COLLEGE PHYSICS

A STRATEGIC APPROACH

SECOND EDITION

VOLUME 1

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KNIGHT · JONES · FIELD

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COLLEGE PHYSICS

A STRATEGIC APPROACH

SECOND EDITION

RANDALL D. KNIGHT
California Polytechnic State University, San Luis Obispo

BRIAN JONES
Colorado State University

STUART FIELD
Colorado State University

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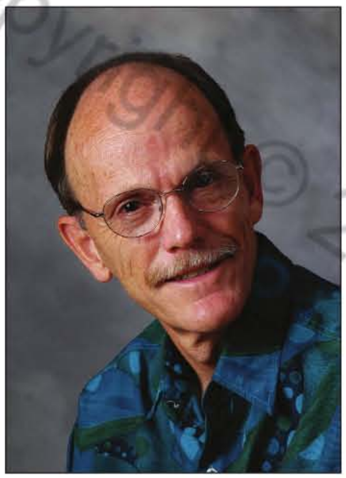
About the Authors



Randy Knight has taught introductory physics for 28 years at Ohio State University and California Polytechnic University, where he is currently Professor of Physics and Director of the Minor in Environmental Studies. Randy received a Ph.D. in physics from the University of California, Berkeley and was a post-doctoral fellow at the Harvard-Smithsonian Center for Astrophysics before joining the faculty at Ohio State University. It was at Ohio that he began to learn about the research in physics education that, many years later, led to *Five Easy Lessons: Strategies for Successful Physics Teaching, Physics for Scientists and Engineers: A Strategic Approach,* and now to this book. Randy's research interests are in the field of lasers and spectroscopy. He also directs the environmental studies program at Cal Poly. When he's not in the classroom or in front of a computer, you can find Randy hiking, sea kayaking, playing the piano, or spending time with his wife Sally and their six cats.

Brian Jones has won several teaching awards at Colorado State University during his 20 years teaching in the Department of Physics. His teaching focus in recent years has been the College Physics class, including writing problems for the MCAT exam and helping students review for this test. Brian is also Director of the *Little Shop of Physics,* the Department's engaging and effective hands-on outreach program, which has merited coverage in publications ranging from the *APS News* to *People* magazine. Brian has been invited to give workshops on techniques of science instruction throughout the United States and internationally, including Belize, Chile, Ethiopia, Azerbaijan, Mexico and Slovenia. Previously, he taught at Waterford Kamhlaba United World College in Mbabane, Swaziland, and Kenyon College in Gambier, Ohio. Brian and his wife Carol have dozens of fruit trees and bushes in their yard, including an apple tree that was propagated from a tree in Isaac Newton's garden, and they have traveled and camped in most of the United States.

Stuart Field has been interested in science and technology his whole life. While in school he built telescopes, electronic circuits, and computers. After attending Stanford University, he earned a Ph.D. at the University of Chicago, where he studied the properties of materials at ultralow temperatures. After completing a postdoctoral position at the Massachusetts Institute of Technology, he held a faculty position at the University of Michigan. Currently at Colorado State University, Stuart teaches a variety of physics courses, including algebra-based introductory physics, and was an early and enthusiastic adopter of Knight's *Physics for Scientists and Engineers.* Stuart maintains an active research program in the area of superconductivity. His hobbies include woodworking; enjoying Colorado's great outdoors; and ice hockey, where he plays goalie for a local team.

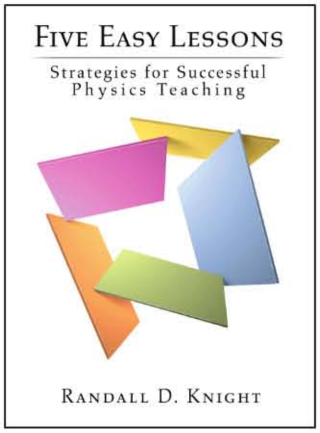
Preface to the Instructor

In 2006, we published *College Physics: A Strategic Approach,* a new algebra-based physics textbook for students majoring in the biological and life sciences, architecture, natural resources, and other disciplines. As the first such book built from the ground up on research into how students can more effectively learn physics, it quickly gained widespread critical acclaim from professors and students alike. In this second edition, we build on the research-proven instructional techniques introduced in the first edition and the extensive feedback from thousands of users to take student learning even further.

Objectives

Our primary goals in writing *College Physics: A Strategic Approach* have been:

- To provide students with a textbook that's a more manageable size, less encyclopedic in its coverage, and better designed for learning.
- To integrate proven techniques from physics education research into the classroom in a way that accommodates a range of teaching and learning styles.
- To help students develop both quantitative reasoning skills and solid conceptual understanding, with special focus on concepts well documented to cause learning difficulties.
- To help students develop problem-solving skills and confidence in a systematic manner using explicit and consistent tactics and strategies.
- To motivate students by integrating real-world examples relevant to their majors—especially from biology, sports, medicine, the animal world—and that build upon their everyday experiences.
- To utilize proven techniques of visual instruction and design from educational research and cognitive psychology that improve student learning and retention and address a range of learner styles.



A more complete explanation of these goals and the rationale behind them can be found in Randy Knight's paperback book, *Five Easy Lessons: Strategies for Successful Physics Teaching*. Please request a copy from your local Pearson sales representative if it would be of interest to you (ISBN 978-0-805-38702-5).

What's New to This Edition

Our goal from the beginning has been a textbook combining the best results from physics education research with inspiring photographs and examples connecting physics to the many fields of study of students taking College Physics. In other words, to provide both the motivation needed and the tools required for students to succeed. Our commitment to this goal is undiminished. At the same time, the extensive feedback we've received from scores of instructors and hundreds of students, as well as our own experiences teaching from the book, have led to numerous changes and improvements to the text, figures, and the end-of-chapter problems. These include:

- New illustrated **Chapter Previews** at the start of each chapter provide visual, hierarchical, and non-technical previews proven to help students organize their thinking and improve their understanding of the upcoming material.
- New **Integrated Examples** at the end of each chapter give students additional help in solving general problems not tied to particular sections. Many integrate material from other chapters.

- New **Part Summary Problems** at the end of each of the seven parts of the book test students' abilities to draw on concepts and techniques from multiple chapters. Most of these are MCAT-style passage problems.
- **More streamlined presentations** throughout the text. Based on extensive feedback, we've pared some topics, reconfigured others, and provided a more readable, student-friendly text.
- **Improved and more varied end-of-chapter problems.** Using data from MasteringPhysics, we have reworked the problem sets to enhance clarity, topic coverage, and variety—adding, in particular, more problems based on real-world situations and more problems using ratio reasoning.

Your Instructor's Professional Copy contains a 9-page illustrated overview of the pedagogical features in this second edition.

The more significant content changes include:

- The treatment of Newton's third law in Chapters 4 and 5 has been better focused on the types of problems that students will be asked to solve.
- Angular position and angular velocity are now developed together in Chapter 6, rather then being divided between Chapters 3 and 6. More emphasis has been given to angular position and angular velocity graphs, emphasizing the analogy with the linear position and velocity graphs of Chapter 2.
- The Chapter 10 presentation of work and energy has been streamlined and clarified. The problem-solving strategy for conservation of energy problems now plays a more prominent role.
- Chapter 11, Using Energy, is now more focused on concrete applications of energy use. All discussions of thermal properties have matter have been moved to Chapter 12, which has been reorganized to emphasize the single theme, "What happens to matter when you heat or cool it?"
- The ordering of topics within Chapters 18 and 19 has been revised. Ray tracing and the thin-lens equation are now paired together in Chapter 18; the pinhole camera and color/dispersion have moved to Chapter 19.
- Chapter 21 has been significantly rewritten to make the difficult idea of electric potential more concrete and usable.
- The section on household electricity has been moved from Chapter 23 to Chapter 26. Chapter 23 is now better focused on resistors and capacitors while Chapter 26, AC Circuits, has become a more practical chapter with sections on household electricity and electrical safety.
- Chapters 28–30 on quantum, atomic, and nuclear physics have been significantly streamlined in the hope that more instructors will be able to teach these important topics.

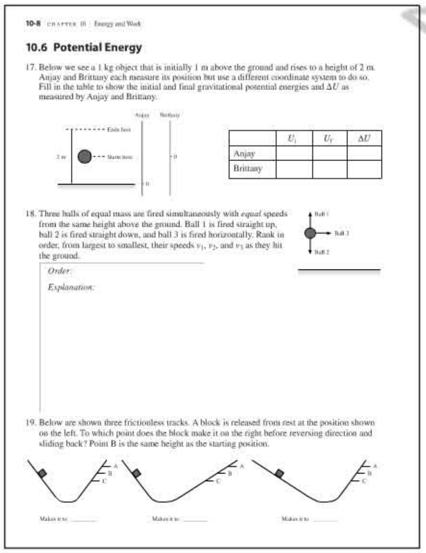
Textbook Organization

College Physics: A Strategic Approach is a 30-chapter text intended for use in a two-semester course. The textbook is divided into seven parts: Part I: *Force and Motion*, Part II: *Conservation Laws*, Part III: *Properties of Matter*, Part IV: *Oscillations and Waves*, Part V: *Optics*, Part VI: *Electricity and Magnetism*, and Part VII: *Modern Physics*.

Part I covers Newton's laws and their applications. The coverage of two fundamental conserved quantities, momentum and energy, is in Part II, for two reasons. First, the way that problems are solved using conservation laws—comparing an *after* situation to a *before* situation—differs fundamentally from the problem-solving strategies used in Newtonian dynamics. Second, the concept of energy has a significance far beyond mechanical (kinetic and potential) energies. In particular, the key idea in thermodynamics is energy, and moving from the study of energy in Part II into thermal physics in Part III allows the uninterrupted development of this important idea.

- **Complete edition,** with MasteringPhysics™ (ISBN 978-0-321-59548-5): Chapters 1–30.
- **Volume 1** with MasteringPhysics™ (ISBN 978-0-321-59850-9): Chapters 1–16.
- **Volume 2** with MasteringPhysics™ (ISBN 978-0-321-59851-6): Chapters 17–30.
- **Complete edition,** without MasteringPhysics™ (ISBN 978-0-321-60228-2): Chapters 1– 30.
- **Volume 1** without MasteringPhysics™ (ISBN 978-0-321-59852-3): Chapters 1–16.
- **Volume 2** without MasteringPhysics™ (ISBN 978-0-321-59853-0): Chapters 17–30.

Optics (Part V) is covered directly after oscillations and waves (Part IV), but *before* electricity and magnetism (Part VI). Further, we treat wave optics before ray optics. Our motivations for this organization are twofold. First, wave optics is largely just an extension of the general ideas of waves; in a more traditional organization, students will have forgotten much of what they learned about waves by the time they get to wave optics. Second, optics as it is presented in introductory physics makes no use of the properties of electromagnetic fields. The documented difficulties that students have with optics are difficulties with waves, not difficulties with electricity and magnetism. There's little reason other than historical tradition to delay optics. However, the optics chapters are easily deferred until after Part VI for instructors who prefer that ordering of topics.


10-8 CHAPTER 10 · Energy and Work

10.6 Potential Energy

17. Below we see a 1 kg object that is initially 1 m above the ground and rises to a height of 2 m. Anjay and Brittany each measure its position but use a different coordinate system to do so. Fill in the table to show the initial and final gravitational potential energies and ΔU as measured by Anjay and Brittany.

	U_i	U_f	ΔU
Anjay			
Brittany			

18. Three balls of equal mass are fired simultaneously with *equal* speeds from the same height above the ground. Ball 1 is fired straight up, ball 2 is fired straight down, and ball 3 is fired horizontally. Rank in order, from largest to smallest, their speeds v_1, v_2, and v_3 as they hit the ground.

Order:

Explanation:

19. Below are shown three frictionless tracks. A block is released from rest at the position shown on the left. To which point does the block make it on the right before reversing direction and sliding back? Point B is the same height as the starting position.

Makes it to: ______ Makes it to: ______ Makes it to: ______

The Student Workbook

A key component of *College Physics: A Strategic Approach* is the accompanying *Student Workbook*. The workbook bridges the gap between textbook and homework problems by providing students the opportunity to learn and practice skills prior to using those skills in quantitative end-of-chapter problems, much as a musician practices technique separately from performance pieces. The workbook exercises, which are keyed to each section of the textbook, focus on developing specific skills, ranging from identifying forces and drawing free-body diagrams to interpreting field diagrams.

The workbook exercises, which are generally qualitative and/or graphical, draw heavily upon the physics education research literature. The exercises deal with issues known to cause student difficulties and employ techniques that have proven to be effective at overcoming those difficulties. The workbook exercises can be used in-class as part of an active-learning teaching strategy, in recitation sections, or as assigned homework. More information about effective use of the *Student Workbook* can be found in the *Instructor's Guide*.

Available versions: Volume 1 (ISBN 978-0-321-59632-1): Chapters 1–16, and Volume 2 (ISBN 978-0-321-59633-8): Chapters 17–30. A package of both volumes is also available (ISBN 978-0-321-59607-9).

Instructor Supplements

NOTE ▶ For convenience, all of the following instructor supplements (except for the Instructor Resource DVD) can be downloaded from the "Instructor Area," accessed via the left-hand navigation bar of MasteringPhysics (www.masteringphysics.com). ◀

- The **Instructor Guide for *College Physics: A Strategic Approach,*** a comprehensive and highly acclaimed resource, provides chapter-by-chapter creative ideas and teaching tips for using *College Physics: A Strategic Approach* in your class. In addition, it contains an extensive review of what has been learned from physics education research, and provides guidelines for using active-learning techniques in your classroom. Instructor Guide chapters are provided in Word and PDF formats, and are also found on the *Instructor Resource DVD*.
- The **Instructor Solutions Manual,** written by Professor Larry Smith, Snow College; Professor Pawan Kahol, Missouri State University; and Professor Marllin Simon, Auburn University, provides *complete* solutions to all the end-of-chapter questions and problems. All solutions follow the Prepare/Solve/Assess problem-solving strategy used in the textbook for quantitative problems, and Reason/ Assess strategy for qualitative ones. The solutions are available by chapter in Word and PDF format, and can also be downloaded from the *Instructor Resource Center* (www.pearsonhighered.com/educator).
- The cross-platform **Instructor Resource DVD** (ISBN 978-0-321-59628-4) provides invaluable and easy-to-use resources for your class, organized by textbook chapter. The contents include a comprehensive library of more than 220 applets from **ActivPhysics OnLine™,** as well as all figures, photos, tables, and summaries from the textbook in JPEG format. In addition, all the Problem-Solving Strategies, Math Relationships Boxes, Tactics Boxes, and Key Equations are provided in editable Word as well as JPEG format. The **Instructor Guide** is also included as editable Word files, along with pdfs of answers to the **Student Workbook** exercises, and **Lecture Outlines (with Classroom Response System "Clicker" Questions)** in PowerPoint.

- **MasteringPhysics™** (www.masteringphysics.com) is a homework, tutorial, and assessment system designed to assign, assess, and track each student's progress using a wide diversity of tutorials and extensively pre-tested problems. In addition to the textbook's end-of-chapter and new end-of-part problems, MasteringPhysics for *College Physics, Second Edition,* also includes author-selected prebuilt assignments, specific tutorials for all the textbook's Problem-Solving Strategies, Tactics Boxes, and Math Relationship boxes, as well as Reading Quizzes and Test Bank questions for each chapter.

  MasteringPhysics provides instructors with a fast and effective way to assign uncompromising, wide-ranging online homework assignments of just the right difficulty and duration. The tutorials coach 90% of students to the correct answer with specific wrong-answer feedback. The powerful post-assignment diagnostics allow instructors to assess the progress of their class as a whole or to quickly identify individual student's areas of difficulty.
- **ActivPhysics OnLine™** (accessed through the Self Study area within www.masteringphysics.com) provides a comprehensive library of more than 420 tried and tested *ActivPhysics* applets updated for web delivery using the latest online technologies. In addition, it provides a suite of highly regarded applet-based tutorials developed by education pioneers Professors Alan Van Heuvelen and Paul D'Alessandris. The *ActivPhysics* margin icon directs students to specific exercises that complement the textbook discussion.

  The online exercises are designed to encourage students to confront misconceptions, reason qualitatively about physical processes, experiment quantitatively, and learn to think critically. They cover all topics from mechanics to electricity and magnetism and from optics to modern physics. The highly acclaimed *ActivPhysics OnLine* companion workbooks help students work through complex concepts and understand them more clearly. More than 220 applets from the *ActivPhysics OnLine* library are also available on the *Instructor Resource DVD*.
- The **Test Bank**, prepared by Wayne Anderson, contains more than 2,000 high-quality problems, with a range of multiple-choice, true/false, short-answer, and regular homework-type questions. Test files are provided in both TestGen® (an easy-to-use, fully networkable program for creating and editing quizzes and exams) and Word format, and can also be downloaded from www.pearsonhighered.com/educator.

