilities are the easiest to check and should be tested first (step 4 in our method). A simple remedy such as plugging in the coffeemaker or flipping on a circuit breaker may put you back in business. If the power is off in the building, other appliances (lights, clocks, and so on) will not work, either, which provides an easy test. There may be little that you can do in this case, but at least you have identified the problem. Abusing the coffeemaker will not help.

The appliance may or may not have an internal fuse. If it is blown, a trip to the hardware store may be necessary. A problem like a loose wire or a burnt-out connection often becomes obvious by looking inside after you remove the bottom of the coffeemaker or the panel where the power cord comes in. (You must unplug the appliance before making such an inspection!) If one of these alternatives is the case, you have identified the problem, but the repair is likely to take more time or expertise. The same is true of the last alternative.

Regardless of what you find, this systematic (and calm) approach to the problem is likely to be more productive and satisfying than the other approaches. Troubleshooting, if done this way, is an example of applying the scientific method on a small scale to an ordinary problem. We are all scientists if we approach problems in this manner.

How is physics defined?

Physics can be defined as the *study of the basic nature of matter and the interactions that govern its behavior*. It is the most fundamental of the sciences. The principles and theories of physics can be used to explain the fundamental interactions involved in chemistry, biology, and other sciences at

the atomic or molecular level. Modern chemistry, for example, uses the physical theory of *quantum mechanics* to explain how atoms combine to form molecules. Quantum mechanics was developed primarily by physicists in the early part of the twentieth century, but chemists and chemical knowledge also played important roles. Ideas about

energy that arose initially in physics are now used extensively in chemistry, biology, and other sciences.

The general realm of science is often divided into the life sciences and the physical sciences. The life sciences include the various subfields of biology and the health-related disciplines that deal with living organisms. The physical sciences deal with the behavior of matter in both living and nonliving systems. In addition to physics, the physical sciences include chemistry, geology, astronomy, oceanography, and meteorology (the study of weather). Physics underlies all of them.

Physics is also generally regarded as the most quantitative of the sciences. It makes heavy use of mathematics and numerical measurements to develop and test its theories. This aspect of physics has often made it seem less accessible to students, even though the models and ideas of physics can be described more simply and cleanly than those of other sciences. As we will discuss in section 1.4, mathematics serves as a compact language, allowing briefer and more precise statements than would be possible without its use. However, the quantitative skills needed to understand this book are minimal.

What are the major subfields of physics?

The primary subfields of physics are listed and identified in table 1.2. Mechanics, which deals with the motion (or lack of motion) of objects under the influence of forces, was the first subfield to be explained with a comprehensive theory. Newton’s theory of mechanics, which he developed in the last half of the seventeenth century, was the first full-fledged physical theory that made extensive use of mathematics. It became a prototype for subsequent theories in physics.

The first four subfields listed in table 1.2 were well developed by the beginning of the twentieth century, although all have continued to advance since then. These subfields—mechanics, thermodynamics, electricity and magnetism, and

optics—are sometimes grouped as **classical physics**. The last four subfields—atomic physics, nuclear physics, particle physics, and condensed-matter physics—are often grouped under the heading of **modern physics**, even though all of the subfields are part of the modern practice of physics. The distinction is made because the last four subfields all emerged during the twentieth century and only existed in rudimentary forms before the turn of that century. In addition to the subfields listed in table 1.2, many physicists work in interdisciplinary fields such as biophysics, geophysics, or astrophysics.

The photographs in this section (fig 1.6, fig. 1.7, fig. 1.8, and fig. 1.9) illustrate characteristic activities or applications



Figure 1.6 A surgeon using a laser. Larry Mulvehill/Corbis/SuperStock



Figure 1.7 An infrared photograph showing patterns of heat loss from a house is an application of thermodynamics. Dirk Püschel/Hemera/Getty Images

Table 1.2
The Major Subfields of Physics
Mechanics. The study of forces and motion.
Thermodynamics. The study of temperature, heat, and energy.
Electricity and magnetism. The study of electric and magnetic forces and electric current.
Optics. The study of light.
Atomic physics. The study of the structure and behavior of atoms.
Nuclear physics. The study of the nucleus of the atom.
Particle physics. The study of subatomic particles (quarks, etc.).
Condensed-matter physics. The study of the properties of matter in the solid and liquid states.



Figure 1.8 A power plant at Nellis Air Force Base utilizes photovoltaic solar cells. *Stocktrek Images/Getty Images*



Figure 1.9 The Large Hadron Collider (LHC) is an accelerator used to study interactions of subatomic particles at very high energies. It is located at CERN, the European Particle-physics laboratory in Switzerland. *Fabrice Coffrini/AFP/Getty Images*

of the subfields. The invention of the laser has been an extremely important factor in the rapid advances now taking place in optics, as well as many advances in the medical field (fig. 1.6). The development of the infrared camera has provided a tool for the study of heat flow from buildings, which involves thermodynamics (fig. 1.7). The rapid growth in consumer electronics, as seen in the availability of laptop computers, smartphones, and many other “essential” personal paraphernalia, has been made possible by developments in condensed-matter physics. These developments, as well as the development of photovoltaic solar cells (fig 1.8), all involve applications of semiconductors. Particle physicists use particle accelerators to study the interactions of subatomic particles in high-energy collisions. The Large Hadron Collider (fig. 1.9) was used in the discovery of the Higgs Boson in 2012.

Science and technology depend on each other for progress. Physics plays an important role in the education and work of engineers, whether they specialize in electrical, mechanical, nuclear, or other engineering fields. In fact, people with physics degrees often work as engineers when they are employed in industry. The lines between physics and engineering, or research and development, often blur. Physicists are generally concerned with developing a fundamental understanding of phenomena, and engineers with applying that understanding to practical tasks or products, but these functions often overlap.

One final point: Physics is fun. Understanding how a bicycle works or how a rainbow is formed has an appeal that anyone can appreciate. The thrill of gaining insight into the workings of the universe can be experienced at any level. In this sense, we can all be physicists.

Physics is the study of the basic characteristics of matter and its interactions. It is the most fundamental of the sciences; many other sciences build on ideas from physics. The major subfields of physics are mechanics, electricity and magnetism, optics, thermodynamics, atomic and nuclear physics, particle physics, and condensed-matter physics. Physics plays an important role in engineering and technology, but the real fun of physics comes from understanding how the universe works.

1.4 The Role of Measurement and Mathematics in Physics

If you go into your college library, find a volume of *Physical Review* or some other major physics journal, and open it at random, you are likely to find a page with many mathematical symbols and formulas. It would probably be incomprehensible to you. In fact, even many physicists who are not specialists in the particular subfield covered by the article might have difficulty making sense of that page, because they would not be familiar with the particular symbols and definitions.

Why do physicists make such extensive use of mathematics in their work? Is knowledge of mathematics essential to understanding the ideas being discussed? Mathematics is a compact language for representing the ideas of physics that makes it easier to precisely state and manipulate the relationships between the quantities that we measure in physics. Once you are familiar with the language, its mystery disappears and its usefulness becomes more obvious. Still, this book uses mathematics in a very limited manner, because most ideas of physics can be discussed without extensive use of mathematics.

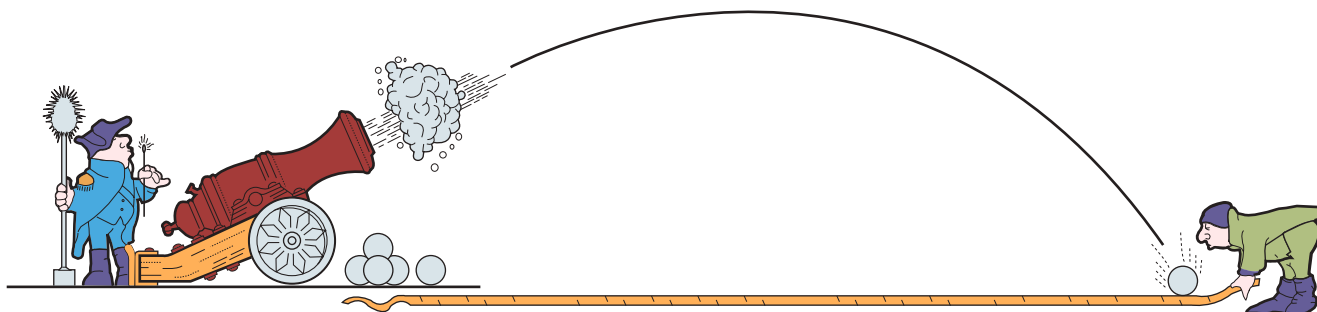


Figure 1.10 Cannonballs and a measuring tape: the proof lies in the measurement.

Why are measurements so important?

How do we test theories in physics? Without careful measurements, vague predictions and explanations may seem reasonable, and making choices between competing explanations may not be possible. A quantitative prediction, on the other hand, can be tested against reality, and an explanation or theory can be accepted or rejected based on the results of measurements. If, for example, one hypothesis predicts that a cannonball will land 100 meters from us and another predicts a distance of 200 meters under the same conditions, firing the cannon and measuring the actual distance provide persuasive evidence for one of these hypotheses (fig. 1.10). The rapid growth and successes of physics began when the idea of making precise measurements as a test was accepted.

Life is full of situations in which measurements and measurable quantities, as well as the ability to express relationships between them, are important. Imagine that you are working on a tree farm and want to impress your boss. You have just finished planting 300 seedlings on 2.4 acres, when your boss asks how many seedlings will be needed for a second location of 4 acres. You don't want to waste money on too many seedlings; nor do you want too few. Perhaps you can solve the problem in your head, but this might be hard to describe in words to your boss and might just confuse the issue.

How can mathematics help?

You can reduce the confusion by creating a word statement for this situation. You can say, "The quantity needed for 4 acres is related to the quantity for 2.4 acres as 4 is to 2.4." This still takes quite a few words, though, and such a **proportion** statement may not be familiar to the boss.

To make your statement briefer, you can use the symbols Q to represent the quantity of seedlings needed for 4 acres and Q_o to represent the quantity needed for the original 2.4 acres, then express them as a mathematical equation:

$$\frac{Q}{Q_o} = \frac{4}{2.4}$$

Using symbols is simply a compact way of saying the same thing you previously expressed in words. This compact

statement also has the advantage of making it easier for you to manipulate the relationship. For example, if you multiply both sides of this equation by Q_o , it takes the form

$$Q = \left(\frac{4}{2.4}\right) Q_o$$

which, in words, says that the quantity needed for 4 acres is $(4/2.4)$ times the quantity needed for 2.4 acres. If, instead, you want to find the number needed for 8 acres, you can easily see it is just $Q = (8/2.4) Q_o$. If you are comfortable with fractions, you can use this relationship to quickly find the proper quantity for any number of acres.

A common, everyday situation in which you might use this idea of proportion to your advantage is with recipes. Everyday phenomenon box 1.2 addresses the challenge of taking a frosting recipe for two cakes and scaling it up for five cakes.

There are a few important points to these examples. First, making measurements and using measurable quantities are both a routine and an important part of everyday experience. Second, using symbols to represent quantities in a mathematical statement is a shorter way of expressing an idea involving numbers than the same statement in words. Using mathematics also makes it easier to manipulate relationships to construct concise arguments. These are the reasons that physicists (and many other people) find mathematical statements useful.

Why are metric units used?

