



Karen Cummings

Priscilla Laws

Edward Redish

Patrick Cooney

# UNDERSTANDING PHYSICS

---



# eGrade Plus

[www.wiley.com/college/cummings](http://www.wiley.com/college/cummings)

Based on the Activities You Do Every Day

**Keep All of Your Class Materials in One Location**

**Enhance the Power of Your Class Preparation and Presentations**

**Assess Student Understanding More Closely and Analyze Results with Our Automatic Gradebook**

**Create Your Own Assignments or Use Ours, All with Automatic Grading**

**Help Your Students Study More Effectively and Get Immediate Feedback**

Type	Creation date	Created by	Ch	cov
Questions/Exercises	05.22.2003	default	1	
Chapter 10 Default Assignment	Questions/Exercises	07.04.2003	default	10
Questions/Exercises	07.04.2003	default	11	
Questions/Exercises	07.04.2003	default	12	Unassigned
Questions/Exercises	07.04.2003	default	13	Unassigned
Questions/Exercises	07.04.2003	default	14	
Questions/Exercises	07.04.2003	default	15	
Questions/Exercises	07.04.2003	default	16	
Questions/Exercises	07.04.2003	default	17	
Questions/Exercises	07.04.2003	default	18	
Chapter 19 Default Assignment	Questions/Exercises	07.04.2003	default	19
Chapter 2 Default Assignment	Questions/Exercises	07.04.2003	default	2
Chapter 20 Default Assignment	Questions/Exercises	07.04.2003	default	20

**All the content and tools you need, all in one location, in an easy-to-use browser format.**

**Choose the resources you need, or rely on the arrangement supplied by us.**

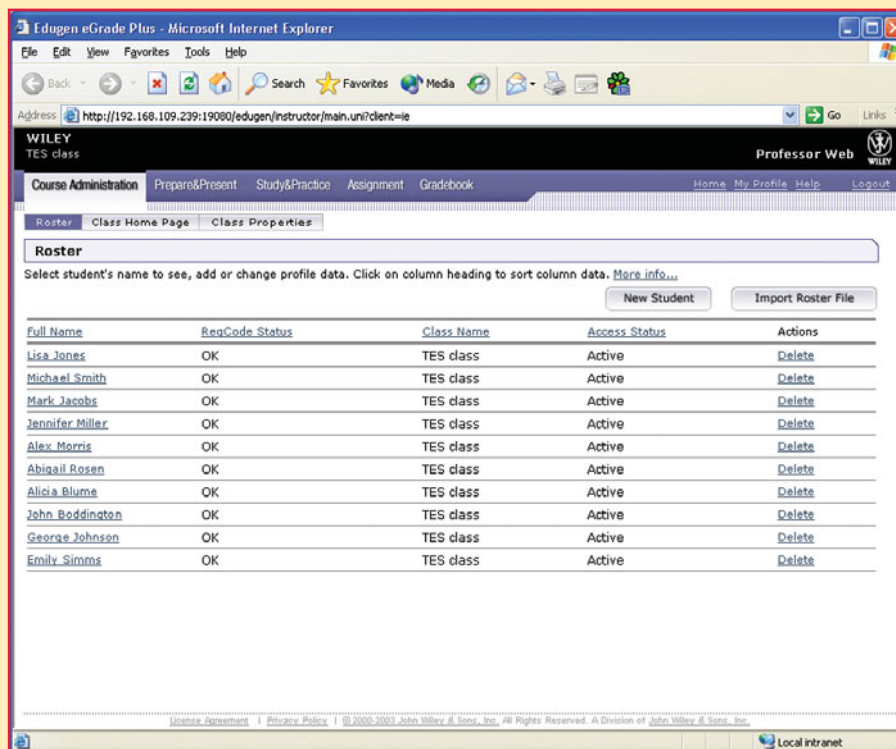
Now, many of Wiley's textbooks are available with eGrade Plus, a powerful online tool that provides a completely integrated suite of teaching and learning resources in one easy-to-use website. eGrade Plus integrates Wiley's world-renowned content with media, including a multimedia version of the text, PowerPoint slides, and more. Upon adoption of eGrade Plus, you can begin to customize your course with the resources shown here.

**See for yourself!**

**Go to [www.wiley.com/college/egradeplus](http://www.wiley.com/college/egradeplus) for an online demonstration of this powerful new software.**

## Keep All of Your Class Materials in One Location

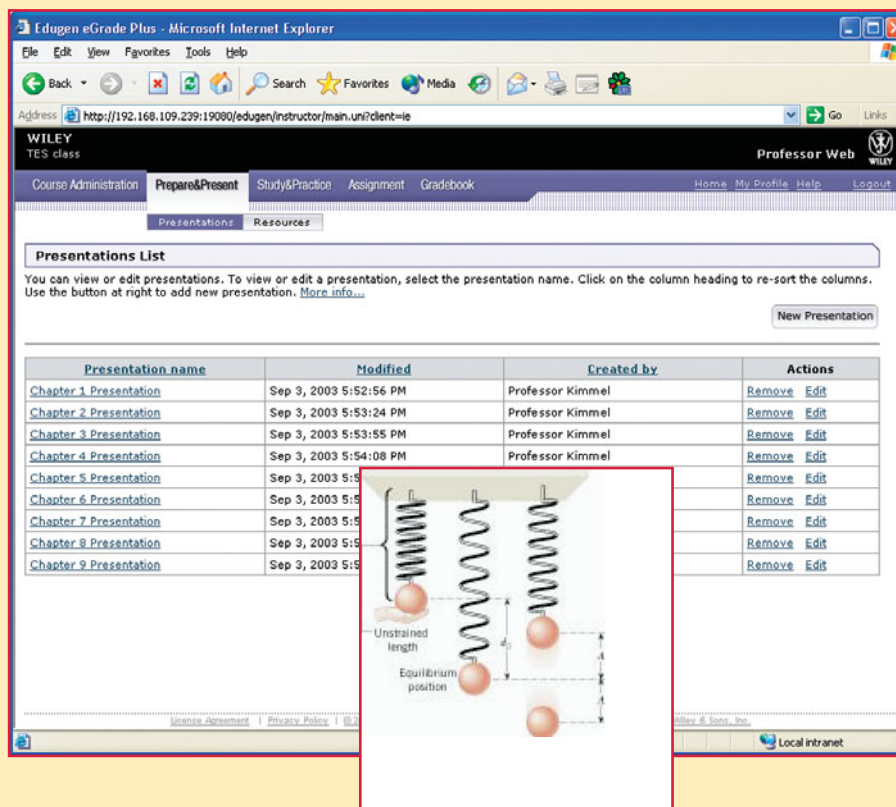
**Course Administration tools** allow you to manage your class and integrate your eGrade Plus resources with most Course Management Systems, allowing you to keep all of your class materials in one location.



The screenshot shows the 'Course Administration' tab in the Edugen eGrade Plus interface. The 'Roster' section is active, displaying a table of students enrolled in the 'TES class'. The table includes columns for Full Name, RegCode, Status, Class Name, Access Status, and Actions. A 'New Student' button and an 'Import Roster File' button are located above the table.

Full Name	RegCode	Status	Class Name	Access Status	Actions
Lisa Jones	OK	Active	TES class	Active	<a href="#">Delete</a>
Michael Smith	OK	Active	TES class	Active	<a href="#">Delete</a>
Mark Jacobs	OK	Active	TES class	Active	<a href="#">Delete</a>
Jennifer Miller	OK	Active	TES class	Active	<a href="#">Delete</a>
Alex Morris	OK	Active	TES class	Active	<a href="#">Delete</a>
Abigail Rosen	OK	Active	TES class	Active	<a href="#">Delete</a>
Alicia Blume	OK	Active	TES class	Active	<a href="#">Delete</a>
John Boddington	OK	Active	TES class	Active	<a href="#">Delete</a>
George Johnson	OK	Active	TES class	Active	<a href="#">Delete</a>
Emily Simms	OK	Active	TES class	Active	<a href="#">Delete</a>

## Enhance the Power of Your Class Preparation and Presentations



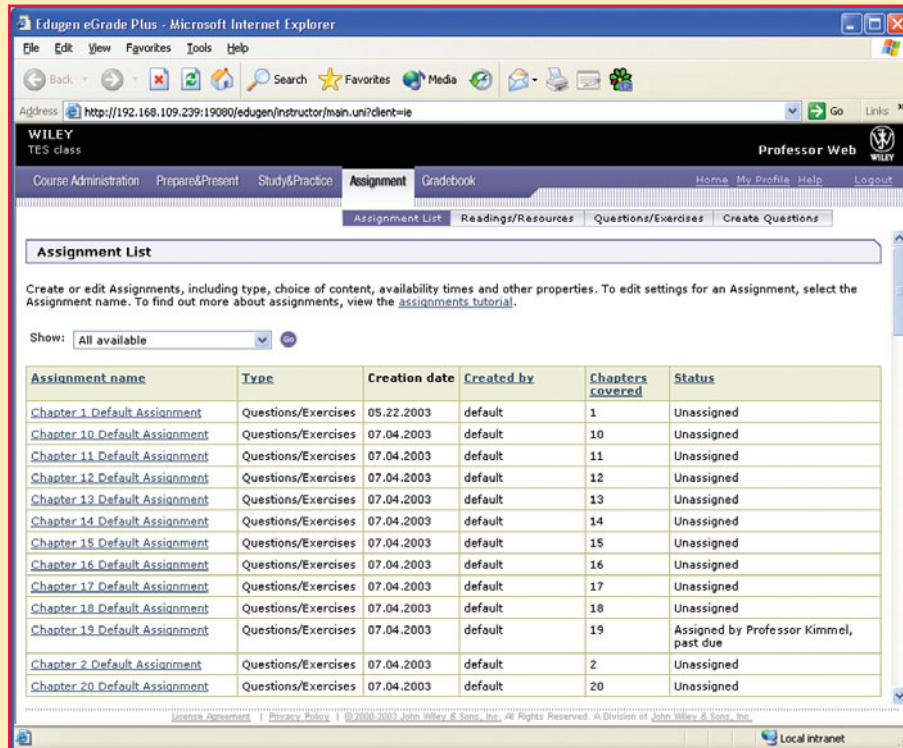
The screenshot shows the 'Prepare and Present' tab in the Edugen eGrade Plus interface. The 'Presentations List' section is active, displaying a table of presentations. The table includes columns for Presentation name, Modified, Created by, and Actions. A 'New Presentation' button is located above the table. An inset image shows a diagram of a spring with a mass attached, illustrating the concept of equilibrium position.

Presentation name	Modified	Created by	Actions
<a href="#">Chapter 1 Presentation</a>	Sep 3, 2003 5:52:56 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>
<a href="#">Chapter 2 Presentation</a>	Sep 3, 2003 5:53:24 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>
<a href="#">Chapter 3 Presentation</a>	Sep 3, 2003 5:53:55 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>
<a href="#">Chapter 4 Presentation</a>	Sep 3, 2003 5:54:08 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>
<a href="#">Chapter 5 Presentation</a>	Sep 3, 2003 5:54:11 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>
<a href="#">Chapter 6 Presentation</a>	Sep 3, 2003 5:54:14 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>
<a href="#">Chapter 7 Presentation</a>	Sep 3, 2003 5:54:17 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>
<a href="#">Chapter 8 Presentation</a>	Sep 3, 2003 5:54:20 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>
<a href="#">Chapter 9 Presentation</a>	Sep 3, 2003 5:54:23 PM	Professor Kimmel	<a href="#">Remove</a> <a href="#">Edit</a>

A **Prepare and Present tool** contains all of the Wiley-provided resources, such as **a multimedia version of the text, interactive chapter reviews, and PowerPoint slides**, making your preparation time more efficient. You may easily adapt, customize, and add to Wiley content to meet the needs of your course.

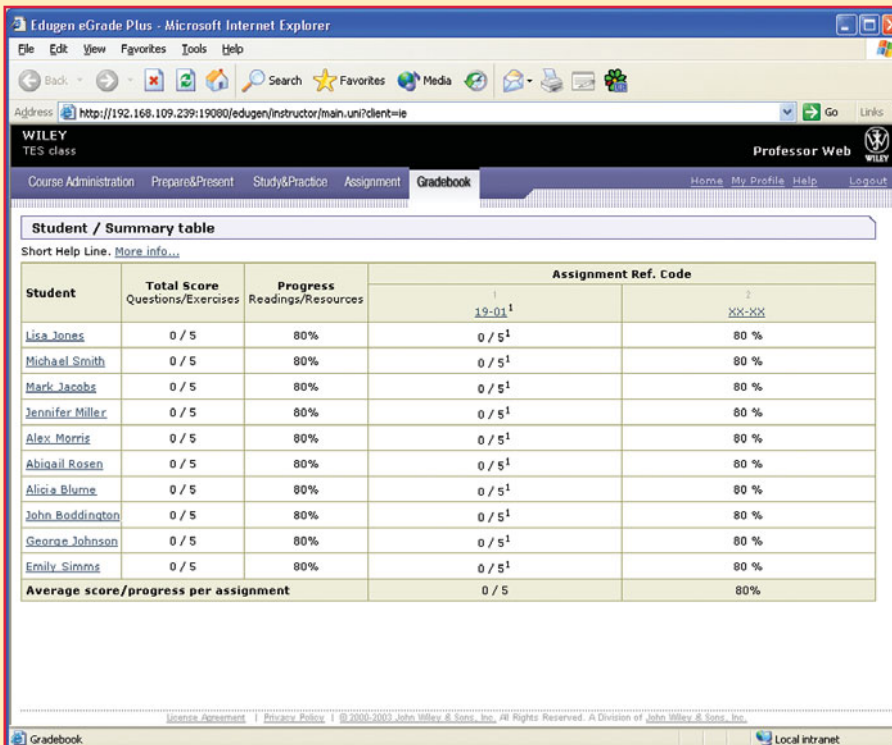
## Create Your Own Assignments or Use Ours, All with Automatic Grading

An **Assignment** area allows you to create **student homework** and **quizzes** that utilize **Wiley-provided question banks**, and an **electronic version of the text**. One of the most powerful features of eGrade Plus is that student assignments will be automatically graded and recorded in your gradebook. This will not only save you time but will provide your students with immediate feedback on their work.



Assignment name	Type	Creation date	Created by	Chapters covered	Status
<a href="#">Chapter 1 Default Assignment</a>	Questions/Exercises	05.22.2003	default	1	Unassigned
<a href="#">Chapter 10 Default Assignment</a>	Questions/Exercises	07.04.2003	default	10	Unassigned
<a href="#">Chapter 11 Default Assignment</a>	Questions/Exercises	07.04.2003	default	11	Unassigned
<a href="#">Chapter 12 Default Assignment</a>	Questions/Exercises	07.04.2003	default	12	Unassigned
<a href="#">Chapter 13 Default Assignment</a>	Questions/Exercises	07.04.2003	default	13	Unassigned
<a href="#">Chapter 14 Default Assignment</a>	Questions/Exercises	07.04.2003	default	14	Unassigned
<a href="#">Chapter 15 Default Assignment</a>	Questions/Exercises	07.04.2003	default	15	Unassigned
<a href="#">Chapter 16 Default Assignment</a>	Questions/Exercises	07.04.2003	default	16	Unassigned
<a href="#">Chapter 17 Default Assignment</a>	Questions/Exercises	07.04.2003	default	17	Unassigned
<a href="#">Chapter 18 Default Assignment</a>	Questions/Exercises	07.04.2003	default	18	Unassigned
<a href="#">Chapter 19 Default Assignment</a>	Questions/Exercises	07.04.2003	default	19	Assigned by Professor Kimmel, past due
<a href="#">Chapter 2 Default Assignment</a>	Questions/Exercises	07.04.2003	default	2	Unassigned
<a href="#">Chapter 20 Default Assignment</a>	Questions/Exercises	07.04.2003	default	20	Unassigned

## Assess Student Understanding More Closely



Student	Total Score Questions/Exercises	Progress Readings/Resources	Assignment Ref. Code
<a href="#">Lisa Jones</a>	0 / 5	80%	19-01 <sup>1</sup> XX-XX
<a href="#">Michael Smith</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
<a href="#">Mark Jacobs</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
<a href="#">Jennifer Miller</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
<a href="#">Alex Morris</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
<a href="#">Abigail Rosen</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
<a href="#">Alicia Blume</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
<a href="#">John Boddington</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
<a href="#">George Johnson</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
<a href="#">Emily Simms</a>	0 / 5	80%	0 / 5 <sup>1</sup> 80 %
Average score/progress per assignment			0 / 5 80%

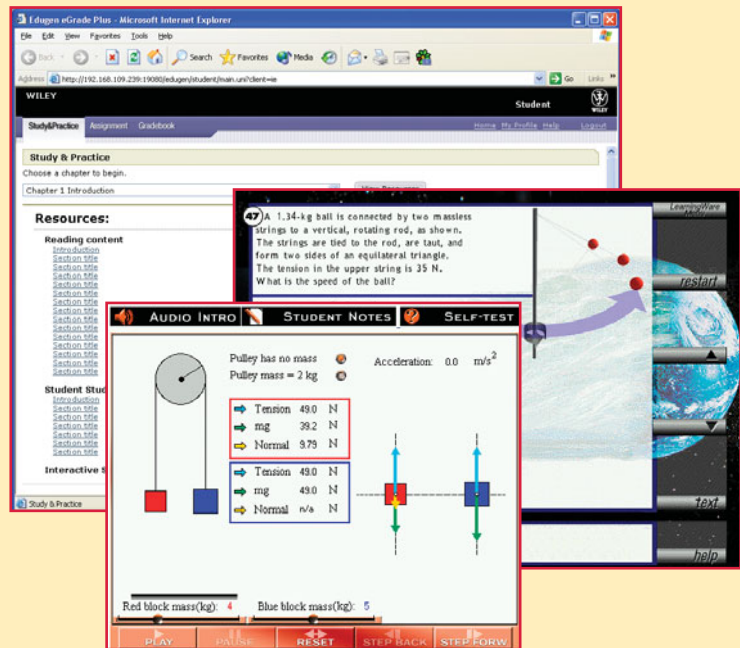
An **Instructor's Gradebook** will keep track of your students' progress and allow you to analyze individual and overall class results to determine their progress and level of understanding.



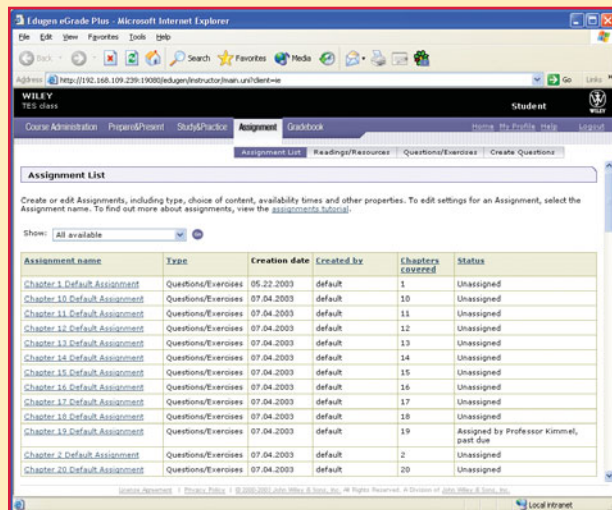
# Students, eGrade Plus Allows You to:

## Study More Effectively Get Immediate Feedback When You Practice on Your Own

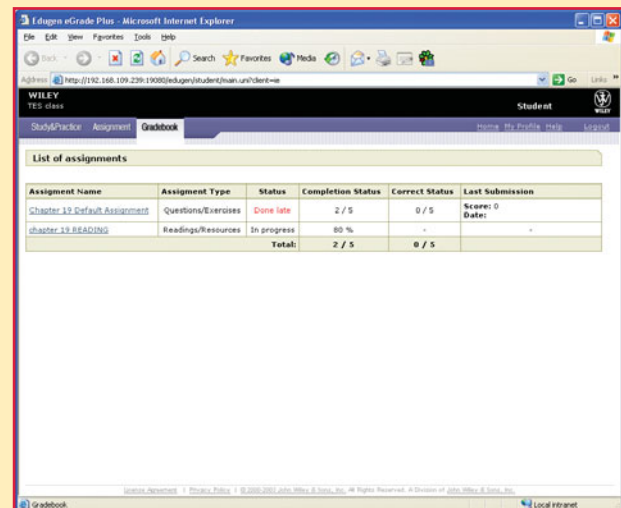
eGrade Plus problems links directly to the relevant sections of the **electronic book content**, so that you can review the text while you study and complete homework online. Additional resources include **self-assessment quizzing** with detailed feedback, **Interactive Learningware** with step-by-step problem solving tutorials, and **interactive simulations** to help you review key topics.



## Complete Assignments / Get Help with Problem Solving



An **Assignment** area keeps all your assigned work in one location, making it easy for you to stay on task. In addition, many homework problems contain a **link** to the relevant section of the **electronic book**, providing you with a text explanation to help you conquer problem-solving obstacles as they arise.



## Keep Track of How You're Doing

A **Personal Gradebook** allows you to view your results from past assignments at any time.

# UNDERSTANDING PHYSICS

---

Karen Cummings

*Rensselaer Polytechnic Institute*

*Southern Connecticut State University*

Priscilla W. Laws

*Dickinson College*

Edward F. Redish

*University of Maryland*

Patrick J. Cooney

*Millersville University*

---

GUEST AUTHOR

Edwin F. Taylor

*Massachusetts Institute of Technology*

ADDITIONAL MEMBERS OF ACTIVITY BASED PHYSICS GROUP

David R. Sokoloff

*University of Oregon*

Ronald K. Thornton

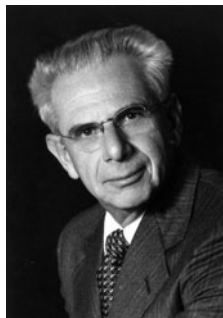
*Tufts University*

*Understanding Physics* is based on *Fundamentals of Physics*  
by David Halliday, Robert Resnick, and Jearl Walker.



WILEY

**John Wiley & Sons, Inc.**



This book is dedicated to Arnold Arons,  
whose pioneering work in physics education  
and reviews of early chapters have had  
a profound influence on our work.

SENIOR ACQUISITIONS EDITOR	Stuart Johnson
SENIOR DEVELOPMENT EDITOR	Ellen Ford
MARKETING MANAGER	Bob Smith
SENIOR PRODUCTION EDITOR	Elizabeth Swain
SENIOR DESIGNER	Kevin Murphy
INTERIOR DESIGN	Circa 86, Inc.
COVER DESIGN	David Levy
COVER PHOTO	© Antonio M. Rosario/The Image Bank/Getty Images
ILLUSTRATION EDITOR	Anna Melhorn
PHOTO EDITOR	Hilary Newman

This book was set in 10/12 Times Ten Roman by Progressive and  
printed and bound by Von Hoffmann Press. The cover was printed by Von Hoffmann Press.

This book is printed on acid free paper.    ∞

Copyright © 2004 John Wiley & Sons, Inc. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system  
or transmitted in any form or by any means, electronic, mechanical, photocopying,  
recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the  
1976 United States Copyright Act, without either the prior written permission of the  
Publisher, or authorization through payment of the appropriate per-copy fee to the  
Copyright Clearance Center, Inc. 222 Rosewood Drive, Danvers, MA 01923 (978)750-8400,  
fax (978)646-8600. Requests to the Publisher for permission should be addressed  
to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ  
07030-5774, (201)748-6011, fax (201)748-6008. To order books or for customer service please call 1-800-  
CALL WILEY (225-5945).

***Library of Congress Cataloging in Publication Data:***

Understanding physics / Karen Cummings . . . [et al.]; with additional members of the  
Activity Based Physics Group.

p. cm.

Includes index.

ISBN 0-471-37099-1

1. Physics. I. Cummings, Karen. II. Activity Based Physics Group.

QC23.2.U54 2004

530—dc21

2003053481

L.C. Call no.

Dewey Classification No.

L.C. Card No.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1



# Preface

Welcome to *Understanding Physics*. This book is built on the foundations of the 6th Edition of Halliday, Resnick, and Walker's *Fundamentals of Physics* which we often refer to as HRW 6th. The HRW 6th text and its ancestors, first written by David Halliday and Robert Resnick, have been best-selling introductory physics texts for the past 40 years. It sets the standard against which many other texts are judged. You are probably thinking, "Why mess with success?" Let us try to explain.