Student Supplements

- The **Student Solutions Manuals Chapters 1–16** (ISBN 978-0-321-59629-1) and **Chapters 17–30** (ISBN 978-0-321-59630-7), written by Professor Larry Smith, Snow College; Professor Pawan Kahol, Missouri State University; and Marllin Simon, Auburn University, provide *detailed* solutions to more than half of the odd-numbered end-of-chapter problems. Following the problem-solving strategy presented in the text, thorough solutions are provided to carefully illustrate both the qualitative (Reason/Assess) and quantitative (Prepare/Solve/Assess) steps in the problem-solving process.
- **MasteringPhysics™** (www.masteringphysics.com) is a homework, tutorial, and assessment system based on years of research into how students work physics problems and precisely where they need help. Studies show that students who use MasteringPhysics significantly increase their final scores compared to hand-written homework. MasteringPhysics achieves this improvement by providing students with instantaneous feedback specific to their wrong answers, simpler sub-problems upon request when they get stuck, and partial credit for their method(s) used. This individualized, 24/7 Socratic tutoring is recommended by nine out of ten students to their peers as the most effective and time-efficient way to study.
- **Pearson eText** is available through MasteringPhysics, either automatically when MasteringPhysics is packaged with new books, or available as a purchased upgrade online. Allowing students access to the text wherever they have access to the Internet, Pearson eText comprises the full text, including figures that can be enlarged for better viewing. Within eText, students are also able to pop up definitions and terms to help with vocabulary and the reading of the material. Students can also take notes in eText using the annotation feature at the top of each page.
- **Pearson Tutor Services** (www.pearsontutorservices.com) Each student's subscription to MasteringPhysics also contains complimentary access to Pearson Tutor Services, powered by Smarthinking, Inc. By logging in with their MasteringPhysics ID and password, they will be connected to highly qualified e-instructors™ who provide additional, interactive online tutoring on the major concepts of physics. Some restrictions apply; offer subject to change.
- **ActivPhysics OnLine™** (accessed via www.masteringphysics.com), provides students with a suite of highly regarded applet-based tutorials (see above). The following workbooks help students work though complex concepts and understand them more clearly. The *ActivPhysics* margin icons throughout the book direct students to specific exercises that complement the textbook discussion.
- **ActivPhysics OnLine Workbook Volume 1: Mechanics • Thermal Physics • Oscillations & Waves** (ISBN 978-0-805-39060-5)
- **ActivPhysics OnLine Workbook Volume 2: Electricity & Magnetism • Optics • Modern Physics** (ISBN 978-0-805-39061-2)

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Reviewers and Classroom Testers

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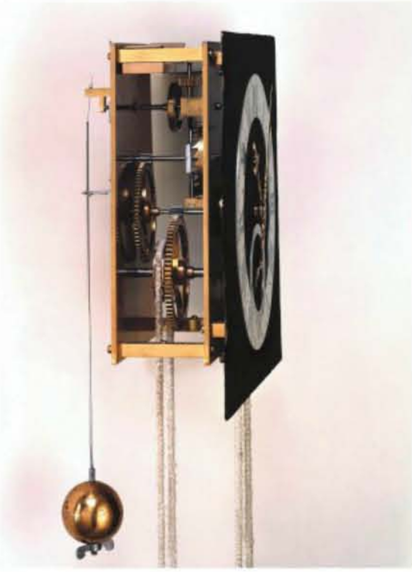
Rajive Tiwari, *Belmont Abbey College*
Herman Trivilino, *College of the Mainland*
Douglas Tussey, *Pennsylvania State University*
Stephen Van Hook, *Pennsylvania State University*
James Vesenka, *University of New England*
Christos Valiotis, *Antelope Valley College*
Stamatis Vokos, *Seattle Pacific University*
James Wanliss, *Embry-Riddle Aeronautical University*
Henry Weigel, *Arapahoe Community College*
Courtney Willis, *University of Northern Colorado*
Katherine Wu, *University of Tampa*
Ali Yazdi, *Jefferson State Community College*
David Young, *Louisiana State University*
Hsiao-Ling Zhou, *Georgia State University*
Ulrich Zurcher, *Cleveland State University*

Preface to the Student

The most incomprehensible thing about the universe is that it is comprehensible.
—Albert Einstein

(a) Pendulum clock



(b) Gibbon locomotion

If you are taking a course for which this book is assigned, you probably aren't a physics major or an engineering major. It's likely that you aren't majoring in a physical science. So why are you taking physics?

It's almost certain that you are taking physics because you are majoring in a discipline that requires it. Someone, somewhere, has decided that it's important for you to take this course. And they are right. There is a lot you can learn from physics, even if you don't plan to be a physicist. We regularly hear from doctors, physical therapists, biologists and others that physics was one of the most interesting and valuable courses they took in college.

So, what can you expect to learn in this course? Let's start by talking about what physics is. Physics is a way of thinking about the physical aspects of nature. Physics is not about "facts." It's far more focused on discovering *relationships* between facts and the *patterns* that exist in nature than on learning facts for their own sake. Our emphasis will be on thinking and reasoning. We are going to look for patterns and relationships in nature, develop the logic that relates different ideas, and search for the reasons *why* things happen as they do.

Once we've figured out a pattern, a set of relationships, we'll look at applications to see where this understanding takes us. Let's look at an example. Part (a) of the figure shows an early mechanical clock. The clock uses a *pendulum,* a mass suspended by a thin rod free to pivot about its end, as its timekeeping element. When you study oscillatory motion, you will learn about the motion of a pendulum. You'll learn that the *period* of its motion, the time for one swing, doesn't depend on the amplitude, the size of the swing. This makes a pendulum the ideal centerpiece of a clock.

But there are other systems that look like pendulums too. The gibbon in part (b) of the figure is moving through the trees by swinging from successive handholds. The gibbon's mass is suspended below a point about which it is free to pivot, so the gibbon's motion can be understood as pendulum motion. You can then use your knowledge of pendulums to describe the motion, explaining, for example, why this gibbon is raising its feet as it swings.

Like any subject, physics is best learned by doing. "Doing physics" in this course means solving problems, applying what you have learned to answer questions at the end of the chapter. When you are given a homework assignment, you may find yourself tempted to simply solve the problems by thumbing through the text looking for a formula that seems like it will work. This isn't how to do physics; if it was, whoever required you to take this course wouldn't bother. The folks who designed your major want you to learn to *reason,* not to "plug and chug." Whatever you end up studying or doing for a career, this ability will serve you well. And that's why someone, somewhere, wants you to take physics.

How do you learn to reason in this way? There's no single strategy for studying physics that will work for all students, but we can make some suggestions that will certainly help:

- **Read each chapter *before* it is discussed in class.** Class attendance is much less effective if you have not prepared. When you first read a chapter, focus on learning new vocabulary, definitions, and notation. You won't understand what's being discussed or how the ideas are being used if you don't know what the terms and symbols mean.
- **Participate actively in class.** Take notes, ask and answer questions, take part in discussion groups. There is ample scientific evidence that *active participation* is far more effective for learning science than is passive listening.
- **After class, go back for a careful rereading of the chapter.** In your second reading, pay close attention to the details and the worked examples. Look for the *logic* behind each example, not just at what formula is being used. We have a three-step process by which we solve all of the worked examples in the text. Most chapters have detailed Problem-Solving Strategies to help you see how to apply this procedure to particular topics, and Tactics Boxes that explain specific steps in your analysis.
- **Apply what you have learned to the homework problems at the end of each chapter.** By following the techniques of the worked examples, applying the tactics and problem-solving strategies, you'll learn how to apply the knowledge you are gaining. In short, you'll learn to reason like a physicist.
- **Form a study group with two or three classmates.** There's good evidence that students who study regularly with a group do better than the rugged individualists who try to go it alone.

And we have one final suggestion. As you read the book, take part in class, and work through problems, step back every now and then to appreciate the big picture. You are going to study topics that range from motions in the solar system to the electrical signals in the nervous system that let you order your hand to turn the pages of this book. You will learn quantitative methods to calculate things such as how far a car will move as it brakes to a stop and how to build a solenoid for an MRI machine. It's a remarkable breadth of topics and techniques that is based on a very compact set of organizing principles. It's quite remarkable, really, well worthy of your study.

Now, let's get down to work.

Real-World Applications

Applications of biological or medical interest are marked BIO in the list below. MCAT-style Passage Problems are marked BIO below. Other end-of-chapter problems of biological or medical interest are marked BIO in the chapter. "Try It Yourself" experiments are marked **TIY**.

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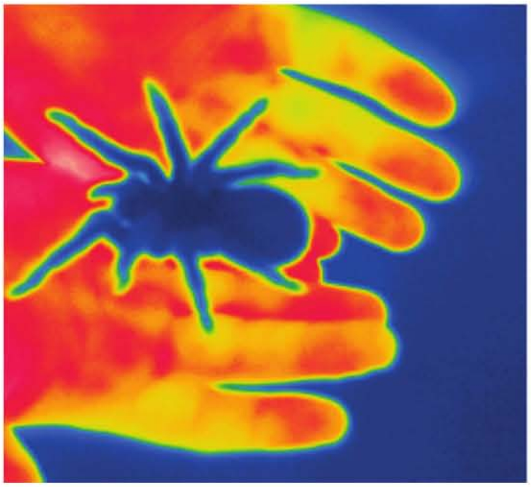

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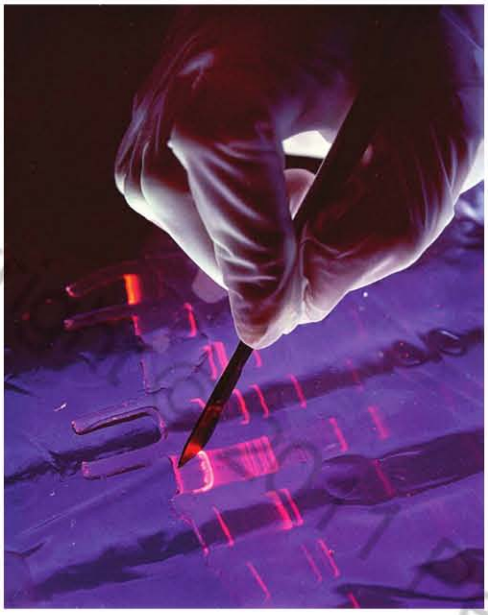

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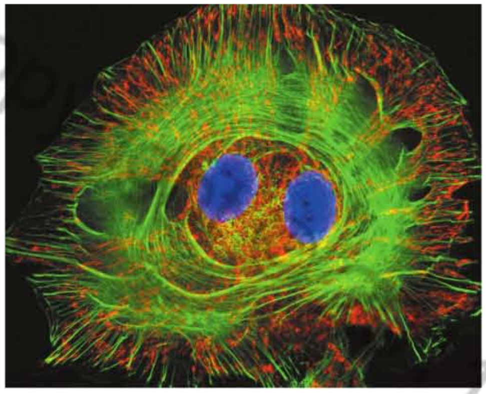

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PART

I

Force and Motion

The cheetah is the fastest land animal, able to run at speeds exceeding 60 miles per hour. Nonetheless, the rabbit has an advantage in this chase. It can *change* its motion more quickly and will likely escape. How can you tell, by looking at the picture, that the cheetah is changing its motion?

OVERVIEW

Why Things Change

Each of the seven parts of this book opens with an overview that gives you a look ahead, a glimpse of where your journey will take you in the next few chapters. It's easy to lose sight of the big picture while you're busy negotiating the terrain of each chapter. In Part I, the big picture is, in a word, *change*.

Simple observations of the world around you show that most things change. Some changes, such as aging, are biological. Others, such as sugar dissolving in your coffee, are chemical. We will look at changes that involve *motion* of one form or another—running and jumping, throwing balls, lifting weights.

There are two big questions we must tackle to study how things change by moving:

- **How do we describe motion?** How should we measure or characterize the motion if we want to analyze it mathematically?
- **How do we explain motion?** Why do objects have the particular motion they do? Why, when you toss a ball upward, does it go up and then come back down rather than keep going up? What are the "laws of nature" that allow us to predict an object's motion?

Two key concepts that will help answer these questions are *force* (the "cause") and *acceleration* (the "effect"). Our basic tools will be three laws of motion elucidated by Isaac Newton. Newton's laws relate force to acceleration, and we will use them to explain and explore a wide range of problems. As we learn to solve problems dealing with motion, we will learn basic techniques that we can apply in all the parts of this book.

Simplifying Models

Reality is extremely complicated. We would never be able to develop a science if we had to keep track of every detail of every situation. Suppose we analyze the tossing of a ball. Is it necessary to analyze the way the atoms in the ball are connected? Do we need to analyze what you ate for breakfast and the biochemistry of how that was translated into muscle power? These are interesting questions, of course. But if our task is to understand the motion of the ball, we need to simplify!

We can do a perfectly fine analysis if we treat the ball as a round solid and your hand as another solid that exerts a force on the ball. This is a *model* of the situation. A model is a simplified description of reality—much as a model airplane is a simplified version of a real airplane—that is used to reduce the complexity of a problem to the point where it can be analyzed and understood.

Model building is a major part of the strategy that we will develop for solving problems in all parts of the book. We will introduce different models in different parts. We will pay close attention to where simplifying assumptions are being made, and why. Learning *how* to simplify a situation is the essence of successful modeling—and successful problem solving.

1 Representing Motion

As this skier moves in a graceful arc through the air, the direction of his motion, and the distance between each of his positions and the next, are constantly changing. What language should we use to describe this motion?

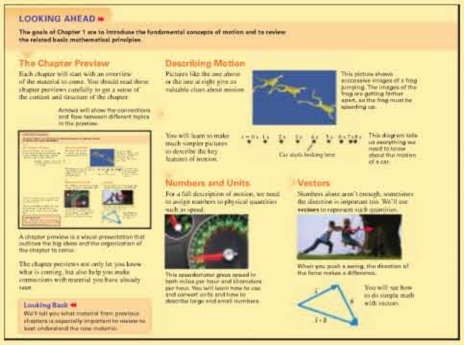
LOOKING AHEAD ▸▸

The goals of Chapter 1 are to introduce the fundamental concepts of motion and to review the related basic mathematical principles.

The Chapter Preview

Each chapter will start with an overview of the material to come. You should read these chapter previews carefully to get a sense of the content and structure of the chapter.

Arrows will show the connections and flow between different topics in the preview.



A chapter preview is a visual presentation that outlines the big ideas and the organization of the chapter to come.

The chapter previews not only let you know what is coming, but also help you make connections with material you have already seen.

Looking Back ◂◂

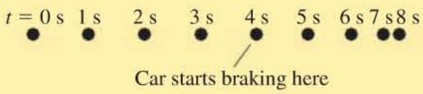
We'll tell you what material from previous chapters is especially important to review to best understand the new material.

Describing Motion

Pictures like the one above or the one at right give us valuable clues about motion.

This picture shows successive images of a frog jumping. The images of the frog are getting farther apart, so the frog must be speeding up.

You will learn to make much simpler pictures to describe the key features of motion.



This diagram tells us everything we need to know about the motion of a car.

Numbers and Units

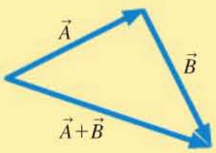
For a full description of motion, we need to assign numbers to physical quantities such as speed.

This speedometer gives speed in both miles per hour and kilometers per hour. You will learn how to use and convert units and how to describe large and small numbers.

Vectors

Numbers alone aren't enough, sometimes the direction is important too. We'll use **vectors** to represent such quantities.

When you push a swing, the direction of the force makes a difference.



You will see how to do simple math with vectors.

1.1 Motion: A First Look

The concept of motion is a theme that will appear in one form or another throughout this entire book. You have a well-developed intuition about motion, based on your experiences, but you'll see that some of the most important aspects of motion can be rather subtle. We need to develop some tools to help us explain and understand motion, so rather than jumping immediately into a lot of mathematics and calculations, this first chapter focuses on visualizing motion and becoming familiar with the concepts needed to describe a moving object.