Units of measurement are an essential part of any measurement. We do not communicate clearly if we just state a number. If you just talked about adding $1\frac{1}{3}$ of milk, for example, your statement would be incomplete. You need to indicate whether you are talking about cups, pints, or milliliters.

The liter and milliliter are *metric* units of volume. Cups, pints, quarts, and gallons are holdovers from the older English system of units. Most countries have now adopted the **metric system**, which has several advantages over the English system still used in the United States. The main advantage of the metric system is its use of standard prefixes to represent multiples of 10, making unit conversion within the

Everyday Phenomenon

Box 1.2

Scaling a Recipe

The Situation. You have an excellent recipe for vanilla frosting, which you have made to ice two cakes. However, your friends want you to take five cakes to your annual club meeting. How do you scale up the recipe, so that you have just enough icing for five cakes? How can your newfound understanding of proportions help you?



Putting finishing touches on a cake.

The Analysis. According to our understanding of proportions, the quantity of frosting needed for five cakes is to the quantity needed for two cakes as 5 is to 2. Another way we can look at this is by using symbols. If we let Q_2 be the quantity needed for two cakes and Q_5 be the quantity needed for five cakes, then we can write the relationship as

$$\frac{Q_5}{Q_2} = \frac{5}{2}$$

We can rewrite this equation to solve for Q_5 (which is the quantity we are looking for) by multiplying both sides by Q_2 :

$$(Q_2)\left(\frac{Q_5}{Q_2}\right) = (Q_2)\left(\frac{5}{2}\right)$$

Notice that on the left-hand side the Q_2 in the numerator cancels the Q_2 in the denominator, so the equation becomes

$$Q_5 = (Q_2)\left(\frac{5}{2}\right)$$

In words, this translates to “the quantity needed for five cakes is equal to the quantity used for two cakes times the ratio (5/2).”

Now, let’s look at the recipe. The recipe for two cakes is as follows:

- 16 cups confectioners’ sugar
- 1 cup butter, softened
- 1 cup whole milk
- 1 tablespoon vanilla extract

Combine butter, milk, and vanilla. Beat on medium speed until smooth. Gradually add sugar while beating until smooth and fluffy.

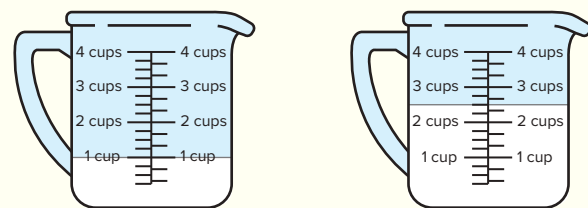
To expand the recipe for five cakes, we would multiply each quantity by (5/2). Let’s look at the amount of milk:

$$(1 \text{ cup})\left(\frac{5}{2}\right) = \frac{5}{2} \text{ cups} = 2\frac{1}{2} \text{ cups} = 2.5 \text{ cups}$$

We can do the same for the other ingredients. Our revised frosting recipe for five cakes is thus

- 40 cups confectioners’ sugar
- 2.5 cups butter, softened
- 2.5 cups whole milk
- 2.5 tablespoons vanilla extract

Once you know how to use proportions to scale recipes up (or down), you will be much more confident when determining the quantities needed. This skill is useful in many aspects of everyday living. Determining quantities such as the amount of paint needed for a project, or the number of pizzas to order, becomes less problematic. In fact, you just might find yourself the person your friends turn to when scaling quantities up or down.



Two measuring cups, one containing enough milk for frosting two cakes and one for frosting five cakes.

system quite easy. The fact that a kilometer (km) is 1000 meters and a centimeter (cm) is $1/100$ of a meter, and that the prefixes *kilo* and *centi* always mean 1000 and $1/100$, makes these conversions easy to remember (see table 1.3).

To convert 30 centimeters to meters, all we have to do is move the decimal point two places to the left to get 0.30 meter. Moving the decimal point two places to the left is equivalent to dividing by 100.

Table 1.3

Commonly Used Metric Prefixes

Prefix	Meaning		
	in figures	in scientific notation	in words
tera	1 000 000 000 000	$= 10^{12}$	= 1 trillion
giga	1 000 000 000	$= 10^9$	= 1 billion
mega	1 000 000	$= 10^6$	= 1 million
kilo	1000	$= 10^3$	= 1 thousand
centi	$\frac{1}{100}$ = 0.01	$= 10^{-2}$	= 1 hundredth
milli	$\frac{1}{1000}$ = 0.001	$= 10^{-3}$	= 1 thousandth
micro	$\frac{1}{1\,000\,000}$ = $\frac{1}{10^6}$	$= 10^{-6}$	= 1 millionth
nano	$\frac{1}{1\,000\,000\,000}$ = $\frac{1}{10^9}$	$= 10^{-9}$	= 1 billionth
pico	$= \frac{1}{10^{12}}$	$= 10^{-12}$	= 1 trillionth

Table 1.3 is a list of the common prefixes used in the metric system. (See appendix B for a discussion of the **powers of 10**, or **scientific notation**, used for describing very large and very small numbers.) The basic unit of volume in the metric system is the liter (L), which is slightly larger than a quart (1 liter = 1.057 quarts). A milliliter (mL) is $\frac{1}{1000}$ of a liter, a convenient size for quantities in recipes. One milliliter is also equal to 1 cm³, or 1 cubic centimeter, so there is a simple relationship between the length and volume measurements in the metric system. Such simple relationships are hard to find in the English system, where 1 cup is $\frac{1}{4}$ of a quart, and a quart is 67.2 cubic inches.

Example Box 1.2

Sample Exercise: Length Conversions

If you are told that there are 2.54 cm in 1 inch,

- How many centimeters are there in 1 foot (12 inches)?
- How many meters does 1 foot represent?

- 1 inch = 2.54 cm
1 foot = 12 inches
1 foot = ? (in cm)

$$(1 \text{ ft}) \left(\frac{12 \text{ in}}{1 \text{ ft}} \right) \left(\frac{2.54 \text{ cm}}{1 \text{ in}} \right) = 30.5 \text{ cm}$$

$$\mathbf{1 \text{ foot} = 30.5 \text{ cm}}$$

- 1 foot = 30.5 cm
1 m = 100 cm
1 foot = ? (in m)

$$(1 \text{ ft}) \left(\frac{30.5 \text{ cm}}{1 \text{ ft}} \right) \left(\frac{1 \text{ m}}{100 \text{ cm}} \right) = 0.305 \text{ m}$$

$$\mathbf{1 \text{ foot} = 0.305 \text{ m}}$$

Lines drawn through the units indicate cancellation.

The metric system predominates in this book. English units will be used occasionally because they are familiar to many and can help in learning new concepts. Most people in the United States still relate more readily to distances in miles than in kilometers, for example. That there are 5280 feet in a mile is a nuisance, however, compared to the tidy 1000 meters in 1 kilometer. Becoming familiar with the metric system is a worthy objective. Your ability to participate in international trade (for business or pleasure) will be enhanced if you are familiar with the system of units used in most of the world. Example boxes 1.2 and 1.3 provide unit conversion exercises involving metric units.

Example Box 1.3

Sample Exercise: Rate Conversions

If the rate of flow in an automatic watering system is 2 gallons/hour, how many milliliters per minute is this?

- 1 gallon = 3.786 liters
1 liter = 1000 mL
2 gal/h = ? (in mL/min)

$$\left(\frac{2 \text{ gallons}}{1 \text{ hour}} \right) \left(\frac{3.786 \text{ liter}}{1 \text{ gallon}} \right) \left(\frac{1000 \text{ mL}}{1 \text{ liter}} \right) \left(\frac{1 \text{ hour}}{60 \text{ min}} \right) = 126.2 \text{ mL/min}$$

$$\mathbf{2 \text{ gallons/hour} = 126.2 \text{ mL/min}}$$

Lines drawn through the units indicate cancellation.

Stating a result or prediction in numbers lends precision to otherwise vague claims. Measurement is an essential part of science and of everyday life. Using mathematical symbols and statements is an efficient way of stating the results of measurements and eases manipulating the relationships between quantities. Units of measurement are an essential part of any measurement, and the metric system of units used in most of the world has a number of advantages over the older English system.

1.5 Physics and Everyday Phenomena

Studying physics can and will lead us to ideas as earthshaking as the fundamental nature of matter and the structure of the universe. With ideas like these available, why spend time on more mundane matters like explaining how a bicycle stays upright or how a flashlight works? Why not just plunge into far-reaching discussions of the fundamental nature of reality?

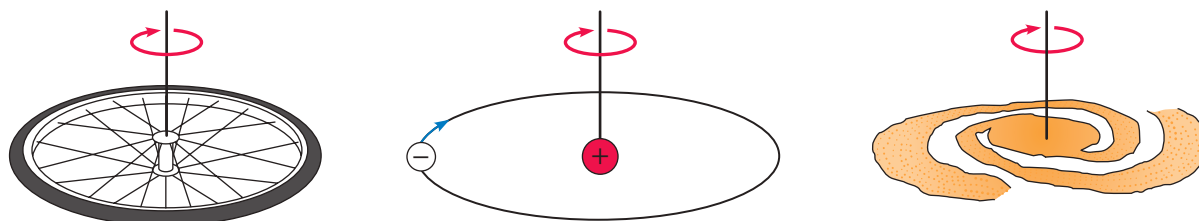


Figure 1.11 A bicycle wheel, a model of an atom, and a galaxy all involve the concept of angular momentum.

Why study everyday phenomena?

Our understanding of the fundamental nature of the universe is based on concepts such as mass, energy, and electric charge that are abstract and not directly accessible to our senses. It is possible to learn some of the words associated with these concepts and to read and discuss ideas involving them without ever acquiring a good understanding of their meaning. This is one risk of playing with the grand ideas without laying the proper foundation.

Using everyday experience to raise questions, introduce concepts, and practice devising physical explanations has the advantage of dealing with examples that are familiar and concrete. These examples also appeal to your natural curiosity about how things work, which, in turn, can motivate you to understand the underlying concepts. If you can clearly describe and explain common events, you gain confidence in dealing with more abstract concepts. With familiar examples, the concepts are set on firmer ground, and their meaning becomes more real.

For example, why a bicycle (or a top) stays upright while moving but falls over when at rest involves the concept of angular momentum, which is discussed in chapter 8. Angular momentum also plays a role in our understanding of atoms and the atomic nucleus—both in the realm of the very small—and the structure of galaxies at the opposite end of the scale (fig. 1.11). You are more likely to understand angular momentum, though, by discussing it first in the context of bicycle wheels or tops.

The principles explaining falling bodies, such as the acorn mentioned in the chapter introduction, involve the concepts of velocity, acceleration, force, and mass, which are discussed in chapter 2, chapter 3, and chapter 4. Like angular momentum, these concepts are also important to

our understanding of atoms and the universe. Energy ideas, introduced initially in chapter 6, appear throughout the chapters that follow in the textbook. These ideas are crucial to the understanding of the universe, as well as to everyday concerns such as climate change and energy conservation.

Our “common sense” sometimes misleads us in our understanding of everyday phenomena. Adjusting common sense to incorporate well-established physical principles is one of the challenges we face in dealing with everyday experience. By performing simple experiments, either in laboratories and demonstrations associated with your course in physics or at home (as is often suggested in this book), you can take an active part in building your own scientific worldview.

Although it may seem like an oxymoron, everyday experience is extraordinary. A bright rainbow is an incredible sight. Understanding how rainbows originate does not detract from the experience. It adds excitement to explain such a beautiful display with just a few elegant concepts. In fact, people who understand these ideas see more rainbows because they know where to look. This excitement, and the added appreciation of nature that is a part of it, is accessible to all of us.