## Why a Revised Text?

A physics major recently remarked that after struggling through the first half of his junior level mechanics course, he felt that the course was now going much better. What had changed? Did he have a better background in the material they were covering now? "No," he responded. "I started reading the book before every class. That helps me a lot. I wish I had done it in Physics One and Two." Clearly, this student learned something very important. It is something most physics instructors wish they could teach all of their students as soon as possible. Namely, no matter how smart your students are, no matter how well your introductory courses are designed and taught, your students will master more physics if they learn how to read an "understandable" textbook carefully.

We know from surveys that the vast majority of introductory physics students do not read their textbooks carefully. We think there are two major reasons why: (1) many students complain that physics textbooks are impossible to understand and too abstract, and (2) students are extremely busy juggling their academic work, jobs, personal obligations, social lives and interests. So they develop strategies for passing physics without spending time on careful reading. We address both of these reasons by making our revision to the sixth edition of *Fundamentals of Physics* easier for students to understand and by providing the instructor with more **Reading Exercises** (formerly known as Checkpoints) and additional strategies for encouraging students to read the text carefully. Fortunately, we are attempting to improve a fine textbook whose active author, Jearl Walker, has worked diligently to make each new edition more engaging and understandable.

In the next few sections we provide a summary of how we are building upon HRW 6th and shaping it into this new textbook.

## A Narrative That Supports Student Learning

One of our primary goals is to help students make sense of the physics they are learning. We cannot achieve this goal if students see physics as a set of disconnected mathematical equations that each apply only to a small number of specific situations. We stress conceptual and qualitative understanding and continually make connections between mathematical equations and conceptual ideas. We also try to build on ideas that students can be expected to already understand, based on the resources they bring from everyday experiences.

In *Understanding Physics* we have tried to tell a story that flows from one chapter to the next. Each chapter begins with an introductory section that discusses why new topics introduced in the chapter are important, explains how the chapter builds on previous chapters, and prepares students for those that follow. We place explicit emphasis on basic concepts that recur throughout the book. We use extensive forward and backward referencing to reinforce connections between topics. For example, in the introduction of Chapter 16 on Oscillations we state: “Although your study of simple harmonic motion will enhance your understanding of mechanical systems it is also vital to understanding the topics in electricity and magnetism encountered in Chapters 30-37. Finally, a knowledge of SHM provides a basis for understanding the wave nature of light and how atoms and nuclei absorb and emit energy.”

## Emphasis on Observation and Experimentation

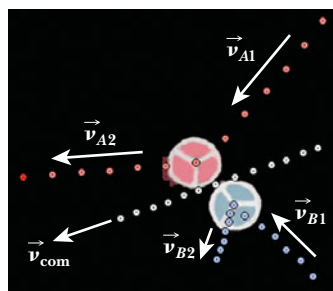
Observations and concrete everyday experiences are the starting points for development of mathematical expressions. Experiment-based theory building is a major feature of the book. We build ideas on experience that students either already have or can easily gain through careful observation.

Whenever possible, the physical concepts and theories developed in *Understanding Physics* grow out of simple observations or experimental data that can be obtained in typical introductory physics laboratories. We want our readers to develop the habit of asking themselves: What do our observations, experiences and data imply about the natural laws of physics? How do we know a given statement is true? Why do we believe we have developed correct models for the world?

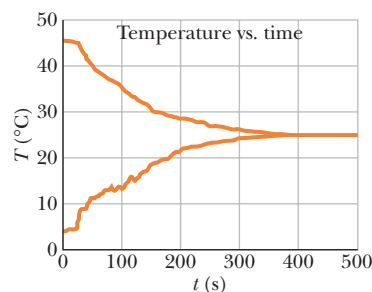
Toward this end, the text often starts a chapter by describing everyday observations with which students are familiar. This makes *Understanding Physics* a text that is both relevant to students’ everyday lives and draws on existing student knowledge. We try to follow Arnold Arons’ principle “idea first, name after.” That is, we make every attempt to begin a discussion by using everyday language to describe common experiences. Only then do we introduce formal physics terminology to represent the concepts being discussed. For example, everyday pushes, pulls, and their impact on the motion of an object are discussed before introducing the term “force” or Newton’s Second Law. We discuss how a balloon shrivels when placed in a cold environment and how a pail of water cools to room temperature before introducing the ideal gas law or the concept of thermal energy transfer.

The “idea first, name after” philosophy helps build patterns of association between concepts students are trying to learn and knowledge they already have. It also helps students reinterpret their experiences in a way that is consistent with physical laws.

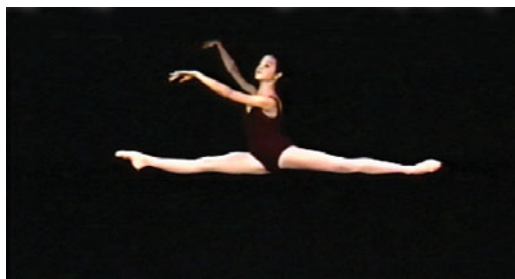
Examples and illustrations in *Understanding Physics* often present data from modern computer-based laboratory tools. These tools include computer-assisted data acquisition systems and digital video analysis software. We introduce students to these tools at the end of Chapter 1. Examples of these techniques are shown in Figs. P-1 and P-2 (on the left) and Fig. P-3 on the next page. Since many instructors use these computer tools in the laboratory or in lecture demonstrations, these tools are part of the introductory physics experience for more and more of our students. The use of real data has a number of advantages. It connects the text to the students’ experience in other parts of the course and it connects the text directly to real world experience. Regardless of whether data acquisition and analysis tools are used in the student’s own laboratory, our use of realistic rather than idealized data helps students develop an appreciation of the role that data evaluation and analysis plays in supporting theory.



**FIGURE P-1** ■ A video analysis shows that the center of mass of a two-puck system moves at a constant velocity.



**FIGURE P-2** ■ Electronic temperature sensors reveal that if equal amounts of hot and cold water mix the final temperature is the average of the initial temperatures.



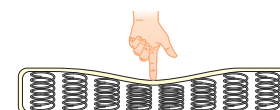
**FIGURE P-3** ■ A video analysis of human motion reveals that in free fall the center of mass of an extended body moves in a parabolic path under the influence of the Earth's gravitational force.

## Using Physics Education Research

In re-writing the text we have taken advantage of two valuable findings of physics education research. One is the identification of concepts that are especially difficult for many students to learn. The other is the identification of active learning strategies to help students develop a more robust understanding of physics.

### Addressing Learning Difficulties

Extensive scholarly research exists on the difficulties students have in learning physics.<sup>1</sup> We have made a concerted effort to address these difficulties. In *Understanding Physics*, issues that are known to confuse students are discussed with care. This is true even for topics like the nature of force and its effect on velocity and velocity changes that may seem trivial to professional physicists. We write about subtle, often counter-intuitive topics with carefully chosen language and examples designed to draw out and remediate common alternative student conceptions. For example, we know that students have trouble understanding passive forces such as normal and friction forces.<sup>2</sup> How can a rigid table exert a force on a book that rests on it? In Section 6-4 we present an idealized model of a solid that is analogous to an inner spring mattress with the repulsion forces between atoms acting as the springs. In addition, we invite our readers to push on a table with a finger and experience the fact that as they push harder on the table the table pushes harder on them in the opposite direction.



**FIGURE P-4** ■ Compressing an innerspring mattress with a force. The mattress exerts an oppositely directed force, with the same magnitude, back on the finger.

### Incorporating Active Learning Opportunities

We designed *Understanding Physics* to be more interactive and to foster thoughtful reading. We have retained a number of the excellent Checkpoint questions found at the end of HRW 6th chapter sections. We now call these questions **Reading Exercises**. We have created many new Reading Exercises that require students to reflect on the material in important chapter sections. For example, just after reading Section 6-2 that introduces the two-dimensional free-body diagram, students encounter Reading Exercise 6-1. This multiple-choice exercise requires students to identify the free-body diagram for a helicopter that experiences three non-collinear forces. The distractors were based on common problems students have with the construction of free-body diagrams. When used in “Just-In-Time Teaching” assignments or for in-class group discussion, this type of reading exercise can help students learn a vital problem solving skill as they read.

<sup>1</sup> L. C. McDermott and E. F. Redish, “Resource Letter PER-1: Physics Education Research,” *Am. J. Phys.* **67**, 755-767 (1999)

<sup>2</sup> John J. Clement, “Expert novice similarities and instruction using analogies,” *Int. J. Sci. Ed.* **20**, 1271-1286 (1998)

We also created a set of **Touchstone Examples**. These are carefully chosen sample problems that illustrate key problem solving skills and help students learn how to use physical reasoning and concepts as an essential part of problem solving. We selected some of these touchstone examples from the outstanding collection of sample problems in HRW 6th and we created some new ones. In order to retain the flow of the narrative portions of each chapter, we have reduced the overall number of sample problems to those necessary to exemplify the application of fundamental principles. Also, we chose touchstone examples that require students to combine conceptual reasoning with mathematical problem-solving skills. Few, if any, of our touchstone examples are solvable using simple “plug-and-chug” or algorithmic pattern matching techniques.

**Alternative problems** have been added to the extensive, classroom tested end-of-chapter problem sets selected from HRW 6th. The design of these new problems are based on the authors’ knowledge of research on student learning difficulties. Many of these new problems require careful qualitative reasoning. They explicitly connect conceptual understanding to quantitative problem solving. In addition, estimation problems, video analysis problems, and “real life” or “context rich” problems have been included.

The organization and style of *Understanding Physics* has been modified so that it can be easily used with other research-based curricular materials that make up what we call *The Physics Suite*. The *Suite* and its contents are explained at length at the end of this preface.

## Reorganizing for Coherence and Clarity

---

For the most part we have retained the organization scheme inherited from HRW 6th. Instructors are familiar with the general organization of topics in a typical course sequence in calculus-based introductory physics texts. In fact, ordering of topics and their division into chapters is the same for 27 of the 38 chapters. The order of some topics has been modified to be more pedagogically coherent. Most of the reorganization was done in Chapters 3 through 10 where we adopted a sequence known as *New Mechanics*. In addition, we decided to move HRW 6th Chapter 25 on capacitors so it becomes the last chapter on DC circuits. Capacitors are now introduced in Chapter 28 in *Understanding Physics*.

## The New Mechanics Sequence

HRW 6th and most other introductory textbooks use a familiar sequence in the treatment of classical mechanics. It starts with the development of the kinematic equations to describe constantly accelerated motion. Then two-dimensional vectors and the kinematics of projectile motion are treated. This is followed by the treatment of dynamics in which Newton’s Laws are presented and used to help students understand both one- and two-dimensional motions. Finally energy, momentum conservation, and rotational motion are treated.

About 12 years ago when Priscilla Laws, Ron Thornton, and David Sokoloff were collaborating on the development of research-based curricular materials, they became concerned about the difficulties students had working with two-dimensional vectors and understanding projectile motion before studying dynamics.

At the same time Arnold Arons was advocating the introduction of the concept of momentum before energy.<sup>3</sup> Arons argued that (1) the momentum concept is simpler than the energy concept, in both historical and modern contexts and (2) the study

---

<sup>3</sup> Private Communication between Arnold Arons and Priscilla Laws by means of a document entitled “Preliminary Notes and Suggestions,” August 19, 1990; and Arnold Arons, *Development of Concepts of Physics* (Addison-Wesley, Reading MA, 1965)

of momentum conservation entails development of the concept of center-of-mass which is needed for a proper development of energy concepts. Additionally, the impulse-momentum relationship is clearly an alternative statement of Newton's Second Law. Hence, its placement immediately after the coverage of Newton's laws is most natural.

In order to address these concerns about the traditional mechanics sequence, a small group of physics education researchers and curriculum developers convened in 1992 to discuss the introduction of a new order for mechanics.<sup>4</sup> One result of the conference was that Laws, Sokoloff, and Thornton have successfully incorporated a new sequence of topics in the mechanics portions of various curricular materials that are part of the Physics Suite discussed below.<sup>5</sup> These materials include *Workshop Physics*, the *RealTime Physics Laboratory Module in Mechanics*, and the *Interactive Lecture Demonstrations*. This sequence is incorporated in this book and has required a significant reorganization and revisions of HRW 6th Chapters 2 through 10.

The New Mechanics sequence incorporated into Chapters 2 through 10 of understanding physics includes:

- Chapter 2: One-dimensional kinematics using constant horizontal accelerations and vertical free fall as applications.
- Chapter 3: The study of one-dimensional dynamics begins with the application of Newton's laws of motion to systems with one or more forces acting along a single line. Readers consider observations that lead to the postulation of "gravity" as a constant invisible force acting vertically downward.
- Chapter 4: Two-dimensional vectors, vector displacements, unit vectors and the decomposition of vectors into components are treated.
- Chapter 5: The study of kinematics and dynamics is extended to two-dimensional motions with forces along only a single line. Examples include projectile motion and circular motion.
- Chapter 6: The study of kinematics and dynamics is extended to two-dimensional motions with two-dimensional forces.
- Chapters 7 & 8: Topics in these chapters deal with impulse and momentum change, momentum conservation, particle systems, center of mass, and the motion of the center-of-mass of an isolated system.
- Chapters 9 & 10: These chapters introduce kinetic energy, work, potential energy, and energy conservation.

### Just-in-Time Mathematics

In general, we introduce mathematical topics in a "just-in-time" fashion. For example, we treat one-dimensional vector concepts in Chapter 2 along with the development of one-dimensional velocity and acceleration concepts. We hold the introduction of two- and three-dimensional vectors, vector addition and decomposition until Chapter 4, immediately before students are introduced to two-dimensional motion and forces in Chapters 5 and 6. We do not present vector products until they are needed. We wait to introduce the dot product until Chapter 9 when the concept of physical work is presented. Similarly, the cross product is first presented in Chapter 11 in association with the treatment of torque.

<sup>4</sup> The New Mechanics Conference was held August 6-7, 1992 at Tufts University. It was attended by Pat Cooney, Dewey Dykstra, David Hammer, David Hestenes, Priscilla Laws, Suzanne Lea, Lillian McDermott, Robert Morse, Hans Pfister, Edward F. Redish, David Sokoloff, and Ronald Thornton.

<sup>5</sup> Laws, P. W. "A New Order for Mechanics" pp. 125-136, *Proceedings of the Conference on the Introductory Physics Course*, Rensselaer Polytechnic Institute, Troy New York, May 20-23, Jack Wilson, Ed. 1993 (John Wiley & Sons, New York 1997)



## Notation Changes

Mathematical notation is often confusing, and ambiguity in the meaning of a mathematical symbol can prevent a student from understanding an important relationship. It is also difficult to solve problems when the symbols used to represent different quantities are not distinctive. Some key features of the new notation include:

- We adhere to recent notation guidelines set by the U.S. National Institute of Standard and Technology Special Publication 811 (SP 811).
- We try to balance our desire to use familiar notation and our desire to avoid using the same symbol for different variables. For example,  $p$  is often used to denote momentum, pressure, and power. We have chosen to use lower case  $p$  for momentum and capital  $P$  for pressure since both variables appear in the kinetic theory derivation. But we stick with the convention of using capital  $P$  for power since it does not commonly appear side by side with pressure in equations.
- We denote vectors with an arrow instead of bolding so handwritten equations can be made to look like the printed equations.
- We label each vector component with a subscript that explicitly relates it to its coordinate axis. This eliminates the common ambiguity about whether a quantity represents a magnitude which is a scalar or a vector component which is not a scalar.
- We often use subscripts to spell out the names of objects that are associated with mathematical variables even though instructors and students will tend to use abbreviations. We also stress the fact that one object is exerting a force on another with an arrow in the subscript. For example, the force exerted by a rope on a block would be denoted as  $\vec{F}_{\text{rope} \rightarrow \text{block}}$ .

Our notation scheme is summarized in more detail in Appendix A4.

## Encouraging Text Reading

We have described a number of changes that we feel will improve this textbook and its readability. But even the best textbook in the world is of no help to students who do not read it. So it is important that instructors make an effort to encourage busy students to develop effective reading habits. In our view the single most effective way to get students to read this textbook is to assign appropriate reading, reading exercises, and other reading questions after every class. Some effective ways to follow up on reading question assignments include:

1. Employ a method called “Just-In-Time-Teaching” (or JiTT) in which students submit their answers to questions about reading before class using just plain email or one of the many available computer based homework systems (Web Assign or E-Grade for example). You can often read enough answers before class to identify the difficult questions that need more discussion in class;
2. Ask students to bring the assigned questions to class and use the answers as a basis for small group discussions during the class period;
3. Assign multiple choice questions related to each section or chapter that can be graded automatically with a computer-based homework system; and
4. Require students to submit chapter summaries. Because this is a very effective assignment, we intentionally avoided doing chapter summaries for students.

Obviously, all of these approaches are more effective when students are given some credit for doing them. Thus you should arrange to grade all, or a random sample, of the submissions as incentives for students to read the text and think about the answers to Reading Exercises on a regular basis.

## The Physics Suite

In 1997 and 1998, Wiley's physics editor, Stuart Johnson, and an informally constituted group of curriculum developers and educational reformers known as the *Activity Based Physics Group* began discussing the feasibility of integrating a broad array of curricular materials that are physics education research-based. This led to the assembly of an *Activity Based Physics Suite* that includes this textbook. The *Physics Suite* also includes materials that can be combined in different ways to meet the needs of instructors working in vastly different learning environments. The *Interactive Lecture Demonstration Series*<sup>6</sup> is designed primarily for use in lecture sessions. Other *Suite* materials can be used in laboratory settings including the *Workshop Physics Activity Guide*,<sup>7</sup> the *Real Time Physics Laboratory* modules,<sup>8</sup> and *Physics by Inquiry*.<sup>9</sup> Additional elements in the collection are suitable for use in recitation sessions such as the University of Washington *Tutorials in Introductory Physics* (available from Prentice Hall)<sup>10</sup> and a set of *Quantitative Tutorials*<sup>11</sup> developed at the University of Maryland. The *Activity Based Physics Suite* is rounded out with a collection of thinking problems developed at the University of Maryland. In addition to this **Understanding Physics** text, the Physics Suite elements include:

1. **Teaching Physics with the Physics Suite** by Edward F. Redish (University of Maryland). This book is not only the “Instructors Manual” for *Understanding Physics*, but it is also a book for anyone who is interested in learning about recent developments in physics education. It is a handbook with a variety of tools for improving both teaching and learning of physics—from new kinds of homework and exam problems, to surveys for figuring out what has happened in your class, to tools for taking and analyzing data using computers and video. The book comes with a Resource CD containing 14 conceptual and 3 attitude surveys, and more than 250 thinking problems covering all areas of introductory physics, resource materials from commercial vendors on the use of computerized data acquisition and video, and a variety of other useful reference materials. (Instructors can obtain a complimentary copy of the book and Resource CD, from John Wiley & Sons.)
2. **RealTime Physics** by David Sokoloff (University of Oregon), Priscilla Laws (Dickinson College), and Ronald Thornton (Tufts University). *RealTime Physics* is a set of laboratory materials that uses computer-assisted data acquisition to help students build concepts, learn representation translation, and develop an understanding of the empirical base of physics knowledge. There are three modules in the collection: Module 1: Mechanics (12 labs), Module 2: Heat and Thermodynamics (6 labs), and Module 3: Electric Circuits (8 labs). (Available both in print and in electronic form on *The Physics Suite CD*.)

<sup>6</sup>David R. Sokoloff and Ronald K. Thornton, “Using Interactive Lecture Demonstrations to Create an Active Learning Environment.” *The Physics Teacher*, **35**, 340-347, September 1997.

<sup>7</sup>Priscilla W. Laws, *Workshop Physics Activity Guide*, Modules 1-4 w/ Appendices (John Wiley & Sons, New York, 1997).

<sup>8</sup>David R. Sokoloff, *RealTime Physics*, Modules 1-2, (John Wiley & Sons, New York, 1999).

<sup>9</sup>Lillian C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry* (John Wiley & Sons, New York, 1996).

<sup>10</sup>Lillian C. McDermott, Peter S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics*, First Edition (Prentice-Hall, Upper Saddle River, NJ, 2002).

<sup>11</sup>Richard N. Steinberg, Michael C. Wittmann, and Edward F. Redish, “Mathematical Tutorials in Introductory Physics,” in, *The Changing Role Of Physics Departments In Modern Universities*, Edward F. Redish and John S. Rigden, editors, AIP Conference Proceedings **399**, (AIP, Woodbury NY, 1997), 1075-1092.

3. **Interactive Lecture Demonstrations** by David Sokoloff (University of Oregon) and Ronald Thornton (Tufts University). ILDs are worksheet-based guided demonstrations designed to focus on fundamental principles and address specific naïve conceptions. The demonstrations use computer-assisted data acquisition tools to collect and display high quality data in real time. Each ILD sequence is designed for delivery in a single lecture period. The demonstrations help students build concepts through a series of instructor led steps involving prediction, discussions with peers, viewing the demonstration and reflecting on its outcome. The ILD collection includes sequences in mechanics, thermodynamics, electricity, optics and more. (Available both in print and in electronic form on *The Physics Suite CD*.)
4. **Workshop Physics** by Priscilla Laws (Dickinson College). *Workshop Physics* consists of a four part activity guide designed for use in calculus-based introductory physics courses. Workshop Physics courses are designed to replace traditional lecture and laboratory sessions. Students use computer tools for data acquisition, visualization, analysis and modeling. The tools include computer-assisted data acquisition software and hardware, digital video capture and analysis software, and spreadsheet software for analytic mathematical modeling. Modules include classical mechanics (2 modules), thermodynamics & nuclear physics, and electricity & magnetism. (Available both in print and in electronic form on *The Physics Suite CD*.)
5. **Tutorials in Introductory Physics** by Lillian C. McDermott, Peter S. Shaffer and the Physics Education Group at the University of Washington. These tutorials consist of a set of worksheets designed to supplement instruction by lectures and textbook in standard introductory physics courses. Each tutorial is designed for use in a one-hour class session in a space where students can work in small groups using simple inexpensive apparatus. The emphasis in the tutorials is on helping students deepen their understanding of critical concepts and develop scientific reasoning skills. There are tutorials on mechanics, electricity and magnetism, waves, optics, and other selected topics. (Available in print from Prentice Hall, Upper Saddle River, New Jersey.)
6. **Physics by Inquiry** by Lillian C. McDermott and the Physics Education Group at the University of Washington. This self-contained curriculum consists of a set of laboratory-based modules that emphasize the development of fundamental concepts and scientific reasoning skills. Beginning with their observations, students construct a coherent conceptual framework through guided inquiry. Only simple inexpensive apparatus and supplies are required. Developed primarily for the preparation of precollege teachers, the modules have also proven effective in courses for liberal arts students and for underprepared students. The amount of material is sufficient for two years of academic study. (Available in print.)
7. **The Activity Based Physics Tutorials** by Edward F. Redish and the University of Maryland Physics Education Research Group. These tutorials, like those developed at the University of Washington, consist of a set of worksheets developed to supplement lectures and textbook work in standard introductory physics courses. But these tutorials integrate the computer software and hardware tools used in other Suite elements including computer data acquisition, digital video analysis, simulations, and spreadsheet analysis. Although these tutorials include a range of classical physics topics, they also include additional topics in modern physics. (Available only in electronic form on *The Physics Suite CD*.)
8. **The Understanding Physics Video CD for Students** by Priscilla Laws, et. al.: This CD contains a collection of the video clips that are introduced in *Understanding Physics* narrative and alternative problems. The CD includes a number of QuickTime movie segments of physical phenomena along with the QuickTime player

software. Students can view video clips as they read the text. If they have video analysis software available, they can reproduce data presented in text graphs or complete video analyses based on assignments designed by instructors.

9. **The Physics Suite CD.** This CD contains a variety of the Suite Elements in electronic format (Microsoft Word files). The electronic format allows instructors to modify and reprint materials to better fit into their individual course syllabi. The CD contains much useful material including complete electronic versions of the following: *RealTime Physics*, *Interactive Lecture Demonstrations*, *Workshop Physics*, *Activity Based Physics Tutorials*.

## A Final Word to the Instructor

Over the past decade we have learned how valuable it is for us as teachers to focus on what most students actually need to do to learn physics, and how valuable it can be for students to work with research-based materials that promote active learning. We hope you and your students find this book and the other *Physics Suite* materials helpful in your quest to make physics both more exciting and understandable to your students.