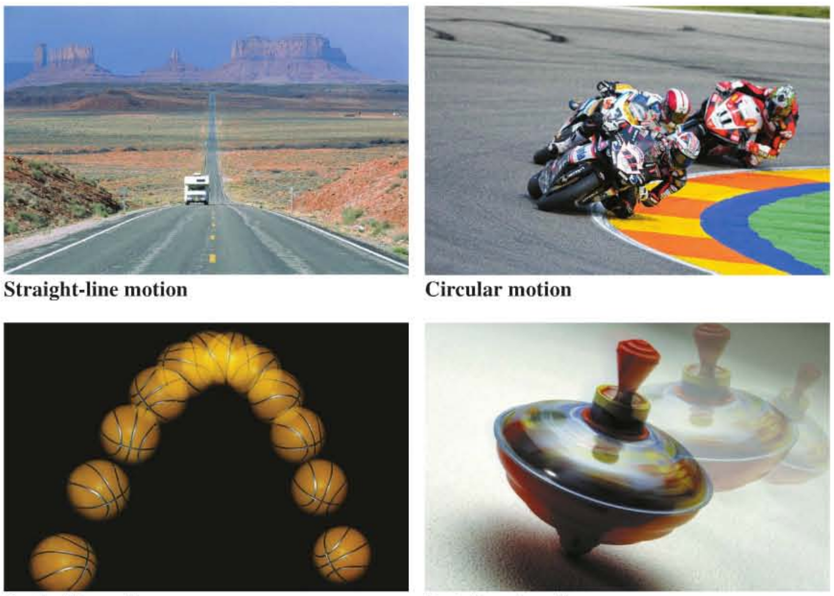
One key difference between physics and other sciences is how we set up and solve problems. We'll often use a two-step process to solve motion problems. The first step is to develop a simplified *representation* of the motion so that key elements stand out. For example, the photo of the skier at the start of the chapter allows us to observe his position at many successive times. It is precisely by considering this sort of picture of motion that we will begin our study of this topic. The second step is to analyze the motion with the language of mathematics. The process of putting numbers on nature is often the most challenging aspect of the problems you will solve. In this chapter, we will explore the steps in this process as we introduce the basic concepts of motion.

Types of Motion

As a starting point, let's define **motion** as the change of an object's position or orientation with time. Examples of motion are easy to list. Bicycles, baseballs, cars, airplanes, and rockets are all objects that move. The path along which an object moves, which might be a straight line or might be curved, is called the object's **trajectory.**

FIGURE 1.1 shows four basic types of motion that we will study in this book. In this chapter, we will start with the first type of motion in the figure, motion along a straight line. In later chapters, we will learn about circular motion, which is the motion of an object along a circular path; projectile motion, the motion of an object through the air; and rotational motion, the spinning of an object about an axis.

FIGURE 1.1 Four basic types of motion.



Straight-line motion **Circular motion**

Projectile motion **Rotational motion**

FIGURE 1.2 Several frames from the video of a car.

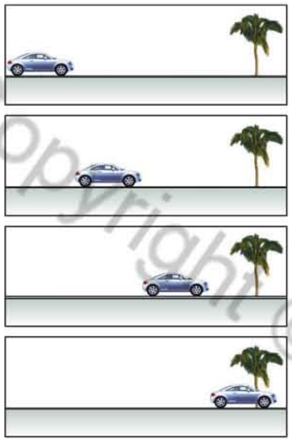
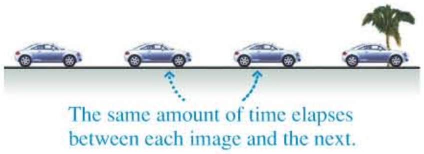


FIGURE 1.3 A motion diagram of the car shows all the frames simultaneously.



Making a Motion Diagram

An easy way to study motion is to record a video of a moving object with a stationary camera. A video camera takes images at a fixed rate, typically 30 images every second. Each separate image is called a *frame*. As an example, FIGURE 1.2 shows several frames from a video of a car going past. Not surprisingly, the car is in a different position in each frame.

NOTE ► It's important to keep the camera in a *fixed position* as the object moves by. Don't "pan" it to track the moving object. ◄

Suppose we now edit the video by layering the frames on top of each other and then look at the final result. We end up with the picture in FIGURE 1.3. This composite image, showing an object's positions at several *equally spaced instants of time,* is called a **motion diagram.** As simple as motion diagrams seem, they will turn out to be powerful tools for analyzing motion.

Now let's take our camera out into the world and make some motion diagrams. The following table illustrates how a motion diagram shows important features of different kinds of motion.

Examples of motion diagrams

An object that occupies only a *single position* in a motion diagram is *at rest.*

A stationary ball on the ground.

Images that are *equally spaced* indicate an object moving with *constant speed.*

A skateboarder rolling down the sidewalk.

An *increasing distance* between the images shows that the object is *speeding up.*

A sprinter starting the 100-meter dash.

A *decreasing distance* between the images shows that the object is *slowing down.*

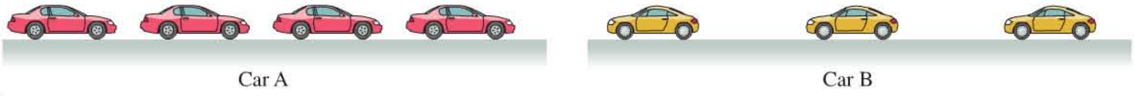
A car stopping for a red light.

A more complex motion diagram shows changes in speed and direction.

A basketball free throw.

We have defined several concepts (at rest, constant speed, speeding up, and slowing down) in terms of how the moving object appears in a motion diagram. These are called **operational definitions,** meaning that the concepts are defined in terms of a particular procedure or operation performed by the investigator. For example, we could answer the question Is the airplane speeding up? by checking whether or not the images in the plane's motion diagram are getting farther apart. Many of the concepts in physics will be introduced as operational definitions. This reminds us that physics is an experimental science.

STOP TO THINK 1.1 Which car is going faster, A or B? Assume there are equal intervals of time between the frames of both videos.



NOTE ▶ Each chapter in this textbook has several *Stop to Think* questions. These questions are designed to see if you've understood the basic ideas that have just been presented. The answers are given at the end of the chapter, but you should make a serious effort to think about these questions before turning to the answers. If you answer correctly and are sure of your answer rather than just guessing, you can proceed to the next section with confidence. But if you answer incorrectly, it would be wise to reread the preceding sections carefully before proceeding onward. ◀

The Particle Model

For many objects, the motion of the object *as a whole* is not influenced by the details of the object's size and shape. To describe the object's motion, all we really need to keep track of is the motion of a single point: You could imagine looking at the motion of a dot painted on the side of the object.

In fact, for the purposes of analyzing the motion, we can often consider the object *as if* it were just a single point, without size or shape. We can also treat the object *as if* all of its mass were concentrated into this single point. An object that can be represented as a mass at a single point in space is called a **particle.**

If we treat an object as a particle, we can represent the object in each frame of a motion diagram as a simple dot. **FIGURE 1.4** shows how much simpler motion diagrams appear when the object is represented as a particle. Note that the dots have been numbered 0, 1, 2, . . . to tell the sequence in which the frames were exposed. These diagrams still convey a complete understanding of the object's motion.

Treating an object as a particle is, of course, a simplification of reality. Such a simplification is called a **model.** Models allow us to focus on the important aspects of a phenomenon by excluding those aspects that play only a minor role. The **particle model** of motion is a simplification in which we treat a moving object as if all of its mass were concentrated at a single point. Using the particle model may allow us to see connections that are very important but that are obscured or lost by examining all the parts of an extended, real object. Consider the motion of the two objects shown in **FIGURE 1.5**. These two very different objects have exactly the same motion diagram. As we will see, all objects falling under the influence of gravity move in exactly the same manner if no other forces act. The simplification of the particle model has revealed something about the physics that underlies both of these situations.

Not all motions can be reduced to the motion of a single point, as we'll see. But for now, the particle model will be a useful tool in understanding motion.

FIGURE 1.4 Simplifying a motion diagram using the particle model.

(a) Motion diagram of a car stopping

(b) Same motion diagram using the particle model

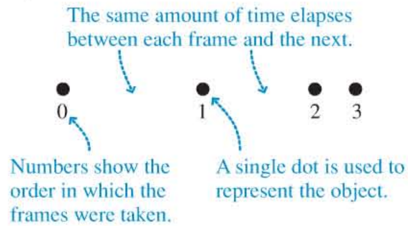
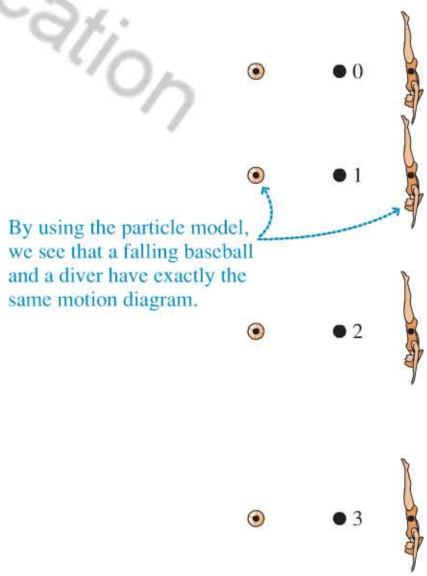
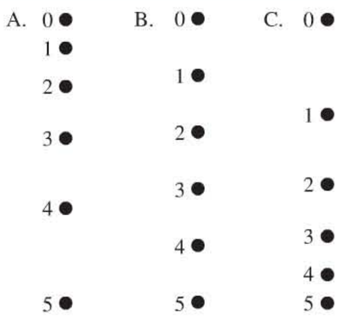


FIGURE 1.5 The particle model for two falling objects.



STOP TO THINK 1.2 Three motion diagrams are shown. Which is a dust particle settling to the floor at constant speed, which is a ball dropped from the roof of a building, and which is a descending rocket slowing to make a soft landing on Mars?

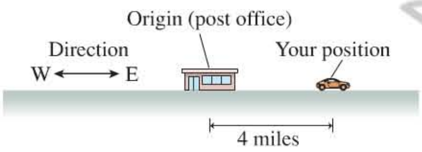


1.2 Position and Time: Putting Numbers on Nature

To develop our understanding of motion further, we need to be able to make quantitative measurements: We need to use numbers. As we analyze a motion diagram, it is useful to know where the object is (its *position*) and when the object was at that position (the *time*). We'll start by considering the motion of an object that can move only along a straight line. Examples of this **one-dimensional** or "1-D" motion are a bicyclist moving along the road, a train moving on a long straight track, and an elevator moving up and down a shaft.

Position and Coordinate Systems

FIGURE 1.6 Describing your position.



Suppose you are driving along a long, straight country road, as in **FIGURE 1.6**, and your friend calls and asks where you are. You might reply that you are 4 miles east of the post office, and your friend would then know just where you were. Your location at a particular instant in time (when your friend phoned) is called your **position.** Notice that to know your position along the road, your friend needed three pieces of information. First, you had to give her a reference point (the post office) from which all distances are to be measured. We call this fixed reference point the **origin.** Second, she needed to know how far you were from that reference point or origin—in this case, 4 miles. Finally, she needed to know which side of the origin you were on: You could be 4 miles to the west of it or 4 miles to the east.

Sometimes measurements have a natural origin. This snow depth gauge has its origin set at road level.

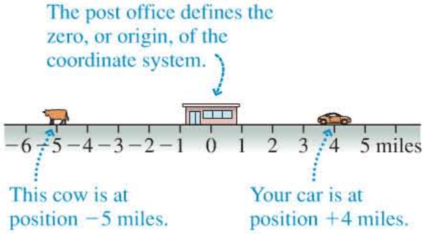
We will need these same three pieces of information in order to specify any object's position along a line. We first choose our origin, from which we measure the position of the object. The position of the origin is arbitrary, and we are free to place it where we like. Usually, however, there are certain points (such as the well-known post office) that are more convenient choices than others.

In order to specify how far our object is from the origin, we lay down an imaginary axis along the line of the object's motion. Like a ruler, this axis is marked off in equally spaced divisions of distance, perhaps in inches, meters, or miles, depending on the problem at hand. We place the zero mark of this ruler at the origin, allowing us to locate the position of our object by reading the ruler mark where the object is.

Finally, we need to be able to specify which side of the origin our object is on. To do this, we imagine the axis extending from one side of the origin with increasing positive markings; on the other side, the axis is marked with increasing *negative* numbers. By reporting the position as either a positive or a negative number, we know on what side of the origin the object is.

These elements—an origin and an axis marked in both the positive and negative directions—can be used to unambiguously locate the position of an object. We call this a **coordinate system.** We will use coordinate systems throughout this book, and we will soon develop coordinate systems that can be used to describe the positions of objects moving in more complex ways than just along a line. **FIGURE 1.7** shows a coordinate system that can be used to locate various objects along the country road discussed earlier.

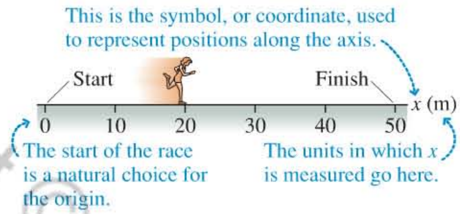
FIGURE 1.7 The coordinate system used to describe objects along a country road.



Although our coordinate system works well for describing the positions of objects located along the axis, our notation is somewhat cumbersome. We need to keep saying things like "the car is at position +4 miles." A better notation, and one that will become particularly important when we study motion in two dimensions, is to use a symbol such as x or y to represent the position along the axis. Then we can say "the cow is at $x = -5$ miles." The symbol that represents a position along an axis is called a **coordinate.** The introduction of symbols to represent positions (and, later, velocities and accelerations) also allows us to work with these quantities mathematically.

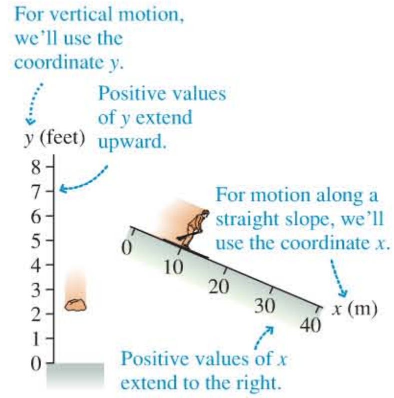
FIGURE 1.8 below shows how we would set up a coordinate system for a sprinter running a 50-meter race (we use the standard symbol "m" for meters). For horizontal motion like this we usually use the coordinate x to represent the position.

FIGURE 1.8 A coordinate system for a 50-meter race.



Motion along a straight line need not be horizontal. As shown in **FIGURE 1.9**, a rock falling vertically downward and a skier skiing down a straight slope are also examples of straight-line or one-dimensional motion.

FIGURE 1.9 Examples of one-dimensional motion.



Time

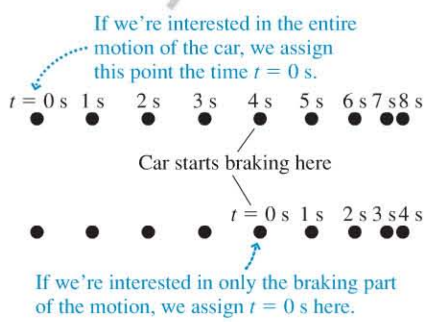
The pictures in Figure 1.9 show the position of an object at just one instant of time. But a full motion diagram represents how an object moves as time progresses. So far, we have labeled the dots in a motion diagram by the numbers 0, 1, 2, . . . to indicate the order in which the frames were exposed. But to fully describe the motion, we need to indicate the *time,* as read off a clock or a stopwatch, at which each frame of a video was made. This is important, as we can see from the motion diagram of a stopping car in **FIGURE 1.10**. If the frames were taken 1 second apart, this motion diagram shows a leisurely stop; if 1/10 of a second apart, it represents a screeching halt.

FIGURE 1.10 Is this a leisurely stop or a screeching halt?

For a complete motion diagram, we thus need to label each frame with its corresponding time (symbol t) as read off a clock. But when should we start the clock? Which frame should be labeled $t = 0$? This choice is much like choosing the origin $x = 0$ of a coordinate system: You can pick any arbitrary point in the motion and label it "$t = 0$ seconds." This is simply the instant you decide to start your clock or stopwatch, so it is the origin of your time coordinate. A video frame labeled "$t = 4$ seconds" means it was taken 4 seconds after you started your clock. We typically choose $t = 0$ to represent the "beginning" of a problem, but the object may have been moving before then.

To illustrate, **FIGURE 1.11** shows the motion diagram for a car moving at a constant speed and then braking to a halt. Two possible choices for the frame labeled $t = 0$ seconds are shown; our choice depends on what part of the motion we're interested in. Each successive position of the car is then labeled with the clock reading in seconds (abbreviated by the symbol "s").

FIGURE 1.11 The motion diagram of a car that travels at constant speed and then brakes to a halt.



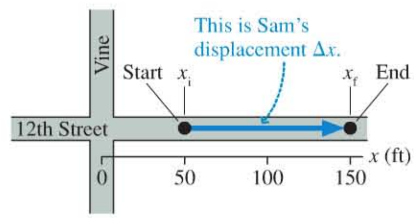
Changes in Position and Displacement

Now that we've seen how to measure position and time, let's return to the problem of motion. To describe motion we'll need to measure the *changes* in position that occur with time. Consider the following:

> Sam is standing 50 feet (ft) east of the corner of 12th Street and Vine. He then walks to a second point 150 ft east of Vine. What is Sam's change of position?