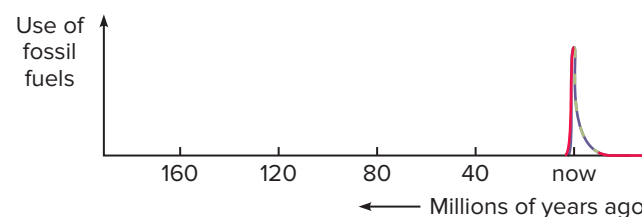
Studying everyday phenomena can make abstract ideas more accessible. These ideas are needed to understand the fundamental nature of matter and the universe, but they are best encountered first in familiar examples. Being able to explain common phenomena builds confidence in using the ideas and enhances our appreciation of what happens around us.

Summary

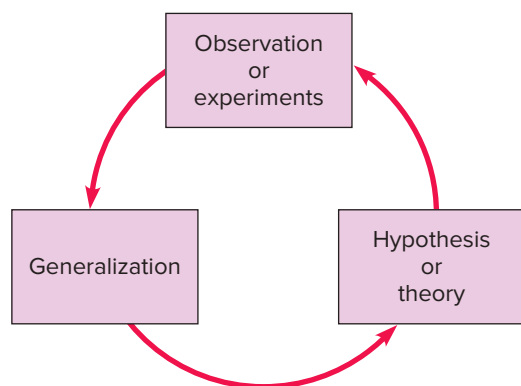
This first chapter introduces the connections between physics and everyday phenomena, including current issues involving energy. We also introduce the scientific enterprise and its methods, the scope of physics, and the use of mathematics and measurement in physics. The key points include the following:

- 1 **What about energy?** Most of our use of energy involves the burning of fossil fuels, which release carbon, and this affects many aspects of the Earth’s climate, including global warming. The definition and science of energy are in the realm of physics,

and therefore some understanding of this physics is crucial to meaningful participation in these debates.



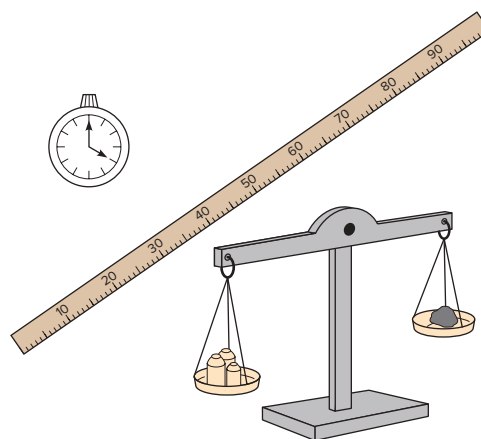
2 The scientific enterprise. Scientific explanations are developed by generalizing from observations of nature; forming hypotheses, or theories; and then testing these theories by further experiments or observations. This process is often called the *scientific method*, but actual practice may depart in various ways from this model.



3 The scope of physics. Physics is the most fundamental of the natural sciences, because physical theories often underlie explanations in the other sciences. Its major subfields include mechanics, thermodynamics, electricity and magnetism, optics, atomic physics, nuclear physics, condensed-matter physics, and particle physics.

4 The role of measurement and mathematics in physics. Much of the progress in physics can be attributed to its use of quantitative models, which yield precise predictions that can be tested by making physical measurements (with well-defined

units). Mathematics is a compact language for describing and manipulating these results. The basic concepts of physics can often be described and understood with a minimum of mathematics.



5 Physics and everyday phenomena. Many of the basic concepts of physics become clearer if applied to everyday phenomena. Being able to understand and explain familiar phenomena makes the concepts more vivid. This adds to the enjoyment of studying physics.



If you want an extra drill in doing algebraic manipulations of equations, or doing unit conversions, try the practice problems in Connect.

Key Terms

Hypothesis, 4
Theory, 5
Scientific method, 5
Empirical law, 5
Classical physics, 8
Modern physics, 8

Mechanics, 8
Thermodynamics, 8
Electricity and magnetism, 8
Optics, 8
Atomic physics, 8
Nuclear physics, 8

Particle physics, 8
Condensed-matter physics, 8
Proportion, 10
Metric system, 10
Powers of 10, 12
Scientific notation, 12

Conceptual Questions

* = more open-ended questions, requiring lengthier responses, suitable for group discussion

Q = sample responses are available in appendix D

Q = sample responses are available on Connect

Q1. Are fossil fuels produced within a few hundred years after dead plant remains are covered by dirt? Explain.

Q2. Do trees and other green plants have any impact on the amount of carbon dioxide in the atmosphere? Explain.

Q3. Since burning wood releases carbon dioxide to the atmosphere, should wood be considered a fossil fuel? Explain.

***Q4.** If the amount of carbon dioxide in the atmosphere is increasing with time, should we expect an increase in the average global temperature? Explain.

Q5. Has the burning of fossil fuels been taking place on a significant scale over many thousands of years? Explain.

Q6. Does the use of nuclear power significantly increase the amount of carbon dioxide in the atmosphere? Explain.

***Q7.** Which of these criteria best distinguish between explanations provided by science and those provided by religion: truth, testability, or appeal to authority? How do religious explanations differ from scientific explanations?

Q8. A person claiming to have paranormal powers states that she can predict which card will come up next in a shuffled deck of cards simply by exercising her mental powers. Is this a testable claim? Explain.

Q9. Historians sometimes develop theories to explain observed patterns in the history of different countries. Are these

theories testable in the same sense as a theory in physics? Explain.

- *Q10. Over the years, there have been several credible claims by experienced observers of sightings of unidentified flying objects (UFOs). Despite this, scientists have shied away from taking up a serious study of UFOs, although there are ongoing searches for signals from extraterrestrial intelligent beings. Can you think of reasons that scientists have not taken UFOs seriously? What problems can you see in trying to study UFOs?
- Q11. Suppose that your car will not start and you form the hypothesis that the battery is dead. How would you test this hypothesis? Explain. (See everyday phenomenon box 1.1.)
- Q12. Suppose that your phone has not rung in several days, but a friend tells you he has tried to call. Develop two hypotheses that could explain why the phone has not rung and state how you would test these hypotheses. (See everyday phenomenon box 1.1.)
- *Q13. Suppose that a friend states the hypothesis that the color of socks that he wears on a given day, brown or black, will determine whether the stock market will go up or down. He can cite several instances in which this hypothesis has been apparently verified. How would you go about evaluating this hypothesis?
- Q14. Which of the three science fields—biology, chemistry, or physics—would you say is the most fundamental? Explain by describing in what sense one of these fields may be more fundamental than the others.
- Q15. Based on the brief descriptions provided in table 1.2, which subfield of physics would you say is involved in the explanation of rainbows? Which subfield is involved in describing how an acorn falls? Explain.
- Q16. Based on the descriptions provided in table 1.2, which subfields of physics are involved in explaining why an ice cube melts? Which subfields are involved in explaining how an airplane flies? Explain.
- Q17. Suppose you are told that speed is defined by the relationship $s = d/t$, where s represents speed, d represents distance, and t represents time. State this relationship in words, using no mathematical symbols.
- Q18. Impulse is defined as the average force acting on an object multiplied by the time the force acts. If we let I represent impulse, F the average force, and t the time, is $I = F/t$ a correct way of expressing this definition? Explain.
- Q19. The distance that an object travels when it starts from rest and undergoes constant acceleration is one-half the acceleration multiplied by the square of the time. Invent your own symbols and express this statement in symbolic form.
- Q20. What are the primary advantages of the metric system of units over the older English system of units? Explain.
- Q21. What are the advantages, if any, of continuing to use the English system of units in industry and commerce rather than converting to the metric system? Explain.
- Q22. Which system of units, the metric system or English system, is used more widely throughout the world? Explain.
- Q23. The width of a man's hand was used as a common unit of length several hundred years ago. What are the advantages and disadvantages of using such a unit? Explain.
- Q24. A pirate map indicates that a treasure is buried 50 paces due east and 120 paces due north of a big rock. Will you know where to dig? Explain.
- Q25. List the following volumes in descending order: gallon, quart, liter, milliliter. The conversion factors given in appendix E may be useful.
- Q26. List the following lengths in descending order: kilometer, foot, mile, centimeter, inch. The conversion factors given in appendix E may be useful.

Exercises

- E1. Suppose that a pancake recipe designed to feed five people calls for 310 grams of flour. How many grams of flour would you use if you wanted to reduce the recipe to only feed two people? (See everyday phenomenon box 1.2.)
- E2. Suppose that a cupcake recipe designed to produce 16 cupcakes calls for 240 grams of flour. How many grams of flour would you use if you wanted to make 20 cupcakes? (See everyday phenomenon box 1.2.)
- E3. It is estimated that eight medium pizzas are about right to serve a physics club meeting of 32 students. How many pizzas would be required if the group, due to a conflicting math club meeting, were only going to have 20 students in attendance? (See everyday phenomenon box 1.2.)
- E4. A child uses her hand to measure the width of a tabletop. If her hand has a width of 8 cm at its widest point, and she finds the tabletop to be 16.5 hands wide, what is the width of the tabletop in cm? In meters?
- E5. A small woman's foot is 7 inches long. If she steps off the length of a room by placing one foot directly in front of the other, and finds the room to be 15 foot-lengths long, what is the length of the room in inches? In feet?
- E6. A paperback book is 220 mm in height. What is this height in centimeters? In meters?
- E7. A crate has a mass of 8.30×10^6 mg (milligrams). What is this mass in grams? In kilograms? (Hint: See table 1.3.)
- E8. A tank holds 5260 L (liters) of water. How many kiloliters is this? How many milliliters? (Hint: See table 1.3.)
- E9. A mile is 5280 ft long. The sample exercise in example box 1.2 shows that 1 foot is approximately 0.305 m. How many meters are in a mile? How many kilometers (km) are in a mile?
- E10. If a mile is 5280 ft long and a yard contains 3 ft, how many yards are in a mile?

- E11. Area is found by multiplying the length of a surface times the width. If a floor measures 5.28 m^2 , how many square centimeters does this represent? How many square centimeters are in 1 m^2 ?
- E12. A common speed limit in Vancouver, British Columbia, is 70 km/h . If you are going 45 MPH , are you speeding? Show by converting 45 MPH to km/h using the conversion factors in appendix E.
- E13. If gas costs $\$1.27$ a liter, how much does a gallon of gas cost? Show by converting gallons to liters using the conversion factors in appendix E.
- E14. The volume of a cube is found by multiplying length times width times height. If an object has a volume of 1.44 m^3 , what is the volume in cubic centimeters? Remember to multiply each side by the conversion factor.
- E15. If the area of a square has increased by a factor of 16, by how much has each side increased?
- E16. A cube has a certain volume. If the length of each side is tripled, by what factor will the volume increase?