## Supplements for Use with Understanding Physics

---

### Instructor Supplements

1. **Instructor's Solution Manual** prepared by Anand Batra (Howard University). This manual provides worked-out solutions for most of the end-of-chapter problems.
2. **Test Bank** by J. Richard Christman (U. S. Coast Guard Academy). This manual includes more than 2500 multiple-choice questions adapted from HRW 6th. These items are also available in the *Computerized Test Bank* (see below).
3. **Instructor's Resource CD.** This CD contains: The entire *Instructor's Solutions Manual* in both Microsoft Word® (IBM and Macintosh) and PDF files. A *Computerized Test Bank*, for use with both PCs and Macintosh computers with full editing features to help you customize tests. And all text illustrations, suitable for classroom projection, printing, and web posting.
4. **Online Homework and Quizzing:** *Understanding Physics* supports WebAssign and eGrade, two programs that give instructors the ability to deliver and grade homework and quizzes over the Internet.
5. **The Wiley Physics Demonstration Videos** by David Maiullo of Rutgers University consist of over a hundred classic physics demonstrations that will engage and instruct your students. Filmed, edited and produced by a professional film crew, the demonstrations include lying on a bed of nails, breaking glass with sound, and, in a show of atmospheric pressure, crushing a 55-gallon drum. Each demonstration is labeled according to the Physics Instructional Resource Association's demonstration classifying system. This system identifies the area, topic and concept presented in each demonstration. Go to [www.pira.nu](http://www.pira.nu) for more information about the Physics Instructional Resources Association and to download a spreadsheet of the demonstration classification systems.
6. **Wiley Physics Simulations CD-ROM** contains 50 interactive simulations (Java applets) that can be used for classroom demonstrations.

### Student Supplements

1. **Student Study Guide** by J. Richard Christman (U. S. Coast Guard Academy). This student study guide provides chapter overviews, hints for solving selected end-of-chapter problems, and self-quizzes.

2. **Student Solutions Manual** by J. Richard Christman (U. S. Coast Guard Academy). This manual provides students with complete worked-out solutions for approximately 450 of the odd-numbered end-of-chapter problems.

## Acknowledgements

---

Many individuals helped us create this book. The authors are grateful to the individuals who attended the weekend retreats at Airlie Center in 1997 and 1998 and to our editor, Stuart Johnson and to John Wiley & Sons for sponsoring the sessions. It was in these retreats that the ideas for *Understanding Physics* crystallized. We are grateful to Jearl Walker, David Halliday and Bob Resnick for graciously allowing us to attempt to make their already fine textbook better.

The authors owe special thanks to Sara Settlemyer who served as an informal project manager for the past few years. Her contributions included physics advice (based on her having completed Workshop Physics courses at Dickinson College), her use of Microsoft Word, Adobe Illustrator, Adobe Photoshop and Quark XPress to create the manuscript and visuals for this edition, and skillful attempts to keep our team on task—a job that has been rather like herding cats.

**Karen Cummings:** I would like to say “Thanks!” to: Bill Lanford (for endless advice, use of the kitchen table and convincing me that I really could keep the same address for more than a few years in a row), Ralph Kartel Jr. and Avery Murphy (for giving me an answer when people asked why I was working on a textbook), Susan and Lynda Cummings (for the comfort, love and support that only sisters can provide), Jeff Marx, Tim French and the poker crew (for their friendship and laughter), my colleagues at Southern Connecticut and Rensselaer, especially Leo Schowalter, Jim Napolitano and Jack Wilson (for the positive influence you have had on my professional life) and my students at Southern Connecticut and Rensselaer, Ron Thornton, Priscilla Laws, David Sokoloff, Pat Cooney, Joe Redish, Ken and Pat Heller and Lillian C. McDermott (for helping me learn how to teach).

**Priscilla Laws:** First of all I would like thank my husband and colleague Ken Laws for his quirky physical insights, for the Chapter 11 Kneecap puzzler, for the influence of his physics of dance work on this book, and for waiting for me countless times while I tried to finish “just one more thing” on this book. Thanks to my daughter Virginia Jackson and grandson Adam for all the fun times that keep me sane. My son Kevin Laws deserves special mention for sharing his creativity with us—best exemplified by his murder mystery problem, *A(dam)nable Man*, reprinted here as problem 5-68. I would like to thank Juliet Brosing of Pacific University who adapted many of the Workshop Physics problems developed at Dickinson for incorporation into the alternative problem collection in this book. Finally, I am grateful to my Dickinson College colleagues Robert Boyle, Kerry Browne, David Jackson, and Hans Pfister for advice they have given me on a number of topics.

**Joe Redish:** I would like to thank Ted Jacobsen for discussions of our chapter on relativity and Dan Lathrop for advice on the sources of the Earth’s magnetic field, as well as many other of my colleagues at the University of Maryland for discussions on the teaching of introductory physics over many years.

**Pat Cooney:** I especially thank my wife Margaret for her patient support and constant encouragement and I am grateful to my colleagues at Millersville University: John Dooley, Bill Price, Mike Nolan, Joe Grosh, Tariq Gilani, Conrad Miziumski, Zenaida Uy, Ned Dixon, and Shawn Reinfried for many illuminating conversations.

We also appreciate the absolutely essential role many reviewers and classroom testers played. We took our reviewers very seriously. Several reviewers and testers deserve special mention. First and foremost is Arnold Arons who managed to review 29 of the 38 chapters either from the original HRW 6th material or from our early drafts before he passed away in February 2001. Vern Lindberg from the Rochester



Institute of Technology deserves special mention for his extensive and very insightful reviews of most of our first 18 chapters. Ed Adelson from Ohio State did a particularly good job reviewing most of our electricity chapters. Classroom tester Maxine Willis from Gettysburg Area High School deserves special recognition for compiling valuable comments that her advanced placement physics students made while class testing Chapters 1-12 of the preliminary version. Many other reviewers and class testers gave us useful comments in selected chapters.

### **Class Testers**

Gary Adams Rensselaer Polytechnic Institute	Diane Dutkevitch Yavapai College	Stephen Luzader Frostburg State	Paul Stoler Rensselaer Polytechnic Institute
Marty Baumberger Chestnut Hill Academy	Timothy Hayes Rensselaer Polytechnic Institute	Dawn Meredith University of New Hampshire	Daniel F. Styer Oberlin College
Gary Bedrosian Rensselaer Polytechnic Institute	Brant Hinrichs Drury College	Larry Robinson Austin College	Rebecca Surman Union College
Joseph Bellina, Saint Mary's College	Kurt Hoffman Whitman College	Michael Roth University of Northern Iowa	Robert Teese Muskingum College
Juliet W. Brosing Pacific University	James Holliday John Brown University	John Schroeder Rensselaer Polytechnic Institute	Maxine Willis Gettysburg Area High School
Shao-Hsuan Chiu Frostburg State	Michael Huster Simpson College	Cindy Schwarz Vassar College	Gail Wyant Cecil Community College
Chad Davies Gordon College	Dennis Kuhl Marietta College	William Smith Boise State University	Anne Young Rochester Institute of Technology
Hang Deng-Luzader Frostburg State	John Lindberg Seattle Pacific University	Dan Sperber Rensselaer Polytechnic Institute	David Ziegler Sedro-Woolley High School
John Dooley Millersville University	Vern Lindberg Rochester Institute of Technology	Roger Stockbauer Louisiana State University	

### **Reviewers**

Edward Adelson Ohio State University	Harold Hastings Hofstra University	Debora Katz U. S. Naval Academy	Gregor Novak U. S. Air Force Academy
Arnold Arons University of Washington	Laurent Hodges Iowa State University	Todd Lief Cloud Community College	Jacques Richard Chicago State University
Arun Bansil Northeastern University	Robert Hilborn Amherst College	Vern Lindberg Rochester Institute of Technology	Cindy Schwarz Vassar College
Chadan Djalali University of South Carolina	Theodore Jacobson University of Maryland	Mike Loverude California State University-Fullerton	Roger Sipson Moorhead State University
William Dawicke Milwaukee School of Engineering	Leonard Kahn University of Rhode Island	Robert Luke Boise State University	George Spagna Randolf-Macon College
Robert Good California State University-Hayware	Stephen Kanim New Mexico State University	Robert Marchini Memphis State University	Gay Stewart University of Arkansas-Fayetteville
Harold Hart Western Illinois University	Hamed Kastro Georgetown University	Tamar More Portland State University	Sudha Swaminathan Boise State University

We would like to thank our proof readers Georgia Mederer and Ernestine Franco, our copyeditor Helen Walden, and our illustrator Julie Horan.

Last but not least we would like to acknowledge the efforts of the Wiley staff; Senior Acquisitions Editor, Stuart Johnson, Ellen Ford (Senior Development Editor), Justin Bow (Program Assistant), Geraldine Osnato (Project Editor), Elizabeth Swain (Senior Production Editor), Hilary Newman (Senior Photo Editor), Anna Melhorn (Illustration Editor), Kevin Murphy (Senior Designer), and Bob Smith (Marketing Manager). Their dedication and attention to endless details was essential to the production of this book.

# Brief Contents

## PART ONE

- Chapter 1 Measurement
- Chapter 2 Motion Along a Straight Line
- Chapter 3 Forces and Motion Along a Line
- Chapter 4 Vectors
- Chapter 5 Net Force and Two-Dimensional Motion
- Chapter 6 Identifying and Using Forces
- Chapter 7 Translational Momentum
- Chapter 8 Extended Systems
- Chapter 9 Kinetic Energy and Work
- Chapter 10 Potential Energy and Energy Conservation
- Chapter 11 Rotation
- Chapter 12 Complex Rotations

## PART TWO

- Chapter 13 Equilibrium and Elasticity
- Chapter 14 Gravitation
- Chapter 15 Fluids
- Chapter 16 Oscillations
- Chapter 17 Transverse Mechanical Waves
- Chapter 18 Sound Waves
- Chapter 19 The First Law of Thermodynamics
- Chapter 20 The Kinetic Theory of Gases
- Chapter 21 Entropy and the Second Law of Thermodynamics

## PART THREE

- Chapter 22 Electric Charge
- Chapter 23 Electric Fields
- Chapter 24 Gauss' Law
- Chapter 25 Electric Potential
- Chapter 26 Current and Resistance
- Chapter 27 Circuits
- Chapter 28 Capacitance
- Chapter 29 Magnetic Fields
- Chapter 30 Magnetic Fields Due to Currents
- Chapter 31 Induction and Maxwell's Equations
- Chapter 32 Inductors and Magnetic Materials
- Chapter 33 Electromagnetic Oscillations and Alternating Current

## PART FOUR

- Chapter 34 Electromagnetic Waves
- Chapter 35 Images
- Chapter 36 Interference
- Chapter 37 Diffraction
- Chapter 38 Special Relativity

Appendices  
Answers to Reading Exercises and Odd-Numbered Problems  
Index

# Contents

## **INTRODUCTION** 1

## **CHAPTER 1** Measurement 5

- 1-1 Introduction 6
- 1-2 Basic Measurements in the Study of Motion 6
- 1-3 The Quest for Precision 7
- 1-4 The International System of Units 8
- 1-5 The SI Standard of Time 11
- 1-6 The SI Standards of Length 12
- 1-7 SI Standards of Mass 13
- 1-8 Measurement Tools for Physics Labs 14
- 1-9 Changing Units 16
- 1-10 Calculations with Uncertain Quantities 17

## **CHAPTER 2** Motion Along a Straight Line 25

- 2-1 Motion 26
- 2-2 Position and Displacement Along a Line 27
- 2-3 Velocity and Speed 31
- 2-4 Describing Velocity Change 37
- 2-5 Constant Acceleration: A Special Case 41

## **CHAPTER 3** Forces and Motion Along a Line 57

- 3-1 What Causes Acceleration? 58
- 3-2 Newton's First Law 58
- 3-3 A Single Force and Acceleration Along a Line 60
- 3-4 Measuring Forces 61
- 3-5 Defining and Measuring Mass 63
- 3-6 Newton's Second Law for a Single Force 65
- 3-7 Combining Forces Along a Line 68
- 3-8 All Forces Result from Interaction 71
- 3-9 Gravitational Forces and Free Fall Motion 73
- 3-10 Newton's Third Law 76
- 3-11 Comments on Classical Mechanics 81

## **CHAPTER 4** Vectors 89

- 4-1 Introduction 90
- 4-2 Vector Displacements 90

- 4-3 Adding Vectors Graphically 92
- 4-4 Rectangular Vector Components 94
- 4-5 Unit Vectors 98
- 4-6 Adding Vectors Using Components 98
- 4-7 Multiplying and Dividing a Vector by a Scalar 100
- 4-8 Vectors and the Laws of Physics 101

## **CHAPTER 5** Net Force and Two-Dimensional Motion 107

- 5-1 Introduction 108
- 5-2 Projectile Motion 108
- 5-3 Analyzing Ideal Projectile Motion 111
- 5-4 Displacement in Two Dimensions 116
- 5-5 Average and Instantaneous Velocity 119
- 5-6 Average and Instantaneous Acceleration 121
- 5-7 Uniform Circular Motion 123

## **CHAPTER 6** Identifying and Using Forces 139

- 6-1 Combining Everyday Forces 140
- 6-2 Net Force as a Vector Sum 140
- 6-3 Gravitational Force and Weight 143
- 6-4 Contact Forces 145
- 6-5 Drag Force and Terminal Speed 159
- 6-6 Applying Newton's Laws 161
- 6-7 The Fundamental Forces of Nature 166

## **CHAPTER 7** Translational Momentum 180

- 7-1 Collisions and Explosions 181
- 7-2 Translational Momentum of a Particle 181
- 7-3 Isolated Systems of Particles 183
- 7-4 Impulse and Momentum Change 184
- 7-5 Newton's Laws and Momentum Conservation 189
- 7-6 Simple Collisions and Conservation of Momentum 190
- 7-7 Conservation of Momentum in Two Dimensions 193
- 7-8 A System with Mass Exchange—A Rocket and Its Ejected Fuel 196

**CHAPTER 8** Extended Systems 209

- 8-1 The Motion of Complex Objects 210
- 8-2 Defining the Position of a Complex Object 210
- 8-3 The Effective Position—Center of Mass 211
- 8-4 Locating a System's Center of Mass 212
- 8-5 Newton's Laws for a System of Particles 217
- 8-6 The Momentum of a Particle System 219

**CHAPTER 9** Kinetic Energy and Work 226

- 9-1 Introduction 227
- 9-2 Introduction to Work and Kinetic Energy 228
- 9-3 The Concept of Physical Work 231
- 9-4 Calculating Work for Constant Forces 232
- 9-5 Work Done by a Spring Force 234
- 9-6 Work for a One-Dimensional Variable Force—General Considerations 237
- 9-7 Force and Displacement in More Than One Dimension 239
- 9-8 Multiplying a Vector by a Vector: The Dot Product 243
- 9-9 Net Work and Translational Kinetic Energy 244
- 9-10 Power 249

**CHAPTER 10** Potential Energy and Energy Conservation 259

- 10-1 Introduction 260
- 10-2 Work and Path Dependence 260
- 10-3 Potential Energy as “Stored Work” 265
- 10-4 Mechanical Energy Conservation 270
- 10-5 Reading a Potential Energy Curve 273
- 10-6 Nonconservative Forces and Energy 276
- 10-7 Conservation of Energy 278
- 10-8 One-Dimensional Energy and Momentum Conservation 279
- 10-9 One-Dimensional Elastic Collisions 282
- 10-10 Two-Dimensional Energy and Momentum Conservation 286

**CHAPTER 11** Rotation 299

- 11-1 Translation and Rotation 300
- 11-2 The Rotational Variables 300
- 11-3 Rotation with Constant Rotational Acceleration 306
- 11-4 Relating Translational and Rotational Variables 308
- 11-5 Kinetic Energy of Rotation 311
- 11-6 Calculating Rotational Inertia 312
- 11-7 Torque 315
- 11-8 Newton's Second Law for Rotation 317
- 11-9 Work and Rotational Kinetic Energy 320

**CHAPTER 12** Complex Rotations 332

- 12-1 About Complex Rotations 333
- 12-2 Combining Translations with Simple Rotations 334
- 12-3 Rotational Variables as Vectors 337
- 12-4 The Vector or Cross Product 340
- 12-5 Torque as a Vector Product 342
- 12-6 Rotational Form of Newton's Second Law 344
- 12-7 Rotational Momentum 345
- 12-8 The Rotational Momentum of a System of Particles 346
- 12-9 The Rotational Momentum of a Rigid Body Rotating About a Fixed Axis 347
- 12-10 Conservation of Rotational Momentum 350

**CHAPTER 13** Equilibrium and Elasticity 361

- 13-1 Introduction 362
- 13-2 Equilibrium 362
- 13-3 The Center of Gravity 365
- 13-4 Indeterminate Equilibrium Problems 370
- 13-5 Elasticity 371

**CHAPTER 14** Gravitation 385

- 14-1 Our Galaxy and the Gravitational Force 386
- 14-2 Newton's Law of Gravitation 386
- 14-3 Gravitation and Superposition 390
- 14-4 Gravitation in the Earth's Vicinity 392
- 14-5 Gravitation Inside Earth 396
- 14-6 Gravitational Potential Energy 398
- 14-7 Einstein and Gravitation 404

**CHAPTER 15** Fluids 410

- 15-1 Fluids and the World Around Us 411
- 15-2 What Is a Fluid 411
- 15-3 Pressure and Density 411
- 15-4 Gravitational Forces and Fluids at Rest 415
- 15-5 Measuring Pressure 419
- 15-6 Pascal's Principle 421
- 15-7 Archimedes' Principle 424
- 15-8 Ideal Fluids in Motion 428
- 15-9 The Equation of Continuity 429
- 15-10 Volume Flux 431
- 15-11 Bernoulli's Equation 434

**CHAPTER 16** Oscillations 444

- 16-1 Periodic Motion: An Overview 445
- 16-2 The Mathematics of Sinusoidal Oscillations 446

- 16-3** Simple Harmonic Motion: The Mass–Spring System 450
- 16-4** Velocity and Acceleration for SHM 454
- 16-5** Gravitational Pendula 456
- 16-6** Energy in Simple Harmonic Motion 461
- 16-7** Damped Simple Harmonic Motion 463
- 16-8** Forced Oscillations and Resonance 467

## **CHAPTER 17** Transverse Mechanical Waves 475

- 17-1** Waves and Particles 476
- 17-2** Types of Waves 476
- 17-3** Pulses and Waves 477
- 17-4** The Mathematical Expression for a Sinusoidal Wave 481
- 17-5** Wave Velocity 486
- 17-6** Wave Speed on a Stretched String 489
- 17-7** Energy and Power Transported by a Traveling Wave in a String 491
- 17-8** The Principle of Superposition for Waves 493
- 17-9** Interference of Waves 495
- 17-10** Reflections at a Boundary and Standing Waves 498
- 17-11** Standing Waves and Resonance 500
- 17-12** Phasors 502

## **CHAPTER 18** Sound Waves 512

- 18-1** Sound Waves 513
- 18-2** The Speed of Sound 515
- 18-3** Interference 519
- 18-4** Intensity and Sound Level 521
- 18-5** Sources of Musical Sound 524
- 18-6** Beats 527
- 18-7** The Doppler Effect 529
- 18-8** Supersonic Speeds; Shock Waves 533

## **CHAPTER 19** The First Law of Thermodynamics 539

- 19-1** Thermodynamics 540
- 19-2** Thermometers and Temperature Scales 540
- 19-3** Thermal Interactions 543
- 19-4** Heating, Cooling, and Temperature 545
- 19-5** Thermal Energy Transfer to Solids and Liquids 548
- 19-6** Thermal Energy and Work 553
- 19-7** The First Law of Thermodynamics 555
- 19-8** Some Special Cases of the First Law of Thermodynamics 556
- 19-9** More on Temperature Measurement 558
- 19-10** Thermal Expansion 563
- 19-11** More on Thermal Energy Transfer Mechanisms 566

## **CHAPTER 20** The Kinetic Theory of Gases 576

- 20-1** Molecules and Thermal Gas Behavior 577
- 20-2** The Macroscopic Behavior of Gases 577
- 20-3** Work Done by Ideal Gases 581
- 20-4** Pressure, Temperature, and Molecular Kinetic Energy 583
- 20-5** Mean Free Path 586
- 20-6** The Distribution of Molecular Speeds 588
- 20-7** The Molar Specific Heats of an Ideal Gas 590
- 20-8** Degrees of Freedom and Molar Specific Heats 595
- 20-9** A Hint of Quantum Theory 597
- 20-10** The Adiabatic Expansion of an Ideal Gas 598

## **CHAPTER 21** Entropy and the Second Law of Thermodynamics 607

- 21-1** Some One-Way Processes 608
- 21-2** Change in Entropy 609
- 21-3** The Second Law of Thermodynamics 613
- 21-4** Entropy in the Real World: Engines 614
- 21-5** Entropy in the Real World: Refrigerators 620
- 21-6** Efficiency Limits of Real Engines 622
- 21-7** A Statistical View of Entropy 623

## **CHAPTER 22** Electric Charge 633

- 22-1** The Importance of Electricity 634
- 22-2** The Discovery of Electric Interactions 634
- 22-3** The Concept of Charge 636
- 22-4** Using Atomic Theory to Explain Charging 637
- 22-5** Induction 641
- 22-6** Conductors and Insulators 642
- 22-7** Coulomb's Law 644
- 22-8** Solving Problems Using Coulomb's Law 647
- 22-9** Comparing Electrical and Gravitational Forces 651
- 22-10** Many Everyday Forces Are Electrostatic 653

## **CHAPTER 23** Electric Fields 659

- 23-1** Implications of Strong Electric Forces 660
- 23-2** Introduction to the Concept of a Field 660
- 23-3** Gravitational and Electric Fields 662
- 23-4** The Electric Field Due to a Point Charge 665
- 23-5** The Electric Field Due to Multiple Charges 667
- 23-6** The Electric Field Due to an Electric Dipole 670
- 23-7** The Electric Field Due to a Ring of Charge 671
- 23-8** Motion of Point Charges in an Electric Field 675
- 23-9** A Dipole in an Electric Field 677
- 23-10** Electric Field Lines 678



**CHAPTER 24** Gauss' Law 689

- 24-1** An Alternative to Coulomb's Law 690
- 24-2** Electric Flux 691
- 24-3** Net Flux at a Closed Surface 692
- 24-4** Gauss' Law 694
- 24-5** Symmetry in Charge Distributions 698
- 24-6** Application of Gauss' Law to Symmetric Charge Distributions 699
- 24-7** Gauss' Law and Coulomb's Law 705
- 24-8** A Charged Isolated Conductor 706

**CHAPTER 25** Electric Potential 714

- 25-1** Introduction 715
- 25-2** Electric Potential Energy 715
- 25-3** Electric Potential 718
- 25-4** Equipotential Surfaces 721
- 25-5** Calculating Potential from an  $E$ -Field 723
- 25-6** Potential Due to a Point Charge 725
- 25-7** Potential and Potential Energy Due to a Group of Point Charges 727
- 25-8** Potential Due to an Electric Dipole 730
- 25-9** Potential Due to a Continuous Charge Distribution 732
- 25-10** Calculating the Electric Field from the Potential 733
- 25-11** Potential of a Charged Isolated Conductor 735

**CHAPTER 26** Current and Resistance 744

- 26-1** Introduction 745
- 26-2** Batteries and Charge Flow 745
- 26-3** Batteries and Electric Current 746
- 26-4** Circuit Diagrams and Meters 751
- 26-5** Resistance and Ohm's Law 752
- 26-6** Resistance and Resistivity 755
- 26-7** Power in Electric Circuits 758
- 26-8** Current Density in a Conductor 760
- 26-9** Resistivity and Current Density 761
- 26-10** A Microscopic View of Current and Resistance 762
- 26-11** Other Types of Conductors 766

**CHAPTER 27** Circuits 772

- 27-1** Electric Currents and Circuits 773
- 27-2** Current and Potential Difference in Single-Loop Circuits 774
- 27-3** Series Resistance 776
- 27-4** Multiloop Circuits 778
- 27-5** Parallel Resistance 779