FIGURE 1.12 shows Sam's motion on a map. We've placed a coordinate system on the map, using the coordinate x. We are free to place the origin of our coordinate system wherever we wish, so we have placed it at the intersection. Sam's initial position is then at $x_i = 50$ ft. The positive value for x_i tells us that Sam is east of the origin.

FIGURE 1.12 Sam undergoes a displacement Δx from position x_i to position x_f.



The size and the direction of the displacement both matter. Roy Riegels (pursued above by teammate Benny Lom) found this out in dramatic fashion in the 1928 Rose Bowl when he recovered a fumble and ran 69 yards—toward his own team's end zone. An impressive distance, but in the wrong direction!

NOTE ► We will label special values of x or y with subscripts. The value at the start of a problem is usually labeled with a subscript "i," for *initial,* and the value at the end is labeled with a subscript "f," for *final.* For cases having several special values, we will usually use subscripts "1," "2," and so on. ◄

Sam's final position is $x_f = 150$ ft, indicating that he is 150 ft east of the origin. You can see that Sam has changed position, and a *change* of position is called a **displacement.** His displacement is the distance labeled Δx in Figure 1.12. The Greek letter delta (Δ) is used in math and science to indicate the *change* in a quantity. Thus Δx indicates a change in the position x.

NOTE ► Δx is a *single* symbol. You cannot cancel out or remove the Δ in algebraic operations. ◄

To get from the 50 ft mark to the 150 ft mark, Sam clearly had to walk 100 ft, so the change in his position—his displacement—is 100 ft. We can think about displacement in a more general way, however. **Displacement is the *difference* between a final position x_f and an initial position x_i.** Thus we can write

$$\Delta x = x_f - x_i = 150 \text{ ft} - 50 \text{ ft} = 100 \text{ ft}$$

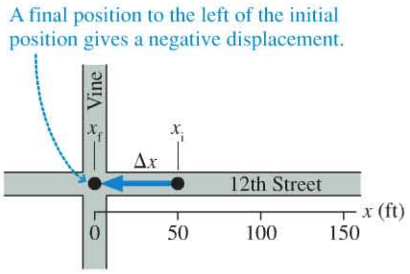
NOTE ► A general principle, used throughout this book, is that the change in any quantity is the final value of the quantity minus its initial value. ◄

Displacement is a *signed quantity;* that is, it can be either positive or negative. If, as shown in **FIGURE 1.13**, Sam's final position x_f had been at the origin instead of the 150 ft mark, his displacement would have been

$$\Delta x = x_f - x_i = 0 \text{ ft} - 50 \text{ ft} = -50 \text{ ft}$$

The negative sign tells us that he moved to the *left* along the x-axis, or 50 ft *west.*

FIGURE 1.13 A displacement is a signed quantity. Here Δx is a negative number.



Change in Time

A displacement is a change in position. In order to quantify motion, we'll need to also consider changes in *time,* which we call **time intervals.** We've seen how we can label each frame of a motion diagram with a specific time, as determined by our stopwatch. **FIGURE 1.14** shows the motion diagram of a bicycle moving at a constant speed, with the times of the measured points indicated.

The displacement between the initial position x_i and the final position x_f is

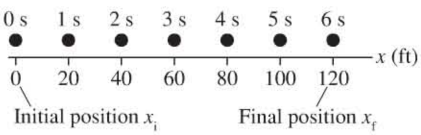
$$\Delta x = x_f - x_i = 120 \text{ ft} - 0 \text{ ft} = 120 \text{ ft}$$

Similarly, we define the time interval between these two points to be

$$\Delta t = t_f - t_i = 6 \text{ s} - 0 \text{ s} = 6 \text{ s}$$

A time interval Δt measures the elapsed time as an object moves from an initial position x_i at time t_i to a final position x_f at time t_f. Note that, unlike Δx, Δt is always positive because t_f is always greater than t_i.

FIGURE 1.14 The motion diagram of a bicycle moving to the right at a constant speed.

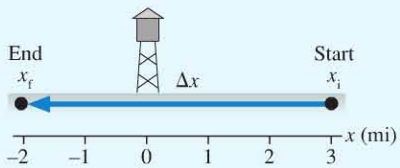


EXAMPLE 1.1 **How long a ride?**

Carol is enjoying a bicycle ride on a country road that runs east-west past a water tower. Define a coordinate system so that increasing x means moving east. At noon, Carol is 3 miles (mi) east of the water tower. A half-hour later, she is 2 mi west of the water tower. What is her displacement during that half-hour?

PREPARE Although it may seem like overkill for such a simple problem, you should start by making a drawing, like the one in **FIGURE 1.15**, with the x-axis along the road. Distances are measured with respect to the water tower, so it is a natural origin for the

FIGURE 1.15 A drawing of Carol's motion.



coordinate system. Once the coordinate system is established, we can show Carol's initial and final positions and her displacement between the two.

SOLVE We've specified values for Carol's initial and final positions in our drawing. We can thus compute her displacement:

$$\Delta x = x_f - x_i = (-2 \text{ mi}) - (3 \text{ mi}) = -5 \text{ mi}$$

ASSESS Once we've completed the solution to the problem, we need to go back to see if it makes sense. Carol is moving to the west, so we expect her displacement to be negative—and it is. We can see from our drawing in Figure 1.15 that she has moved 5 miles from her starting position, so our answer seems reasonable.

NOTE ▶ All of the numerical examples in the book are worked out with the same three-step process: Prepare, Solve, Assess. It's tempting to cut corners, especially for the simple problems in these early chapters, but you should take the time to do all of these steps now, to practice your problem-solving technique. We'll have more to say about our general problem-solving strategy in Chapter 2. ◀

STOP TO THINK 1.3 Sarah starts at a positive position along the *x*-axis. She then undergoes a negative displacement. Her final position

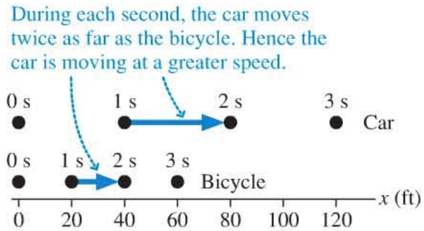
A. Is positive. B. Is negative. C. Could be either positive or negative.

1.3 Velocity

We all have an intuitive sense of whether something is moving very fast or just cruising slowly along. To make this intuitive idea more precise, let's start by examining the motion diagrams of some objects moving along a straight line at a *constant* speed, objects that are neither speeding up nor slowing down. This motion at a constant speed is called **uniform motion.** As we saw for the skateboarder in Section 1.1, for an object in uniform motion, successive frames of the motion diagram are *equally spaced.* We know now that this means that the object's displacement Δx is the same between successive frames.

To see how an object's displacement between successive frames is related to its speed, consider the motion diagrams of a bicycle and a car, traveling along the same street as shown in FIGURE 1.16. Clearly the car is moving faster than the bicycle: In any 1-second time interval, the car undergoes a displacement $\Delta x = 40$ ft, while the bicycle's displacement is only 20 ft.

FIGURE 1.16 Motion diagrams for a car and a bicycle.



The distances traveled in 1 second by the bicycle and the car are a measure of their speeds. The greater the distance traveled by an object in a given time interval, the greater its speed. This idea leads us to define the speed of an object as

$$\text{speed} = \frac{\text{distance traveled in a given time interval}}{\text{time interval}} \quad (1.1)$$

Speed of a moving object

For the bicycle, this equation gives

$$\text{speed} = \frac{20 \text{ ft}}{1 \text{ s}} = 20 \frac{\text{ft}}{\text{s}}$$

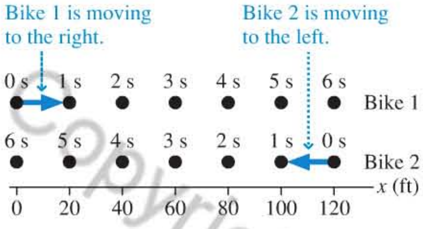
while for the car we have

$$\text{speed} = \frac{40 \text{ ft}}{1 \text{ s}} = 40 \frac{\text{ft}}{\text{s}}$$

The speed of the car is twice that of the bicycle, which seems reasonable.

NOTE ▶ The division gives units that are a fraction: ft/s. This is read as "feet per second," just like the more familiar "miles per hour." ◀

FIGURE 1.17 Two bicycles traveling at the same speed, but with different velocities.



To fully characterize the motion of an object, it is important to specify not only the object's speed but also the *direction* in which it is moving. For example, **FIGURE 1.17** shows the motion diagrams of two bicycles traveling at the same speed of 20 ft/s. The two bicycles have the same speed, but something about their motion is different—the *direction* of their motion.

The problem is that the "distance traveled" in Equation 1.1 doesn't capture any information about the direction of travel. But we've seen that the *displacement* of an object does contain this information. We can then introduce a new quantity, the **velocity,** as

$$\text{velocity} = \frac{\text{displacement}}{\text{time interval}} = \frac{\Delta x}{\Delta t} \quad (1.2)$$

Velocity of a moving object

The velocity of bicycle 1 in Figure 1.17, computed using the 1 second time interval between the $t = 2$ s and $t = 3$ s positions, is

$$v = \frac{\Delta x}{\Delta t} = \frac{x_3 - x_2}{3\text{ s} - 2\text{ s}} = \frac{60\text{ ft} - 40\text{ ft}}{1\text{ s}} = +20\,\frac{\text{ft}}{\text{s}}$$

while the velocity for bicycle 2, during the same time interval, is

$$v = \frac{\Delta x}{\Delta t} = \frac{x_3 - x_2}{3\text{ s} - 2\text{ s}} = \frac{60\text{ ft} - 80\text{ ft}}{1\text{ s}} = -20\,\frac{\text{ft}}{\text{s}}$$

NOTE ► We have used x_2 for the position at time $t = 2$ seconds and x_3 for the position at time $t = 3$ seconds. The subscripts serve the same role as before—identifying particular positions—but in this case the positions are identified by the time at which each position is reached. ◄

The two velocities have opposite signs because the bicycles are traveling in opposite directions. **Speed measures only how fast an object moves, but velocity tells us both an object's speed *and its direction.*** A positive velocity indicates motion to the right or, for vertical motion, upward. Similarly, an object moving to the left, or down, has a negative velocity.

NOTE ► Learning to distinguish between speed, which is always a positive number, and velocity, which can be either positive or negative, is one of the most important tasks in the analysis of motion. ◄

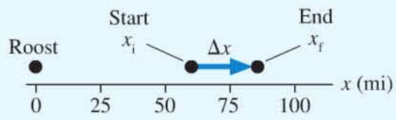
The velocity as defined by Equation 1.2 is actually what is called the *average* velocity. On average, over each 1 s interval bicycle 1 moves 20 ft, but we don't know if it was moving at exactly the same speed at every moment during this time interval. In Chapter 2, we'll develop the idea of *instantaneous* velocity, the velocity of an object at a particular instant in time. Since our goal in this chapter is to *visualize* motion with motion diagrams, we'll somewhat blur the distinction between average and instantaneous quantities, refining these definitions in Chapter 2, where our goal will be to develop the mathematics of motion.

EXAMPLE 1.2 Finding the speed of a seabird

Albatrosses are seabirds that spend most of their lives flying over the ocean looking for food. With a stiff tailwind, an albatross can fly at high speeds. Satellite data on one particularly speedy albatross showed it 60 miles east of its roost at 3:00 PM and then, at 3:20 PM, 86 miles east of its roost. What was its velocity?

PREPARE The statement of the problem provides us with a natural coordinate system: We can measure distances with respect to the roost, with distances to the east as positive. With this coordinate system, the motion of the albatross appears as in **FIGURE 1.18**. The motion takes place between 3:00 and 3:20, a time interval of 20 minutes, or 0.33 hour.

FIGURE 1.18 The motion of an albatross at sea.



SOLVE We know the initial and final positions, and we know the time interval, so we can calculate the velocity:

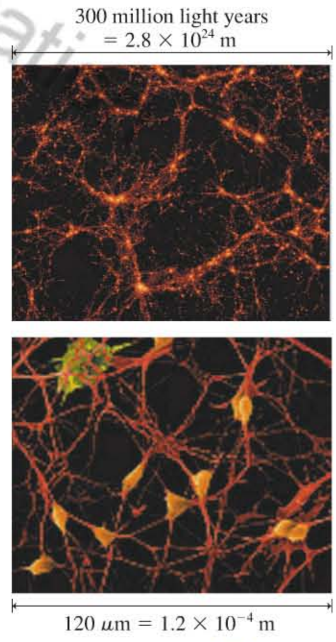
$$v = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{0.33\ \text{h}} = \frac{26\ \text{mi}}{0.33\ \text{h}} = 79\ \text{mph}$$

ASSESS The velocity is positive, which makes sense because Figure 1.18 shows that the motion is to the right. A speed of 79 mph is certainly fast, but the problem said it was a "particularly speedy" albatross, so our answer seems reasonable. (Indeed, albatrosses have been observed to fly at such speeds in the very fast winds of the Southern Ocean. This problem is based on real observations, as will be our general practice in this book.)

The "Per" in Meters Per Second

The units for speed and velocity are a unit of distance (feet, meters, miles) divided by a unit of time (seconds, hours). Thus we could measure velocity in units of m/s or mph, pronounced "meters *per* second" and "miles *per* hour." The word "per" will often arise in physics when we consider the ratio of two quantities. What do we mean, exactly, by "per"?

If a car moves with a speed of 23 m/s, we mean that it travels 23 meters *for each* 1 second of elapsed time. The word "per" thus associates the number of units in the numerator (23 m) with *one* unit of the denominator (1 s). We'll see many other examples of this idea as the book progresses. You may already know a bit about *density;* you can look up the density of gold and you'll find that it is 19.3 g/cm^3 ("grams *per* cubic centimeter"). This means that there are 19.3 grams of gold *for each* 1 cubic centimeter of the metal. Thinking about the word "per" in this way will help you better understand physical quantities whose units are the ratio of two other units.



From galaxies to cells ... BIO In science, we need to express numbers both very large and very small. The top image is a computer simulation of the structure of the universe. Bright areas represent regions of clustered galaxies. The bottom image is cortical nerve cells. Nerve cells relay signals to each other through a complex web of dendrites. These images, though similar in appearance, differ in scale by a factor of about 2×10^{28}!

1.4 A Sense of Scale: Significant Figures, Scientific Notation, and Units

Physics attempts to explain the natural world, from the very small to the exceedingly large. And in order to understand our world, we need to be able to *measure* quantities both minuscule and enormous. A properly reported measurement has three elements. First, we can measure our quantity with only a certain precision. To make this precision clear, we need to make sure that we report our measurement with the correct number of *significant figures.*

Second, writing down the really big and small numbers that often come up in physics can be awkward. To avoid writing all those zeros, scientists use *scientific notation* to express numbers both big and small.

Finally, we need to choose an agreed-upon set of *units* for the quantity. For speed, common units include meters per second and miles per hour. For mass, the kilogram is the most commonly used unit. Every physical quantity that we can measure has an associated set of units.

FIGURE 1.19 The precision of a measurement depends on the instrument used to make it.

These calipers have a precision of 0.01 mm.

Walter Davis's best long jump on this day was reported as 8.24 m. This implies that the actual length of the jump was between 8.235 m and 8.245 m, a spread of only 0.01 m, which is 1 cm. Does this claimed accuracy seem reasonable?

TRY IT YOURSELF

How tall are you really? If you measure your height in the morning, just after you wake up, and then in the evening, after a full day of activity, you'll find that your evening height is *shorter* by as much as 3/4 inch. Your height decreases over the course of the day as gravity compresses and reshapes your spine. If you give your height as 66 3/16 in, you are claiming more significant figures than are truly warranted; the 3/16 in isn't really reliably known because your height can vary by more than this. Expressing your height to the nearest inch is plenty!

Measurements and Significant Figures

When we measure any quantity, such as the length of a bone or the weight of a specimen, we can do so with only a certain *precision*. The digital calipers in FIGURE 1.19 can make a measurement to within ± 0.01 mm, so they have a precision of 0.01 mm. If you made the measurement with a ruler, you probably couldn't do better than about ± 1 mm, so the precision of the ruler is about 1 mm. The precision of a measurement can also be affected by the skill or judgment of the person performing the measurement. A stopwatch might have a precision of 0.001 s, but, due to your reaction time, your measurement of the time of a sprinter would be much less precise.