Synthesis Problems

- SP1. Astrologers claim that they can predict important events in your life by the configuration of the planets and the astrological sign under which you were born. Astrological predictions, called horoscopes, can be found in most daily newspapers. Find these predictions in a newspaper and address the questions:
- Are the astrological predictions testable?
 - Choosing the prediction for your own sign, how would you go about testing its accuracy over the next month or so?
 - Why do newspapers print these readings? What is their appeal?
- SP2. In the United States, a common quantity of hard liquor was historically a fifth, which represents a fifth of a U.S. gallon. However, because the United States wants to market its alcohol globally, and everyone else uses the metric system, it has retooled its packaging, so a common quantity is now 750 mL .
- How many liters are in a fifth?
 - How many milliliters are in a fifth?
 - Which is larger, 750 mL or a fifth of a gallon?
- SP3. A compact fluorescent light (CFL) bulb is very energy-efficient. A 22W CFL bulb has the same brightness as a 100W incandescent bulb. (Note that these calculations ignore the fact that the CFL bulb can last up to 10 times as long as the incandescent bulb. This would increase your savings even more.)
- If you have this lightbulb on for 5 hours a day, for 350 days during a year, how many hours is it on?
 - A kilowatt is 1000 watts. The kilowatt-hour is a common unit for energy, obtained by multiplying the power in kilowatts by the time used in hours. How many kilowatt-hours (kWh) will you use when burning the 100W bulb for the year (don't forget to convert the 100W to kW first)?
 - How many kilowatt-hours (kWh) will you use when burning the 22W bulb for the year (be sure to convert the 22W to kW before multiplying by the time in hours)?
 - Assuming that the cost of electricity is 15¢ per kWh, what is the cost of using the 100W incandescent bulb for the year?
 - Assuming this same cost, what is the cost of using the 22W CFL bulb for the year?
 - How much do you save per year by using the 22W CFL bulb?
 - How much would you save every year if you replaced 20 of the 100W incandescent bulbs with the 22W CFL bulbs?

Home Experiments and Observations

- HE1. Look around your house, car, or dormitory room to see what measuring tools (rulers, measuring cups, speedometers, etc.) you have handy. Which of these tools, if any, provides both English and metric units? For those that do, determine the conversion factor needed to convert the English units to metric units.
- HE2. Find 200 pennies (or other small, identical objects—cardboard squares will work). Create a square with 3 pennies in each of 3 rows. Represent the area as width $\times$ length, or 3×3 pennies, or 9 pennies.
- Double the number of pennies in each row and column. What is the area now? How much bigger is it than the original area? Is it twice as big? Is it four times as big?
 - Now double the number of pennies in each row and column once more. Can you correctly predict the area?
 - What is the pattern? If you started with a square with 2 pennies to the side, and you tripled the number of pennies in each row and column, how much greater would the area be? See if you can predict the answer before trying it.
 - Can you state the rule? If you multiply each side of an area by “n,” by how much does the area increase, in terms of “n”?

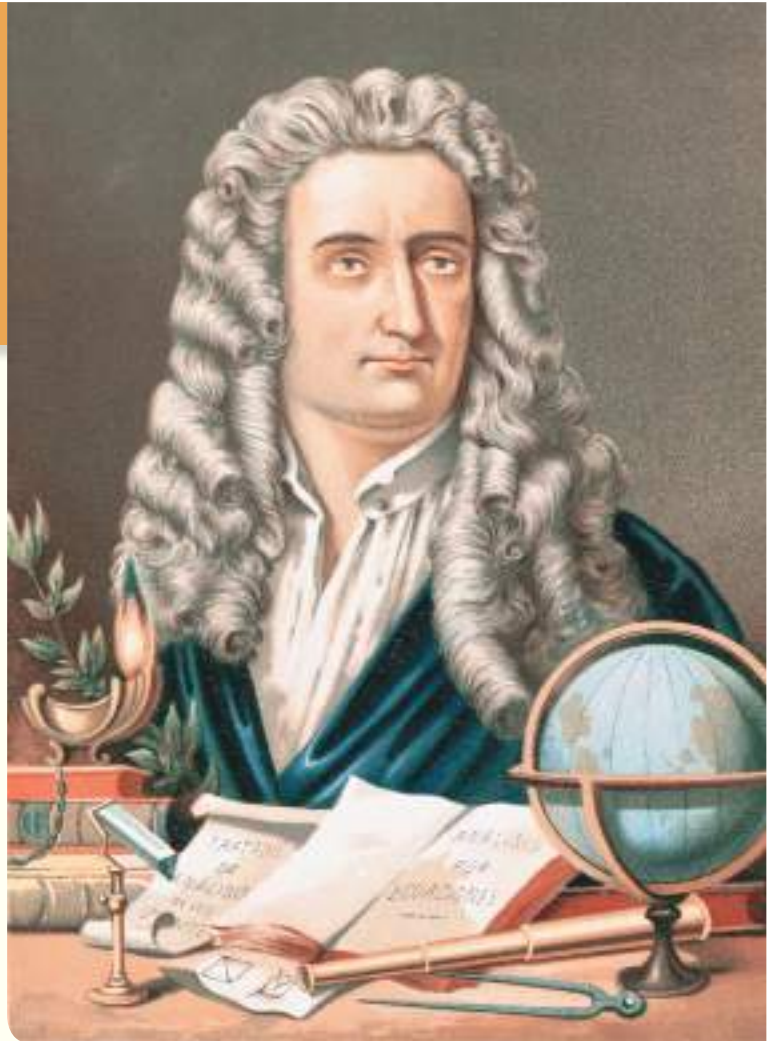
UNIT 1

The Newtonian Revolution

In 1687, Isaac Newton published his *Philosophiae Naturalis Principia Mathematica*, or *Mathematical Principles of Natural Philosophy*. This treatise, often called simply Newton's *Principia*, presented his theory of motion, which included his three laws of motion and his law of universal gravitation. Together these *laws* explain most of what was then known about the motion of ordinary objects near Earth's surface (terrestrial mechanics), as well as the motion of the planets around the sun (celestial mechanics). Along the way, Newton had to invent the mathematical techniques that we call calculus.

Newton's theory of mechanics described in the *Principia* was an incredible intellectual achievement that revolutionized both science and philosophy. The revolution did not begin with Newton, though. The true rebel was Italian scientist Galileo Galilei, who died just a few months after Newton was born in 1642. Galileo championed the sun-centered view of the solar system proposed a hundred years earlier by Nicolaus Copernicus and stood trial under the Inquisition for his pains. Galileo also challenged the conventional wisdom, based on Aristotle's teachings, about the motion of ordinary objects. In the process, he developed many of the principles of terrestrial mechanics that Newton later incorporated into his theory.

Although Newton's theory of motion does not accurately describe the motion of very fast objects (which are now described using Einstein's theory of relativity) and very small objects (for which quantum mechanics must be used), it is still used extensively in physics and engineering to explain motion and to analyze structures. Newton's



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theory has had enormous influence over the last three hundred years in realms of thought that extend well beyond the natural sciences and deserves to be understood by anyone claiming to be well educated.

Central to Newton's theory is his second law of motion. It states that the acceleration of an object is proportional to the net force acting on the object and inversely proportional to the mass of the object. Push an object and that object accelerates in the direction of the applied force. Contrary to intuition and to Aristotle's teachings, acceleration, not velocity, is proportional to the applied force. To understand this idea, we will thoroughly examine acceleration, which involves a *change* in the motion of an object.

Rather than plunging into Newton's theory, we begin this unit by studying Galileo's insights into motion and free fall. This provides the necessary foundation to tackle Newton's ideas. To see well, we need to stand on the shoulders of these giants.



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Describing Motion

Chapter Overview

The main purpose of this chapter is to provide clear definitions and illustrations of the terms used in physics to describe motion, such as the motion of the car described in this chapter's opening example. Speed, velocity, and acceleration are crucial concepts for the analysis of motion in later chapters. Precise description is the first step toward understanding. Without it, we remain awash in vague ideas that are not defined well enough to test our explanations.

Each numbered topic in this chapter builds on the previous section, so it is important to obtain a clear understanding of each topic before going on. The distinctions between speed and velocity and velocity and acceleration are particularly important.

Chapter Outline

1

Average and instantaneous speed. How do we describe how fast an object is moving? How does instantaneous speed differ from average speed?

2

Velocity. How do we introduce direction into descriptions of motion? What is the distinction between speed and velocity?

3

Acceleration. How do we describe changes in motion? What is the relationship between velocity and acceleration?

4

Graphing motion. How can graphs be used to describe motion? How can the use of graphs help us gain a clearer understanding of speed, velocity, and acceleration?

5

Uniform acceleration. What happens when an object accelerates at a steady rate? How do the velocity and distance traveled vary with time when an object is uniformly accelerating?

Imagine that you are in your car, stopped at an intersection. After waiting for cross traffic, you pull away from the stop sign, accelerating eventually to a speed of 56 kilometers per hour (35 miles per hour). You maintain that speed until a dog runs in front of your car and you hit the brakes, reducing your speed rapidly to 10 km/h (fig. 2.1). Having missed the dog, you speed up again to 56 km/h. After another block, you come to another stop sign and reduce your speed gradually to zero.

We can all relate to this description. Measuring speed in miles per hour (MPH) may be more familiar than the use of kilometers per hour (km/h), but speedometers in cars now show both. The use of the term *acceleration* to describe an increase in speed is also common. In physics, however, these concepts take on more precise and specialized meanings that make them even more useful in describing exactly what

is happening. These meanings are sometimes different from those in everyday use. The term *acceleration*, for example, is used by physicists to describe any situation in which velocity is changing, even when the speed is decreasing or only the direction of the motion is changing.

How would you define the term *speed* if you were explaining the idea to a younger brother or sister? Does *velocity* mean the same thing? What about *acceleration*—is the notion vague or does it have a precise meaning? Is it the same thing as velocity? Clear definitions are essential to developing clear explanations. The language used by physicists differs from our everyday language, even though the ideas are related and the same words are used. What are the exact meanings that physicists attach to these concepts, and how can they help us to understand motion?

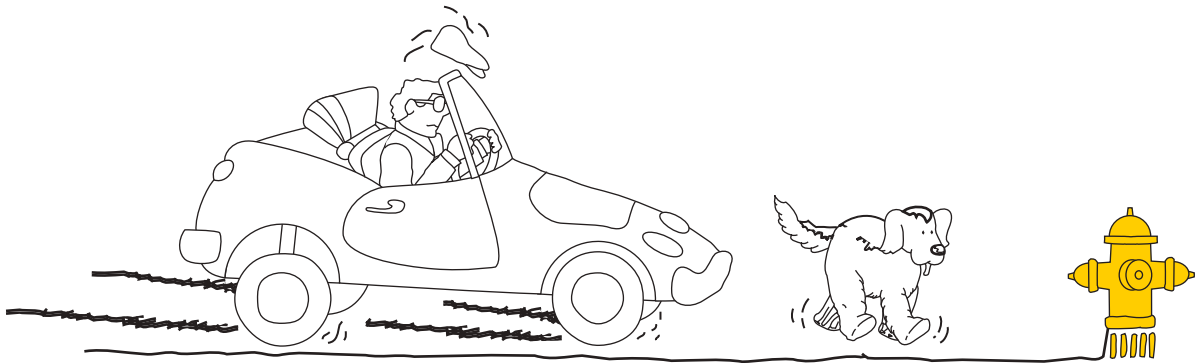


Figure 2.1 As the car brakes for the dog, there is a sudden change in speed.

2.1 Average and Instantaneous Speed

Since driving or riding in cars is a common activity in our daily lives, we are familiar with the concept of speed. Most of us have had experience in reading a speedometer (or perhaps failing to read it carefully enough to avoid the attention of law enforcement). If you describe how fast something is moving, as we did in our example in the introduction, you are talking about **speed**.

How is average speed defined?