- 27-6** Batteries and Energy 784
- 27-7** Internal Resistance and Power 785

**CHAPTER 28** Capacitance 799

- 28-1** The Uses of Capacitors 800
- 28-2** Capacitance 801
- 28-3** Calculating the Capacitance 804
- 28-4** Capacitors in Parallel and in Series 808
- 28-5** Energy Stored in an Electric Field 812
- 28-6** Capacitor with a Dielectric 815
- 28-7** Dielectrics: An Atomic View 817
- 28-8** Dielectrics and Gauss' Law 818
- 28-9**  $RC$  Circuits 821

**CHAPTER 29** Magnetic Fields 829

- 29-1** A New Kind of Force? 830
- 29-2** Probing Magnetic Interactions 830
- 29-3** Defining a Magnetic Field  $\vec{B}$  831
- 29-4** Relating Magnetic Force and Field 833
- 29-5** A Circulating Charged Particle 839
- 29-6** Crossed Fields: Discovery of the Electron 843
- 29-7** The Hall Effect 844
- 29-8** Magnetic Force on a Current-Carrying Wire 847
- 29-9** Torque on a Current Loop 849
- 29-10** The Magnetic Dipole Moment 850
- 29-11** The Cyclotron 852

**CHAPTER 30** Magnetic Fields Due to Currents 861

- 30-1** Introduction 862
- 30-2** Magnetic Effects of Currents—Oersted's Observations 862
- 30-3** Calculating the Magnetic Field Due to a Current 864
- 30-4** Force Between Parallel Currents 870
- 30-5** Ampère's Law 871
- 30-6** Solenoids and Toroids 875
- 30-7** A Current-Carrying Coil as a Magnetic Dipole 877

**CHAPTER 31** Induction and Maxwell's Equations 888

- 31-1** Introduction 889
- 31-2** Induction by Motion in a Magnetic Field 889
- 31-3** Induction by a Changing Magnetic Field 891
- 31-4** Faraday's Law 893
- 31-5** Lenz's Law 896

- 31-6** Induction and Energy Transfers 899
- 31-7** Induced Electric Fields 901
- 31-8** Induced Magnetic Fields 906
- 31-9** Displacement Current 908
- 31-10** Gauss' Law for Magnetic Fields 910
- 31-11** Maxwell's Equations in a Vacuum 912

## **CHAPTER 32** Inductors and Magnetic Materials 922

- 32-1** Introduction 923
- 32-2** Self-Inductance 923
- 32-3** Mutual Induction 926
- 32-4**  $RL$  Circuits (with Ideal Inductors) 929
- 32-5** Inductors, Transformers, and Electric Power 932
- 32-6** Magnetic Materials—An Introduction 935
- 32-7** Ferromagnetism 940
- 32-8** Other Magnetic Materials 943
- 32-9** The Earth's Magnetism 945

## **CHAPTER 33** Electromagnetic Oscillations and Alternating Current 954

- 33-1** Advantages of Alternating Current 955
- 33-2** Energy Stored in a  $\vec{B}$ -Field 956
- 33-3** Energy Density of a  $\vec{B}$ -Field 957
- 33-4**  $LC$  Oscillations, Qualitatively 958
- 33-5** The Electrical–Mechanical Analogy 960
- 33-6**  $LC$  Oscillations, Quantitatively 961
- 33-7** Damped Oscillations in an  $RLC$  Circuit 965
- 33-8** More About Alternating Current 967
- 33-9** Forced Oscillations 968
- 33-10** Representing Oscillations with Phasors: Three Simple Circuits 968
- 33-11** The Series  $RLC$  Circuit 972
- 33-12** Power in Alternating-Current Circuits 978

## **CHAPTER 34** Electromagnetic Waves 985

- 34-1** Introduction 986
- 34-2** Maxwell's Prediction of Electromagnetism 986
- 34-3** The Generation of Electromagnetic Waves 988
- 34-4** Describing Electromagnetic Wave Properties Mathematically 992
- 34-5** Transporting Energy with Electromagnetic Waves 997
- 34-6** Radiation Pressure 1001
- 34-7** Polarization 1004
- 34-8** Maxwell's Rainbow 1007

## **CHAPTER 35** Images 1015

- 35-1** Introduction 1016
- 35-2** Reflection and Refraction 1017
- 35-3** Total Internal Reflection 1021
- 35-4** Polarization by Reflection 1023
- 35-5** Two Types of Image 1024
- 35-6** Plane Mirrors 1026
- 35-7** Spherical Mirrors 1027
- 35-8** Images from Spherical Mirrors 1029
- 35-9** Spherical Refracting Surfaces 1033
- 35-10** Thin Lenses 1035
- 35-11** Optical Instruments 1041
- 35-12** Three Proofs 1045

## **CHAPTER 36** Interference 1056

- 36-1** Interference 1057
- 36-2** Light as a Wave 1057
- 36-3** Diffraction 1062
- 36-4** Young's Interference Experiment 1062
- 36-5** Coherence 1066
- 36-6** Intensity in Double-Slit Interference 1066
- 36-7** Interference from Thin Films 1070
- 36-8** Michelson's Interferometer 1076

## **CHAPTER 37** Diffraction 1083

- 37-1** Diffraction and the Wave Theory of Light 1084
- 37-2** Diffraction by a Single Slit: Locating the Minima 1085
- 37-3** Intensity in Single-Slit Diffraction, Qualitatively 1088
- 37-4** Intensity in Single-Slit Diffraction, Quantitatively 1089
- 37-5** Diffraction by a Circular Aperture 1092
- 37-6** Diffraction by a Double Slit 1094
- 37-7** Diffraction Gratings 1097
- 37-8** Gratings: Dispersion and Resolving Power 1100
- 37-9** X-Ray Diffraction 1103

## **CHAPTER 38** Special Relativity 1111

- 38-1** Introduction 1112
- 38-2** Origins of Special Relativity 1112
- 38-3** The Principle of Relativity 1113
- 38-4** Locating Events with an Intelligent Observer 1114
- 38-5** Laboratory and Rocket Latticeworks of Clocks 1116
- 38-6** Time Stretching 1118
- 38-7** The Metric Equation 1121
- 38-8** Cause and Effect 1124
- 38-9** Relativity of Simultaneity 1125

## xxiv Appendix

**38-10** Momentum and Energy 1127

**38-11** The Lorentz Transformation 1131

**38-12** Lorentz Contraction 1132

**38-13** Relativity of Velocities 1133

**38-14** Doppler Shift 1135

## Appendices

A. The International System of Units (SI) A-1

B. Some Fundamental Constants of Physics A-6

C. Some Astronomical Data A-7

D. Conversion Factors A-8

E. Mathematical Formulas A-11

F. Properties of Common Elements A-14

G. Periodic Table of the Elements A-16

Answers to Reading Exercises and  
Odd-Numbered Problems Ans-1

Photo Credits C-1

Index I-1









## 4 Introduction

do the *Reading Exercises* at the end of many sections in each chapter. We attempt to present both the experimental results that support theories and some of the reasoning that has gone into the development of theories. However, you will understand the physics only when you make your own observations and are actively engaged in reasoning. So, it is critical that you observe a physical phenomenon directly or ponder the outcome of an experiment that we describe. Then you need to *think* about whether the explanation of the phenomenon we present makes sense. In addition, you must test and refine your understanding of theoretical concepts by applying them to solving problems included at the end of each chapter. Solving problems requires you to use both the physical principles you have learned and the mathematical relationships that describe these principles. Finally, if possible, you will want to test your understanding of physical systems by predicting the outcomes of experiments that you can perform in a basic introductory physics laboratory.

We hope this book will help you enjoy the practice of physics as much as we do.



(Left to right): Priscilla W. Laws, Edward F. Redish, Karen Cummings, and Patrick J. Cooney. Photo by David Hildebrand.

# 1 Measurement



You can watch the Sun set and disappear over a calm ocean, once while lying on the beach, and then once again if you stand up. This is a surprising observation! Furthermore, if you measure the time between the two sunsets, you can approximate the Earth's radius by using an understanding of the shape and motion of the Earth relative to the Sun along with some basic high school mathematics.

**How can such a simple observation be used to measure the Earth?**

---

*The answer is in this chapter.*

## 1-1 Introduction

---

Physics is the study of the basic components of the universe and their interactions. The fact that you can use the time difference between sunsets while lying on the beach and then standing to estimate the size of the earth is indeed surprising to most people. It is one example of how the interplay between mathematics, theoretical principles, and observations allow us to develop a deeper understanding of the physical world. In fact, the ongoing quest of physics is to develop a unified set of ideas to explain apparently different phenomena. Scientific theories are only valid if they serve to explain and predict the outcomes of new observations and experiments. Many theories in physics are expressed in mathematical equations, and predictions usually involve quantities that can be measured.

Measurement is the process of associating numbers with physical quantities. In fact, *physical quantities are defined in terms of the procedures used to measure them*. But the numbers that result from measurements are not meaningful unless people who are using and interpreting them know what was measured and what units were used to obtain the numbers. For example, if you were asked to go to a store to buy 27, you would immediately ask 27 of what? If you were told 27 containers of milk, you might ask 27 of what size or unit—pints, quarts, or gallons? Unambiguous communication with others about the results of a scientific measurement requires agreement on (1) the definition of the physical quantity and (2) the basic units used for comparison when the measurements are made.

The focus in this chapter will be on the fundamental physical quantities and measurement processes used to study motion. Later on we introduce additional physical quantities defined for the study of thermal interactions, electricity, magnetism, and light. You will learn about common elements of physical measurements, reasons why precise measurements are highly valued, and the international system of standard basic units that allows scientists all over the world to communicate with each other.

## 1-2 Basic Measurements in the Study of Motion

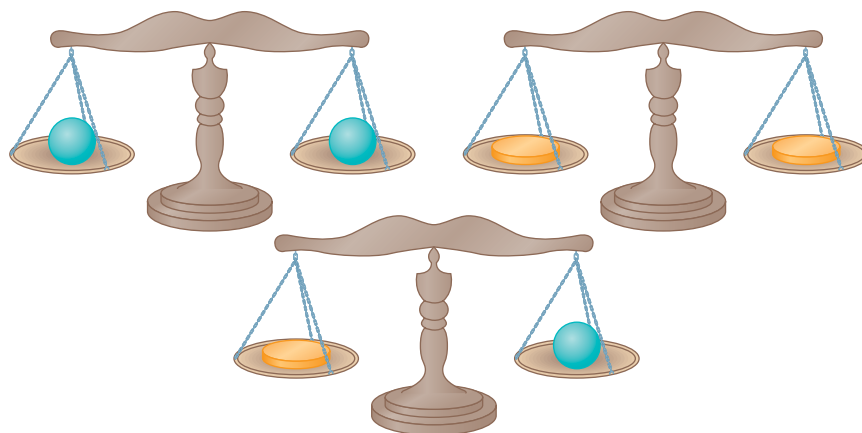
---

A long jumper speeds up along a runway, leaps into the air, and then comes to a sudden stop in a sand pit. How can such a motion be described and studied scientifically?

In studying motion, at least three questions come to mind. How far has something moved and in what directions? How long did it take? How much stuff was moved? Let's consider length, time, and mass, the three basic physical quantities used in the study of motion. How are they usually defined? What procedures are used to measure them on an everyday basis?

**Length:** Our “How far?” question involves being able to measure the distance between two points. Suppose you had no measuring instrument. Is there any way you could meaningfully ask and answer the question, “What is the total distance that the jumper ran?” The only approach possible would be to compare this distance to the size of one of your body parts such as your hand or foot. It is not surprising that the hand and the foot have been used throughout history as basic units of measurement. The distance can then be described as a ratio between it and a convenient item chosen to be a length standard.

**Time:** To answer the question, “How long did it take?” you need to be able to measure a time interval. To do this, you define the time between repetitive events as a standard. Historically, repetitive events that have been used as time standards have included the day (the time it takes for the Sun to appear to revolve around the Earth), the year, and the time it takes for a pendulum of a certain length to swing back and



**FIGURE 1-1** ■ A common method of determining mass assumes two objects have the same mass if they balance each other.

forth. A time interval, or time duration, is measured by determining how many years have passed or how many swings of a pendulum have occurred during the interval being measured.

**Mass:** Mass is a measure of “amount of stuff.” Throughout recorded history, merchants and scientists have used balances to determine how many units of “standard mass” are needed to balance whatever is being measured. (See Fig. 1-1.) A standard of mass can be a certain object that everyone agrees should be used. Replicas of the standard mass that balance with it can be passed around and used by many people.

The everyday procedures outlined above for measuring length, time, and mass share common elements that characterize all physical quantities.

1. These quantities are defined by the procedures used to measure them.
2. Their measurement always involves the determination of a ratio between a unit, known as a base quantity, and the quantity being measured.
3. Such comparisons can only be made with limited precision.

As you will see, there are often many alternative procedures that can be used to measure the same quantity. Indeed, a major factor in the progress of science and technology has been the discovery of better, more **precise** methods of measurement.

---

**READING EXERCISE 1-1:** List one common base unit used for time, for length, and for mass not mentioned in the discussion in this section. ■

---

**READING EXERCISE 1-2:** What is a more precise base unit for length measurement that is reliable over a period of years—a 12-inch ruler or your foot? Explain the reason for your answer. ■

---

**READING EXERCISE 1-3:** What problems might arise when using the length of the day as a standard unit of time? ■

## 1-3 The Quest for Precision

---

Using a grocery store spring scale to find an apple’s mass is fine for shopping purposes. But a mass can be determined to a far greater precision with a chemical microbalance. At best, the apple’s mass can only be determined to the nearest



gram, whereas the chemistry lab sample can be determined to the nearest hundred-thousandth of a gram.

Throughout history people have sought to measure physical quantities as precisely as possible, because reducing measurement uncertainties has been of tremendous importance in commerce, navigation, astronomical observation, engineering, and scientific research. For example, in 1707, the British navy lost almost 2000 men when four warships ran aground because navigators were unable to measure longitude with sufficient precision. In 1714, as a result of this mishap and others, the British government offered a prize of £20,000 (current value about \$12 million) to anyone who could devise a scheme to measure longitude to within half a degree. John Harrison, a self-educated clockmaker, collected the prize in 1765 after designing a series of elaborate chronometers. His early models were driven by a combination of rust-proof brass and self-lubricating wooden gears that kept time to within 1 second per day.

**HOW CAN TIME MEASUREMENTS BE USED TO DETERMINE LONGITUDE?** Harrison's measurement technique is one of several examples of how a time standard and a knowledge of how fast something is moving are used to measure distance more precisely. In this case, since the Earth turns through  $360^\circ$  on its axis in 24 hours, a precise chronometer can be set so that it reads exactly noon when the Sun is at its highest point in a port with known longitude. Out at sea, the clock time that was set in port will differ from the local solar time by 4 minutes for each degree of longitude difference. Thus, the difference between the observed local noon and the clock reading can then be used to calculate longitude.

Of all the measured quantities, time and other measurements based on time are the most precise. By the end of the 20th century, many of us were wearing inexpensive digital watches driven by the oscillations of quartz crystals. These watches are 1000 times better than John Harrison's chronometer, since they are accurate to within 1 part in  $10^8$  or 1 thousandth of a second per day. Atomic clocks, precise to 3 billionths of a second per day, are now being used as time standards in many countries.

**READING EXERCISE 1-4:** A ship embarks from Southampton, England where its clock was set to 12:00:00 at local noon. After 14 days under sail its chronometer reads 12 h 20 min 13 s at the moment the Sun is highest in the sky (local noon). (a) By how many degrees has the ship's longitude changed? (b) Suppose the clock is not precise and has gained 2 minutes out of the 20 160 minutes that have elapsed since it set sail. How far off will the longitude measurement be? (c) The circumference of the Earth is 24 000 nautical miles. Suppose the ship was traveling along the equator. How many miles off course could the ship be if the uncertainty of longitude is  $0.5^\circ$  ■

## 1-4 The International System of Units

In the past, communication between scientists was complicated by the fact that for every physical quantity there were a multitude of measurement procedures and basic units of comparison. In addition, there are so many physical quantities that it is a problem to organize them. Fortunately, these quantities are not all independent; for example, speed is the ratio of a length to a time. Thus, what we do is pick out—by international agreement—a small number of physical quantities, such as length and time, and assign standards to them alone. We then define all other physical quantities in terms of these *base quantities* and their standards (which we now call *base standards*). Speed, for example, is defined in terms of the base quantities length and time.

**WHY IS IT IMPORTANT TO HAVE A STANDARD SYSTEM OF UNITS THAT IS USED BY ALL SCIENTISTS AND ENGINEERS?**

In December 1998, the National Aeronautics and Space Administration launched the *Mars Climate Orbiter* on a scientific mission to collect Martian climate data. Nine months later, on September 23, 1999, the *Orbiter* disappeared while approaching Mars at an unexpectedly low altitude. (See Fig. 1-2). An investigation revealed that the orbital calculations were incorrect due to an error in the transfer of information between the spacecraft's team in Colorado and the mission navigation team in California. One team was using English units such as feet and pounds for a critical calculation, while the other group assumed the result of the calculation was being reported in metric units such as meters and kilograms. This misunderstanding about the units being used cost U.S. taxpayers approximately 125 million dollars.

In 1971, the 14th General Conference on Weights and Measures recognized the need to use standard units for physical quantities. Conference attendees chose seven physical quantities as base quantities and defined a standard unit of measure for each one. Although other sets of physical quantities could be defined, the seven shown in Table 1-1 form the basis of the widely accepted International System of Units. The system is popularly known as the *metric system* or by its abbreviation, SI, which derives from its French name, *Système International*.

All other SI units are known as *derived units* because they can be expressed in terms of the base units. For example, the SI unit for power, called the **watt** (symbol: W), is defined in terms of the base units for mass, length, and time. As you will see in Chapter 9,

$$1 \text{ watt} = 1 \text{ W} = 1 \text{ kg} \cdot \text{m}^2/\text{s}^3. \quad (1-1)$$

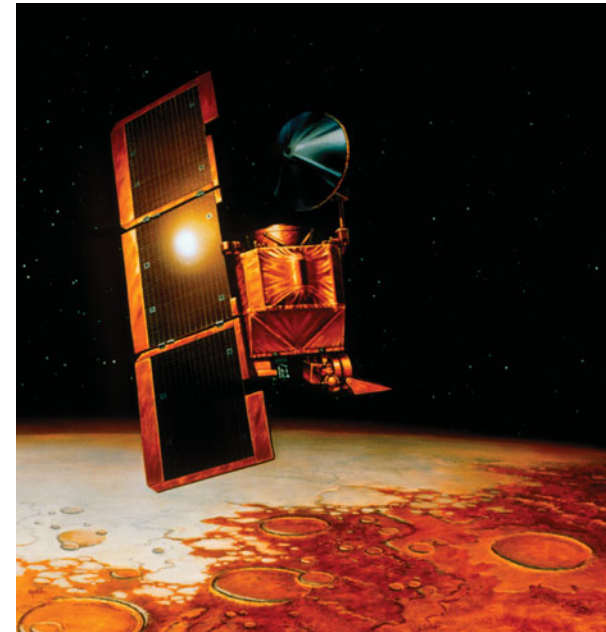
The fact that the dozens of units used in different branches of physics can all be derived from a set of seven base units seems incredible and is a profound testimonial to the unity of physics.

To express the very large and very small quantities that we often run into in physics, we use *scientific notation*, which employs powers of 10. In this notation,

$$3\,560\,000\,000 \text{ m} = 3.56 \times 10^9 \text{ m} \quad (1-2)$$

$$\text{and} \quad 0.000\,000\,492 \text{ s} = 4.92 \times 10^{-7} \text{ s}. \quad (1-3)$$

Scientific notation on computers sometimes takes on an even briefer look, as in 3.56 E9 and 4.92 E-7, where E stands for “exponent of ten.” It is briefer still on some calculators, where E is replaced with an empty space.



**FIGURE 1-2** ■ The *Mars Climate Orbiter* failed to go into orbit around Mars and disappeared due to a miscalculation that resulted from confusion about what units were being used.

**TABLE 1-1**  
**The SI Base Units**

Quantity	Unit Name	Unit Symbol
Length	meter	m
Time	second	s
Mass	kilogram	kg
Amount of substance	mole	mol
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd

TABLE 1-2  
Common Prefixes for SI Units

Factor	Prefix	Symbol	Factor	Prefix	Symbol
$10^{12}$	tera-	T	$10^{-15}$	femto-	f
$10^9$	giga-	G	$10^{-12}$	pico-	p
$10^6$	mega-	M	$10^{-9}$	nano-	n
$10^3$	kilo-	k	$10^{-6}$	micro-	$\mu$
			$10^{-3}$	milli-	m
			$10^{-2}$	centi-	c
			$10^{-1}$	deci-	d

When reporting the results of very large or very small measurements, it is convenient to define prefixes that designate what power of ten a number has. For example, we can use the prefix kilo-, which represents  $10^3$ , to express  $1.0 \times 10^3$  grams as 1.0 kilogram. Some of the most common prefixes used in physics and engineering are listed in Table 1-2. A complete list of SI prefixes is included on the inside front cover. As you can see, each prefix represents a certain power of 10 as a factor. Attaching a prefix to an SI unit has the effect of multiplying it by the associated factor. Thus, we can express a particular electric power as

$$1.27 \times 10^9 \text{ watts} = 1.27 \text{ gigawatts} = 1.27 \text{ GW}, \tag{1-4}$$

or a particular length as

$$2.35 \times 10^{-9} \text{ m} = 2.35 \text{ nanometers} = 2.35 \text{ nm}. \tag{1-5}$$

Some prefixes, as used in milliliter, centimeter, kilogram, and megabyte, may be familiar to you.

Once we have set up a standard unit—say, for length—we must work out procedures by which any length, be it the distance to a star or the radius of a hydrogen atom, can be expressed in terms of the standard. Rulers, which approximate our length standard, give us one such procedure for measuring length. We can use a ruler to measure another length by counting how many times the standard can be fit, laid end-to-end, to the other length. The count is our assigned length and is given in terms of the standard’s unit. However, many of our comparisons must be indirect. You cannot use a ruler, for example, to measure the distance to a star or the radius of an atom. Figure 1-3 shows an image of the surface of a crystal of silicon obtained with a modern scanning probe microscope.

Base standards must be both accessible and invariable. If we define the length standard as the distance between one’s nose and the index finger on an outstretched arm, we certainly have an accessible standard—but it will, of course, vary from person to person. The demand for precision in science and engineering pushes us to aim first for invariability. We then exert great effort to make duplicates of the base standards that are accessible to those who need them. In the United States, the National Institute of Standards and Technology (NIST) is responsible for maintaining base standards and researching issues related to measurement.

The topics that we will investigate first, those related to the physics of forces and motion, require that we make measurements of time, length, and mass. Therefore, we begin by discussing the formal SI definitions of these quantities.

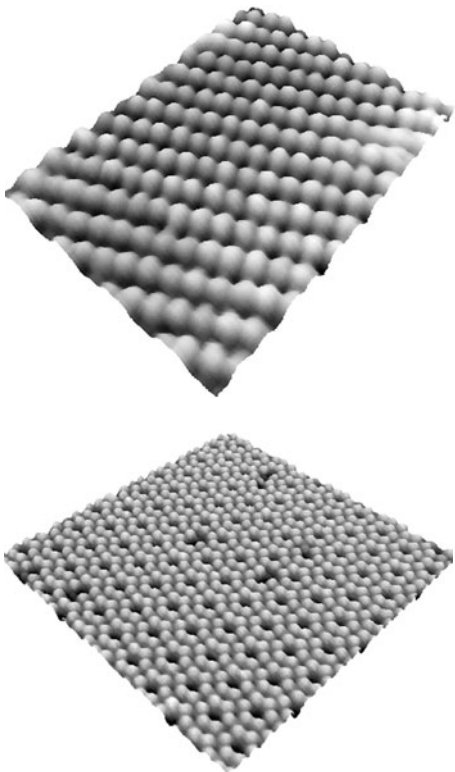


FIGURE 1-3 ■ Two different surfaces of a crystal of pure silicon.

## 1-5 The SI Standard of Time

Time has two separate aspects that are important in physics. We may want to note at what moment an event occurred or began, or we may want to know how long the event lasted. These are two very different aspects of the measurement of time. For example, the moment at which your physics teacher walks into the room for class on a given day will be measured differently by different students because their watches will not all be synchronized. However, the measured duration of the class will not be affected by the fact that the watches are not synchronized. Thus, “*When* did it happen?” and “What is its *duration*?” are two different questions.