It is important that your measurement be reported in a way that reflects its actual precision. Suppose you use a ruler to measure the length of a particular specimen of a newly discovered species of frog. You judge that you can make this measurement with a precision of about 1 mm, or 0.1 cm. In this case, the frog's length should be reported as, say, 6.2 cm. We interpret this to mean that the actual value falls between 6.15 cm and 6.25 cm and thus rounds to 6.2 cm. Reporting the frog's length as simply 6 cm is saying less than you know; you are withholding information. On the other hand, to report the number as 6.213 cm is wrong. Any person reviewing your work would interpret the number 6.213 cm as meaning that the actual length falls between 6.2125 cm and 6.2135 cm, thus rounding to 6.213 cm. In this case, you are claiming to have knowledge and information that you do not really possess.

The way to state your knowledge precisely is through the proper use of **significant figures.** You can think of a significant figure as a digit that is reliably known. A measurement such as 6.2 cm has *two* significant figures, the 6 and the 2. The next decimal place—the hundredths—is not reliably known and is thus not a significant figure. Similarly, a time measurement of 34.62 s has four significant figures, implying that the 2 in the hundredths place is reliably known.

When we perform a calculation such as adding or multiplying two or more measured numbers, we can't claim more accuracy for the result than was present in the initial measurements. Nine out of ten numbers used in a calculation might be known with a precision of 0.01%, but if the tenth number is poorly known, with a precision of only 10%, then the result of the calculation cannot possibly be more precise than 10%.

Determining the proper number of significant figures is straightforward, but there are a few definite rules to follow. We will often spell out such technical details in what we call a "Tactics Box." A Tactics Box is designed to teach you particular skills and techniques. Each Tactics Box will use the icon to designate exercises in the *Student Workbook* that you can use to practice these skills.

TACTICS BOX 1.1 Using significant figures

MP™

1. When you multiply or divide several numbers, or when you take roots, the number of significant figures in the answer should match the number of significant figures of the *least* precisely known number used in the calculation:

Three significant figures

$$3.73 \times 5.7 = 21$$

Two significant figures

Answer should have the *lower* of the two, or two significant figures.

Continued

❷ When you add or subtract several numbers, the number of decimal places in the answer should match the *smallest* number of decimal places of any number used in the calculation:

$$\begin{array}{r l} 18.54 & \text{— Two decimal places} \\ +106.6 & \text{— One decimal place} \\ \hline 125.1 & \end{array}$$

Answer should have the *lower* of the two, or one decimal place.

❸ **Exact numbers** have no uncertainty and, when used in calculations, do not change the number of significant figures of measured numbers. Examples of exact numbers are π and the number 2 in the relation $d = 2r$ between a circle's diameter and radius.

There is one notable exception to these rules:

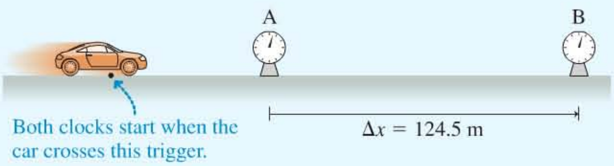
- It is acceptable to keep one or two extra digits during *intermediate* steps of a calculation. The goal here is to minimize round-off errors in the calculation. But the *final* answer must be reported with the proper number of significant figures.

Exercise 15

EXAMPLE 1.3 Measuring the velocity of a car

To measure the velocity of a car, clocks A and B are set up at two points along the road, as shown in **FIGURE 1.20**. Clock A is precise to 0.01 s, while B is precise to only 0.1 s. The distance between these two clocks is carefully measured to be 124.5 m. The two clocks are automatically started when the car passes a trigger in the road; each clock stops automatically when the car passes that clock. After the car has passed both clocks, clock A is found to read $t_A = 1.22$ s, and clock B to read $t_B = 4.5$ s. The time from the less-precise clock B is correctly reported with fewer significant figures than that from A. What is the velocity of the car, and how should it be reported with the correct number of significant figures?

FIGURE 1.20 Measuring the velocity of a car.



PREPARE To calculate the velocity, we need the displacement Δx and the time interval Δt as the car moves between the two clocks. The displacement is given as $\Delta x = 124.5$ m; we can calculate the time interval as the difference between the two measured times.

SOLVE The time interval is:

This number has one decimal place.

This number has two decimal places.

$$\Delta t = t_B - t_A = (4.5 \text{ s}) - (1.22 \text{ s}) = 3.3 \text{ s}$$

By rule 2 of Tactics Box 1.1, the result should have *one* decimal place.

We can now calculate the velocity with the displacement and the time interval:

The displacement has four significant figures.

$$v = \frac{\Delta x}{\Delta t} = \frac{124.5 \text{ m}}{3.3 \text{ s}} = 38 \text{ m/s}$$

The time interval has two significant figures.

By rule 1 of Tactics Box 1.1, the result should have *two* significant figures.

ASSESS Our final value has two significant figures. Suppose you had been hired to measure the speed of a car this way, and you reported 37.72 m/s. It would be reasonable for someone looking at your result to assume that the measurements you used to arrive at this value were correct to four significant figures and thus that you had measured time to the nearest 0.001 second. Our correct result of 38 m/s has all of the accuracy that you can claim, but no more!

Scientific Notation

It's easy to write down measurements of ordinary-sized objects: Your height might be 1.72 meters, the weight of an apple 0.34 pound. But the radius of a hydrogen atom is 0.000000000053 m, and the distance to the moon is 384000000 m. Keeping track of all those zeros is quite cumbersome.

Beyond requiring you to deal with all the zeros, writing quantities this way makes it unclear how many significant figures are involved. In the distance to the moon given above, how many of those digits are significant? Three? Four? All nine?

Writing numbers using scientific notation avoids both these problems. A value in scientific notation is a number with one digit to the left of the decimal point and zero or more to the right of it, multiplied by a power of ten. This solves the problem of all the zeros and makes the number of significant figures immediately apparent. In scientific notation, writing the distance to the sun as 1.50×10^{11} m implies that three digits are significant; writing it as 1.5×10^{11} m implies that only two digits are.

Even for smaller values, scientific notation can clarify the number of significant figures. Suppose a distance is reported as 1200 m. How many significant figures does this measurement have? It's ambiguous, but using scientific notation can remove any ambiguity. If this distance is known to within 1 m, we can write it as 1.200×10^3 m, showing that all four digits are significant; if it is accurate to only 100 m or so, we can report it as 1.2×10^3 m, indicating two significant figures.

Tactics Box 1.2 shows how to convert a number to scientific notation, and how to correctly indicate the number of significant figures.

TACTICS BOX 1.2 Using scientific notation

To convert a number into scientific notation:

1. For a number greater than 10, move the decimal point to the left until only one digit remains to the left of the decimal point. The remaining number is then multiplied by 10 to a power; this power is given by the number of spaces the decimal point was moved. Here we convert the diameter of the earth to scientific notation:

   We move the decimal point until there is only one digit to its left, counting the number of steps.

   Since we moved the decimal point 6 steps, the power of ten is 6.

   $$6\,370\,000 \text{ m} = \underbrace{6.37}_{} \times 10^6 \text{ m}$$

   The number of digits here equals the number of significant figures.

2. For a number less than 1, move the decimal point to the right until it passes the first digit that isn't a zero. The remaining number is then multiplied by 10 to a negative power; the power is given by the number of spaces the decimal point was moved. For the diameter of a red blood cell we have:

   We move the decimal point until it passes the first digit that is not a zero, counting the number of steps.

   Since we moved the decimal point 6 steps, the power of ten is -6.

   $$0.000\,007\,5 \text{ m} = \underbrace{7.5}_{} \times 10^{-6} \text{ m}$$

   The number of digits here equals the number of significant figures.

Exercise 16

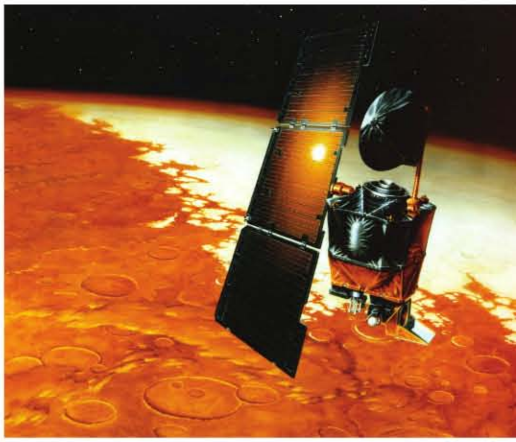
Proper use of significant figures is part of the "culture" of science. We will frequently emphasize these "cultural issues" because you must learn to speak the same language as the natives if you wish to communicate effectively! Most students know the rules of significant figures, having learned them in high school, but many fail to apply them. It is important that you understand the reasons for significant figures and that you get in the habit of using them properly.

Units

As we have seen, in order to measure a quantity we need to give it a numerical value. But a measurement is more than just a number—it requires a *unit* to be given. You can't go to the deli and ask for "three quarters of cheese." You need to use a unit—here, one of weight, such as pounds—in addition to the number.

In your daily life, you probably use the English system of units, in which distances are measured in inches, feet, and miles. These units are well adapted for daily life, but they are rarely used in scientific work. Given that science is an international discipline, it is also important to have a system of units that is recognized around the world. For these reasons, scientists use a system of units called *le Système Internationale d'Unités,* commonly referred to as **SI units.** SI units were originally developed by the French in the late 1700s as a way of standardizing and regularizing numbers for commerce and science. We often refer to these as *metric units* because the meter is the basic standard of length.

The three basic SI quantities, shown in Table 1.1, are time, length (or distance), and mass. Other quantities needed to understand motion can be expressed as combinations of these basic units. For example, speed and velocity are expressed in meters per second or m/s. This combination is a ratio of the length unit (the meter) to the time unit (the second).



The importance of units In 1999, the $125 million Mars Climate Orbiter burned up in the Martian atmosphere instead of entering a safe orbit from which it could perform observations. The problem was faulty units! An engineering team had provided critical data on spacecraft performance in English units, but the navigation team assumed these data were in metric units. As a consequence, the navigation team had the spacecraft fly too close to the planet, and it burned up in the atmosphere.

Using Prefixes

We will have many occasions to use lengths, times, and masses that are either much less or much greater than the standards of 1 meter, 1 second, and 1 kilogram. We will do so by using *prefixes* to denote various powers of ten. For instance, the prefix "kilo" (abbreviation k) denotes 10^3, or a factor of 1000. Thus 1 km equals 1000 m, 1 MW equals 10^6 watts, and 1 μV equals 10^{-6} V. Table 1.2 lists the common prefixes that will be used frequently throughout this book. A more extensive list of prefixes is shown inside the cover of the book.

Although prefixes make it easier to talk about quantities, the proper SI units are meters, seconds, and kilograms. Quantities given with prefixed units must be converted to base SI units before any calculations are done. Thus 23.0 cm must be converted to 0.230 m before starting calculations. The exception is the kilogram, which is already the base SI unit.

TABLE 1.1 Common SI units

Quantity	Unit	Abbreviation
time	second	s
length	meter	m
mass	kilogram	kg

TABLE 1.2 Common prefixes

Prefix	Abbreviation	Power of 10
mega-	M	10^6
kilo-	k	10^3
centi-	c	10^{-2}
milli-	m	10^{-3}
micro-	μ	10^{-6}
nano-	n	10^{-9}

Unit Conversions

Although SI units are our standard, we cannot entirely forget that the United States still uses English units. Even after repeated exposure to metric units in classes, most of us "think" in English units. Thus it remains important to be able to convert back and forth between SI units and English units. Table 1.3 shows some frequently used conversions that will come in handy.

One effective method of performing unit conversions begins by noticing that since, for example, 1 mi = 1.609 km, the ratio of these two distances—*including their units*—is equal to 1, so that

$$\frac{1\text{ mi}}{1.609\text{ km}} = \frac{1.609\text{ km}}{1\text{ mi}} = 1$$

A ratio of values equal to 1 is called a **conversion factor.** The following Tactics Box shows how to make a unit conversion.

TABLE 1.3 Useful unit conversions

1 inch (in) = 2.54 cm
1 foot (ft) = 0.305 m
1 mile (mi) = 1.609 km
1 mile per hour (mph) = 0.447 m/s
1 m = 39.37 in
1 km = 0.621 mi
1 m/s = 2.24 mph

TACTICS BOX 1.3 Making a unit conversion

❶ Start with the quantity you wish to convert.

❷ Multiply by the appropriate conversion factor. Because this conversion factor is equal to 1, multiplying by it does not change the value of the quantity—only its units.

❺ Remember to convert your final answer to the correct number of significant figures!

$$60 \text{ mi} = 60 \cancel{\text{mi}} \times \frac{1.609 \text{ km}}{1 \cancel{\text{mi}}} = 96.54 \text{ km} = 97 \text{ km}$$

❸ You can cancel the original unit (here, miles) because it appears in both the numerator and the denominator.

❹ Calculate the answer; it is in the desired units. Remember, 60 mi and 96.54 km are the same distance; they are simply in different units.

Exercise 17

Note that we've rounded the answer to 97 kilometers because the distance we're converting, 60 miles, has only two significant figures.

More complicated conversions can be done with several successive multiplications of conversion factors, as we see in the next example.

EXAMPLE 1.4 Can a bicycle go that fast?

In Section 1.3, we calculated the speed of a bicycle to be 20 ft/s. Is this a reasonable speed for a bicycle?

PREPARE In order to determine whether or not this speed is reasonable, we will convert it to more familiar units. For speed, the unit you are most familiar with is likely miles per hour.

SOLVE We first collect the necessary unit conversions:

$$1 \text{ mi} = 5280 \text{ ft} \qquad 1 \text{ hour } (1 \text{ h}) = 60 \text{ min} \qquad 1 \text{ min} = 60 \text{ s}$$

We then multiply our original value by successive factors of 1 in order to convert the units:

We want to cancel feet here in the numerator . . .

. . . so we multiply by $1 = \dfrac{1 \text{ mi}}{5280 \text{ ft}}$ to get the feet in the denominator.

$$20 \frac{\text{ft}}{\text{s}} = 20 \frac{\cancel{\text{ft}}}{\cancel{\text{s}}} \times \frac{1 \text{ mi}}{5280 \cancel{\text{ft}}} \times \frac{60 \cancel{\text{s}}}{1 \cancel{\text{min}}} \times \frac{60 \cancel{\text{min}}}{1 \text{ h}} = 14 \frac{\text{mi}}{\text{h}} = 14 \text{ mph}$$

The unwanted units cancel in pairs, as indicated by the colors.

ASSESS Our final result of 14 miles per hour (14 mph) is a very reasonable speed for a bicycle, which gives us confidence in our answer. If we had calculated a speed of 140 miles per hour, we would have suspected that we had made an error because this is quite a bit faster than the average bicyclist can travel!

How many jellybeans are in the jar? Some reasoning about the size of one bean and the size of the jar can give you a one-significant-figure estimate.

Estimation

When scientists and engineers first approach a problem, they may do a quick measurement or calculation to establish the rough physical scale involved. This will help establish the procedures that should be used to make a more accurate measurement—or the estimate may well be all that is needed.

Suppose you see a rock fall off a cliff and would like to know how fast it was going when it hit the ground. By doing a mental comparison with the speeds of familiar objects, such as cars and bicycles, you might judge that the rock was traveling at about 20 mph. This is a one-significant-figure estimate. With some luck, you can probably distinguish 20 mph from either 10 mph or 30 mph, but you certainly cannot distinguish 20 mph from 21 mph just from a visual appearance. A one-significant-figure estimate or calculation, such as this estimate of speed, is called an **order-of-magnitude estimate.** An order-of-magnitude estimate is indicated by the symbol $\sim$, which indicates even less precision than the "approximately equal" symbol $\approx$. You would report your estimate of the speed of the falling rock as $v \sim 20$ mph.

A useful skill is to make reliable order-of-magnitude estimates on the basis of known information, simple reasoning, and common sense. This is a skill that is acquired by practice. Tables 1.4 and 1.5 have information that will be useful for doing estimates.

TABLE 1.4 Some approximate lengths

	Length (m)
Circumference of the earth	4×10^7
Distance from New York to Los Angeles	5×10^6
Distance you can drive in 1 hour	1×10^5
Altitude of jet planes	1×10^4
Distance across a college campus	1000
Length of a football field	100
Length of a classroom	10
Length of your arm	1
Width of a textbook	0.1
Length of your little fingernail	0.01
Diameter of a pencil lead	1×10^{-3}
Thickness of a sheet of paper	1×10^{-4}
Diameter of a dust particle	1×10^{-5}

EXAMPLE 1.5 How fast do you walk?

Estimate how fast you walk, in meters per second.

PREPARE In order to compute speed, we need a distance and a time. If you walked a mile to campus, how long would this take? You'd probably say 30 minutes or so—half an hour. Let's use this rough number in our estimate.