What does it mean to say that we are traveling at a speed of 55 MPH? It means that we would cover a distance of 55 miles in a time of 1 hour if we traveled steadily at that speed. Carefully note the structure of this description: There is a number, 55, and some units or dimensions, miles per hour. Numbers and units are both essential parts of a description of speed.

The term *miles per hour* implies that miles are divided by hours in arriving at the speed. This is exactly how we would compute the **average speed** for a trip: Suppose, for example, that we travel a distance of 260 miles in a time of 5 hours, as

shown on the road map of figure 2.2. The average speed is then 260 miles divided by 5 hours, which is equal to 52 MPH. This type of computation is familiar to most of us.

We can also express the definition of average speed in a word equation as

Average speed equals the distance traveled divided by the time of travel.

or

$$\text{Average speed} = \frac{\text{distance traveled}}{\text{time of travel}}$$

We can represent the same definition with symbols by writing

$$s = \frac{d}{t}$$

where the letter *s* represents the speed, *d* represents distance, and *t* represents the time. As noted in chapter 1, letters or

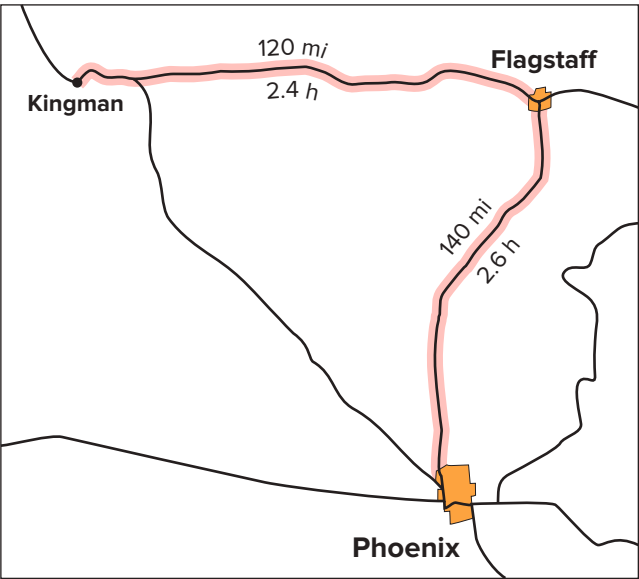


Figure 2.2 A road map showing a trip of 260 miles, with driving times for the two legs of the trip.

symbols are a compact way of saying what could be said with words (and a little more effort and space). Judge for yourself which is the more efficient way of expressing this definition of average speed. Most people find the symbolic expression easier to remember and use.

The average speed that we have just defined is the **rate** at which distance is covered over time. Rates always represent one quantity divided by another. Gallons per minute, pesos per dollar, and points per game are all examples of rates. If we are considering time rates, the quantity that we divide by is *time*, which is the case with average speed. Many other quantities that we will be considering involve time rates.

What are the units of speed?

Units are an essential part of the description of speed. Suppose you say that you were doing 70—without stating the units. In the United States, that would probably be understood as 70 MPH, because that is the unit most frequently used. In Europe, on the other hand, people would probably assume you were talking about the considerably slower speed of 70 km/h. If you do not state the units, you will not communicate effectively.

It is easy to convert from one unit to another if the conversion factors are known. For example, if we want to convert kilometers per hour to miles per hour, we need to know the relationship between miles and kilometers. A kilometer is roughly 6/10 of a mile (0.6214, to be more precise). As shown in example box 2.1, 90 km/h is equal to 55.9 MPH. The process involves multiplication or division by the appropriate conversion factor.

Units of speed will always be a distance divided by a time. In the metric system, the fundamental unit of speed is meters per second (m/s). Example box 2.1 also shows the

Example Box 2.1

Sample Exercise: Speed Conversions

Convert 90 kilometers per hour to (a) miles per hour and (b) meters per second.

a. 1 km = 0.6214 miles
90 km/h = ? (in MPH)
$$\left(\frac{90 \text{ km}}{\text{h}}\right)\left(\frac{0.6214 \text{ miles}}{\text{km}}\right) = 55.9 \text{ MPH}$$

90 km/h = **55.9 MPH**

b. 1 km = 1000 m
$$\left(\frac{90 \text{ km}}{\text{h}}\right)\left(\frac{1000 \text{ m}}{\text{km}}\right) = 90,000 \text{ m/h}$$

However, $(1 \text{ h})\left(\frac{60 \text{ min}}{\text{h}}\right)\left(\frac{60 \text{ sec}}{\text{min}}\right) = 3600 \text{ s}$
$$\left(\frac{90,000 \text{ m}}{\text{h}}\right)\left(\frac{1 \text{ h}}{3600 \text{ s}}\right) = 25.0 \text{ m/s}$$

90 km/h = **25.0 m/s**

Part b can also be done using the conversion factors for speed in appendix E:

1 km/h = 0.278 m/s
$$(90 \text{ km/h})\left(\frac{0.278 \text{ m/s}}{1 \text{ km/h}}\right) = 25.0 \text{ m/s}$$

90 km/h = **25.0 m/s**

Lines drawn through the units indicate cancellation.

conversion of kilometers per hour to meters per second, done as a two-step process. As you can see, 90 km/h can also be expressed as 25.0 m/s. This is a convenient size for discussing the speeds of ordinary objects. (As shown in example box 2.2, the convenient unit for measuring the growth of grass has a very different size.) Table 2.1 shows some familiar speeds expressed in miles per hour, kilometers per hour, and meters per second to give you a sense of their relationships.

Table 2.1		
Familiar Speeds in Different Units		
20 MPH	= 32 km/h	= 9 m/s
40 MPH	= 64 km/h	= 18 m/s
60 MPH	= 97 km/h	= 27 m/s
80 MPH	= 130 km/h	= 36 m/s
100 MPH	= 160 km/h	= 45 m/s

Example Box 2.2

Sample Question: Watching Grass Grow

Question: The units km/h and m/s have an appropriate size for moving cars and people. Many other processes move much more slowly, though. What units would have an appropriate size for measuring the average speed with which a blade of grass grows?

Answer: When grass is well fertilized and watered, it is not unusual for it to grow 3 to 6 centimeters in the course of a week. This can be seen by measuring the length of the clippings after mowing. If we measured the speed in m/s, we would obtain an extremely small number that would not provide a good intuitive sense of the rate of growth. The units of cm/week and mm/day would provide a better indication of this speed.

What is instantaneous speed?

If we travel a distance of 260 miles in 5 hours, as in our earlier example, is it likely that the entire trip takes place at a speed of 52 MPH? Of course not; the speed goes up and down as the road goes up and down, when we overtake slower vehicles, when rest breaks occur, or when the highway patrol looms on the horizon. If we want to know how fast we are going at a given instant in time, we read the speedometer, which displays the **instantaneous speed** (Fig. 2.3). How does instantaneous speed differ from average speed? The instantaneous speed tells us how fast we are going at a given instant but tells us little about how long it will take to travel several miles, unless the speed is held constant. The average speed, on the other hand, allows us to compute how long a trip might take but says little about the variation in speed during the trip. A more complete description of how the speed of a car varies during a portion of a trip could be provided by a graph such as that shown in Figure 2.4. Each point on this graph represents the instantaneous speed at the time indicated on the horizontal axis.

Figure 2.3 A speedometer with two scales for measuring instantaneous speed: MPH and km/h.

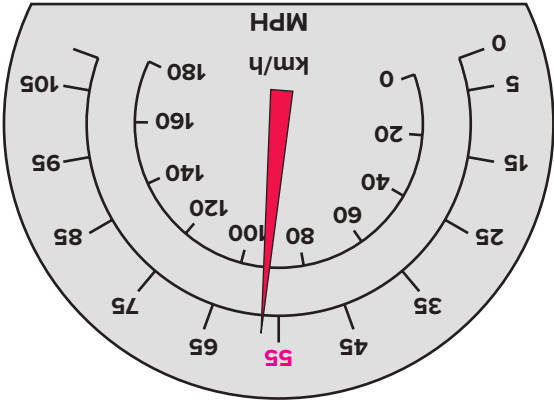
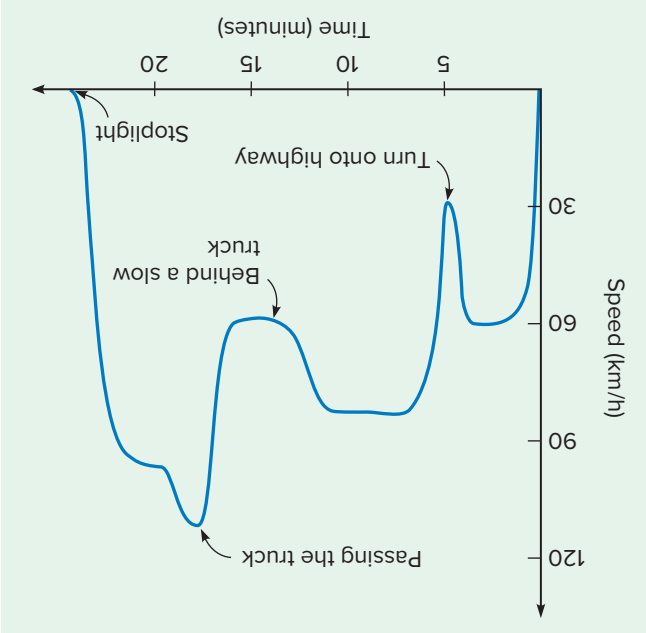


Figure 2.4 Variations in instantaneous speed for a portion of a trip on a local highway.



Even though we all have some intuitive sense of what instantaneous speed means from our experience in reading speedometers, computing this quantity presents some problems that we did not encounter in defining average speed. We could say that instantaneous speed is the rate that distance is being covered at a given instant in time, but how do we compute this rate? What time interval should we use? What is an instant in time? Our solution to this problem is simply to choose a very short interval of time during which a very short distance is covered and the speed does not change drastically. If we know, for example, that in 1 second a distance of 20 meters was covered, dividing 20 meters by 1 second to obtain a speed of 20 m/s would give us a good estimate of the instantaneous speed, provided that the speed did not change much during that single second. If the speed was changing rapidly, we would have to choose an even shorter interval of time. In principle, we can choose time intervals as small as we wish, but in practice it can be hard to measure such small quantities. If we put these ideas into a word definition of instantaneous speed, we could state it as

Instantaneous speed is the rate at which distance is being covered at a given instant in time. It is found by computing the average speed for a very short time interval in which the speed does not change appreciably.

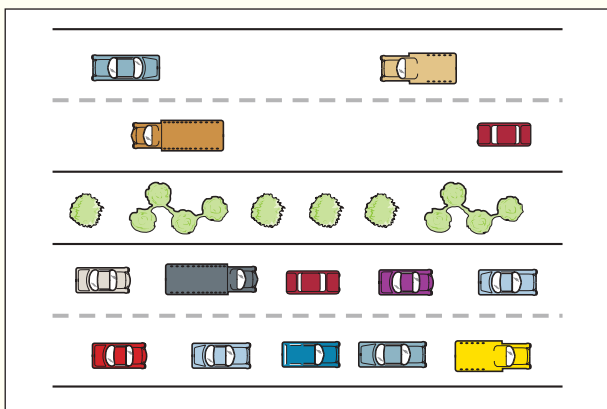
Instantaneous speed is closely related to the concept of average speed but involves very short time intervals. When discussing traffic flow, average speed is the critical issue, as shown in everyday phenomenon box 2.1.