Any phenomenon that regularly repeats itself is a possible time standard. The Earth’s rotation, which determines the length of the day, has been used in this way for centuries. Originally the second was defined as the fraction  $1/86\,400$  of a “mean solar day.” Figure 1-4 shows a two-century-old example of a time-keeping instrument used to measure the Earth’s rotation in terms of a 20-hour day. A quartz clock, in which a quartz ring is made to vibrate continuously, can be calibrated against Earth’s rotation via astronomical observations and used to measure time intervals in the laboratory. However, even this calibration cannot be carried out with the accuracy called for by modern scientific and engineering technology.

To meet the need for more accuracy in the measurement of time, atomic clocks have been developed that replace the use of Earth’s rotation in the definition of our time standard. In 1967, the 13th General Conference on Weights and Measures adopted a standard second based on the radiation absorption characteristics of the cesium-133 atom. Like other atoms, a cesium-133 atom can absorb electromagnetic radiation that has a very precise frequency when the atom makes a transition between two of its well-defined energy states known in technical jargon as “hyperfine levels.” The fixed frequency of this external radiation is used to drive a cesium clock. Such a precisely repetitive event is just what is needed for a high-precision timekeeper. Although the technical details of how a cesium clock works is beyond the scope of this text, interested readers can consult the NIST web site at <http://www.nist.gov> for more information about how the cesium clock is used as a time standard. (See Fig. 1-5.) This new SI standard of time defines the second as follows:

One second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

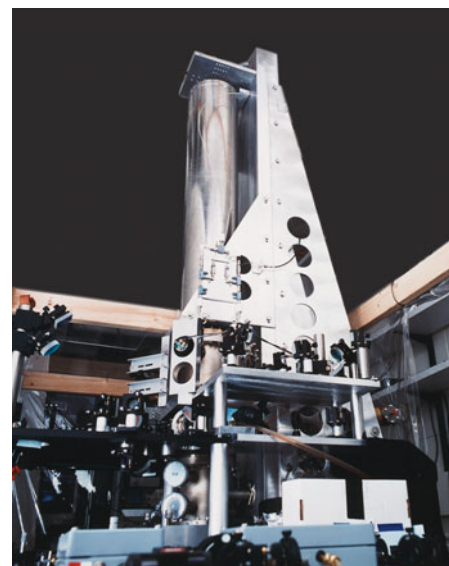
An atomic clock at NIST is the standard for Coordinated Universal Time (CUT) in the United States. Its time signals are available from NIST’s Web site listed previously. You can also download a Java program from this site that will synchronize your computer’s clock to Coordinated Universal Time so you can use your computer as a time standard by which to set other clocks.

Atomic clocks are so consistent that, in principle, two cesium clocks would have to run for 6000 years before their readings would differ by more than 1 second. This amounts to a precision better than 1 part in  $10^{11}$ . Even such accuracy pales in comparison to that of clocks currently being developed; their precision may be as fine as 1 part in  $10^{18}$ .

**READING EXERCISE 1-5:** (a) You and a friend are observing a storm. Each of you has your own watch. Describe under what conditions you will both measure the same time for a flash of lightning. Describe under what conditions you will both measure the same duration of time between the lightning flash and the clap of thunder. (b) Look at Fig. 1-4. Do the 10-hour and 12-hour clocks really show the same time? ■



**FIGURE 1-4** ■ When the metric system was proposed in 1792, the hour was redefined to provide a 20-hour day. The idea did not catch on. The maker of this watch wisely provided a small dial that kept both 10-hour and conventional 12-hour time. Do the two dials indicate the same time?



**FIGURE 1-5** ■ The cesium fountain atomic frequency standard developed at the National Institute of Standards and Technology in Boulder, Colorado. It is the primary standard for the unit of time in the United States. To set your watch by it, call (303) 499-7111, or call (900) 410-8463 or <http://tycho.usno.navy.mil/time.html> for Naval Observatory time signals.



**TOUCHSTONE EXAMPLE 1-1\*: Sunset**

Suppose that while lying on a beach watching the Sun set over a calm ocean, you start a stopwatch just as the top of the Sun disappears. You then stand, elevating your eyes by a height  $h = 1.70$  m, and stop the watch when the top of the Sun again disappears. If the elapsed time on the watch is  $t = 11.1$  s, what is the radius  $r$  of Earth?

**SOLUTION** ■ A **Key Idea** here is that just as the Sun disappears, your line of sight to the top of the Sun is tangent to Earth's surface. Two such lines of sight are shown in Fig. 1-6. There your eyes are located at point  $A$  while you are lying, and at height  $h$  above point  $A$  while you are standing. For the latter situation, the line of sight is tangent to Earth's surface at point  $B$ . Let  $d$  represent the distance between point  $B$  and the location of your eyes when you are standing, and draw radii  $r$  as shown in Fig. 1-6. From the Pythagorean theorem, we then have

$$d^2 + r^2 = (r + h)^2 = r^2 + 2rh + h^2,$$

or 
$$d^2 = 2rh + h^2. \quad (1-6)$$

Because the height  $h$  is so much smaller than Earth's radius  $r$ , the term  $h^2$  is negligible compared to the term  $2rh$ , and we can rewrite Eq. 1-6 as

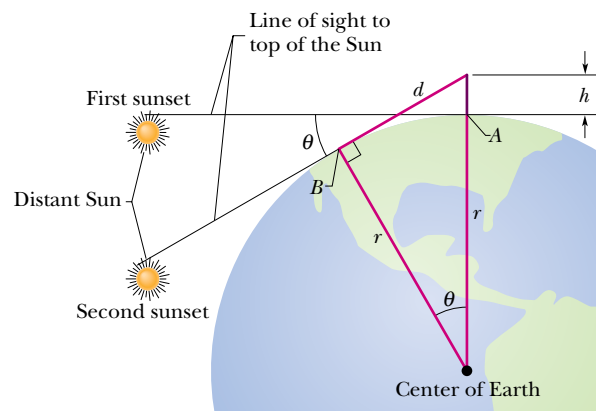
$$d^2 \approx 2rh. \quad (1-7)$$

In Fig. 1-6, the angle between the radii to the two tangent points  $A$  and  $B$  is  $\theta$ , which is also the angle through which the Sun moves about Earth during the measured time  $t = 11.1$  s. During a full day, which is approximately 24 h, the Sun moves through an angle of  $360^\circ$  about Earth. This allows us to write

$$\frac{\theta}{360^\circ} = \frac{t}{24 \text{ h}},$$

which, with  $t = 11.1$  s, gives us

$$\theta = \frac{(360^\circ)(11.1 \text{ s})}{(24 \text{ h})(60 \text{ min/h})(60 \text{ s/min})} = 0.04625^\circ.$$



**FIGURE 1-6** ■ Your line of sight to the top of the setting Sun rotates through the angle  $\theta$  when you stand up at point  $A$ , and elevate your eyes by a distance  $h$ . (Angle  $\theta$  and distance  $h$  are exaggerated here for clarity.)

Again in Fig. 1-6, we see that  $d = r \tan \theta$ . Substituting this for  $d$  in Eq. 1-7 gives us

$$r^2 \tan^2 \theta = 2rh,$$

or

$$r = \frac{2h}{\tan^2 \theta}.$$

Substituting  $\theta = 0.04625^\circ$  and  $h = 1.70$  m, we find

$$r = \frac{(2)(1.70 \text{ m})}{\tan^2 (0.04625^\circ)} = 5.22 \times 10^6 \text{ m}, \quad (\text{Answer})$$

which is within 20% of the accepted value ( $6.37 \times 10^6$  m) for the mean radius of Earth.

\*Adapted from “Doubling Your Sunsets, or How Anyone Can Measure the Earth’s Size with a Wristwatch and Meter Stick,” by Dennis Rawlins, *American Journal of Physics*, Feb. 1979, Vol. 47, pp. 126–128. This technique works best at the equator.

## 1-6 The SI Standards of Length

In 1792, the newly born Republic of France established a new system of weights and measures. Its cornerstone was the meter, defined to be one ten-millionth of the distance from the North Pole to the equator. However, the first prototype of a 1-meter-long rod was short by 0.2 millimeter, because researchers miscalculated the flattening of the Earth due to its rotation. Nonetheless, this shortened length became the standard meter. For practical reasons, the meter came to be defined as the distance between two fine lines engraved near the ends of a special platinum-iridium



bar, the **standard meter bar**, which was kept at the International Bureau of Weights and Measures near Paris. Accurate copies of the bar have been sent to standards laboratories throughout the world including NIST.

Eventually, modern science and technology required an even more precise standard. Today, the length standard is based on the speed of light. As you will learn in Chapter 38, one of the landmark discoveries of the 20th century was Einstein's recognition that the speed of light in a vacuum is the same for all observers. Since the speed of light can be measured to very high precision, it was adopted as a defined quantity in 1983. Time measurements with atomic clocks are also very precise, so it made sense to redefine the meter in terms of the time it takes light to travel 1 meter. By defining the speed of light  $c$  to be exactly

$$c = 299\,792\,458 \text{ m/s}, \quad (1-8)$$

light would travel 1 meter in a time period equal to  $1/299\,792\,458$  of a second. That is, if one takes this speed and multiplies by this time period, then the distance traveled by the light is exactly 1 meter. According to the 17th General Conference on Weights and Measures:

The meter is the length of the path traveled by light in a vacuum during a time interval of  $1/299\,792\,458$  of a second.

This approach of measuring lengths in terms of a speed and time is similar to that taken by John Harrison in the 18th century when he proposed measuring longitude in terms of the angular speed of the Earth's rotation and time.

Defining the standard meter in terms of the time it takes light to travel a meter has not done away with the need for secondary standards like bars of metal with fine lines delineating the beginning and end points of a meter. We currently use the metal bar as a secondary standard against which we can easily compare other objects. Defining the meter in terms of the speed of light simply gives us a more precise way to verify that our secondary standard is correct.

## 1-7 SI Standards of Mass

Currently there are two accepted base units for mass—one suitable for determining large masses and the other for determining masses on an atomic scale.

### The Standard Kilogram

The initial SI standard of mass is a platinum-iridium cylinder (Fig. 1-7) kept at the International Bureau of Weights and Measures near Paris. By international agreement, it is defined as a mass of 1 kilogram. Accurate replicas have been sent to standards laboratories in other countries, and the masses of other bodies can be determined by balancing them against a replica. The United States copy of the standard kilogram is housed in a vault at NIST. It is removed, no more than once a year, for the purpose of checking replicas used elsewhere. Since 1889, the U.S. replica of the standard kilogram has been taken to France twice for comparison with the primary standard.

### The Atomic Mass Unit

The mass of the known universe is estimated to be  $1 \times 10^{53}$  kg. In contrast, the electron, which plays a vital role in chemical bonding, has a mass of  $9 \times 10^{-31}$  kg. Obvi-



**FIGURE 1-7** ■ The international 1 kg standard of mass is a cylinder 39 mm in both height and diameter.

ously, the masses of electrons and atoms can be compared with each other more precisely than they can be compared with the standard kilogram. For this reason, we have a second mass standard. It is the carbon-12 atom, which, by international agreement, has been assigned a mass of 12 **atomic mass units** (u). The relation between the atomic mass unit and the kilogram is

$$1 \text{ u} = 1.660\,538\,73 \times 10^{-27} \text{ kg}, \quad (1-9)$$

with an uncertainty of  $\pm 13$  in the last two decimal places. Scientists can determine the masses of other atoms relative to the mass of carbon-12 with much better precision than they can using a standard kilogram.

We presently lack a reliable way to extend the precision of the atomic mass unit to more common units of mass, such as the kilogram. However, it is not hard to imagine how one might do this. If we had an object made up of carbon-12 atoms and knew the exact number of atoms in the object, then we could build a precise standard kilogram based on the atomic unit. Work on this is currently underway at NIST and other similar institutions.

**READING EXERCISE 1-6:** Describe a procedure for determining the mass of the object that has a mass much less than 1 kilogram. Assume that you have a balance, a replica of a standard kilogram, and a big blob of clay available to you. ■

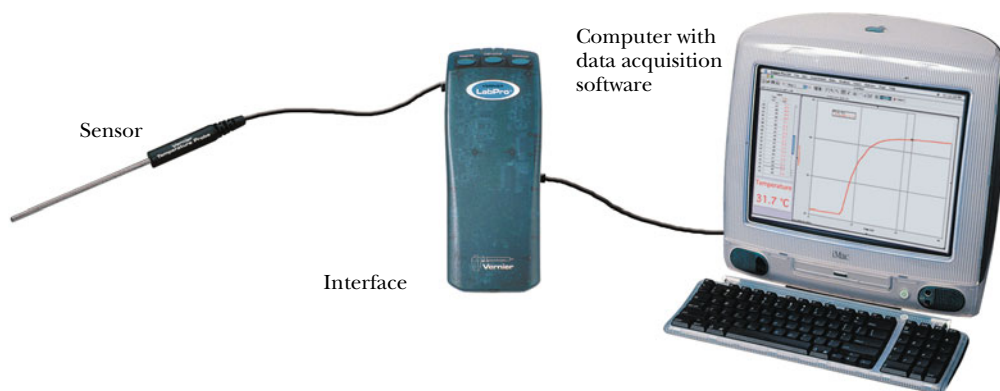
## 1-8 Measurement Tools for Physics Labs

Institutions like NIST and the International Bureau of Weights and Measures in Paris have many exotic instruments for performing extremely precise measurements. Traditionally, physics students use more common measuring tools in the laboratory, such as meter sticks, vernier calipers (Fig. 1-8), mechanical and electronic balances, digital stopwatches, and multimeters. With careful use, these tools provide adequate precision for studying the time durations and distances investigated in introductory physics laboratories.

In the past few years, new computer tools have become popular in introductory laboratories and in interactive lecture demonstrations. These tools greatly enhance the speed and precision of measurements while allowing students to make many measurements easily and accurately. These tools include **computer data acquisition systems** (Fig. 1-9) and **video capture and analysis tools**. Data obtained using these new computer tools will be shown throughout this text. These data will be used to provide



**FIGURE 1-8** ■ Vernier calipers are cleverly designed to make length measurements to within 1/10 of a millimeter.



**FIGURE 1-9** ■ The photo shows a computer data acquisition system consisting of a sensor, an interface, a computer, and software for real-time data collection.

experimental evidence to motivate and test various theories presented in this book. You may be replicating some of these experiments in laboratory or lecture sessions.

## Computer Data Acquisition System

When a sensor is attached to a computer through an interface, a very powerful data collection, analysis, and display system is created.\* Computers coupled with appropriate software packages are capable of analyzing signals and displaying them on the screen in easily understood formats. Using these capabilities, a graphical representation of data can be displayed in “real time.”

A number of different sensors are used in contemporary introductory physics laboratories (Fig. 1-10). These include sensors for the detection of linear and rotational motion (Fig. 1-11), acceleration, force, temperature, pressure, voltage, current, and magnetic field. To determine distances, the most popular motion sensor emits pulses of ultra high frequency sound. Although these ultrasonic pulses are above the range of human hearing, the motion sensor can detect reflections of these pulses after they bounce off objects within the sensor’s field of “view.”



**FIGURE 1-10** ■ An ultrasonic motion detector.



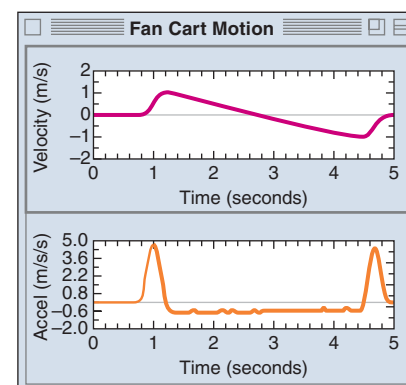
**FIGURE 1-11** ■ Two electronic interfaces used in popular introductory physics computer data acquisition systems: The LabPro Interface (Vernier Software and Technology) and the Science Workshop 500 Interface (PASCO scientific).

Since the speed of ultrasound in room temperature air is known, the computer motion software can calculate the distance to an object by recording how long the pulse takes to reflect off the object and return to the sensor. This is similar to how a bat “sees,” and how some auto-focus cameras determine the distance to an object. This approach to measuring a distance or length is not unlike that used by international standards organizations to define the meter in terms of the speed of light. Since ultrasonic motion detectors can send and receive short pulses up to 50 times a second, the computer software can also make rapid calculations of velocities and accelerations of slowly moving objects “on the fly,” and graph them in real time. Sample graphs are shown in Fig. 1-12.

## Digital Video Capture and Analysis Tools

Software and hardware enable student investigators to digitize images from a video camera, VCR, or videodisc. Once a digital video movie is created, it can be analyzed using video analysis software. Video data are collected by locating items of interest in each frame of a movie as it is displayed on a computer screen. Video analysis is a useful tool for studying one- and two-dimensional motions, electrostatics, and digital simulations of molecular motions. Examples of digital video clips and their analysis will be presented in this text from time to time. (See Figs. 1-13 and 1-14).

\* These systems go by many names, such as computer-based data collection system, e-measure, CADAA (computer-assisted data acquisition and analysis system), or MBL system (Microcomputer Based Laboratory system).



**FIGURE 1-12** ■ Real-time graphs of position, velocity, or acceleration, as a function of time, can be generated by an ultrasonic motion detector.

**FIGURE 1-13** ■ An overlay of five digital video frames showing a ballet dancer moving toward the left while performing a grand jeté.



## 1-9 Changing Units

An American traveling overseas notices a road sign indicating that the distance to the next town is 32 km. She wants to get a feel for how far away the town is, and needs to convert the kilometers to the more familiar units of miles. How would she go about doing that?

We often need to change the units in which a physical quantity is expressed. A good method is called *chain-link conversion*. In this method, we multiply the original measurement by one or more conversion factors. A **conversion factor** is defined as a ratio of units that is equal to 1. For example, because 1 mile and 1.61 kilometers are identical distances, we have

$$\frac{1 \text{ mi}}{1.61 \text{ km}} = 1 \quad \text{and also} \quad \frac{1.61 \text{ km}}{1 \text{ mi}} = 1. \quad (1-10)$$

Thus, the ratios  $(1 \text{ mi})/(1.61 \text{ km})$  and  $(1.61 \text{ km})/(1 \text{ mi})$  can be used as conversion factors. This is *not* the same as writing  $1/1.61 = 1$  or  $1.61 = 1$ ; each *number* and its *unit* must be treated together. Because multiplying any quantity by one leaves it unchanged, we can introduce such conversion factors wherever we find them useful. In chain-link conversion, we use the factors to cancel unwanted units. For example, to convert 32 kilometers to miles, we have

$$32 \text{ km} = (32 \text{ km}) \left( \frac{1 \text{ mi}}{1.61 \text{ km}} \right) = 20 \text{ mi}. \quad (1-11)$$

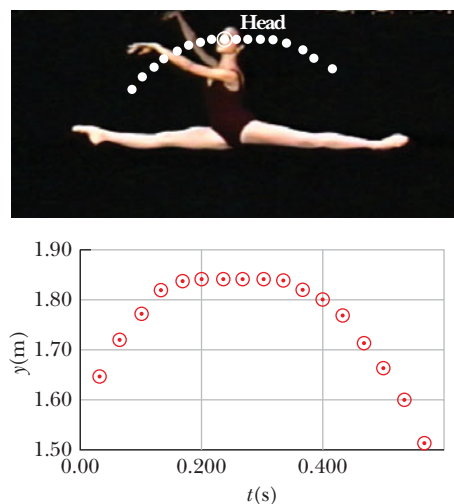
Suppose instead that our traveler wanted to know how many feet there are in 32 kilometers. Then two conversion factors would be needed, so that

$$32 \text{ km} = (32 \text{ km}) \left( \frac{1 \text{ mi}}{1.61 \text{ km}} \right) \left( \frac{5280 \text{ ft}}{1 \text{ mi}} \right) = 1.05 \times 10^5 \text{ ft}. \quad (1-12)$$

The number of feet is expressed in scientific notation so that the correct number of significant figures can be represented. See the next section and Appendix A for more details on how to represent significant figures properly.

Appendix D and the inside back cover give conversion factors between SI and other systems of units, including many of the non-SI units still used in the United States. However, the conversion factors are written in the style of “1 mi = 1.61 km” rather than the ratios we show here.

It is important to note that the **value of a physical quantity** is actually the product of a number and a unit. Thus, the number associated with a particular physical quantity depends on the unit in which it is expressed. For example, the distance to the trav-



**FIGURE 1-14** ■ A video analysis of the motion of the dancer reveals that while performing the grand jeté depicted in Fig. 1-13, her head is moving in a straight horizontal line between the times 0.180 s and 0.330 s. To observers following the motion of her head, the dancer appears to be floating for this short period of time. How does she accomplish this? In Chapter 8 we describe how video analysis helps us explore this question.



eler's town has a value of 32 km. The numerical component of its value expressed in the unit "kilometers" is 32. However, the value of the distance when expressed in miles is 20 mi, and the numerical component of its value when expressed in miles is 20. Since 20 miles is actually the *same distance* as 32 kilometers, it is meaningful to write  $32 \text{ km} = 20 \text{ mi}$ . In this context the equal sign (=) signifies that 32 km is the *same distance* as 20 mi expressed in different units. However, it is totally meaningless to write  $32 = 20$ . Thus it is extremely important to include appropriate units in all calculations.

### TOUCHSTONE EXAMPLE 1-2: Marathon

When Pheidippides ran from Marathon to Athens in 490 B.C.E. to bring word of the Greek victory over the Persians, he probably ran at a speed of about 23 rides per hour (rides/h). The ride is an ancient Greek unit for length, as are the stadium and the plethron: 1 ride was defined to be 4 stadia, 1 stadium was defined to be 6 plethra, and, in terms of a modern unit, 1 plethron is 30.8 m. How fast did Pheidippides run in kilometers per second (km/s)?

**SOLUTION** ■ The **Key Idea** in chain-link conversions is to write the conversion factors as ratios that will eliminate unwanted

units. Here we write

$$23 \text{ rides/h} = \left(23 \frac{\text{rides}}{\text{h}}\right) \left(\frac{4 \text{ stadia}}{1 \text{ ride}}\right) \left(\frac{6 \text{ plethra}}{1 \text{ stadium}}\right) \left(\frac{30.8 \text{ m}}{1 \text{ plethron}}\right) \left(\frac{1 \text{ km}}{1000 \text{ m}}\right) \left(\frac{1 \text{ h}}{3600 \text{ s}}\right) \quad (\text{Answer})$$

$$= 4.7227 \times 10^{-3} \text{ km/s} \approx 4.7 \times 10^{-3} \text{ km/s.}$$

**READING EXERCISE 1-7:** (a) Explain why it is correct to write  $1 \text{ min}/60 \text{ s} = 1$ , but it is not correct to write  $1/60 = 1$ . (b) Use the relevant conversion factors and the method of chain-link conversions to calculate how many seconds there are in a day. ■

## 1-10 Calculations with Uncertain Quantities

### Issue 1: Significant Figures and Decimal Places

In July 1988, in Indianapolis, Indiana, the U.S.'s Florence Griffith Joyner set a world record in the women's 100-meter dash with an official time of 10.49 seconds (Fig. 1-15). The timing in the race is considered good to the nearest 1/100 of a second. Suppose you had been asked to report the time in minutes instead of seconds. If you used a calculator to transform the 10.49 seconds into minutes by multiplying by (1 min)/(60 s), you might report the following by copying all the digits on your display:

$$10.49 \text{ s} = (10.49 \text{ s}) \left(\frac{1 \text{ min}}{60 \text{ s}}\right) = 0.174 \, 833 \, 333 \text{ min.} \quad (1-13)$$

No matter how precise a measuring instrument is, all measured quantities have uncertainties associated with them. The precision implied by the calculated time in minutes shown above is both meaningless and misleading! We should have rounded the answer to four significant digits, 0.1748 min, so as not to imply that it is more precise than the given data. The given time of 10.49 seconds consists of four digits, called **significant figures**. This tells us we should round the answer to four significant figures. In this text, final results of calculations are often rounded to match the least number of significant figures in the given data. *Significant figures* should not be confused with *decimal places*. Consider the lengths 35.6 mm, 3.56 cm, and 0.0356 m. They all have three significant figures, but they have one, two, and four decimal places, respectively.