SOLVE Given this estimate, we compute speed as

$$\text{speed} = \frac{\text{distance}}{\text{time}} \sim \frac{1 \text{ mile}}{1/2 \text{ hour}} = 2\,\frac{\text{mi}}{\text{h}}$$

But we want the speed in meters per second. Since our calculation is only an estimate, we use an approximate form of the conversion factor from Table 1.3:

$$1\,\frac{\text{mi}}{\text{h}} \approx 0.5\,\frac{\text{m}}{\text{s}}$$

This gives an approximate walking speed of 1 m/s.

ASSESS Is this a reasonable value? Let's do another estimate. Your stride is probably about 1 yard long—about 1 meter. And you take about one step per second; next time you are walking, you can count and see. So a walking speed of 1 meter per second sounds pretty reasonable.

TABLE 1.5 Some approximate masses

	Mass (kg)
Large airliner	1×10^5
Small car	1000
Large human	100
Medium-size dog	10
Science textbook	1
Apple	0.1
Pencil	0.01
Raisin	1×10^{-3}
Fly	1×10^{-4}

This sort of estimation is very valuable. We will see many cases in which we need to know an approximate value for a quantity before we start a problem or after we finish a problem, in order to assess our results.

STOP TO THINK 1.4 Rank in order, from the most to the fewest, the number of significant figures in the following numbers. For example, if B has more than C, C has the same number as A, and A has more than D, give your answer as B > C = A > D.

A. 0.43 B. 0.0052 C. 0.430 D. 4.321×10^{-10}

1.5 Vectors and Motion: A First Look

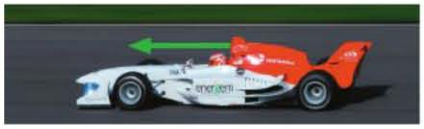
Many physical quantities, such as time, temperature, and weight, can be described completely by a number with a unit. For example, the mass of an object might be 6 kg and its temperature 30° C. When a physical quantity is described by a single number (with a unit), we call it a **scalar quantity.** A scalar can be positive, negative, or zero.

Vectors and scalars

Scalars

Time, temperature and weight are all *scalar* quantities. To specify your weight, the temperature outside, or the current time, you only need a single number.

Vectors



The velocity of the race car is a *vector.* To fully specify a velocity, we need to give its magnitude (e.g., 120 mph) *and* its direction (e.g., west).

The force with which the boy pushes on his friend is another example of a vector. To completely specify this force, we must know not only how hard he pushes (the magnitude) but also in which direction.

The boat's displacement is the straight-line connection from its initial to its final position.

Many other quantities, however, have a directional quality and cannot be described by a single number. To describe the motion of a car, for example, you must specify not only how fast it is moving, but also the *direction* in which it is moving. A **vector quantity** is a quantity that has both a *size* (How far? or How fast?) and a *direction* (Which way?). The size or length of a vector is called its **magnitude.** The magnitude of a vector can be positive or zero, but it cannot be negative.

Some examples of vector and scalar quantities are shown on the left.

We graphically represent a vector as an *arrow,* as illustrated for the velocity and force vectors. The arrow is drawn to point in the direction of the vector quantity, and the *length* of the arrow is proportional to the magnitude of the vector quantity.

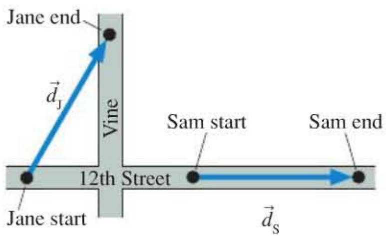
When we want to represent a vector quantity with a *symbol,* we need somehow to indicate that the symbol is for a vector rather than for a scalar. We do this by drawing an arrow over the letter that represents the quantity. Thus $\vec{r}$ and $\vec{A}$ are symbols for vectors, whereas r and A, without the arrows, are symbols for scalars. In handwritten work you *must* draw arrows over all symbols that represent vectors. This may seem strange until you get used to it, but it is very important because we will often use both r and $\vec{r}$, or both A and $\vec{A}$, in the same problem, and they mean different things!

NOTE ▶ The arrow over the symbol always points to the right, regardless of which direction the actual vector points. Thus we write $\vec{r}$ or $\vec{A}$, never $\overleftarrow{r}$ or $\overleftarrow{A}$. ◀

Displacement Vectors

For motion along a line, we found in Section 1.2 that the displacement is a quantity that specifies not only how *far* an object moves but also the *direction*—to the left or to the right—that the object moves. Since displacement is a quantity that has both a magnitude (How far?) and a direction, it can be represented by a vector, the **displacement vector.** FIGURE 1.21 shows the displacement vector for Sam's trip that we discussed earlier. We've simply drawn an arrow—the vector—from his initial to his final position and assigned it the symbol $\vec{d}_S$. Because $\vec{d}_S$ has both a magnitude and a direction, it is convenient to write Sam's displacement as $\vec{d}_S$ = (100 ft, east). The first value in the parentheses is the magnitude of the vector (i.e., the size of the displacement), and the second value specifies its direction.

FIGURE 1.21 Two displacement vectors.



Also shown in Figure 1.21 is the displacement vector $\vec{d}_J$ for Jane, who started on 12th Street and ended up on Vine. As with Sam, we draw her displacement vector as an arrow from her initial to her final position. In this case, $\vec{d}_J$ = 100 ft, 30° east of north).

Jane's trip illustrates an important point about displacement vectors. Jane started her trip on 12th Street and ended up on Vine, leading to the displacement vector shown. But to get from her initial to her final position, she needn't have walked along the straight-line path denoted by $\vec{d}_J$. If she walked east along 12th Street to the intersection and then headed north on Vine, her displacement would still be the vector shown. **An object's displacement vector is drawn from the object's initial position to its final position, regardless of the actual path followed between these two points.**

Vector Addition

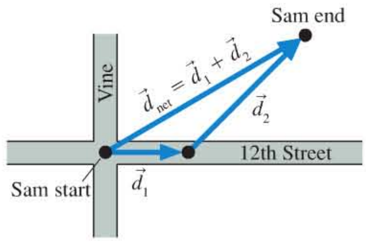
Let's consider one more trip for the peripatetic Sam. In **FIGURE 1.22**, he starts at the intersection and walks east 50 ft; then he walks 100 ft to the northeast through a vacant lot. His displacement vectors for the two legs of his trip are labeled $\vec{d}_1$ and $\vec{d}_2$ in the figure.

Sam's trip consists of two legs that can be represented by the two vectors $\vec{d}_1$ and $\vec{d}_2$, but we can represent his trip as a whole, from his initial starting position to his overall final position, with the *net* displacement vector labeled $\vec{d}_{\text{net}}$. Sam's net displacement is in a sense the *sum* of the two displacements that made it up, so we can write

$$\vec{d}_{\text{net}} = \vec{d}_1 + \vec{d}_2$$

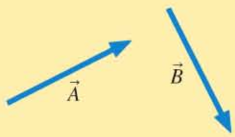
Sam's net displacement thus requires the *addition* of two vectors, but vector addition obeys different rules from the addition of two scalar quantities. The directions of the two vectors, as well as their magnitudes, must be taken into account. Sam's trip suggests that we can add vectors together by putting the "tail" of one vector at the tip of the other. This idea, which is reasonable for displacement vectors, in fact is how *any* two vectors are added. Tactics Box 1.4 shows how to add two vectors $\vec{A}$ and $\vec{B}$.

FIGURE 1.22 Sam undergoes two displacements.

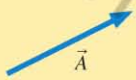


TACTICS BOX 1.4 **Adding vectors**

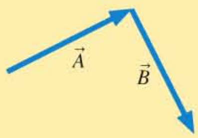
To add $\vec{B}$ to $\vec{A}$:



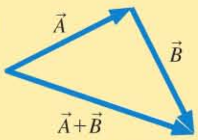
❶ Draw $\vec{A}$.



❷ Place the tail of $\vec{B}$ at the tip of $\vec{A}$.



❸ Draw an arrow from the tail of $\vec{A}$ to the tip of $\vec{B}$. This is vector $\vec{A} + \vec{B}$.



Exercise 21

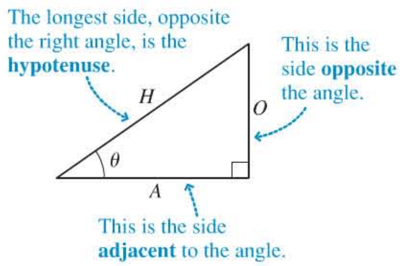
Vectors and Trigonometry

When we need to add displacements or other vectors in more than one dimension, we'll end up computing lengths and angles of triangles. This is the job of trigonometry. Trigonometry will be our primary mathematical tool for vector addition; let's review the basic ideas.

Suppose we have a right triangle with hypotenuse H, angle θ, side opposite the angle O, and side adjacent to the angle A, as shown in **FIGURE 1.23**. The sine, cosine, and tangent (which we write as "sin," "cos," and "tan") of angle θ are defined as ratios of the sides of the triangle:

$$\sin\theta = \frac{O}{H} \qquad \cos\theta = \frac{A}{H} \qquad \tan\theta = \frac{O}{A} \tag{1.3}$$

FIGURE 1.23 A right triangle.



If you know the angle θ and the length of one side, you can use the sine, cosine, or tangent to find the lengths of the other sides. For example, if you know θ and the length A of the adjacent side, you can find the hypotenuse H by rearranging the middle Equation 1.3 to give $H = A/\cos\theta$.

Conversely, if you know two sides of the triangle, you can find the angle θ by using inverse trigonometric functions:

$$\theta = \sin^{-1}\left(\frac{O}{H}\right) \qquad \theta = \cos^{-1}\left(\frac{A}{H}\right) \qquad \theta = \tan^{-1}\left(\frac{O}{A}\right) \tag{1.4}$$

We will make regular use of these relationships in the following chapters.

EXAMPLE 1.6 How far north and east?

Suppose Alex is navigating using a compass. She starts walking at an angle 60° north of east and walks a total of 100 m. How far north is she from her starting point? How far east?

PREPARE A sketch of Alex's motion is shown in **FIGURE 1.24a**. We've shown north and east as they would be on a map, and we've noted Alex's displacement as a vector, giving its magnitude and direction. **FIGURE 1.24b** shows a triangle with this displacement as the hypotenuse. Alex's distance north of her starting point and her distance east of her starting point are the sides of this triangle.

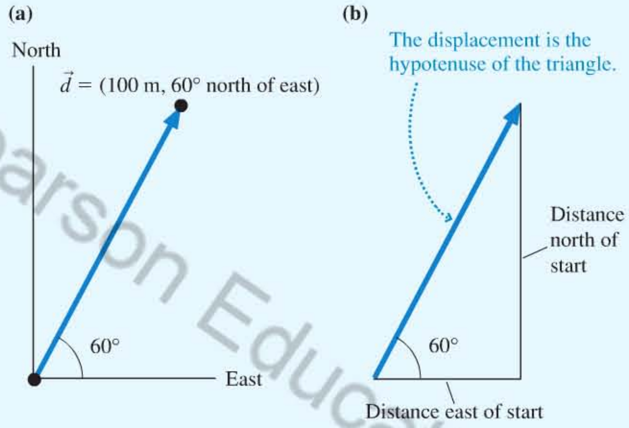
SOLVE The sine and cosine functions are ratios of sides of right triangles, as we saw above. With the 60° angle as noted, the distance north of the starting point is the opposite side of the triangle; the distance east is the adjacent side. Thus:

$$\text{distance north of start} = (100\text{ m})\sin(60°) = 87\text{ m}$$

$$\text{distance east of start} = (100\text{ m})\cos(60°) = 50\text{ m}$$

ASSESS Both of the distances we calculated are less than 100 m, as they must be, and the distance east is less than the distance north, as our diagram in Figure 1.24b shows it should be. Our answers seem reasonable. In finding the solution to this problem, we "broke down" the displacement into two different distances, one north and one east. This hints at the idea of the *components* of a vector, something we'll explore in the next chapter.

FIGURE 1.24 An analysis of Alex's motion.

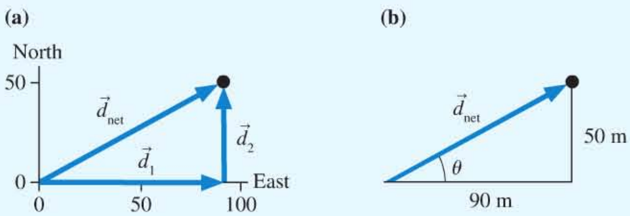


EXAMPLE 1.7 How far away is Anna?

Anna walks 90 m due east and then 50 m due north. What is her displacement from her starting point?

PREPARE Let's start with the sketch in **FIGURE 1.25a**. We set up a coordinate system with Anna's original position as the origin, and then we drew her two subsequent motions as the two displacement vectors $\vec{d}_1$ and $\vec{d}_2$.

FIGURE 1.25 Analyzing Anna's motion.



SOLVE We drew the two vector displacements with the tail of one vector starting at the head of the previous one—exactly what is needed to form a vector sum. The vector $\vec{d}_{net}$ in Figure 1.25a is the vector sum of the successive displacements and thus represents Anna's net displacement from the origin.

Anna's distance from the origin is the length of this vector $\vec{d}_{net}$. **FIGURE 1.25b** shows that this vector is the hypotenuse of a right triangle with sides 50 m (because Anna walked 50 m north) and 90 m (because she walked 90 m east). We can compute the magnitude of this vector, her net displacement, using the Pythagorean theorem (the square of the length of the hypotenuse of a triangle is equal to the sum of the squares of the lengths of the sides):

$$d_{net}^2 = (50\text{ m})^2 + (90\text{ m})^2$$

$$d_{net} = \sqrt{(50\text{ m})^2 + (90\text{ m})^2} = 103\text{ m} \approx 100\text{ m}$$

We have rounded off to the appropriate number of significant figures, giving us 100 m for the magnitude of the displacement vector. How about the direction? Figure 1.25b identifies the angle that gives the angle north of east of Anna's displacement. In the right triangle, 50 m is the opposite side and 90 m is the adjacent side, so the angle is given by

$$\theta = \tan^{-1}\left(\frac{50\text{ m}}{90\text{ m}}\right) = \tan^{-1}\left(\frac{5}{9}\right) = 29°$$

Putting it all together, we get a net displacement of

$$\vec{d}_{net} = (100\text{ m}, 29°\text{ north of east})$$

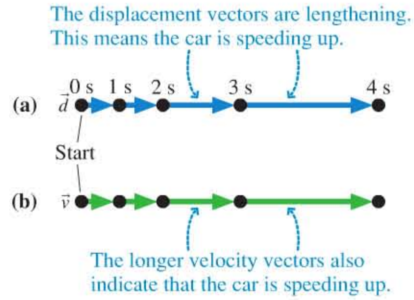
ASSESS We can use our drawing to assess our result. If the two sides of the triangle are 50 m and 90 m, a length of 100 m for the hypotenuse seems about right. The angle is certainly less than 45°, but not too much less, so 29° seems reasonable.

Velocity Vectors

We've seen that a basic quantity describing the motion of an object is its velocity. Velocity is a vector quantity because its specification involves not only how fast an object is moving (its speed) but also the direction in which the object is moving. We thus represent the velocity of an object by a **velocity vector** $\vec{v}$ that points in the direction of the object's motion, and whose magnitude is the object's speed.

FIGURE 1.26a shows the motion diagram of a car accelerating from rest. We've drawn vectors showing the car's displacement between successive positions of the motion diagram. How can we draw the velocity vectors on this diagram? First, note that the direction of the displacement vector is the direction of motion between successive points in the motion diagram. But the velocity of an object also points in the direction of motion, so an object's velocity vector points in the same direction as its displacement vector. Second, we've already noted that the magnitude of the velocity vector—How fast?—is the object's speed. Because higher speeds imply greater displacements in the same time interval, you can see that the length of the velocity vector should be proportional to the length of the displacement vector between successive points on a motion diagram. Consequently, the vectors connecting each dot of a motion diagram to the next, which we previously labeled as displacement vectors, could equally well be identified as velocity vectors. This is shown in FIGURE 1.26b. **From now on, we'll show and label velocity vectors on motion diagrams rather than displacement vectors.**

FIGURE 1.26 The motion diagram for a car starting from rest.