Everyday Phenomenon

Box 2.1

Transitions in Traffic Flow

The Situation. Jennifer commutes into the city on a freeway every day for work. As she approaches the city, the same patterns in traffic flow seem to show up in the same places each day. She will be moving with the flow of traffic at a speed of approximately 60 MPH when suddenly things will come to a screeching halt. The traffic will be stop-and-go briefly and then will settle into a wavelike mode, with speeds varying between 10 and 30 MPH. Unless there is an accident, this will continue for the rest of the way into the city.



The traffic in the upper lanes is flowing freely with adequate spacing to allow higher speeds. The higher-density traffic in the lower lanes moves much more slowly.

What causes these patterns? Why does the traffic stop when there is no apparent reason such as an accident? Why do ramp traffic lights seem to help the situation? Questions like these are the concern of the growing field of traffic engineering.

The Analysis. Although a full analysis of traffic flow is complex, there are some simple ideas that can explain many of the patterns that Jennifer observes. The density of vehicles, measured in vehicles per mile, is a key factor. Adding vehicles at entrance ramps increases this vehicle density.

When Jennifer and other commuters are traveling at 60 MPH, they need to keep a spacing of several car lengths between vehicles. Most drivers do this without thinking about it, although there are always some who follow too closely, or *tailgate*. Tailgating runs the risk of rear-end collisions when the traffic suddenly slows. Reaction time, and its implications for tailgating, is discussed in everyday phenomenon box 3.1.

When more vehicles are added at an entrance ramp, the density of vehicles increases, reducing the distance between vehicles. As the distance between vehicles decreases, drivers should reduce their speed to maintain a safe stopping distance. If this occurred uniformly, there would be a gradual decrease in

the average speed of the traffic to accommodate the greater density. This is not what usually happens, however.

A significant proportion of drivers will attempt to maintain their speed at 50 to 60 MPH, even when densities have increased beyond the point where this is advisable. This creates an unstable situation. At some point, usually near an entrance ramp, the vehicle density becomes too large to sustain these speeds. At this point, there is a sudden drop in average speed and a large increase in the local density. As shown in the drawing, cars can be separated by less than a car length when they are stopped or moving very slowly.

Once the average speed of a few vehicles has slowed to less than 10 MPH, vehicles moving at 50 to 60 MPH begin to pile up behind this slower-moving jam. Because this does not happen smoothly, some vehicles must come to a complete stop, further slowing the flow. At the front end of the jam, on the other hand, the density is reduced due to the slower flow behind. Cars can then start moving at a speed consistent with the new density, perhaps around 30 MPH. If every vehicle moved with the appropriate speed, flow would be smooth and the increased density could be safely accommodated. More often, however, overanxious drivers exceed the appropriate speed, causing fluctuations in the average speed as vehicles begin to pile up again.

Notice that we are using *average speed* with two different meanings in this discussion. One is the average speed of an individual vehicle as its instantaneous speed increases and decreases. The other is the average speed of the overall traffic flow involving many vehicles. When the traffic is flowing freely, the average speed of different vehicles may differ. When the traffic is in a slowly moving jam, the average speeds of different vehicles are essentially the same, at least within a given lane.

Traffic lights at entrance ramps that permit vehicles to enter one-at-a-time at appropriate intervals can help to smoothly integrate the added vehicles to the existing flow. This reduces the sudden changes in speed caused by a rapid increase in density. Once the density increases beyond the certain level, however, a slowing of traffic is inevitable. The abrupt change from low-density, high-speed flow to higher-density, slow flow is analogous to a phase transition from a gas to a liquid. (Phase transitions are discussed in chapter 10.) Traffic engineers have used this analogy to better understand the process.

If we could automatically control and coordinate the speeds of all the vehicles on the highway, the highway could carry a much greater volume of traffic at a smooth rate of flow. Speeds could be adjusted to accommodate changes in density, and smaller vehicle separations could be maintained at higher speeds, because all the vehicles would be moving in a synchronized fashion. Better technology may someday achieve this dream.

We find an average speed by dividing the distance traveled by the time required to cover that distance. Average speed is therefore the average rate at which distance is being covered. Instantaneous speed is the rate that distance is being covered at a given instant in time and is found by considering very small time intervals or by reading a speedometer. Average speed is useful for estimating how long a trip will take, but instantaneous speed is of more interest to the highway patrol.

Debatable Issue

A radar gun used by a police officer measures your speed at a certain instant in time, whereas an officer in a plane measures the time it takes for you to travel the known distance between two stripes painted on the highway. What is the difference in nature between these two types of measurement and which is the fairer basis for issuing a speeding ticket?

2.2 Velocity

Do the words *speed* and *velocity* mean the same thing? They are often used interchangeably in everyday language, but physicists make an important distinction between the two terms. The distinction has to do with direction: Which way is the object moving? This distinction turns out to be essential to understanding Newton's theory of motion (introduced in chapter 4), so it is not just a matter of whim or jargon.

What is the difference between speed and velocity?

Imagine you are driving a car around a curve (as illustrated in fig. 2.5) and you maintain a constant speed of 60 km/h. Is your velocity also constant in this case? The answer is no, because **velocity** involves the direction of motion, as well as how fast the object is going. The direction of motion is changing as the car goes around the curve.

To simply state this distinction, speed as we have defined it tells us how fast an object is moving but says nothing about the direction of the motion. Velocity includes the idea of direction. To specify a velocity, we must give both its size or **magnitude** (how fast) and its direction (north, south, east, up, down, or somewhere in between). If you tell me that an object is moving 15 m/s, you have told me its *speed*. If you tell me that it is moving due west at 15 m/s, you have told me its *velocity*.

At point A on the diagram in figure 2.5, the car is traveling due north at 60 km/h. At point B, because the road curves, the car is traveling northwest at 60 km/h. Its velocity at point B is different from its velocity at point A (because the directions are different). The speeds at points A and B are the same.

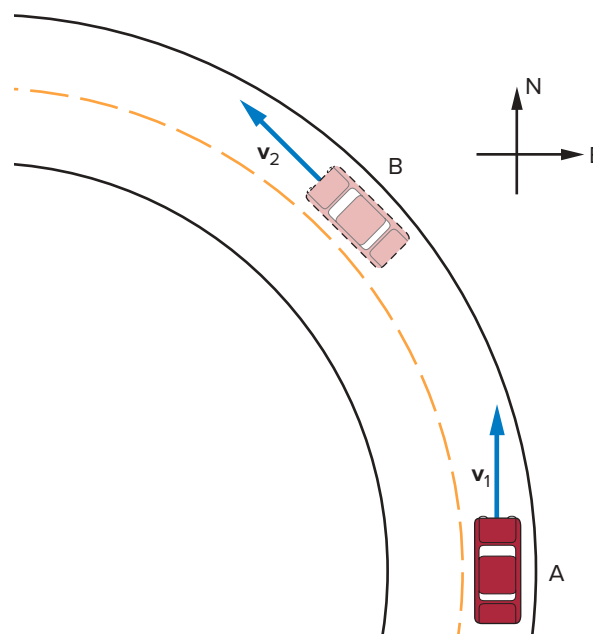


Figure 2.5 The direction of the velocity changes as the car moves around the curve, so that the velocity v_2 is not the same as the velocity v_1 even though the speed has not changed.

Direction is irrelevant in specifying the speed of the object. It has no effect on the reading on your speedometer.

Changes in velocity are produced by forces acting upon the car, as we will discuss further in chapter 4. The most important force involved in changing the velocity of a car is the frictional force exerted on the tires of the car by the road surface. A force is required to change either the size or the direction of the velocity. If no net force were acting on the car, it would continue to move at constant speed in a straight line. This happens sometimes when there is ice or oil on the road surface, which can reduce the frictional force to almost zero.

Study Hint

Science has always relied on pictures and charts to get points across. Throughout the book, a number of concepts will be introduced and illustrated. In the illustrations, the same color will be used for certain phenomena.

-  Blue arrows are velocity vectors.
-  Green arrows depict acceleration vectors.
-  Red arrows depict force vectors.
-  Purple arrows show momentum, a concept we will explore in chapter 7.

What is a vector?

Velocity is a quantity for which both the size and direction are important. We call such quantities **vectors**. To describe

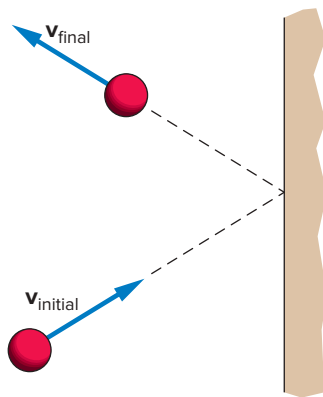


Figure 2.6 The direction of the velocity changes when a ball bounces from a wall. The wall exerts a force on the ball in order to produce this change.

these quantities fully, we need to state *both the size and the direction*. Velocity is a vector that describes how fast an object is moving and in what direction it is moving. Many of the quantities used in describing motion (and in physics more generally) are **vector quantities**. These include velocity, acceleration, force, and momentum.

Think about what happens when you throw a rubber ball against a wall, as shown in figure 2.6. The speed of the ball may be about the same after the collision with the wall as it was before the ball hit the wall. The velocity has clearly changed in the process, though, because the ball is moving in a different direction after the collision. Something has happened to the motion of the ball. A strong force had to be exerted on the ball by the wall to produce this change in velocity.

The velocity vectors in figures 2.5 and 2.6 are represented by arrows. This is a natural choice for depicting vectors, because the direction of the arrow clearly shows the direction of the vector, and the length can be drawn proportional to the size. In other words, the larger the velocity, the longer the arrow (fig. 2.7). In the text, we will represent vectors by printing their symbols in boldface and making them larger than other symbols: $\mathbf{v}$ is thus the symbol for velocity. A fuller description of vectors can be found in appendix C.

How do we define instantaneous velocity?

In considering automobile trips, *average* speed is the most useful quantity. We do not really care about the direction of motion in this case. *Instantaneous* speed is the quantity of

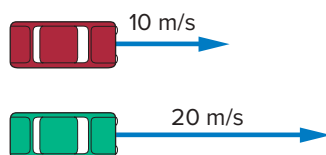


Figure 2.7 The length of the arrows show the relative size of the velocity vectors.

interest to the highway patrol. **Instantaneous velocity**, however, is most useful in considering physical theories of motion. We can define instantaneous velocity by drawing on our earlier definition of instantaneous speed.

Instantaneous velocity is a vector quantity having a size equal to the instantaneous speed at a given instant in time and having a direction corresponding to that of the object's motion at that instant.

Instantaneous velocity and instantaneous speed are closely related, but velocity includes direction as well as size. It is *changes* in instantaneous velocity that require the intervention of forces. These changes will be emphasized when we explore Newton's theory of mechanics in chapter 4. We can also define the concept of average velocity, but that is a much less useful quantity for our purposes than either instantaneous velocity or average speed.*

To specify the velocity of an object, we need to state both how fast and in what direction the object is moving; velocity is a vector quantity. Instantaneous velocity has a magnitude equal to the instantaneous speed, and it points in the direction that the object is moving. Changes in instantaneous velocity are where the action is, so to speak, and we will consider these in more detail when we discuss acceleration in section 2.3.

2.3 Acceleration

Acceleration is a familiar idea. We use the term in speaking of the acceleration of a car away from a stop sign or the acceleration of a running back in football. We feel the effects of acceleration on our bodies when a car's velocity changes rapidly and even more strikingly when an elevator lurches downward, leaving our stomachs slightly behind (fig. 2.8). These are all accelerations. You can think of your stomach as an acceleration detector—a roller coaster gives it a real workout!