**FIGURE 1-15** ■ The late Florence Griffith Joyner set a world's record in the women's 100-meter dash in 1988.

As you work with scientific calculations in data analysis in the laboratory or complete the problems in this text, it is important to pay strict attention to reporting your answer to the same precision as the lowest precision in any of the factors used in your calculation. Information on how to keep track of significant figures and measurement uncertainties in calculations is included in Appendix A, and a table of fundamental constants that have been measured to high precision is in Appendix B.

## Issue 2: Order of Magnitude

In order to make estimations, engineering and science professionals will sometimes round a number to be used in a calculation up or down to the nearest power of ten. This makes the number very easy to use in calculations. The result of this rounding procedure is known as the *order of magnitude* of a number. To determine an order of magnitude, we start by expressing the number of interest in scientific notation. Next, the mantissa is rounded up to 10 or down to 1 depending on which is closest. For example, if  $A = 2.3 \times 10^4$ , then the order of magnitude of  $A$  is  $10^4$  (ten to the fourth) since 2.3 is closer to 1 than it is to 10. On the other hand, if  $B = 7.8 \times 10^4$ , then the order of magnitude of  $B$  is  $10^5$  (ten to the fifth) since 7.8 is closer to 10 than it is to 1. Order of magnitude estimations are common when detailed or precise data are not required in a calculation or are not known.

**READING EXERCISE 1-8:** Using the method outlined in Appendix A, determine the number of significant figures in each of the following numbers: (a) 27 meters, (b) 27 cows, (c) 0.003 429 87 second, (d)  $-1.970\,500 \times 10^{-11}$  coulombs, (e) 5280 ft/mi. (Note: By definition there are exactly 5280 feet in a mile.) ■

**READING EXERCISE 1-9:** A popular science book lists the radius of the Earth as 20 900 000 000 ft. (a) How many significant figures does this number have if you apply the method described in Appendix A for determining the number of significant figures? (b) How many significant figures did the author probably intend to report? (c) How could you rewrite this number so that it represents three significant figures? (d) What order of magnitude is the radius of the Earth in feet? ■

### TOUCHSTONE EXAMPLE 1-3: Ball of String

The world's largest ball of string is about 2 m in radius. To the nearest order of magnitude, what is the total length  $L$  of the string in the ball?

**SOLUTION** ■ We could, of course, take the ball apart and measure the total length  $L$ , but that would take great effort and make the ball's builder most unhappy. A **Key Idea** here is that, because we want only the nearest order of magnitude, we can estimate any quantities required in the calculation.

Let us assume the ball is spherical with radius  $R = 2$  m. The string in the ball is not closely packed (there are uncountable gaps between nearby sections of string). To allow for these gaps, let us somewhat overestimate the cross-sectional area of the string by assuming the cross section is square, with an edge length  $d = 4$  mm. Then, with a cross-sectional area of  $d^2$  and a length  $L$ , the string occupies a total volume of

$$V = (\text{cross-sectional area})(\text{length}) = d^2 L.$$

This is approximately equal to the volume of the ball, given by  $\frac{4}{3}\pi R^3$ , which is about  $4R^3$  because  $\pi$  is about 3. Thus, we have

$$d^2 L = 4R^3,$$

$$\begin{aligned} \text{or} \quad L &= \frac{4R^3}{d^2} = \frac{4(2\text{ m})^3}{(4 \times 10^{-3}\text{ m})^2} && \text{(Answer)} \\ &= 2 \times 10^6\text{ m} \approx 10^6\text{ m} = 10^3\text{ km}. \end{aligned}$$

(Note that you do not need a calculator for such a simplified calculation.) Thus, to the nearest order of magnitude, the ball contains about 1000 km of string!



**READING EXERCISE 1-10:** Suppose you are to calculate the volume of a cube that is  $L = 1.4$  cm on a side and you start by calculating the area,  $A$ , of a face of the cube  $A = L^2$  and then calculating  $V = AL$ . (a) What intermediate value for  $A$  should you use in the calculation for  $V$ ? (b) What is the value of the volume to the correct number of significant figures? (c) What value do you get for  $V$  if you incorrectly retain only two significant figures after you calculate  $A$ ? ■

**READING EXERCISE 1-11:** Perform the following calculations and express the answers to the correct number of significant figures. (a) Multiply 3.4 by 7.954. (b) Add 99.3 and 98.7. (c) Subtract 98.7 from 99.3. (d) Evaluate the cosine of  $3^\circ$ . (e) If five railroad track segments have an average length of 2.134 meters, what is the total length of these five rails when they lie end to end? ■

**READING EXERCISE 1-12:** Suppose you measure a time to the nearest  $1/100$  of a second and get a value of 1.78 s. (a) What is the absolute precision of your measurement? (b) What is the relative precision of your measurement? ■

## Problems

### SEC. 1-5 ■ THE SI STANDARD OF TIME

**1. Speed of Light** Express the speed of light,  $3.0 \times 10^8$  m/s, in (a) feet per nanosecond and (b) millimeters per picosecond.

**2. Fermi** Physicist Enrico Fermi once pointed out that a standard lecture period (50 min) is close to 1 microcentury. (a) How long is a microcentury in minutes? (b) Using

$$\text{percentage difference} = \left( \frac{\text{actual} - \text{approximation}}{\text{actual}} \right) 100,$$

find the percentage difference from Fermi's approximation.

**3. Five Clocks** Five clocks are being tested in a laboratory. Exactly at noon, as determined by the WWV time signal, on successive days of a week the clocks read as in the following table. Rank the five clocks according to their relative value as good timekeepers, best to worst. Justify your choice.

Clock	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
A	12:36:40	12:36:56	12:37:12	12:37:27	12:37:44	12:37:59	12:38:14
B	11:59:59	12:00:02	11:59:57	12:00:07	12:00:02	11:59:56	12:00:03
C	15:50:45	15:51:43	15:52:41	15:53:39	15:54:37	15:55:35	15:56:33
D	12:03:59	12:02:52	12:01:45	12:00:38	11:59:31	11:58:24	11:57:17
E	12:03:59	12:02:49	12:01:54	12:01:52	12:01:32	12:01:22	12:01:12

**4. The Shake** A unit of time sometimes used in microscopic physics is the *shake*. One shake equals  $10^{-8}$  s. (a) Are there more shakes in a second than there are seconds in a year? (b) Humans have existed for about  $10^6$  years, whereas the universe is about  $10^{10}$  years old. If the age of the universe now is taken to be 1 “universe day,” for how many “universe seconds” have humans existed?

**5. Astronomical Units** An astronomical unit (AU) is the average distance of Earth from the Sun, approximately  $1.50 \times 10^8$  km. The

speed of light is about  $3.0 \times 10^8$  m/s. Express the speed of light in terms of astronomical units per minute.

**6. Digital Clocks** Three digital clocks  $A$ ,  $B$ , and  $C$  run at different rates and do not have simultaneous readings of zero. Figure 1-16 shows simultaneous readings on pairs of the clocks for four occasions. (At the earliest occasion, for example,  $B$  reads 25.0 s and  $C$  reads 92.0 s.) If two events are 600 s apart on clock  $A$ , how far apart are they on (a) clock  $B$  and (b) clock  $C$ ? (c) When clock  $A$  reads 400 s, what does clock  $B$  read? (d) When clock  $C$  reads 15.0 s, what does clock  $B$  read? (Assume negative readings for prezero times.)

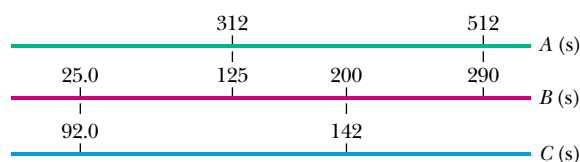


FIGURE 1-16 ■ Problem 6.

**7. Length of Day** Assuming the length of the day uniformly increases by 0.0010 s per century, calculate the cumulative effect on the measure of time over 20 centuries. (Such slowing of Earth's rotation is indicated by observations of the occurrences of solar eclipses during this period.)

**8. Time Zones** Until 1883, every city and town in the United States kept its own local time. Today, travelers reset their watches only when the time change equals 1.0 h. How far, on the average, must you travel in degrees of longitude until your watch must be reset by 1.0 h? (*Hint:* Earth rotates  $360^\circ$  in about 24 h.)

**9. A Fortnight** A fortnight is a charming English measure of time equal to 2.0 weeks (the word is a contraction of “fourteen nights”). That is a nice amount of time in pleasant company but perhaps a painful string of microseconds in unpleasant company. How many microseconds are in a fortnight?

**10. Time Standards** Time standards are now based on atomic clocks. A promising second standard is based on *pulsars*, which are rotating neutron stars (highly compact stars consisting only of neutrons). Some rotate at a rate that is highly stable, sending out a radio beacon that sweeps briefly across Earth once with each rotation, like a lighthouse beacon. Pulsar PSR 1937 + 21 is an example; it rotates once every  $1.557\,806\,448\,872\,75 \pm 3$  ms, where the trailing  $\pm 3$  indicates the uncertainty in the last decimal place (it does *not* mean  $\pm 3$  ms). (a) How many times does PSR 1937 + 21 rotate in 7.00 days? (b) How much time does the pulsar take to rotate  $1.0 \times 10^6$  times, and (c) what is the associated uncertainty?

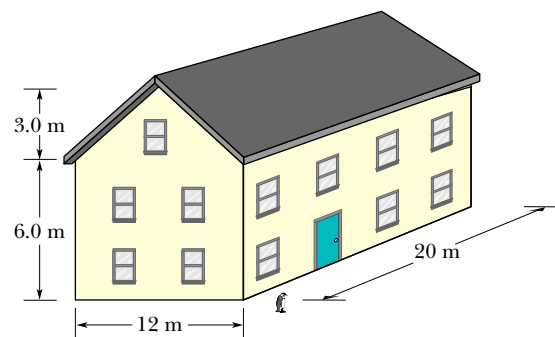


FIGURE 1-18 ■ Problem 18.

### SEC. 1-6 ■ THE SI STANDARDS OF LENGTH

**11. Furlongs** Horses are to race over a certain English meadow for a distance of 4.0 furlongs. What is the race distance in units of (a) rods and (b) chains? (1 furlong = 201.168 m, 1 rod = 5.0292 m, and 1 chain = 20.117 m.)

**12. Types of Barrels** Two types of *barrel* units were in use in the 1920s in the United States. The apple barrel had a legally set volume of 7056 cubic inches; the cranberry barrel, 5826 cubic inches. If a merchant sells 20 cranberry barrels of goods to a customer who thinks he is receiving apple barrels, what is the discrepancy in the shipment volume in liters?

**13. The Earth** Earth is approximately a sphere of radius  $6.37 \times 10^6$  m. What are (a) its circumference in kilometers, (b) its surface area in square kilometers, and (c) its volume in cubic kilometers?

**14. Points and Picas** Spacing in this book was generally done in units of points and picas: 12 points = 1 pica, and 6 picas = 1 inch. If a figure was misplaced in the page proofs by 0.80 cm, what was the misplacement in (a) points and (b) picas?

**15. Antarctica** Antarctica is roughly semicircular, with a radius of 2000 km (Fig. 1-17). The average thickness of its ice cover is 3000 m. How many cubic centimeters of ice does Antarctica contain? (Ignore the curvature of Earth.)

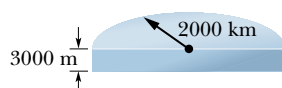


FIGURE 1-17 ■ Problem 15.

**16. Roods and Perches** An old manuscript reveals that a landowner in the time of King Arthur held 3.00 acres of plowed land plus a livestock area of 25.0 perches by 4.00 perches. What was the total area in (a) the old unit of roods and (b) the more modern unit of square meters? Here, 1 acre is an area of 40 perches by 4 perches, 1 rood is 40 perches by 1 perch, and 1 perch is 16.5 ft.

**17. The Acre-Foot** Hydraulic engineers in the United States often use, as a unit of volume of water, the *acre-foot*, defined as the volume of water that will cover 1 acre of land to a depth of 1 ft. A severe thunderstorm dumped 2.0 in. of rain in 30 min on a town of area  $26 \text{ km}^2$ . What volume of water, in acre-feet, fell on the town?

**18. A Doll House** In the United States, a doll house has the scale of 1:12 of a real house (that is, each length of the doll house is  $\frac{1}{12}$  that of the real house) and a miniature house (a doll house to fit within a doll house) has the scale of 1:144 of a real house. Suppose a real house (Fig. 1-18) has a front length of 20 m, a depth of 12 m, a height of 6.0 m, and a standard sloped roof (vertical triangular faces on the ends) of height 3.0 m. In cubic meters, what are the volumes of the corresponding (a) doll house and (b) miniature house?

### SEC. 1-7 ■ THE SI STANDARDS OF MASS

**19. Earth's Mass** Earth has a mass of  $5.98 \times 10^{24}$  kg. The average mass of the atoms that make up Earth is 40 u. How many atoms are there in Earth?

**20. Gold** Gold, which has a mass of 19.32 g for each cubic centimeter of volume, is the most ductile metal and can be pressed into a thin leaf or drawn out into a long fiber. (a) If 1.000 oz of gold, with a mass of 27.63 g, is pressed into a leaf of  $1.000 \mu\text{m}$  thickness, what is the area of the leaf? (b) If, instead, the gold is drawn out into a cylindrical fiber of radius  $2.500 \mu\text{m}$ , what is the length of the fiber?

**21. Mass of Water** (a) Assuming that each cubic centimeter of water has a mass of exactly 1 g, find the mass of one cubic meter of water in kilograms. (b) Suppose that it takes 10.0 h to drain a container of  $5700 \text{ m}^3$  of water. What is the “mass flow rate,” in kilograms per second, of water from the container?

**22. The Thunderstorm** What mass of water fell on the town in Problem 17 during the thunderstorm? One cubic meter of water has a mass of  $10^3$  kg.

**23. Iron** Iron has a mass of 7.87 g per cubic centimeter of volume, and the mass of an iron atom is  $9.27 \times 10^{-26}$  kg. If the atoms are spherical and tightly packed, (a) what is the volume of an iron atom and (b) what is the distance between the centers of adjacent atoms?

**24. Grains of Sand** Grains of fine California beach sand are approximately spheres with an average radius of  $50 \mu\text{m}$  and are made of silicon dioxide. A solid cube of silicon dioxide with a volume of  $1.00 \text{ m}^3$  has a mass of 2600 kg. What mass of sand grains would have a total surface area (the total area of all the individual spheres) equal to the surface area of a cube 1 m on an edge?

### SEC. 1-9 ■ CHANGING UNITS

**25. A Diet** A person on a diet might lose 2.3 kg per week. Express the mass loss rate in milligrams per second, as if the dieter could sense the second-by-second loss.

**26. Cats and Moles** A mole of atoms is  $6.02 \times 10^{23}$  atoms. To the nearest order of magnitude, how many moles of atoms are in a large domestic cat? The masses of a hydrogen atom, an oxygen atom, and a carbon atom are 1.0 u, 16 u, and 12 u, respectively. (Hint: Cats are sometimes known to kill moles.)

**27. Sugar Cube** A typical sugar cube has an edge length of 1 cm. If you had a cubical box that contained a mole of sugar cubes, what would its edge length be? (One mole =  $6.02 \times 10^{23}$  units.)

- 28. Micrometer** The micrometer ( $1\ \mu\text{m}$ ) is often called the *micron*. (a) How many microns make up  $1.0\ \text{km}$ ? (b) What fraction of a centimeter equals  $1.0\ \mu\text{m}$ ? (c) How many microns are in  $1.0\ \text{yd}$ ?
- 29. Hydrogen** Using conversions and data in the chapter, determine the number of hydrogen atoms required to obtain  $1.0\ \text{kg}$  of hydrogen. A hydrogen atom has a mass of  $1.0\ \text{u}$ .

- 30. A Gry** A *gry* is an old English measure for length, defined as  $1/10$  of a line, where *line* is another old English measure for length, defined as  $1/12$  inch. A common measure for length in the publishing business is a *point*, defined as  $1/72$  inch. What is an area of  $0.50\ \text{gry}^2$  in terms of points squared ( $\text{points}^2$ )?

## Additional Problems

**31. Harvard Bridge** Harvard Bridge, which connects MIT with its fraternities across the Charles River, has a length of  $364.4$  Smoots plus one ear. The unit of one Smoot is based on the length of Oliver Reed Smoot, Jr., class of 1962, who was carried or dragged length by length across the bridge so that other pledge members of the Lambda Chi Alpha fraternity could mark off (with paint) 1-Smoot lengths along the bridge. The marks have been repainted biannually by fraternity pledges since the initial measurement, usually during times of traffic congestion so that the police could not easily interfere. (Presumably, the police were originally upset because a Smoot is not an SI base unit, but these days they seem to have accepted the unit.) Figure 1-19 shows three parallel paths, measured in Smoots (S), Willies (W), and Zeldas (Z). What is the length of  $50.0$  Smoots in (a) Willies and (b) Zeldas?



FIGURE 1-19 ■ Problem 31.

**32. Little Miss Muffet** An old English children's rhyme states, "Little Miss Muffet sat on her tuffet, eating her curds and whey, when along came a spider who sat down beside her. . . ." The spider sat down not because of the curds and whey but because Miss Muffet had a stash of 11 tuffets of dried flies. The volume measure of a tuffet is given by  $1\ \text{tuffet} = 2\ \text{pecks} = 0.50\ \text{bushel}$ , where 1 Imperial (British) bushel =  $36.3687\ \text{liters (L)}$ . What was Miss Muffet's stash in (a) pecks, (b) bushels, and (c) liters?

**33. Noctilucent Clouds** During the summers at high latitudes, ghostly, silver-blue clouds occasionally appear after sunset when common clouds are in Earth's shadow and are no longer visible. The ghostly clouds have been called *noctilucent clouds* (NLC), which means "luminous night clouds," but now are often called *mesospheric clouds*, after the *mesosphere*, the name of the atmosphere at the altitude of the clouds.

These clouds were first seen in June 1885, after dust and water from the massive 1883 volcanic explosion of Krakatoa Island (near Java in the Southeast Pacific) reached the high altitudes in the Northern Hemisphere. In the low temperatures of the mesosphere, the water collected and froze on the volcanic dust (and perhaps on comet and meteor dust already present there) to form the particles that made up the first clouds. Since then, mesospheric clouds have generally increased in occurrence and brightness, probably because of the increased production of methane by industries, rice paddies, landfills, and livestock flatulence. The methane works its way into the upper atmosphere, undergoes chemical changes, and results in an increase of water molecules there, and also in bits of ice for the mesospheric clouds.

If mesospheric clouds are spotted 38 min after sunset and then quickly dim, what is their altitude if they are directly over the observer?

**34. Staircase** A standard interior staircase has steps each with a rise (height) of  $19\ \text{cm}$  and a run (horizontal depth) of  $23\ \text{cm}$ . Research suggests that the stairs would be safer for descent if the run were, instead,  $28\ \text{cm}$ . For a particular staircase of total height  $4.57\ \text{m}$ , how much farther would the staircase extend into the room at the foot of the stairs if this change in run were made?

**35. Large and Small** As a contrast between the old and the modern and between the large and the small, consider the following: In old rural England 1 hide (between 100 and 120 acres) was the area of land needed to sustain one family with a single plough for one year. (An area of 1 acre is equal to  $4047\ \text{m}^2$ .) Also, 1 wapentake was the area of land needed by 100 such families. In quantum physics, the cross-sectional area of a nucleus (defined in terms of the chance of a particle hitting and being absorbed by it) is measured in units of barns, where 1 barn is  $1 \times 10^{-28}\ \text{m}^2$ . (In nuclear physics jargon, if a nucleus is "large," then shooting a particle at it is like shooting a bullet at a barn door, which can hardly be missed.) What is the ratio of 25 wapentakes to 11 barns?

**36. Cumulus Cloud** A cubic centimeter in a typical cumulus cloud contains 50 to 500 water droplets, which have a typical radius of  $10\ \mu\text{m}$ . (a) How many cubic meters of water are in a cylindrical cumulus cloud of height  $3.0\ \text{km}$  and radius  $1.0\ \text{km}$ ? (b) How many 1-liter pop bottles would that water fill? (c) Water has a mass per unit volume (or density) of  $1000\ \text{kg/m}^3$ . How much mass does the water in the cloud have?

**37. Oysters** In purchasing food for a political rally, you erroneously order shucked medium-size Pacific oysters (which come 8 to 12 per U.S. pint) instead of shucked medium-size Atlantic oysters (which come 26 to 38 per U.S. pint). The filled oyster container delivered to you has the interior measure of  $1.0\ \text{m} \times 12\ \text{cm} \times 20\ \text{cm}$ , and a U.S. pint is equivalent to  $0.4732\ \text{liter}$ . By how many oysters is the order short of your anticipated count?

**38. U.K. Gallons** A tourist purchases a car in England and ships it home to the United States. The car sticker advertised that the car's fuel consumption was at the rate of 40 miles per gallon on the open road. The tourist does not realize that the U.K. gallon differs from the U.S. gallon:

$$\begin{aligned} 1\ \text{U.K. gallon} &= 4.545\ 963\ 1\ \text{liters} \\ 1\ \text{U.S. gallon} &= 3.785\ 306\ 0\ \text{liters}. \end{aligned}$$

For a trip of 750 miles (in the United States), how many gallons of fuel does (a) the mistaken tourist believe she needs and (b) the car actually require?

**39. Types of Tons** A ton is a measure of volume frequently used in shipping, but that use requires some care because there are at least three types of tons: A *displacement ton* is equal to 7 barrels bulk, a *freight ton* is equal to 8 barrels bulk, and a *register ton* is equal to 20 barrels bulk. A *barrel bulk* is another measure of volume: 1 barrel bulk = 0.1415 m<sup>3</sup>. Suppose you spot a shipping order for “73 tons” of M&M candies, and you are certain that the client who sent the order intended “ton” to refer to volume (instead of weight or mass, as discussed in Chapter 6). If the client actually meant displacement tons, how many extra U.S. bushels of the candies will you erroneously ship to the client if you interpret the order as (a) 73 freight tons and (b) 73 register tons? One cubic meter is equivalent to 28.378 U.S. bushels.

**40. Wine Bottles** The wine for a large European wedding reception is to be served in a stunning cut-glass receptacle with the interior dimensions of 40 cm × 40 cm × 30 cm (height). The receptacle is to be initially filled to the top. The wine can be purchased in bottles of the sizes given in the following table, where the volumes of the larger bottles are given in terms of the volume of a standard wine bottle. Purchasing a larger bottle instead of multiple smaller bottles decreases the overall cost of the wine. To minimize that overall cost, (a) which bottle sizes should be purchased and how many of each should be purchased, and (b) how much wine is left over once the receptacle is filled?

- 1 standard
- 1 magnum = 2 standard
- 1 jeroboam = 4 standard
- 1 rehoboam = 6 standard
- 1 methuselah = 8 standard
- 1 salmanazar = 12 standard
- 1 balthazar = 16 standard = 11.356 L
- 1 nebuchadnezzar = 20 standard

**41. The Corn–Hog Ratio** The *corn-hog ratio* is a financial term commonly used in the pig market and presumably is related to the cost of feeding a pig until it is large enough for market. It is defined as the ratio of the market price of a pig with a mass of 1460 slugs to the market price of a U.S. bushel of corn. The slug is the unit of mass in the English system. (The word “slug” is derived from an old German word that means “to hit”; we have the same meaning for “slug” as a verb in modern English.) A U.S. bushel is equal to 35.238 L. If the corn–hog ratio is listed as 5.7 on the market exchange, what is it in the metric units of

$$\frac{\text{price of 1 kilogram of pig}}{\text{price of 1 liter of corn}}?$$

(Hint: See the Mass table in Appendix D.)

**42. Volume Measures in Spain** You can easily convert common units and measures electronically, but you still should be able to use a conversion table, such as those in Appendix D. Table 1-3 is part of a conversion table for a system of volume measures once common in Spain; a volume of 1 fanega is equivalent to 55.501 dm<sup>3</sup> (cubic decimeters). (a) Complete the table, using three significant figures.

Then express 7.00 almude in terms of (b) medio, (c) cahiz, and (d) cubic centimeters (cm<sup>3</sup>).