NOTE ► The velocity vectors shown in Figure 1.26b are actually *average* velocity vectors. Because the velocity is steadily increasing, it's a bit less than this average at the start of each time interval, and a bit more at the end. In Chapter 2 we'll refine these ideas as we develop the idea of instantaneous velocity. ◄

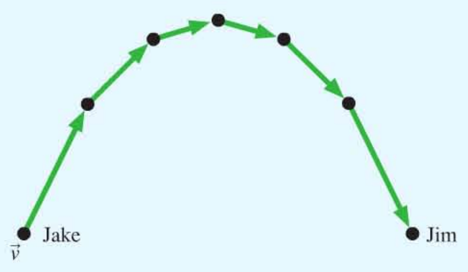
EXAMPLE 1.8 Drawing a ball's motion diagram

Jake hits a ball at a 60° angle from the horizontal. It is caught by Jim. Draw a motion diagram of the ball that shows velocity vectors rather than displacement vectors.

PREPARE This example is typical of how many problems in science and engineering are worded. The problem does not give a clear statement of where the motion begins or ends. Are we interested in the motion of the ball only during the time it is in the air between Jake and Jim? What about the motion *as* Jake hits it (ball rapidly speeding up) or *as* Jim catches it (ball rapidly slowing down)? Should we include Jim dropping the ball after he catches it? The point is that *you* will often be called on to make a *reasonable interpretation* of a problem statement. In this problem, the details of hitting and catching the ball are complex. The motion of the ball through the air is easier to describe, and it's a motion you might expect to learn about in a physics class. So our *interpretation* is that the motion diagram should start as the ball leaves Jake's bat (ball already moving) and should end the instant it touches Jim's hand (ball still moving). We will model the ball as a particle.

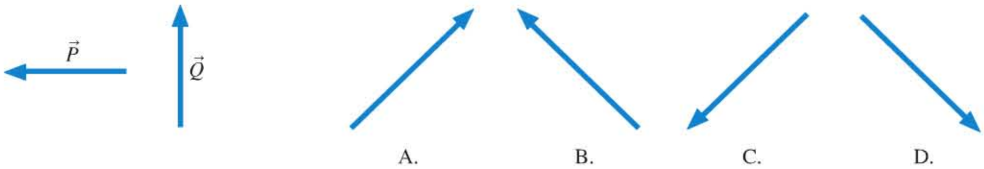
SOLVE With this interpretation in mind, FIGURE 1.27 shows the motion diagram of the ball. Notice how, in contrast to the car of Figure 1.26, the ball is already moving as the motion diagram movie begins. As before, the velocity vectors are shown by connecting the dots with arrows. You can see that the velocity vectors get shorter (ball slowing down), get longer (ball speeding up), and change direction. Each $\vec{v}$ is different, so this is *not* constant-velocity motion.

FIGURE 1.27 The motion diagram of a ball traveling from Jake to Jim.



ASSESS We haven't learned enough to make a detailed analysis of the motion of the ball, but it's still worthwhile to do a quick assessment. Does our diagram make sense? Think about the velocity of the ball—we show it moving upward at the start and downward at the end. This does match what happens when you toss a ball back and forth, so our answer seems reasonable.

STOP TO THINK 1.5 $\vec{P}$ and $\vec{Q}$ are two vectors of equal length but different direction. Which vector shows the sum $\vec{P} + \vec{Q}$?



1.6 Where Do We Go from Here?

This first chapter has been an introduction to some of the fundamental ideas about motion and some of the basic techniques that you will use in the rest of the course. You have seen some examples of how to make *models* of a physical situation, thereby focusing in on the essential elements of the situation. You have learned some practical ideas, such as how to convert quantities from one kind of units to another. The rest of this book—and the rest of your course—will extend these themes. You will learn how to model many kinds of physical systems, and learn the technical skills needed to set up and solve problems using these models.

In each chapter of this book, you'll learn both new principles and more tools and techniques. We are starting with motion, but, by the end of the book, you'll have learned about more abstract concepts such as magnetic fields and the structure of the nucleus of the atom. As you proceed, you'll find that each new chapter depends on those that preceded it. The principles and the problem-solving strategies you learned in this chapter will still be needed in Chapter 30.

We'll give you some assistance integrating new ideas with the material of previous chapters. When you start a chapter, the **chapter preview** will let you know which topics are especially important to review. And the last element in each chapter will be an **integrated example** that brings together the principles and techniques you have just learned with those you learned previously. The integrated nature of these examples will also be a helpful reminder that the problems of the real world are similarly complex, and solving such problems requires you to do just this kind of integration.

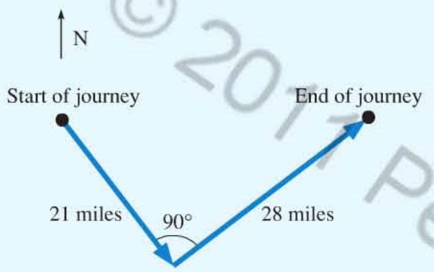
Our first integrated example is reasonably straightforward because there's not much to integrate yet. The examples in future chapters will be much richer.

◀ Chapter 28 ends with an integrated example that explores the basic physics of magnetic resonance imaging (MRI), explaining how the interaction of magnetic fields with the nuclei of atoms in the body can be used to create an image of the body's interior.

INTEGRATED EXAMPLE 1.9 A goose gets its bearings

Migrating geese determine direction using many different tools: by noting local landmarks, by following rivers and roads, and by using the position of the sun in the sky. When the weather is overcast so that they can't use the sun's position to get their bearings, geese may start their day's flight in the wrong direction. **FIGURE 1.28** shows the path of a Canada goose that flew in a straight line for some time before making a corrective right-angle turn. One hour after beginning, the goose made a rest stop on a lake due east of its original position.

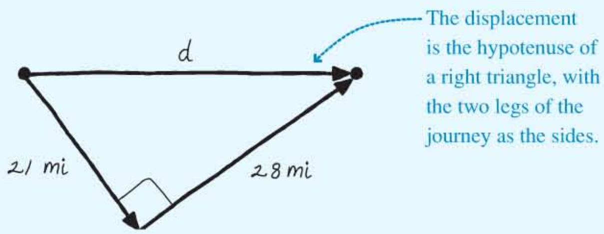
FIGURE 1.28 Trajectory of a misdirected goose.



a. How much extra distance did the goose travel due to its initial error in flight direction? That is, how much farther did it fly than if it had simply flown directly to its final position on the lake?
b. What was the flight speed of the goose?
c. A typical flight speed for a migrating goose is 80 km/h. Given this, does your result seem reasonable?

PREPARE Figure 1.28 shows the trajectory of the goose, but it's worthwhile to redraw Figure 1.28 and note the displacement from the start to the end of the journey, the shortest distance the goose could have flown. (The examples in the chapter to this point have used professionally rendered drawings, but these are much more careful and detailed than you are likely to make. **FIGURE 1.29** shows a drawing that is more typical of what you might actually do when working problems yourself.) Drawing and labeling the displacement between the starting and ending points in Figure 1.29 show that it is the hypotenuse of a right triangle, so we can use our rules for triangles as we look for a solution.

FIGURE 1.29 A typical student sketch shows the motion and the displacement of the goose.



SOLVE

a. The minimum distance the goose *could* have flown, if it flew straight to the lake, is the hypotenuse of a triangle with sides 21 mi and 28 mi. This straight-line distance is

$$d = \sqrt{(21\text{ mi})^2 + (28\text{ mi})^2} = 35\text{ mi}$$

The actual distance the goose flew is the sum of the distances traveled for the two legs of the journey:

$$\text{distance traveled} = 21\text{ mi} + 28\text{ mi} = 49\text{ mi}$$

The extra distance flown is the difference between the actual distance flown and the straight-line distance—namely, 14 miles.

b. To compute the flight speed, we need to consider the distance that the bird actually flew. The flight speed is the total distance flown divided by the total time of the flight:

$$v = \frac{49\text{ mi}}{1.0\text{ h}} = 49\text{ mi/h}$$

c. To compare our calculated speed with a typical flight speed, we must convert our solution to km/h, rounding off to the correct number of significant digits:

$$49\,\frac{\text{mi}}{\text{h}} \times \frac{1.61\text{ km}}{1.00\text{ mi}} = 79\,\frac{\text{km}}{\text{h}}$$

A calculator will return many more digits, but the original data had only two significant figures, so we report the final result to this accuracy.

ASSESS In this case, an assessment was built into the solution of the problem. The calculated flight speed matches the expected value for a goose, which gives us confidence that our answer is correct. As a further check, our calculated net displacement of 35 mi seems about right for the hypotenuse of the triangle in Figure 1.29.

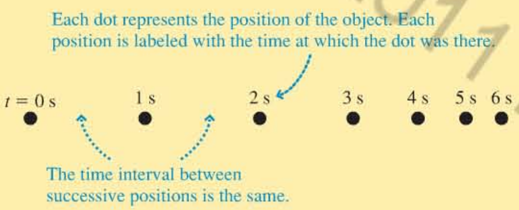
SUMMARY

The goals of Chapter 1 have been to introduce the fundamental concepts of motion and to review the related basic mathematical principles.

IMPORTANT CONCEPTS

Motion Diagrams

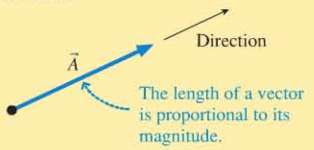
The **particle model** represents a moving object as if all its mass were concentrated at a single point. Using this model, we can represent motion with a **motion diagram,** where dots indicate the object's positions at successive times. In a motion diagram, the time interval between successive dots is always the same.



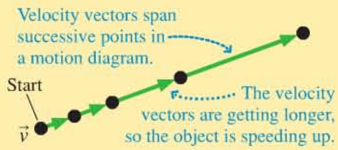
Scalars and Vectors

Scalar quantities have only a magnitude and can be represented by a single number. Temperature, time, and mass are scalars.

A **vector** is a quantity described by both a magnitude and a direction. Velocity and displacement are vectors.

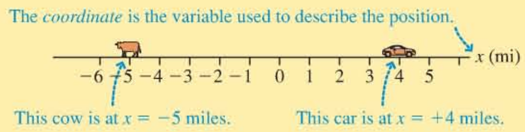


Velocity vectors can be drawn on a motion diagram by connecting successive points with a vector.



Describing Motion

Position locates an object with respect to a chosen coordinate system. It is described by a **coordinate.**



A change in position is called a **displacement.** For motion along a line, a displacement is a signed quantity. The displacement from x_i to x_f is $\Delta x = x_f - x_i$.

Time is measured from a particular instant to which we assign $t = 0$. A **time interval** is the elapsed time between two specific instants t_i and t_f. It is given by $\Delta t = t_f - t_i$.

Velocity is the ratio of the displacement of an object to the time interval during which this displacement occurs:

$$v = \frac{\Delta x}{\Delta t}$$

Units

Every measurement of a quantity must include a **unit.**

The standard system of units used in science is the **SI system.** Common SI units include:

- Length: meters (m)
- Time: seconds (s)
- Mass: kilograms (kg)

APPLICATIONS

Working with Numbers

In **scientific notation,** a number is expressed as a decimal number between 1 and 10 multiplied by a power of ten. In scientific notation, the diameter of the earth is 1.27×10^7 m.

A **prefix** can be used before a unit to indicate a multiple of 10 or 1/10. Thus we can write the diameter of the earth as 12,700 km, where the k in km denotes 1000.

We can perform a **unit conversion** to convert the diameter of the earth to a different unit, such as miles. We do so by multiplying by a conversion factor equal to 1, such as 1 = 1 mi/1.61 km.

Significant figures are reliably known digits. The number of significant figures for:

- **Multiplication, division, and powers** is set by the value with the fewest significant figures.
- **Addition and subtraction** is set by the value with the smallest number of decimal places.

An **order-of-magnitude estimate** is an estimate that has an accuracy of about one significant figure. Such estimates are usually made using rough numbers from everyday experience.

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Problems labeled BIO are of biological or medical interest.

Problem difficulty is labeled as | (straightforward) to ||||| (challenging).

QUESTIONS

Conceptual Questions

1. a. Write a paragraph describing the *particle model.* What is it, and why is it important?
   b. Give two examples of situations, different from those described in the text, for which the particle model is appropriate.
   c. Give an example of a situation, different from those described in the text, for which it would be inappropriate.
2. A softball player slides into second base. Use the particle model to draw a motion diagram of the player from the time he begins to slide until he reaches the base. Number the dots in order, starting with zero.
3. A car travels to the left at a steady speed for a few seconds, then brakes for a stop sign. Use the particle model to draw a motion diagram of the car for the entire motion described here. Number the dots in order, starting with zero.
4. A ball is dropped from the roof of a tall building and students in a physics class are asked to sketch a motion diagram for this situation. A student submits the diagram shown in Figure Q1.4. Is the diagram correct? Explain.

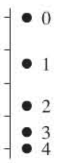


FIGURE Q1.4

5. Write a sentence or two describing the difference between position and displacement. Give one example of each.
6. Give an example of a trip you might take in your car for which the distance traveled as measured on your car's odometer is not equal to the displacement between your initial and final positions.
7. Write a sentence or two describing the difference between speed and velocity. Give one example of each.
8. The motion of a skateboard along a horizontal axis is observed for 5 s. The initial position of the skateboard is negative with respect to a chosen origin, and its velocity throughout the 5 s is also negative. At the end of the observation time, is the skateboard closer to or farther from the origin than initially? Explain.
9. Can the velocity of an object be positive during a time interval in which its position is always negative? Can its velocity be positive during a time interval in which its displacement is negative?
10. Two friends watch a jogger complete a 400 m lap around the track in 100 s. One of the friends states, "The jogger's velocity was 4 m/s during this lap." The second friend objects, saying, "No, the jogger's speed was 4 m/s." Who is correct? Justify your answer.
11. A softball player hits the ball and starts running toward first base. Draw a motion diagram, using the particle model, showing her velocity vectors during the first few seconds of her run.
12. A child is sledding on a smooth, level patch of snow. She encounters a rocky patch and slows to a stop. Draw a motion diagram, using the particle model, showing her velocity vectors.
13. A skydiver jumps out of an airplane. Her speed steadily increases until she deploys her parachute, at which point her speed quickly decreases. She subsequently falls to earth at a constant rate, stopping when she lands on the ground. Draw a motion diagram, using the particle model, that shows her position at successive times and includes velocity vectors.
14. Your roommate drops a tennis ball from a third-story balcony. It hits the sidewalk and bounces as high as the second story. Draw a motion diagram, using the particle model, showing the ball's velocity vectors from the time it is released until it reaches the maximum height on its bounce.
15. A car is driving north at a steady speed. It makes a gradual 90° left turn without losing speed, then continues driving to the west. Draw a motion diagram, using the particle model, showing the car's velocity vectors as seen from a helicopter hovering over the highway.
16. A toy car rolls down a ramp, then across a smooth, horizontal floor. Draw a motion diagram, using the particle model, showing the car's velocity vectors.
17. Estimate the average speed with which you go from home to campus (or another trip you commonly make) via whatever mode of transportation you use most commonly. Give your answer in both mph and m/s. Describe how you arrived at this estimate.
18. Estimate the number of times you sneezed during the past year. Describe how you arrived at this estimate.
19. Density is the ratio of an object's mass to its volume. Would you expect density to be a vector or a scalar quantity? Explain.

Multiple-Choice Questions

20. | A student walks 1.0 mi west and then 1.0 mi north. Afterward, how far is she from her starting point?
    A. 1.0 mi B. 1.4 mi
    C. 1.6 mi D. 2.0 mi
21. | Which of the following motions is described by the motion diagram of Figure Q1.21?
    A. An ice skater gliding across the ice.
    B. An airplane braking to a stop after landing.
    C. A car pulling away from a stop sign.
    D. A pool ball bouncing off a cushion and reversing direction.

FIGURE Q1.21

22. | A bird flies 3.0 km due west and then 2.0 km due north. What is the magnitude of the bird's displacement?
    A. 2.0 km B. 3.0 km
    C. 3.6 km D. 5.0 km

23. A bird flies 3.0 km due west and then 2.0 km due north. Another bird flies 2.0 km due west and 3.0 km due north. What is the angle between the net displacement vectors for the two birds?
A. 23° B. 34° C. 56° D. 90°

24. A woman walks briskly at 2.00 m/s. How much time will it take her to walk one mile?
A. 8.30 min B. 13.4 min C. 21.7 min D. 30.0 min

25. Compute 3.24 m + 0.532 m to the correct number of significant figures.
A. 3.7 m B. 3.77 m C. 3.772 m D. 3.7720 m

26. A rectangle has length 3.24 m and height 0.532 m. To the correct number of significant figures, what is its area?
A. 1.72 m^2 B. 1.723 m^2
C. 1.7236 m^2 D. 1.72368 m^2

27. The earth formed 4.57×10^9 years ago. What is this time in seconds?
A. 1.67×10^{12} s B. 4.01×10^{13} s
C. 2.40×10^{15} s D. 1.44×10^{17} s

28. An object's average density ρ is defined as the ratio of its mass to its volume: $\rho = M/V$. The earth's mass is 5.94×10^{24} kg, and its volume is 1.08×10^{12} km^3. What is the earth's average density?
A. 5.50×10^3 kg/m^3 B. 5.50×10^6 kg/m^3
C. 5.50×10^9 kg/m^3 D. 5.50×10^{12} kg/m^3

PROBLEMS

Section 1.1 Motion: A First Look

1. You've made a video of a car as it skids to a halt to avoid hitting an object in the road. Use the images from the video to draw a motion diagram of the car from the time the skid begins until the car is stopped.