Understanding acceleration is crucial to our study of motion. **Acceleration** is the rate at which velocity *changes*. (Note that we said velocity, not speed.) It plays a central role in Newton's theory of motion. How do we go about finding

*Strictly speaking, velocity is the change in displacement divided by time, where displacement is a vector representing the change in position of an object. See appendix C and figure C.2 for a discussion of displacement vectors. In one-dimensional motion when an object does not change direction, the distance traveled is equal to the magnitude of the displacement.

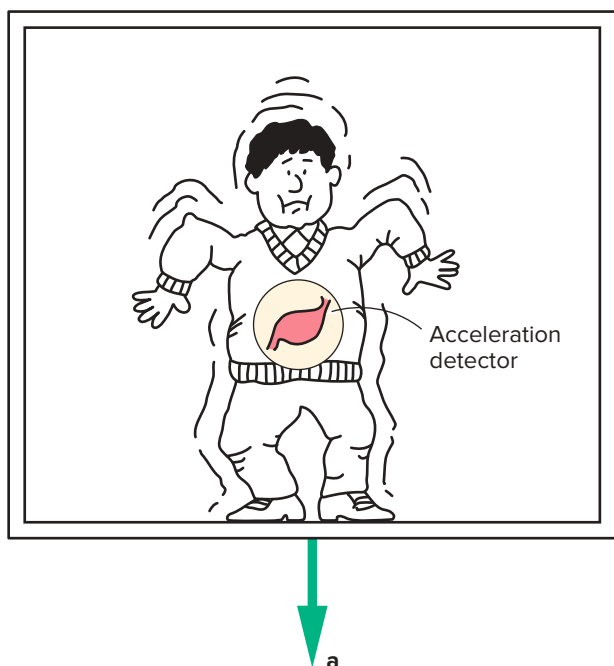


Figure 2.8 Your acceleration detector senses the downward acceleration of the elevator.

a value of an acceleration, though? As with speed, it is convenient to start with a definition of average acceleration and then extend it to the idea of instantaneous acceleration.

How is average acceleration defined?

How would we go about providing a quantitative description of an acceleration? Suppose that your car, pointing due east, starts from a full stop at a stop sign, and its velocity increases from zero to 20 m/s, as shown in figure 2.9. The change in velocity is found simply by subtracting the initial velocity from the final velocity (20 m/s – 0 m/s = 20 m/s). To find its *rate of change*, however, we also need to know the time needed to produce this change. If it took just 5 seconds for the velocity to change, the rate of change would be larger than if it took 30 seconds.

Suppose that a time of 5 seconds was required to produce this change in velocity. The rate of change in velocity could then be found by dividing the size of the change in velocity by the time required to produce that change. Thus, the size

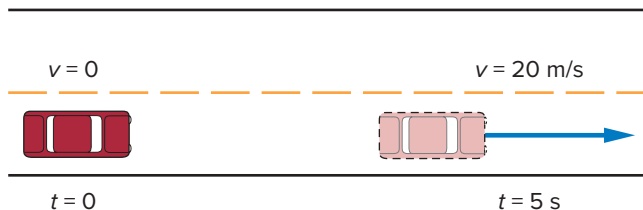


Figure 2.9 A car, starting from rest, accelerates to a velocity of 20 m/s due east in a time of 5 s.

of the **average acceleration**, a , is found by dividing the change in velocity of 20 m/s by the time of 5 seconds,

$$a = \frac{20 \text{ m/s}}{5 \text{ s}} = 4 \text{ m/s/s}$$

The unit m/s/s is usually written m/s^2 and is read as *meters per second squared*. It is easier to understand it, however, as *meters per second per second*. The car's velocity (measured in m/s) is changing at a rate of 4 m/s every second. Other units could be used for acceleration, but they will all have this same form: distance per unit of time per unit of time. In discussing the acceleration of a car on a drag strip, for example, the unit *miles per hour per second* is sometimes used.

The quantity we have just computed is the size of the average acceleration of the car. The average acceleration is found by dividing the total change in velocity for some time interval by that time interval, ignoring possible differences in the rate of change of velocity that might be occurring within the time interval. Its definition can be stated in words as follows:

Average acceleration is the change in velocity divided by the time required to produce that change.

We can restate it in symbols as

$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{elapsed time}}$$

or

$$\mathbf{a} = \frac{\Delta \mathbf{v}}{t}$$

Because change is so important in this definition, we have used the special symbol Δ (the Greek letter delta) to mean a change in a quantity. Thus, $\Delta \mathbf{v}$ is a compact way of writing *the change in velocity*, which otherwise could be expressed as $\mathbf{v}_f - \mathbf{v}_i$, where $\mathbf{v}_f$ is the final velocity and $\mathbf{v}_i$ is the initial velocity. Because the concept of change is critical, this delta (Δ) notation will appear often.

The idea of change is all-important. Acceleration is *not* velocity over time. It is the *change* in velocity divided by time. It is common for people to associate large accelerations with large velocities when, in fact, the opposite is often true. The acceleration of a car may be largest, for example, when it is just starting up and its velocity is near zero. The rate of change of velocity is greatest then. On the other hand, a car can be traveling at 100 MPH but still have a zero acceleration if its velocity is not changing.

What is instantaneous acceleration?

Instantaneous acceleration is similar to average acceleration, with an important exception. Just as with instantaneous speed or velocity, we are now concerned with the rate of

change at a given instant in time. It is *instantaneous* acceleration that our stomachs respond to. It can be defined as follows:

Instantaneous acceleration is the rate at which velocity is changing at a given instant in time. It is computed by finding the average acceleration for a very short time interval during which the acceleration does not change appreciably.

If the acceleration is changing with time, choosing a very short time interval guarantees that the acceleration computed for that time interval will not differ too much from the instantaneous acceleration at any time within the interval. This is the same idea used in finding an instantaneous speed or instantaneous velocity.

What is the direction of an acceleration?

Like velocity, acceleration is a vector quantity. Its direction is important. The direction of the acceleration vector is that of the *change* in velocity Δv . If, for example, a car is moving in a straight line and its velocity is increasing, the change in velocity is in the same direction as the velocity itself, as shown in figure 2.10. The change in velocity Δv must be added to the initial velocity v_i to obtain the final velocity v_f . All three vectors point forward. The process of adding vectors can be readily seen when we represent the vectors as arrows on a graph. (More information on vector addition can be found in appendix C.)

If the velocity is decreasing, however, the change in velocity Δv points in the opposite direction to the two velocity vectors, as shown in figure 2.11. Because the initial velocity v_i is larger than the final velocity v_f , the change in velocity must point in the opposite direction to produce a shorter v_f arrow. The acceleration is also in the opposite direction to the velocity, because it is in the direction of the *change* in velocity.

In Newton's theory of motion (chapter 4), the force required to produce this acceleration would also be opposite in direction to the velocity. It must push backward on the car to slow it down. In general, if an object's velocity is decreasing, velocity and acceleration vectors point in opposite directions and therefore have opposite signs. If an object is speeding up, the signs of the velocity and acceleration are the same.

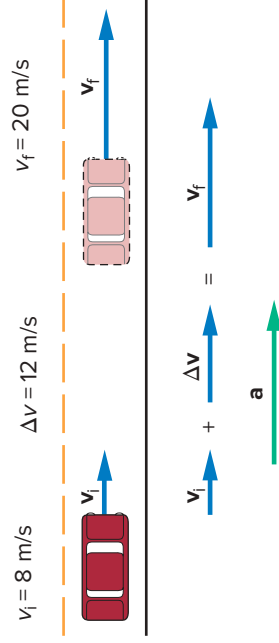


Figure 2.10 The acceleration vector is in the same direction as the velocity vectors when the velocity is increasing.

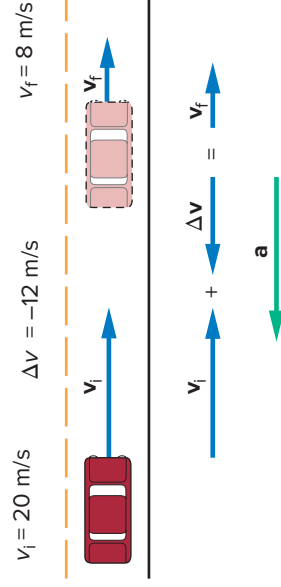


Figure 2.11 The velocity and acceleration vectors for decreasing velocity: Δv and a are now opposite in direction to the velocity. The acceleration a is proportional to Δv .

The term *acceleration* describes the rate of *any* change in an object's velocity. The change could be an increase (as in our initial example), a decrease, or a change in direction. The term applies even to decreases in velocity (*decelerations*). To a physicist these are simply accelerations with a direction opposite that of the velocity. If a car is braking while traveling in a straight line, its velocity is decreasing and its acceleration is negative if the velocity is positive. This situation is illustrated in the sample exercise in example box 2.3. If, on the other hand, the car is moving in the negative direction and slowing down, the acceleration is in the positive direction. When an object is slowing down, the velocity and acceleration vectors point in opposite directions.

The minus sign is an important part of the result in the example in example box 2.3, because it indicates that the change in velocity is negative. The velocity is getting smaller. We can call it a deceleration if we like, but it is the same thing as a negative acceleration. One word, *acceleration*, covers all situations in which the velocity is changing.

Example Box 2.3

Sample Exercise: Negative Accelerations

The driver of a car steps on the brakes, and the velocity drops from 30 m/s due east to 10 m/s due east in a time of 4.0 seconds. What is the acceleration?

$$\begin{aligned} v_i &= 30 \text{ m/s due east} & a &= \frac{\Delta v}{t} = \frac{v_f - v_i}{t} \\ v_f &= 10 \text{ m/s due east} & &= \frac{10 \text{ m/s} - 30 \text{ m/s}}{4.0 \text{ s}} \\ t &= 4.0 \text{ s} & &= \frac{-20 \text{ m/s}}{4.0 \text{ s}} \\ a &= ? & &= -5 \text{ m/s}^2 \\ & & & \mathbf{a = 5.0 \text{ m/s}^2 \text{ due west}} \end{aligned}$$

Notice that when we are dealing just with the magnitude of a vector quantity, we do not use the boldface notation. The sign can indicate direction, however, in a problem involving straight-line motion.

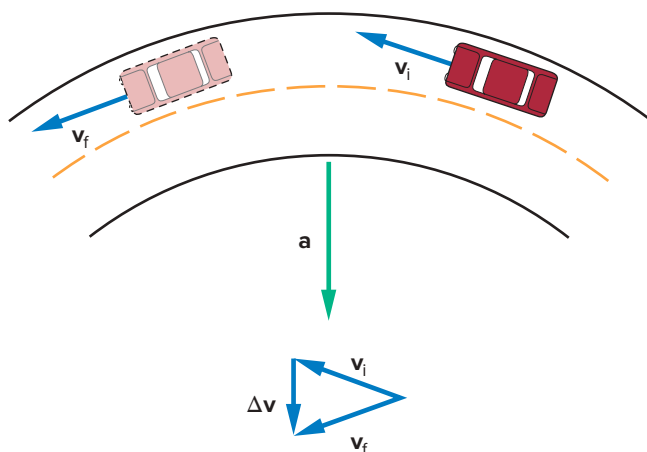


Figure 2.12 A change in the direction of the velocity vector also involves an acceleration, even though the speed may be constant.