TABLE 1-3  
Problem 42

	cahiz	fanega	cuartilla	almude	medio
1 cahiz =	1	12	48	144	288
1 fanega =		1	4	12	24
1 quartilla =			1	3	6
1 almude =				1	2
1 medio =					1

**43. Pirate Ship** You receive orders to sail due east for 24.5 mi to put your salvage ship directly over a sunken pirate ship. However, when your divers probe the ocean floor at that location and find no evidence of a ship, you radio back to your source of information, only to discover that the sailing distance was supposed to be 24.5 *nautical miles*, not regular miles. Use the Length table in Appendix D to calculate how far horizontally you are from the pirate ship in kilometers.

**44. The French Revolution** For about 10 years after the French revolution, the French government attempted to base measures of time on multiples of ten: One week consisted of 10 days, 1 day consisted of 10 hours, 1 hour consisted of 100 minutes, and 1 minute consisted of 100 seconds. What are the ratios of (a) the French decimal week to the standard week and (b) the French decimal second to the standard second?

**45. Heavy Rain** During heavy rain, a rectangular section of a mountainside measuring 2.5 km wide (horizontally), 0.80 km long (up along the slope), and 2.0 m deep suddenly slips into a valley in a mud slide. Assume that the mud ends up uniformly distributed over a valley section measuring 0.40 km × 0.40 km and that the mass of a cubic meter of mud is 1900 kg. What is the mass of the mud sitting above an area of 4.0 m<sup>2</sup> in that section?

**46. Liquid Volume** Prior to adopting metric systems of measurement, the United Kingdom employed some challenging measures of liquid volume. A few are shown in Table 1-4. (a) Complete the table, using three significant figures. (b) The volume of 1 bag is equivalent to a volume of 0.1091 m<sup>3</sup>. If an old British story has a witch cooking up some vile liquid in a cauldron with a volume of 1.5 chaldrons, what is the volume in terms of cubic meters?

TABLE 1-4  
Problem 46

	wey	chaldron	bag	pottle	gill
1 wey =	1	10/9	40/3	640	120 240
1 chaldron =					
1 bag =					
1 pottle =					
1 gill =					

**47. The Dbug** Traditional units of time have been based on astronomical measurements, such as the length of the day or year. How-



ever, one human-based measure of time can be found in Tibet, where the *dbug* is the average time between exhaled breaths. Estimate the number of dbugs in a day.

**48. Tower of Pisa** The following photograph of the Leaning Tower of Pisa was taken from an advertisement found in a 1994 airline magazine. Assume that the photo of the man talking on the telephone to the left has been dubbed in and is not part of the original photograph.

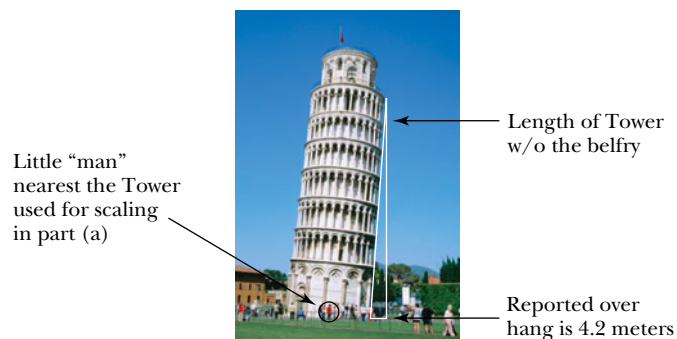


FIGURE 1-20 ■ Problem 48.

(a) Examine the photograph. Take the measurements in centimeters that are needed to find a scale factor that enables you to estimate the length of the tower in meters (i.e., its height if it were standing up straight.) Use only the evidence in the photograph—no other data are allowed. Then estimate the tower length in meters.

(b) According to data published in Sir Bannister Fletcher's *A History of Architecture* (U. of London Athlone Press, 1975, p. 470) the diameter of the lower part of the tower is 16.0 m. Using these data, find another scale factor for estimating the length of the tower, and then re-estimate the length of the tower using this new scale factor.

(c) Which of the scale factors (a) or (b) do you think will give the best estimate of the length of the tower? Explain the reasons for your answer.

(d) Using the scale factor you found in part (b), what is the length of the tower without the belfry or narrow top segment (i.e., just consider the bottom 7 stories)?

**49. Mexican Food** You are to fix dinners for 400 people at a convention of Mexican food fans. Your recipe calls for 2 jalapeño peppers per serving (one serving per person). However, you have only habanero peppers on hand. The spiciness of peppers is measured in terms of the *scoville heat unit* (SHU). On average, one jalapeño pepper has a spiciness of 4000 SHU and one habanero pepper has a spiciness of 300 000 SHU. To salvage the situation, how many (total) habanero peppers should you substitute for the jalapeño peppers in the recipe for the convention?

**50. Big or Small?** Discuss the question: “Is 500 feet big or small?” Before you do so, carry out the following estimates.

(a) You are on the top floor of a 500-ft-tall building. A fire breaks out in the building and the elevator stops working. You have to walk down to the ground floor. Estimate how long this would take you. (Your stairwell is on the other side of the building from the fire.)

(b) You are hiking the Appalachian Trail on a beautiful fall morning as part of a 10 mi hike with a group of friends. You are walking

along a well-tended, level part of the trail. Estimate how long it would take you to walk 500 ft.

(c) You are driving on the New Jersey Turnpike at 65 mi/hr. You pass a sign that says “Lane ends 500 feet.” How much time do you have in order to change lanes?

**51. Doubling System** Historically the English had a doubling system when measuring volumes; 2 mouthfuls equal 1 jigger, 2 jiggers equal 1 jack (also called a jackpot); 2 jacks equal 1 jill; 2 jills = 1 cup; 2 cups = 1 pint; 2 pints = 1 quart; 2 quarts = 1 pottle; 2 pottles = 1 gallon; 2 gallons = 1 pail. (The nursery rhyme “Jack and Jill” refers to these units and was a protest against King Charles I of England for his taxes on the jacks of liquor sold in the tavern. (See A. Kline, *The World of Measurement*, New York: Simon and Schuster, 1975, pp. 32–39.) American and British cooks today use teaspoons, tablespoons, and cups; 3 teaspoons = 1 tablespoon; 4 tablespoons = 1/4 cup. Assume that you find an old English recipe requiring 3 jiggers of milk. How many cups does this represent? How many tablespoons? You can assume that the cups in the two systems represent the same volume.

**52. Fuel Efficiency** In America, we measure fuel efficiency of our cars by citing the number of miles you can drive on 1 gallon of gas (miles/gallon). In Europe, the same information is given by quoting how many liters of gas it takes to go 100 kilometers (liter/100 kilometers).

(a) My current car gets 21 miles/gallon in highway travel. What number (in liter/100 kilometers) should I give to my Swedish friend so that he can compare it to the mileage for his Volvo?

(b) The car I drove in England last summer needed 6 liters of gas to go 100 kilometers. How many miles/gallon did it get?

(c) If my car has a fuel efficiency,  $f$ , in miles/gallon, what is its European efficiency,  $e$ , in liters/100 kilometers? (Write an equation that would permit an easy conversion.)

**53. Pizza Sale** Two terrapins decide to go to Jerry's for a pizza. When they get there they find that Jerry's is having a special:

<b>SPECIAL TODAY:</b>	one 20" pizza	\$15
<b>REGULAR PRICE</b>	one 10" pizza	\$5
	one 20" pizza	\$18

Raphael: “Great! Let's get a large one.”

Donatello: “Don't be dumb. Let's get three of the small ones for the same price. That'll give us more pizza and be cheaper.”

Raphael: “Why would it be a special if it's more than we could get for the regular price? Let's get the large.”

Who's right? Which would you buy? What would the difference be if you were buying them at Ledo's (square pizzas)?

**54. Dollar and Penny** A student makes the following argument: “I can prove a dollar equals a penny. Since a dime (10 cents) is one-tenth of a dollar, I can write:

$$10 \text{ ¢} = \$0.1.$$

Square both sides of the equation. Since squares of equals are equal,

$$100 \text{ ¢} = \$0.1.$$

Since  $100 \text{ ¢} = \$1$  and  $\$0.01 = 1 \text{ ¢}$ , it follows that  $\$1 = 1 \text{ ¢}$ ."

What's wrong with the argument?

**55. Scaling Up** Here are two related problems—one precise, one an estimation.

(a) A sculptor builds a model for a statue of a terrapin to replace Testudo.\* She discovers that to cast her small scale model she needs 2 kg of bronze. When she is done, she finds that she can give it two coats of finishing polyurethane varnish using exactly one small can of varnish.



FIGURE 1-21 ■ Problem 55.

The final statue is supposed to be 5 times as large as the model in each dimension. How much bronze will she need? How much varnish should she buy? (*Hint:* If this seems difficult, you might start by writing a simpler question that is easier to work on before tackling this one.)

(b) The human brain has 1000 times the surface area of a mouse's brain. The human brain is convoluted, the mouse's is not. How much of this factor is due just to size (the human brain is bigger)? How sensitive is your result to your estimations of the approximate dimensions of a human brain and a mouse brain?

**56. Finding the Right Dose** We know from our dimensional analysis that if an object maintains its shape but changes its size, its area changes as the square of its length and its volume changes as the cube of its length. Suppose you are a parent and your child is sick and has to take some medicine. You have taken this medicine previously and you know its dose for you. You are 5'10" tall and weigh 180 lb, and your child is 2'11" tall and weighs 30 lb. Estimate an appropriate dosage for your child's medicine in the following cases. Be sure to discuss your reasoning.

(a) The medicine is one that will enter the child's bloodstream and reach every cell in the body. Your dose is 250 mg.

(b) The medicine is one that is meant to coat the child's throat. Your dose is 15 ml.

**57. Ping-Pong Ball Packing** Estimate how many Ping-Pong balls it would take to fill your classroom (assuming all the doors and windows are closed).

**58. Feeding the Cougar** When visiting the Como Park Zoo in St. Paul, Minnesota, with my young grandson, we encountered the sign shown at the right on the cage of the mountain lion. The detailed numbers surprised me. The amount of food given to the cat was specified to the tenth of a gram and the average cat's weight was specified to within 10 grams—about  $1/3$  of an ounce. This seemed to be overly precise. Can you figure out what they were trying to say and what a plausible accuracy might be for those two numbers—the amount of food given and the average cat's weight?

### COUGAR North America



Natural Diet:	Hoofed animals, small animals
Zoo diet:	1.3608 kg. commercially prepared diet for large cats, six days a week
Average Weight:	90.72 kg.
Average Lifespan:	20 years

The cougar is also called mountain lion or puma.

It is the only large cat at Como Zoo that purrs.

Cougars are very solitary animals. They are seldom seen by humans.

FIGURE 1-22 ■ Problem 58.

**59. Blowing Off the Units.** Throughout your physics course, your instructor will expect you to be careful with the units in your calculations. Yet, some students tend to neglect them and just trust that they always work out properly. Maybe this real-world example will keep you from such a sloppy habit.

On July 23, 1983, Air Canada Flight 143 was being readied for its long trip from Montreal to Edmonton when the flight crew asked the ground crew to determine how much fuel was already onboard the airplane. The flight crew knew that they needed to begin the trip with 22 300 kg of fuel. They knew that amount in kilograms because Canada had recently switched to the metric system: previously fuel had been measured in pounds. The ground crew could measure the onboard fuel only in liters, which they reported as 7 682 L. Thus, to determine how much fuel was onboard and how much additional fuel must be added, the flight crew asked the ground crew for the conversion factor from liters to kilograms of fuel. The response was 1.77, which the flight crew used (1.77 kg corresponds to 1 L). (a) How many kilograms of fuel did the flight crew think they had? (In this problem, take all the given data as being exact.) (b) How many liters did they ask to be added to the airplane?

Unfortunately, the response from the ground crew was based on pre-metric habits—the number 1.77 was actually the conversion factor from liters to pounds of fuel (1.77 lb corresponds to 1 L). (c) How many kilograms of fuel were actually onboard? (Except for the given 1.77, use four significant figures for other conversion factors.) (d) How many liters of additional fuel were actually needed? (e) When the airplane left Montreal, what percentage of the required fuel did it actually have?

On route to Edmonton, at an altitude of 7.9 km, the airplane ran out of fuel and began to fall. Although the airplane then had no power, the pilot somehow managed to put it into a downward glide. However, the nearest working airport was too far to reach by only gliding, so the pilot somehow angled the glide toward an old non-working airport.

Unfortunately, the runway at that airport had been converted to a track for race cars, and a steel barrier had been constructed across it. Fortunately, as the airplane hit the runway, the front landing gear collapsed, dropping the nose of the airplane onto the runway. The skidding slowed the airplane so that it stopped just short of the steel barrier, with stunned race drivers and fans looking on. All on board the airplane emerged safely. The point here is this: Take care of the units.

\* Testudo is the statue of a terrapin (the university mascot) in front of the main library on the University of Maryland campus.



# The International System of Units (SI)\*

## 1 SI Base Units

1. The SI Base Units			
Quantity	Name	Symbol	Definition
length	meter	m	"... the length of the path traveled by light in vacuum in 1/299 792 458 of a second." (1983)
mass	kilogram	kg	"... this prototype [a certain platinum–iridium cylinder] shall henceforth be considered to be the unit of mass." (1889)
time	second	s	"... the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom." (1967)
electric current	ampere	A	"... that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ newton per meter of length." (1946)
thermodynamic temperature	kelvin	K	"... the fraction 1/273.16 of the thermodynamic temperature of the triple point of water." (1967)
amount of substance	mole	mol	"... the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12." (1971)
luminous intensity	candela	cd	"... the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ hertz and that has a radiant intensity in that direction of 1/683 watt per steradian." (1979)

## 2 The SI Supplementary Units

2. The SI Supplementary Units		
Quantity	Name of Unit	Symbol
plane angle	radian	rad
solid angle	steradian	sr

\*Adapted from "The International System of Units (SI)," National Bureau of Standards Special Publication 330, 2001 edition. The definitions above were adopted by the General Conference of Weights and Measures, an international body, on the dates shown. In this book we do not use the candela.

3 Some SI Derivations

3. Some SI Derived Units			
Quantity	Name of Unit	Symbol	In Terms of other SI Units
area	square meter	m <sup>2</sup>	
volume	cubic meter	m <sup>3</sup>	
frequency	hertz	Hz	s <sup>-1</sup>
mass density (density)	kilogram per cubic meter	kg/m <sup>3</sup>	
speed, velocity	meter per second	m/s	
rotational velocity	radian per second	rad/s	
acceleration	meter per second per second	m/s <sup>2</sup>	
rotational acceleration	radian per second per second	rad/s <sup>2</sup>	
force	newton	N	kg · m/s <sup>2</sup>
pressure	pascal	Pa	N/m <sup>2</sup>
work, energy, quantity of heat	joule	J	N · m
power	watt	W	J/s
quantity of electric charge	coulomb	C	A · s
potential difference, electromotive force	volt	V	W/A
electric field strength	volt per meter (or newton per coulomb)	V/m	N/C
electric resistance	ohm	Ω	V/A
capacitance	farad	F	A · s/V
magnetic flux	weber	Wb	V · s
inductance	henry	H	V · s/A
magnetic flux density	tesla	T	Wb/m <sup>2</sup>
magnetic field strength	ampere per meter	A/m	
entropy	joule per kelvin	J/K	
specific heat	joule per kilogram kelvin	J/(kg · K)	
thermal conductivity	watt per meter kelvin	W/(m · K)	
radiant intensity	watt per steradian	W/sr	

4 Mathematical Notation

Poorly chosen mathematical notation can be a source of considerable confusion to those trying to learn and to do physics. For example, ambiguity in the meaning of a mathematical symbol can prevent a reader from understanding the meaning of a crucial relationship. It is also difficult to solve problems when the symbols used to represent different quantities are not distinctive. In this text we have taken special care to use mathematical notation in ways that allow important distinctions to be easily visible both on the printed page and in handwritten work.

An excellent starting point for clear mathematical notation is the U.S. National Institute of Standard and Technology’s Special Publication 811 (SP 811), *Guide for the Use of the International System of Units (SI)*, available at <http://physics.nist.gov/cuu/Units/bibliography.html>. In addition to following the National Institute guidelines, we have made a number of systematic choices to facilitate the translation of printed notation into handwritten mathematics. For example:

- Instead of making vectors bold, vector quantities (even in one dimension) are denoted by an arrow above the symbol. So printed equations look like handwritten equations. Example:  $\vec{v}$  rather than  $\mathbf{v}$  is used to denote an instantaneous velocity.

- In general, each vector component has an explicit subscript denoting that it represents the component along a chosen coordinate axis. The one exception is the position vector,  $\vec{r}$ , whose components are simply written as  $x$ ,  $y$ , and  $z$ . For example,  $\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}$ , whereas,  $\vec{v} = v_x\hat{i} + v_y\hat{j} + v_z\hat{k}$ .
- To emphasize the distinction between a vector's components and its magnitude, we write the magnitude of a vector, such as  $\vec{F}$ , as  $|\vec{F}|$ . However, when it is obvious that a magnitude is being described, we use the plain symbol (such as  $F$  with no coordinate subscript) to denote a vector's magnitude.
- We often choose to spell out the names of objects that are associated with mathematical variables—writing, for example,  $\vec{v}_{\text{ball}}$  and not  $\vec{v}_b$  for the velocity of a ball.
- Numerical subscripts most commonly denote sequential times, positions, velocities, and so on. For example,  $x_1$  is the  $x$ -component of the position of some object at time  $t_1$ , whereas  $x_2$  is the value of that parameter at some later time  $t_2$ . We have avoided using the subscript zero to denote initial values, as in  $x_0$  to denote “the initial position along the  $x$  axis,” to emphasize that *any* time can be chosen as the initial time for consideration of the subsequent time evolution of a system.
- To avoid confusing the numerical time sequence labels with object labels, we prefer to use capital letters as object labels. For example, we would label two particles A and B rather than 1 and 2. Thus,  $\vec{p}_{A1}$  and  $\vec{p}_{B1}$  would represent the translational momenta of two particles before a collision whereas  $\vec{p}_{A2}$  and  $\vec{p}_{B2}$  would be their momenta after a collision.
- To avoid excessively long strings of subscripts, we have made the unconventional choice to write all adjectival labels as *superscripts*. Thus, Newton's Second Law is written  $\vec{F}_{\text{net}} = m\vec{a}$  whereas the sum of the forces acting on a certain object might be written as  $\vec{F}_{\text{net}} = \vec{F}_{\text{grav}} + \vec{F}_{\text{app}}$ . To avoid confusion with mathematical exponents, an adjectival label is never a single letter.
- Following a usage common in contemporary physics, the time average of a variable  $\vec{v}$  is denoted as  $\langle \vec{v} \rangle$  and not as  $\vec{v}_{\text{avg}}$ .
- Physical constants such as  $e$ ,  $c$ ,  $g$ ,  $G$ , are all **positive** scalar quantities.

## 5 Significant Figures and the Precision of Numerical Results

Quoting the result of a calculation or a measurement to the correct number of significant figures is merely a way of telling your reader roughly how precise you believe the result to be. Quoting too many significant figures overstates the precision of your result and quoting too few implies less precision than the result may actually possess. So how many significant figures should you quote when reporting your result.

### Determining Significant Figures

Before answering the question of how many significant figures to quote, we need to have a clear method for determining how many significant figures a reported number has. The standard method is quite simple:

**METHOD FOR COUNTING SIGNIFICANT FIGURES:** Read the number from left to right, and count the first nonzero digit and all the digits (zero or not) to the right of it as significant.

Using this rule, 350 mm, 0.000350 km, and 0.350 m each has *three* significant figures. In fact, each of these numbers merely represents the same distance, expressed in different units. As you can see from this example, the number of *decimal places* that a number has is *not* the same as its number of *significant figures*. The first of these distances has zero decimal places, the second has six decimal places, and the third has three, yet all three of these numbers have three significant figures.

One consequence of this method is especially worth noting. Trailing zeros count as significant figures. For example, 2700 m/s has four significant figures. If you really meant it to have only three significant figures, you would have to write it either as 2.70 km/s (changing the unit) or  $2.70 \times 10^3$  m/s (using scientific notation.)

### A Simple Rule for Reporting Significant Figures in a Calculated Result

Now that you know how to count significant figures, how many should the result of a calculation have? A simple rule that will work in most calculations is:

**SIGNIFICANT FIGURES IN A CALCULATED RESULT:** The common practice is to quote the result of a calculation to the number of significant figures of the *least* precise number used in the calculation.

Although this simple rule will often either understate or (less frequently) overstate the precision of a result, it still serves as a good rule-of-thumb for everyday numerical work. In introductory physics you will only rarely encounter data that are known to better than two, three, or four significant figures. This simple rule then tells you that you can't go very far wrong if you round off all your final results to three significant figures.

There are two situations in which the simple rule should *not* be applied to a calculation. One is when an exact number is involved in the calculation and another is when a calculation is done in parts so that intermediate results are used.

1. **Using Exact Data** There are some obvious situations in which a number used in a calculation is exact. Numbers based on counting items are exact. For example, if you are told that there are 5 people on an elevator, there are exactly 5 people, not 4.7 or 5.1. Another situation arises when a number is exact by definition. For example, the conversion factor 2.54 cm/inch does *not* have three significant figures because the inch is *defined* to be exactly 2.5400000 . . . cm. *Data that are known exactly should not be included when deciding which of the original data has the fewest significant figures.*
2. **Significant Figures in Intermediate Results** Only the final result at the end of your calculation should be rounded using the simple rule. Intermediate results should never be rounded. Spreadsheet software takes care of this for you, as does your calculator if you store your intermediate results in its memory rather than writing them down and then rekeying them. If you must write down intermediate results, keep a few more significant figures than your final result will have.

### Understanding and Refining the Simple Significant Figure Rule

Quoting the result of a calculation or measurement to the correct number of significant figures is a way of indicating its precision. You need to understand what limits the precision of data before you fully understand how to use the simple rule or its exceptions.

**Absolute Precision** There are two ways of talking about precision. First there is *absolute precision*, which tells you explicitly the smallest scale division of the measurement. It's always quoted in the same units as the measured quantity. For example, saying "I measured the length of the table to the nearest centimeter" states the absolute precision of the measurement. The absolute precision tells you how many *decimal places* the measurement has; it alone does not determine the number of significant figures. Example: if a table is 235 cm long, then 1 cm of absolute precision translates into three significant figures. On the other hand, if a table is for a doll's house and is only 8 cm long, then the same 1 cm of absolute precision has only one significant figure.

**Relative Precision** Because of this problem with absolute precision, scientists often prefer to describe the precision of data *relative* to the size of the quantity being measured. To use the previous examples, the *relative precision* of the length of the real table in the previous example is 1 cm out of 235 cm. This is usually stated as a ratio (1 part in 235) or as a percentage ( $1/235 = 0.004255 \approx 0.4\%$ ). In the case of the toy table, the same 1 cm of absolute precision yields a relative precision of only 1 part in 8 or  $1/8 = 0.125 = 12.5\%$ .

**Inconsistencies between Significant Figures and Relative Precision** There is an inconsistency that goes with using a certain number of significant figures to express relative precision. Quoted to the same number of significant figures, the relative precision of results can be quite different. For example, 13 cm and 94 cm both have two significant figures. Yet the first is specified to only 1 part in 13 or  $1/13 \approx 10\%$ , whereas the second is known to 1 part in 94 or  $1/94 \approx 1\%$ . This bias toward greater relative precision for results with larger first significant figures is one weakness of using significant figures to track the precision of calculated results. You can partially address this problem, by including one more significant figure than the simple rule suggests, when the final result of a calculation has a 1 as its first significant figure.

**Multiplying and Dividing** When multiplying or dividing numbers, the *relative* precision of the result cannot exceed that of the least precise number used. Since the number of significant figures in the result tells us its relative precision, the simple rule is all that you need when you multiply or divide. For example, the area of a strip of paper of measured size is 280 cm by 2.5 cm would be correctly reported, according to the simple rule, as  $7.0 \times 10^2 \text{ cm}^2$ . This result has only two significant figures since the less precise measurement, 2.5 cm, that went into the calculation had only two significant figures. Reporting this result as  $700 \text{ cm}^2$  would not be correct since this result has three significant figures, exceeding the relative precision of the 2.5 cm measurement.