2. A man rides a bike along a straight road for 5 min, then has a flat tire. He stops for 5 min to repair the flat, but then realizes he cannot fix it. He continues his journey by walking the rest of the way, which takes him another 10 min. Use the particle model to draw a motion diagram of the man for the entire motion described here. Number the dots in order, starting with zero.

3. A jogger running east at a steady pace suddenly develops a cramp. He is lucky: A westbound bus is sitting at a bus stop just ahead. He gets on the bus and enjoys a quick ride home. Use the particle model to draw a motion diagram of the jogger for the entire motion described here. Number the dots in order, starting with zero.

Section 1.2 Position and Time: Putting Numbers on Nature

4. Figure P1.4 shows Sue between her home and the cinema. What is Sue's position x if
a. Her home is the origin?
b. The cinema is the origin?

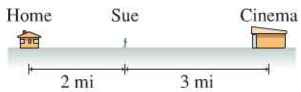


FIGURE P1.4

5. Keira starts at position $x = 23$ m along a coordinate axis. She then undergoes a displacement of -45 m. What is her final position?

6. A car travels along a straight east-west road. A coordinate system is established on the road, with x increasing to the east. The car ends up 14 mi west of the intersection with Mulberry Road. If its displacement was -23 mi, how far from and on which side of Mulberry Road did it start?

7. BIO Foraging bees often move in straight lines away from and toward their hives. Suppose a bee starts at its hive and flies 500 m due east, then flies 400 m west, then 700 m east. How far is the bee from the hive?

Section 1.3 Velocity

8. A security guard walks 110 m in one trip around the perimeter of the building. It takes him 240 s to make this trip. What is his speed?

9. List the following items in order of decreasing speed, from greatest to least: (i) A wind-up toy car that moves 0.15 m in 2.5 s. (ii) A soccer ball that rolls 2.3 m in 0.55 s. (iii) A bicycle that travels 0.60 m in 0.075 s. (iv) A cat that runs 8.0 m in 2.0 s.

10. Figure P1.10 shows the motion diagram for a horse galloping in one direction along a straight path. Not every dot is labeled, but the dots are at equally spaced instants of time. What is the horse's velocity
a. During the first ten seconds of its gallop?
b. During the interval from 30 s to 40 s?
c. During the interval from 50 s to 70 s?

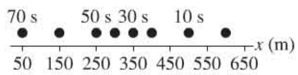


FIGURE P1.10

11. It takes Harry 35 s to walk from $x = -12$ m to $x = -47$ m. What is his velocity?

12. A dog trots from $x = -12$ m to $x = 3$ m in 10 s. What is its velocity?

13. A ball rolling along a straight line with velocity 0.35 m/s goes from $x = 2.1$ m to $x = 7.3$ m. How much time does this take?

Section 1.4 A Sense of Scale: Significant Figures, Scientific Notation, and Units

14. Convert the following to SI units:
a. 9.12 μs b. 3.42 km
c. 44 cm/ms d. 80 km/hour

15. Convert the following to SI units:
a. 8.0 in b. 66 ft/s c. 60 mph

16. Convert the following to SI units:
a. 1.0 hour b. 1.0 day c. 1.0 year

17. List the following three speeds in order, from smallest to largest: 1 mm per μs, 1 km per ks, 1 cm per ms.

18. How many significant figures does each of the following numbers have?
a. 6.21 b. 62.1 c. 0.620 d. 0.062

19. How many significant figures does each of the following numbers have?
a. 0.621 b. 0.006200
c. 1.0621 d. 6.21×10^3

20. Compute the following numbers to 3 significant figures.
a. 33.3×25.4 b. $33.3 - 25.4$
c. $\sqrt{33.3}$ d. $333.3 \div 25.4$

21. The Empire State Building has a height of 1250 ft. Express this height in meters, giving your result in scientific notation with three significant figures.

22. Estimate (don't measure!) the length of a typical car. Give your answer in both feet and meters. Briefly describe how you arrived at this estimate.

23. BIO Blades of grass grow from the bottom, so, as growth occurs, the top of the blade moves upward. During the summer, when your lawn is growing quickly, estimate this speed in m/s. Explain how you made this estimate, and express your result in scientific notation.

24. BIO Estimate the average speed with which the hair on your head grows. Give your answer in both m/s and μm/h. Briefly describe how you arrived at this estimate.

25. BIO Estimate the average speed at which your fingernails grow, in both m/s and μm/h. Briefly describe how you arrived at this estimate.

Section 1.5 Vectors and Motion: A First Look

26. Carol and Robin share a house. To get to work, Carol walks north 2.0 km while Robin drives west 7.5 km. How far apart are their workplaces?

27. Joe and Max shake hands and say goodbye. Joe walks east 0.55 km to a coffee shop, and Max flags a cab and rides north 3.25 km to a bookstore. How far apart are their destinations?

28. A city has streets laid out in a square grid, with each block 135 m long. If you drive north for three blocks, then west for two blocks, how far are you from your starting point?

29. A butterfly flies from the top of a tree in the center of a garden to rest on top of a red flower at the garden's edge. The tree is 8.0 m taller than the flower, and the garden is 12 m wide. Determine the magnitude of the butterfly's displacement.

30. A garden has a circular path of radius 50 m. John starts at the easternmost point on this path, then walks counterclockwise around the path until he is at its southernmost point. What is John's displacement? Use the (magnitude, direction) notation for your answer.

31. BIO Migrating geese tend to travel in straight-line paths at approximately constant speed. A goose flies 32 km south, then turns to fly 20 km west. How far is the goose from its original position?

32. A ball on a porch rolls 60 cm to the porch's edge, drops 40 cm, continues rolling on the grass, and eventually stops 80 cm from the porch's edge. What is the magnitude of the ball's net displacement, in centimeters?

33. A kicker punts a football from the very center of the field to the sideline 43 yards downfield. What is the net displacement of the ball? (A football field is 53 yards wide.)

General Problems

Problems 34 through 40 are motion problems similar to those you will learn to solve in Chapter 2. For now, simply *interpret* the problem by drawing a motion diagram showing the object's position and its velocity vectors. **Do *not* solve these problems** or do any mathematics.

34. BIO In a typical greyhound race, a dog accelerates to a speed of 20 m/s over a distance of 30 m. It then maintains this speed. What would be a greyhound's time in the 100 m dash?

35. Billy drops a watermelon from the top of a three-story building, 10 m above the sidewalk. How fast is the watermelon going when it hits?

36. Sam is recklessly driving 60 mph in a 30 mph speed zone when he suddenly sees the police. He steps on the brakes and slows to 30 mph in three seconds, looking nonchalant as he passes the officer. How far does he travel while braking?

37. A speed skater moving across frictionless ice at 8.0 m/s hits a 5.0-m-wide patch of rough ice. She slows steadily, then continues on at 6.0 m/s. What is her acceleration on the rough ice?

38. BIO The giant eland, an African antelope, is an exceptional jumper, able to leap 1.5 m off the ground. To jump this high, with what speed must the eland leave the ground?

39. A ball rolls along a smooth horizontal floor at 10 m/s, then starts up a 20° ramp. How high does it go before rolling back down?

40. A motorist is traveling at 20 m/s. He is 60 m from a stop light when he sees it turn yellow. His reaction time, before stepping on the brake, is 0.50 s. What steady deceleration while braking will bring him to a stop right at the light?

Problems 41 through 46 show a motion diagram. For each of these problems, write a one or two sentence "story" about a *real object* that has this motion diagram. Your stories should talk about people or objects by name and say what they are doing. Problems 34 through 40 are examples of motion short stories.

41.

FIGURE P1.41

42.

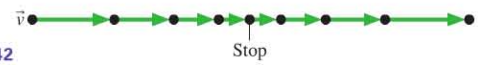


FIGURE P1.42

43.

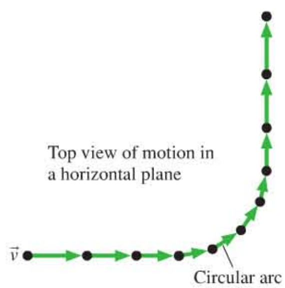


FIGURE P1.43

44. |

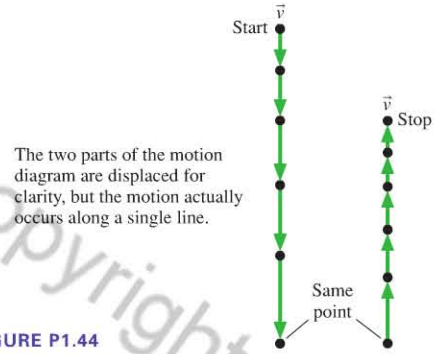


FIGURE P1.44

45. |

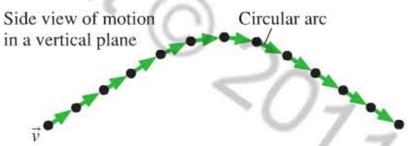


FIGURE P1.45

46. |

FIGURE P1.46

47. ||||| How many inches does light travel in one nanosecond? The speed of light is 3.0×10^8 m/s.

48. | Joseph watches the roadside mile markers during a long car trip on an interstate highway. He notices that at 10:45 A.M. they are passing a marker labeled 101, and at 11:00 A.M. the car reaches marker 119. What is the car's speed, in mph?

49. || Alberta is going to have dinner at her grandmother's house, but she is running a bit behind schedule. As she gets onto the highway, she knows that she must exit the highway within 45 min if she is not going to arrive late. Her exit is 32 mi away. What is the slowest speed at which she could drive and still arrive in time? Express your answer in miles per hour.

50. || The end of Hubbard Glacier in Alaska advances by an average of 105 feet per year. What is the speed of advance of the glacier in m/s?

51. | The earth completes a circular orbit around the sun in one year. The orbit has a radius of 93,000,000 miles. What is the speed of the earth around the sun in m/s? Report your result using scientific notation.

52. ||| Shannon decides to check the accuracy of her speedometer. She adjusts her speed to read exactly 70 mph on her speedometer and holds this steady, measuring the time between successive mile markers separated by exactly 1.00 mile. If she measures a time of 54 s, is her speedometer accurate? If not, is the speed it shows too high or too low?

53. || Motor neurons in mammals transmit signals from the brain to
BIO skeletal muscles at approximately 25 m/s. Estimate how much time in ms (10^{-3} s) it will take for a signal to get from your brain to your hand.

54. ||| Satellite data taken several times per hour on a particular
BIO albatross showed travel of 1200 km over a time of 1.4 days.

a. Given these data, what was the bird's average speed in mph?
b. Data on the bird's position were recorded only intermittently. Explain how this means that the bird's actual average speed was higher than what you calculated in part a.

55. | Your brain communicates with your body using *nerve*
BIO *impulses,* electrical signals propagated along axons. Axons come in two varieties: insulated axons with a sheath made of myelin, and uninsulated axons with no such sheath. Myelinated (sheathed) axons conduct nerve impulses much faster than unmyelinated (unsheathed) axons. The impulse speed depends on the diameter of the axons and the sheath, but a typical myelinated axon transmits nerve impulses at a speed of about 25 m/s, much faster than the typical 2.0 m/s for an unmyelinated axon. Figure P1.55 shows three equal-length nerve fibers consisting of eight axons in a row. Nerve impulses enter at the left side simultaneously and travel to the right.

a. Draw motion diagrams for the nerve impulses traveling along fibers A, B, and C.
b. Which nerve impulse arrives at the right side first?
c. Which will be last?

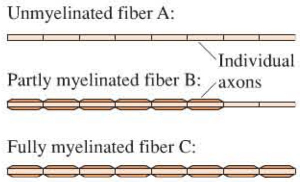
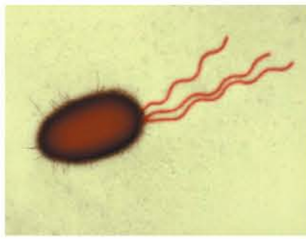


FIGURE P1.55

56. || The bacterium *Escherichia coli* (or *E. coli*) is a single-celled
BIO organism that lives in the gut of healthy humans and animals. Its body shape can be modeled as a 2-μm-long cylinder with a 1 μm diameter, and it has a mass of 1×10^{-12} g. Its chromosome consists of a single double-stranded chain of DNA 700 times longer than its body length. The bacterium moves at a constant speed of 20 μm/s, though not always in the same direction. Answer the following questions about *E. coli* using SI units (unless specifically requested otherwise) and correct significant figures.



a. What is its length?
b. Diameter?
c. Mass?
d. What is the length of its DNA, in millimeters?
e. If the organism were to move along a straight path, how many meters would it travel in one day?

57. || The bacterium *Escherichia*
BIO *coli* (or *E. coli*) is a single-celled organism that lives in the gut of healthy humans and animals. When grown in a uniform medium rich in salts and amino acids, it swims along zig-zag paths at a constant speed. Figure P1.57 shows the positions of an *E. coli* as it moves from point A to point J. Each segment of the motion can be identified by two letters, such as segment BC. During which segments, if any, does the bacterium have the same

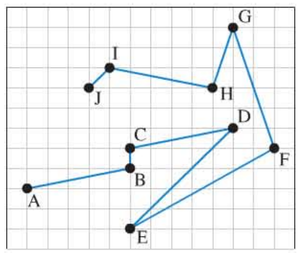


FIGURE P1.57

a. Displacement? b. Speed? c. Velocity?

58. In 2003, the population of the United States was 291 million people. The per-capita income was \$31,459. What was the total income of everyone in the United States? Express your answer in scientific notation, with the correct number of significant figures.
59. The sun is 30° above the horizon. It makes a 52-m-long shadow of a tall tree. How high is the tree?
60. A large passenger aircraft accelerates down the runway for a distance of 3000 m before leaving the ground. It then climbs at a steady 3.0° angle. After the plane has traveled 3000 m along this new trajectory, (a) how high is it, and (b) how far horizontally is it, from its initial position?
61. Starting from its nest, an eagle flies at constant speed for 3.0 min due east, then 4.0 min due north. From there the eagle flies directly to its nest at the same speed. How long is the eagle in the air?
62. John walks 1.00 km north, then turns right and walks 1.00 km east. His speed is 1.50 m/s during the entire stroll.
   a. What is the magnitude of his displacement, from beginning to end?
   b. If Jane starts at the same time and place as John, but walks in a straight line to the endpoint of John's stroll, at what speed should she walk to arrive at the endpoint just when John does?

Passage Problems

Growth Speed

The images of trees in Figure P1.63 come from a catalog advertising fast-growing trees. If we mark the position of the top of the tree in the successive years, as shown in the graph in the figure, we obtain a motion diagram much like ones we have seen for other kinds of motion. The motion isn't steady, of course. In some months the tree grows rapidly; in other months, quite slowly. We can see, though, that the average speed of growth is fairly constant for the first few years.

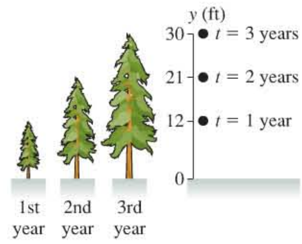


FIGURE P1.63

63. What is the tree's speed of growth, in feet per year, from $t = 1$ yr to $t = 3$ yr?
   A. 12 ft/yr B. 9 ft/yr C. 6 ft/yr D. 3 ft/yr
64. What is this speed in m/s?
   A. 9×10^{-8} m/s B. 3×10^{-9} m/s
   C. 5×10^{-6} m/s D. 2×10^{-6} m/s
65. At the end of year 3, a rope is tied to the very top of the tree to steady it. This rope is staked into the ground 15 feet away from the tree. What angle does the rope make with the ground?
   A. 63° B. 60° C. 30° D. 27°

STOP TO THINK ANSWERS

Stop to Think 1.1: B. The images of B are farther apart, so B travels a greater distance than does A during the same intervals of time.

Stop to Think 1.2: A. Dropped ball. **B.** Dust particle. **C.** Descending rocket.

Stop to Think 1.3: C. Depending on her initial positive position and how far she moves in the negative direction, she could end up on either side of the origin.

Stop to Think 1.4: D > C > B = A.

Stop to Think 1.5: B. The vector sum is found by placing the tail of one vector at the head of the other.