Can a car be accelerating when its speed is constant?

What happens when a car goes around a curve at constant speed? Is it accelerating? The answer is yes, because the direction of its velocity is changing. If the direction of the velocity vector is changing, the velocity is changing. This means there must be an acceleration.

This situation is illustrated in figure 2.12. The arrows in this drawing show the direction of the velocity vector at different points in the motion. The change in velocity $\Delta \mathbf{v}$ is the vector that must be added to the initial velocity $\mathbf{v}_i$ to obtain the final velocity $\mathbf{v}_f$. The vector representing the change in velocity points toward the center of the curve, and therefore the acceleration vector also points in that direction. The size of the change is represented by the length of the arrow $\Delta \mathbf{v}$. From this, we can find the acceleration.

Acceleration is involved whenever there is a change in velocity, regardless of the nature of that change. Cases like figure 2.12 will be considered more fully in chapter 5, where circular motion is discussed.

Acceleration is the rate of change of velocity and is found by dividing the change in the velocity by the time required to produce that change. Any change in velocity involves an acceleration, whether an increase or a decrease in speed, or a change in direction. Acceleration is a vector having a direction corresponding to the direction of the change in velocity, which is not necessarily the same direction as the instantaneous velocity itself. The concept of change is crucial. The graphical representations in section 2.4 will help you visualize changes in velocity as well as changes in other quantities.

2.4 Graphing Motion

It is often said that a picture is worth a thousand words, and the same can be said of graphs. Imagine trying to describe the motion depicted in figure 2.4 precisely in words and numbers. The graph provides a quick overview of what took place. A description in words would be much less efficient. In this section, we will show how graphs can also help us to understand velocity and acceleration.

What can a graph tell us?

How can we produce and use graphs to help us describe motion? Imagine you are watching a battery-powered toy car moving along a meter stick (fig. 2.13). If the car were moving slowly enough, you could record the car's position while also recording the elapsed time using a digital watch. At regular time intervals (say, every 5 seconds), you would note the value of the position of the front of the car on the meter stick and write down these values. The results would be something like those shown in table 2.2.

How do we graph these data? First, we create evenly spaced intervals on each of two perpendicular axes, one for distance traveled (or position) and the other for time. To show how distance varies with time, we usually put time on the horizontal axis and distance on the vertical axis. Such a graph is shown in figure 2.14, where each data point from table 2.2 is plotted and a line is drawn through the points. To make sure you understand this process, choose different points from table 2.2 and find where they are located on the graph. Where would the point go if the car were at 21 centimeters at 25 seconds?

The graph summarizes the information presented in the table in a visual format that makes it easier to grasp at a glance. The graph also contains information on the velocity and acceleration of the car, although that is less obvious.



Figure 2.13 A toy car moving along a meter stick. Its position can be recorded at different times.

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Table 2.2	
Position of the Toy Car along the Meter Stick at Different Times	
Time	Position
0 s	0 cm
5 s	4.1 cm
10 s	7.9 cm
15 s	12.1 cm
20 s	16.0 cm
25 s	16.0 cm
30 s	16.0 cm
35 s	18.0 cm
40 s	20.1 cm
45 s	21.9 cm
50 s	24.0 cm
55 s	22.1 cm
60 s	20.0 cm

For example, what can we say about the average velocity of the car between 20 and 30 seconds? Is the car moving during this time? A glance at the graph shows us that the distance is not changing during that time interval, so the car is *not* moving. The velocity is zero during that time, which is represented by a horizontal line on our graph of distance versus time.

What about the velocity at other points in the motion? The car is moving more rapidly between 0 and 20 seconds than it is between 30 and 50 seconds. The distance curve is rising more rapidly between 0 and 20 seconds than between 30 and 50 seconds. Because more distance is covered in the same time, the car must be moving faster there. A steeper slope to the curve is associated with a larger speed.

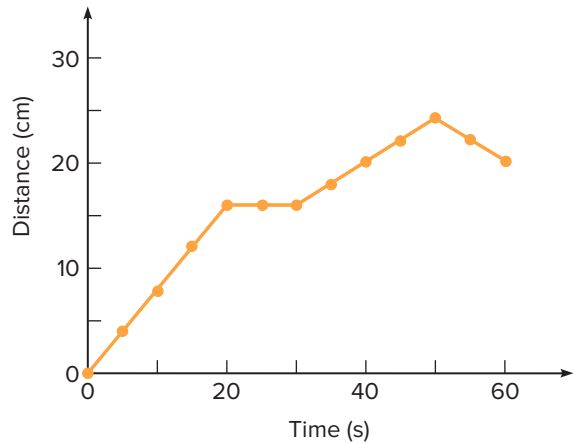


Figure 2.14 Distance plotted against time for the motion of the toy car. The data points are those listed in table 2.2.

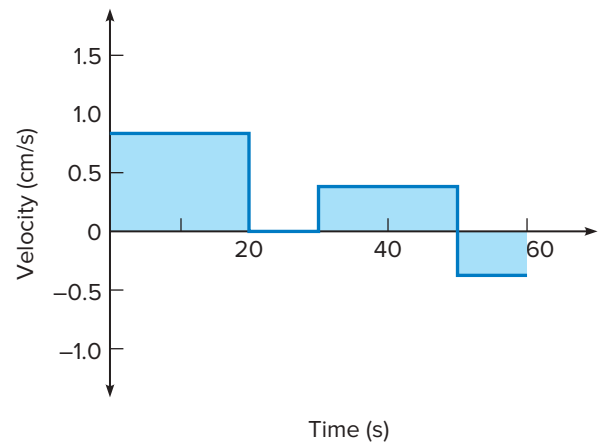


Figure 2.15 Instantaneous velocity plotted against time for the motion of the toy car. The velocity is greatest when distance traveled is changing most rapidly.

In fact, the **slope** of the distance-versus-time curve at any point on the graph is equal to the *instantaneous velocity* of the car.* The slope indicates how rapidly the distance is changing with time at any instant in time. The rate of change of distance with time is the instantaneous speed according to the definition given in section 2.1. Because the motion takes place along a straight line, we can then represent the direction of the velocity with plus or minus signs. There are only two possibilities, forward or backward. We then have the instantaneous velocity, which includes both the size (speed) and direction of the motion.

When the car travels backward, its distance from the starting point decreases. The curve goes down, as it does between 50 and 60 seconds. We refer to this downward-sloping portion of the curve as having a *negative slope* and say that the velocity is negative during this portion of the motion. A large upward slope represents a large instantaneous velocity, a zero slope (horizontal line) a zero velocity, and a downward slope a negative (backward) velocity. Looking at the slope of the graph tells us all we need to know about the velocity of the car.

Velocity and acceleration graphs

These ideas about velocity can be best summarized by plotting a graph of velocity against time for the car (fig. 2.15). The velocity is constant wherever the *slope* of the distance-versus-time graph of figure 2.14 is constant. Any straight-line segment of a graph has a constant slope, so the velocity

*Because the mathematical definition of slope is the change in the vertical coordinate Δd divided by the change in the horizontal coordinate Δt , the slope, $\Delta d/\Delta t$, is equal to the instantaneous velocity, provided that Δt is sufficiently small. It is possible to grasp the concept of slope, however, without appealing to the mathematical definition.

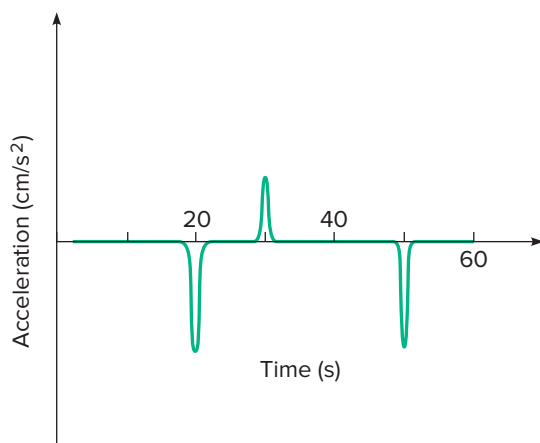


Figure 2.16 An approximate sketch of acceleration plotted against time for the toy-car data. The acceleration is nonzero only when the velocity is changing.

changes only where the slope of the distance graph in figure 2.14 changes. If you carefully compare the graph in figure 2.15 to the graph in figure 2.14, these ideas should become clear.

What can we say about the acceleration from these graphs? Because acceleration is the rate of change of velocity with time, the velocity graph (fig. 2.15) also provides information about the acceleration. In fact, the instantaneous acceleration is equal to the slope of the velocity-versus-time graph. A steep slope represents a rapid change in velocity and thus a large acceleration. A horizontal line has zero slope and represents zero acceleration. The acceleration turns out to be zero for most of the motion described by our data. The velocity changes at only a few points in the motion. The acceleration would be large at these points and zero everywhere else.

Because our data do not indicate how rapidly the changes in velocity actually occur, we do not have enough information to say just how large the acceleration is at those few points where it is not zero. We would need measurements of distance or velocity every tenth of a second or so to get a clear idea of how rapid these changes are. As we will see in chapter 4, we know that these changes in velocity cannot occur instantly. Some time is required. Thus, we can sketch an approximate graph of acceleration versus time, as shown in figure 2.16.

The spikes in figure 2.16 occur when the velocity is changing. At 20 seconds, there is a rapid decrease in the velocity represented by a downward spike or negative acceleration. At 30 seconds, the velocity increases rapidly from zero to a constant value, and this is represented by an upward spike or positive acceleration. At 50 seconds, there is another negative acceleration as the velocity changes from a positive value to a negative value. If you could put yourself

inside the toy car, you would definitely feel these accelerations. (Everyday phenomenon box 2.2 provides another example of how a graph is useful for analyzing motion.)

Can we find the distance traveled from the velocity graph?

What other information can be gleaned from the velocity-versus-time graph of figure 2.15? Think for a moment about how you would find the distance traveled if you knew the velocity. For a constant velocity, you can get the distance simply by multiplying the velocity by the time, $d = vt$. In the first 20 seconds of the motion, for example, the velocity is 0.8 cm/s and the distance traveled is 0.8 cm/s times 20 seconds, which is 16 cm. This is just the reverse of what we used in determining the velocity in the first place. We found the velocity by dividing the distance traveled by the time.

How would this distance be represented on the velocity graph? If you recall formulas for computing areas, you may recognize that the distance d is the area of the shaded rectangle on figure 2.15. The area of a rectangle is found by multiplying the height times the width, just what we have done here. The velocity, 0.8 cm/s, is the height, and the time, 20 seconds, is the width of this rectangle on the graph.

It turns out that we can find the distance this way even when the areas involved on the graph are not rectangles, although the process is more difficult when the curves are more complicated. The general rule is that the distance traveled is equal to the area under the velocity-versus-time curve. When the velocity is negative (below the time axis on the graph), the object is traveling backward and its distance from the starting point is decreasing.

Even without computing the area precisely, it is possible to get a rough idea of the distance traveled by studying the velocity graph. A large area represents a large distance. Quick visual comparisons give a good picture of what is happening without the need for lengthy calculations. This is the beauty of a graph.

A good graph can present a picture of motion that is rich in insight. Not only does distance traveled plotted against time tell us where the object is at any time, but also its slope indicates how fast it was moving. The graph of velocity plotted against time also contains information on acceleration and on the distance traveled. Producing and studying such graphs can give us a more general picture of the motion and the relationships between distance, velocity, and acceleration.