**Addition and Subtraction** When adding or subtracting, you line up the decimal points before you add or subtract. This means that it's the *absolute* precision of the least precise number that limits the precision of the sum or the difference. This can lead to some exceptions to the simple rule. For example, adding 957 cm and 878 cm yields 1835 cm. Here the result is reliable to an absolute precision of about 1 cm since both of the original distances had this reliability. But the result then has four significant figures whereas each of the original numbers had only three. If, on the other hand, you take the difference between these two distances you get 79 cm. The difference is still reliable to about 1 cm, but that absolute precision now translates into only two significant figures worth of relative precision. So, you should be careful when adding or subtracting, since addition can actually increase the relative precision of your result and, more important, subtraction can reduce it.

**Evaluating Functions** What about the evaluation of functions? For example, how many significant figures does the  $\sin(88.2^\circ)$  have? You can use your calculator to answer this question. First use your calculator to note that  $\sin(88.2^\circ) = 0.999506$ . Now add 1 to the least significant decimal place of the argument of the function and evaluate it again. Here this gives  $\sin(88.3^\circ) = 0.999559$ . Take the last significant figure in the result to be *the first one from the left that changed* when you repeated the calculation. In this example the first digit that changed was the 0; it became a 5 (the second 5) in the recalculation. So, using the empirical approach gives you five significant figures.

# APPENDIX B

## Some Fundamental Constants of Physics\*

Constant	Symbol	Computational Value	Best (1998) Value	
			Value <sup>a</sup>	Uncertainty <sup>b</sup>
Speed of light in a vacuum	$c$	$3.00 \times 10^8$ m/s	2.997 924 58	exact
Elementary charge	$e$	$1.60 \times 10^{-19}$ C	1.602 176 462	0.039
Gravitational constant	$G$	$6.67 \times 10^{-11}$ m <sup>3</sup> /s <sup>2</sup> · kg	6.673	1500
Universal gas constant	$R$	8.31 J/mol · K	8.314 472	1.7
Avogadro constant	$N_A$	$6.02 \times 10^{23}$ mol <sup>-1</sup>	6.022 141 99	0.079
Boltzmann constant	$k_B$	$1.38 \times 10^{-23}$ J/K	1.380 650 3	1.7
Stefan–Boltzmann constant	$\sigma$	$5.67 \times 10^{-8}$ W/m <sup>2</sup> · K <sup>4</sup>	5.670 400	7.0
Molar volume of ideal gas at STP <sup>d</sup>	$V_m$	$2.27 \times 10^{-2}$ m <sup>3</sup> /mol	2.271 098 1	1.7
Electric constant (permittivity)	$\epsilon_0$	$8.85 \times 10^{-12}$ C <sup>2</sup> /N · m <sup>2</sup>	8.854 187 817 62	exact
Coulomb constant	$k = 1/4\pi\epsilon_0$	$8.99 \times 10^9$ N · m <sup>2</sup> /C <sup>2</sup>	8.987 551 787	$5 \times 10^{-10}$
Magnetic constant (permeability)	$\mu_0$	$1.26 \times 10^{-6}$ N/A <sup>2</sup>	1.256 637 061 43	exact
Planck constant	$h$	$6.63 \times 10^{-34}$ J · s	6.626 068 76	0.078
Electron mass <sup>c</sup>	$m_e$	$9.11 \times 10^{-31}$ kg $5.49 \times 10^{-4}$ u	9.109 381 88 5.485 799 110	0.079 0.0021
Proton mass <sup>c</sup>	$m_p$	$1.67 \times 10^{-27}$ kg 1.0073 u	1.672 621 58 1.007 276 466 88	0.079 $1.3 \times 10^{-4}$
Ratio of proton mass to electron mass	$m_p/m_e$	1840	1836.152 667 5	0.0021
Electron charge-to-mass ratio	$e/m_e$	$1.76 \times 10^{11}$ C/kg	1.758 820 174	0.040
Neutron mass <sup>c</sup>	$m_n$	$1.68 \times 10^{-27}$ kg 1.0087 u	1.674 927 16 1.008 664 915 78	0.079 $5.4 \times 10^{-4}$
Hydrogen atom mass <sup>c</sup>	$m_{1H}$	1.0078 u	1.007 825 031 6	0.0005
Deuterium atom mass <sup>c</sup>	$m_{2H}$	2.0141 u	2.014 101 777 9	0.0005
Helium atom mass <sup>c</sup>	$m_{4He}$	4.0026 u	4.002 603 2	0.067
Muon mass	$m_\mu$	$1.88 \times 10^{-28}$ kg	1.883 531 09	0.084
Electron magnetic moment	$\mu_e$	$9.28 \times 10^{-24}$ J/T	9.284 763 62	0.040
Proton magnetic moment	$\mu_p$	$1.41 \times 10^{-26}$ J/T	1.410 606 663	0.041
Bohr magneton	$\mu_B$	$9.27 \times 10^{-24}$ J/T	9.274 008 99	0.040
Nuclear magneton	$\mu_N$	$5.05 \times 10^{-27}$ J/T	5.050 783 17	0.040
Bohr radius	$r_B$	$5.29 \times 10^{-11}$ m	5.291 772 083	0.0037
Rydberg constant	$R$	$1.10 \times 10^7$ m <sup>-1</sup>	1.097 373 156 854 8	$7.6 \times 10^{-6}$
Electron Compton wavelength	$\lambda_C$	$2.43 \times 10^{-12}$ m	2.426 310 215	0.0073

<sup>a</sup>Values given in this column should be given the same unit and power of 10 as the computational value.

<sup>b</sup>Parts per million.

<sup>c</sup>Masses given in u are in unified atomic mass units, where 1 u =  $1.660\,538\,73 \times 10^{-27}$  kg.

<sup>d</sup>STP means standard temperature and pressure: 0°C and 1.0 atm (0.1 MPa).

\*The values in this table were selected from the 1998 CODATA recommended values ([www.physics.nist.gov](http://www.physics.nist.gov)).



# Some Astronomical Data

## Some Distances from Earth

To the Moon*	$3.82 \times 10^8 \text{ m}$	To the center of our galaxy	$2.2 \times 10^{20} \text{ m}$
To the Sun*	$1.50 \times 10^{11} \text{ m}$	To the Andromeda Galaxy	$2.1 \times 10^{22} \text{ m}$
To the nearest star (Proxima Centauri)	$4.04 \times 10^{16} \text{ m}$	To the edge of the observable universe	$\sim 10^{26} \text{ m}$

\* Mean distance.

## The Sun, Earth, and the Moon

Property	Unit	Sun	Earth	Moon
Mass	kg	$1.99 \times 10^{30}$	$5.98 \times 10^{24}$	$7.36 \times 10^{22}$
Mean radius	m	$6.96 \times 10^8$	$6.37 \times 10^6$	$1.74 \times 10^6$
Mean density	kg/m <sup>3</sup>	1410	5520	3340
Free-fall acceleration at the surface	m/s <sup>2</sup>	274	9.81	1.67
Escape velocity	km/s	618	11.2	2.38
Period of rotation <sup>a</sup>	—	37 d at poles <sup>b</sup> 26 d at equator <sup>b</sup>	23 h 56 min	27.3 d
Radiation power <sup>c</sup>	W	$3.90 \times 10^{26}$		

<sup>a</sup> Measured with respect to the distant stars; <sup>b</sup> The Sun, a ball of gas, does not rotate as a rigid body; <sup>c</sup> Just outside Earth's atmosphere solar energy is received, assuming normal incidence, at the rate of 1340 W/m<sup>2</sup>.

## Some Properties of the Planets

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mean distance from Sun, 10 <sup>6</sup> km	57.9	108	150	228	778	1430	2870	4500	5900
Period of revolution, y	0.241	0.615	1.00	1.88	11.9	29.5	84.0	165	248
Period of rotation, <sup>a</sup> d	58.7	−243 <sup>b</sup>	0.997	1.03	0.409	0.426	−0.451 <sup>b</sup>	0.658	6.39
Orbital speed, km/s	47.9	35.0	29.8	24.1	13.1	9.64	6.81	5.43	4.74
Equatorial diameter, km	4880	12 100	12 800	6790	143 000	120 000	51 800	49 500	2300
Mass (Earth = 1)	0.0558	0.815	1.000	0.107	318	95.1	14.5	17.2	0.002
Surface value of g, <sup>c</sup> m/s <sup>2</sup>	3.78	8.60	9.78	3.72	22.9	9.05	7.77	11.0	0.5
Escape velocity, <sup>c</sup> km/s	4.3	10.3	11.2	5.0	59.5	35.6	21.2	23.6	1.1

<sup>a</sup> Measured with respect to the distant stars.

<sup>b</sup> Venus and Uranus rotate opposite their orbital motion.

<sup>c</sup> Gravitational acceleration measured at the planet's equator.

APPENDIX  
D

Conversion Factors

Conversion factors may be read directly from these tables. For example, 1 degree =  $2.778 \times 10^{-3}$  revolutions, so  $16.7^\circ = 16.7 \times 2.778 \times 10^{-3}$  rev. The SI units are fully capitalized. Adapted in part from G. Shortley and D. Williams, *Elements of Physics*, 1971, Prentice-Hall, Englewood Cliffs, N.J.

Solid Angle	Plane Angle				
	°	'	"	RADIAN	rev
1 sphere = $4\pi$ steradians = 12.57 steradians	1 degree = 1	60	3600	$1.745 \times 10^{-2}$	$2.778 \times 10^{-3}$
	1 minute = $1.667 \times 10^{-2}$	1	60	$2.909 \times 10^{-4}$	$4.630 \times 10^{-5}$
	1 second = $2.778 \times 10^{-4}$	$1.667 \times 10^{-2}$	1	$4.848 \times 10^{-6}$	$7.716 \times 10^{-7}$
	1 RADIAN = 57.30	3438	$2.063 \times 10^5$	1	0.1592
	1 revolution = 360	$2.16 \times 10^4$	$1.296 \times 10^6$	6.283	1

Length					
cm	METER	km	in.	ft	mi
1 centimeter = 1	$10^{-2}$	$10^{-5}$	0.3937	$3.281 \times 10^{-2}$	$6.214 \times 10^{-6}$
1 METER = 100	1	$10^{-3}$	39.37	3.281	$6.214 \times 10^{-4}$
1 kilometer = $10^5$	1000	1	$3.937 \times 10^4$	3281	0.6214
1 inch = 2.540	$2.540 \times 10^{-2}$	$2.540 \times 10^{-5}$	1	$8.333 \times 10^{-2}$	$1.578 \times 10^{-5}$
1 foot = 30.48	0.3048	$3.048 \times 10^{-4}$	12	1	$1.894 \times 10^{-4}$
1 mile = $1.609 \times 10^5$	1609	1.609	$6.336 \times 10^4$	5280	1
1 angström = $10^{-10}$ m	1 fermi = $10^{-15}$ m	1 light-year = $9.460 \times 10^{12}$ km	1 fathom = 6 ft	1 yard = 3 ft	1 mil = $10^{-3}$ in.
1 nautical mile = 1852 m		1 parsec = $3.084 \times 10^{13}$ km	1 Bohr radius = $5.292 \times 10^{-11}$ m	1 rod = 16.5 ft	1 nm = $10^{-9}$ m
= 1.151 miles = 6076 ft					

Area				
METER <sup>2</sup>	cm <sup>2</sup>	ft <sup>2</sup>	in. <sup>2</sup>	
1 SQUARE METER = 1	$10^4$	10.76	1550	
1 square centimeter = $10^{-4}$	1	$1.076 \times 10^{-3}$	0.1550	
1 square foot = $9.290 \times 10^{-2}$	929.0	1	144	
1 square inch = $6.452 \times 10^{-4}$	6.452	$6.944 \times 10^{-3}$	1	
				<b>key:</b> 1 square mile = $2.788 \times 10^7$ ft <sup>2</sup> = 640 acres; 1 barn = $10^{-28}$ m <sup>2</sup> ; 1 acre = 43 560 ft <sup>2</sup> ; 1 hectare = $10^4$ m <sup>2</sup> = 2.471 acres.

Volume				
METER <sup>3</sup>	cm <sup>3</sup>	L	ft <sup>3</sup>	in. <sup>3</sup>
1 CUBIC METER = 1	10 <sup>6</sup>	1000	35.31	6.102 × 10 <sup>4</sup>
1 cubic centimeter = 10 <sup>-6</sup>	1	1.000 × 10 <sup>-3</sup>	3.531 × 10 <sup>-5</sup>	6.102 × 10 <sup>-2</sup>
1 liter = 1.000 × 10 <sup>-3</sup>	1000	1	3.531 × 10 <sup>-2</sup>	61.02
1 cubic foot = 2.832 × 10 <sup>-2</sup>	2.832 × 10 <sup>4</sup>	28.32	1	1728
1 cubic inch = 1.639 × 10 <sup>-5</sup>	16.39	1.639 × 10 <sup>-2</sup>	5.787 × 10 <sup>-4</sup>	1
<b>key:</b> 1 U.S. fluid gallon = 4 U.S. fluid quarts = 8 U.S. pints = 128 U.S. fluid ounces = 231 in. <sup>3</sup> 1 British imperial gallon = 277.4 in. <sup>3</sup> = 1.201 U.S. fluid gallons.				

Mass

Quantities in the colored areas are not mass units but are often used as such. When we write, for example, 1 kg “=” 2.205 lb, this means that a kilogram is a *mass* that *weighs* 2.205 pounds at a location where *g* has the standard value of 9.80665 m/s<sup>2</sup>.

g	KILOGRAM	slug	u	oz	lb	ton
1 gram = 1	0.001	$6.852 \times 10^{-5}$	$6.022 \times 10^{23}$	$3.527 \times 10^{-2}$	$2.205 \times 10^{-3}$	$1.102 \times 10^{-6}$
1 KILOGRAM = 1000	1	$6.852 \times 10^{-2}$	$6.022 \times 10^{26}$	35.27	2.205	$1.102 \times 10^{-3}$
1 slug = $1.459 \times 10^4$	14.59	1	$8.786 \times 10^{27}$	514.8	32.17	$1.609 \times 10^{-2}$
1 atomic mass unit = $1.661 \times 10^{-24}$	$1.661 \times 10^{-27}$	$1.138 \times 10^{-28}$	1	$5.857 \times 10^{-26}$	$3.662 \times 10^{-27}$	$1.830 \times 10^{-30}$
1 ounce = 28.35	$2.835 \times 10^{-2}$	$1.943 \times 10^{-3}$	$1.718 \times 10^{25}$	1	$6.250 \times 10^{-2}$	$3.125 \times 10^{-5}$
1 pound = 453.6	0.4536	$3.108 \times 10^{-2}$	$2.732 \times 10^{26}$	16	1	0.0005
1 ton = $9.072 \times 10^5$	907.2	62.16	$5.463 \times 10^{29}$	$3.2 \times 10^4$	2000	1

1 metric ton = 1000 kg

Time

y	d	h	min	SECOND
1 year = 1	365.25	$8.766 \times 10^3$	$5.259 \times 10^5$	$3.156 \times 10^7$
1 day = $2.738 \times 10^{-3}$	1	24	1440	$8.640 \times 10^4$
1 hour = $1.141 \times 10^{-4}$	$4.167 \times 10^{-2}$	1	60	3600
1 minute = $1.901 \times 10^{-6}$	$6.944 \times 10^{-4}$	$1.667 \times 10^{-2}$	1	60
1 SECOND = $3.169 \times 10^{-8}$	$1.157 \times 10^{-5}$	$2.778 \times 10^{-4}$	$1.667 \times 10^{-2}$	1

Speed

ft/s	km/h	METER/SECOND	mi/h	cm/s
1 foot per second = 1	1.097	0.3048	0.6818	30.48
1 kilometer per hour = 0.9113	1	0.2778	0.6214	27.78
1 METER per SECOND = 3.281	3.6	1	2.237	100
1 mile per hour = 1.467	1.609	0.4470	1	44.70
1 centimeter per second = $3.281 \times 10^{-2}$	$3.6 \times 10^{-2}$	0.01	$2.237 \times 10^{-2}$	1

1 knot = 1 nautical mi/h = 1.688 ft/s      1 mi/min = 88.00 ft/s = 60.00 mi/h

Force

dyne	NEWTON	lb	pdl
1 dyne = 1	$10^{-5}$	$2.248 \times 10^{-6}$	$7.233 \times 10^{-5}$
1 NEWTON = $10^5$	1	0.2248	7.233
1 pound = $4.448 \times 10^5$	4.448	1	32.17
1 poundal = $1.383 \times 10^4$	0.1383	$3.108 \times 10^{-2}$	1

1 ton = 2000 lb

## Pressure

atm	dyne/cm <sup>2</sup>	inch of water	cm Hg	PASCAL	lb/in. <sup>2</sup>	lb/ft <sup>2</sup>
1 atmosphere = 1	$1.013 \times 10^6$	406.8	76	$1.013 \times 10^5$	14.70	2116
1 dyne per centimeter <sup>2</sup> = $9.869 \times 10^{-7}$	1	$4.015 \times 10^{-4}$	$7.501 \times 10^{-5}$	0.1	$1.405 \times 10^{-5}$	$2.089 \times 10^{-3}$
1 inch of water <sup>a</sup> at 4°C = $2.458 \times 10^{-3}$	2491	1	0.1868	249.1	$3.613 \times 10^{-2}$	5.202
1 centimeter of mercury <sup>a</sup> at 0°C = $1.316 \times 10^{-2}$	$1.333 \times 10^4$	5.353	1	1333	0.1934	27.85
1 PASCAL = $9.869 \times 10^{-6}$	10	$4.015 \times 10^{-3}$	$7.501 \times 10^{-4}$	1	$1.450 \times 10^{-4}$	$2.089 \times 10^{-2}$
1 pound per inch <sup>2</sup> = $6.805 \times 10^{-2}$	$6.895 \times 10^4$	27.68	5.171	$6.895 \times 10^3$	1	144
1 pound per foot <sup>2</sup> = $4.725 \times 10^{-4}$	478.8	0.1922	$3.591 \times 10^{-2}$	47.88	$6.944 \times 10^{-3}$	1

<sup>a</sup> Where the acceleration of gravity has the standard value of 9.80665 m/s<sup>2</sup>.

$$1 \text{ bar} = 10^6 \text{ dyne/cm}^2 = 0.1 \text{ MPa}$$
$$1 \text{ millibar} = 10^3 \text{ dyne/cm}^2 = 10^2 \text{ Pa}$$
$$1 \text{ torr} = 1 \text{ mm Hg}$$

## Energy, Work, Heat

		erg	ft · lb	hp · h	JOULE	cal	kW · h	eV	MeV
1 British thermal unit =	1	1.055 × 10 <sup>10</sup>	777.9	3.929 × 10 <sup>-4</sup>	1055	252.0	2.930 × 10 <sup>-4</sup>	6.585 × 10 <sup>21</sup>	6.585 × 10 <sup>15</sup>
1 erg =	9.481 × 10 <sup>-11</sup>	1	7.376 × 10 <sup>-8</sup>	3.725 × 10 <sup>-14</sup>	10 <sup>-7</sup>	2.389 × 10 <sup>-8</sup>	2.778 × 10 <sup>-14</sup>	6.242 × 10 <sup>11</sup>	6.242 × 10 <sup>5</sup>
1 foot-pound =	1.285 × 10 <sup>-3</sup>	1.356 × 10 <sup>7</sup>	1	5.051 × 10 <sup>-7</sup>	1.356	0.3238	3.766 × 10 <sup>-7</sup>	8.464 × 10 <sup>18</sup>	8.464 × 10 <sup>12</sup>
1 horsepower-hour =	2545	2.685 × 10 <sup>13</sup>	1.980 × 10 <sup>6</sup>	1	2.685 × 10 <sup>6</sup>	6.413 × 10 <sup>5</sup>	0.7457	1.676 × 10 <sup>25</sup>	1.676 × 10 <sup>19</sup>
1 JOULE =	9.481 × 10 <sup>-4</sup>	10 <sup>7</sup>	0.7376	3.725 × 10 <sup>-7</sup>	1	0.2389	2.778 × 10 <sup>-7</sup>	6.242 × 10 <sup>18</sup>	6.242 × 10 <sup>12</sup>
1 calorie =	3.969 × 10 <sup>-3</sup>	4.186 × 10 <sup>7</sup>	3.088	1.560 × 10 <sup>-6</sup>	4.186	1	1.163 × 10 <sup>-6</sup>	2.613 × 10 <sup>19</sup>	2.613 × 10 <sup>13</sup>
1 kilowatt hour =	3413	3.600 × 10 <sup>13</sup>	2.655 × 10 <sup>6</sup>	1.341	3.600 × 10 <sup>6</sup>	8.600 × 10 <sup>5</sup>	1	2.247 × 10 <sup>25</sup>	2.247 × 10 <sup>19</sup>
1 electron-volt =	1.519 × 10 <sup>-22</sup>	1.602 × 10 <sup>-12</sup>	1.182 × 10 <sup>-19</sup>	5.967 × 10 <sup>-26</sup>	1.602 × 10 <sup>-19</sup>	3.827 × 10 <sup>-20</sup>	4.450 × 10 <sup>-26</sup>	1	10 <sup>-6</sup>
1 million electron-volts =	1.519 × 10 <sup>-16</sup>	1.602 × 10 <sup>-6</sup>	1.182 × 10 <sup>-13</sup>	5.967 × 10 <sup>-20</sup>	1.602 × 10 <sup>-13</sup>	3.827 × 10 <sup>-14</sup>	4.450 × 10 <sup>-20</sup>	10 <sup>-6</sup>	1

## Power

Btu/h	ft · lb/s	hp	cal/s	kW	WATT
1 British thermal unit per hour = 1	0.2161	$3.929 \times 10^{-4}$	$6.998 \times 10^{-2}$	$2.930 \times 10^{-4}$	0.2930
1 foot-pound per second = 4.628	1	$1.818 \times 10^{-3}$	0.3239	$1.356 \times 10^{-3}$	1.356
1 horsepower = 2545	550	1	178.1	0.7457	745.7
1 calorie per second = 14.29	3.088	$5.615 \times 10^{-3}$	1	$4.186 \times 10^{-3}$	4.186
1 kilowatt = 3413	737.6	1.341	238.9	1	1000
1 WATT = 3.413	0.7376	$1.341 \times 10^{-3}$	0.2389	0.001	1

## Magnetic Field

<b>gauss</b>	<b>TESLA</b>	<b>milligauss</b>
1 gauss = 1	$10^{-4}$	1000
1 TESLA = $10^4$	1	$10^7$
1 milligauss = 0.001	$10^{-7}$	1

## Magnetic Flux

maxwell	WEBER
1 maxwell = 1	$10^{-8}$
1 WEBER = $10^8$	1

$$1 \text{ tesla} = 1 \text{ weber/meter}^2$$

# APPENDIX E

## Mathematical Formulas

### Geometry

Circle of radius  $r$ : circumference =  $2\pi r$ ; area =  $\pi r^2$ .

Sphere of radius  $r$ : area =  $4\pi r^2$ ; volume =  $\frac{4}{3}\pi r^3$ .

Right circular cylinder of radius  $r$  and height  $h$ :  
area =  $2\pi r^2 + 2\pi rh$ ; volume =  $\pi r^2 h$ .

Triangle of base  $a$  and altitude  $h$ : area =  $\frac{1}{2}ah$ .

### Quadratic Formula

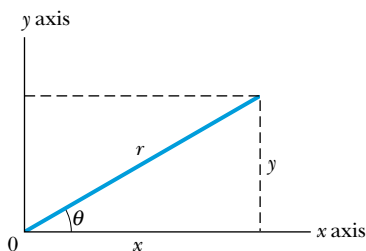
If  $ax^2 + bx + c = 0$ , then  $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$ .

### Trigonometric Functions of Angle $\theta$

$$\sin \theta = \frac{y}{r} \quad \cos \theta = \frac{x}{r}$$

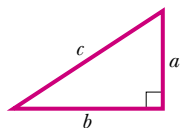
$$\tan \theta = \frac{y}{x} \quad \cot \theta = \frac{x}{y}$$

$$\sec \theta = \frac{r}{x} \quad \csc \theta = \frac{r}{y}$$



### Pythagorean Theorem

In this right triangle,  
 $a^2 + b^2 = c^2$



### Triangles

Angles are  $A, B, C$

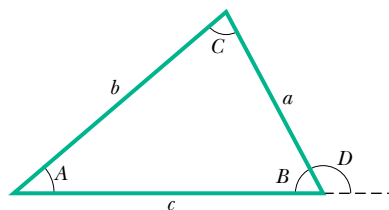
Opposite sides are  $a, b, c$

Angles  $A + B + C = 180^\circ$

$$\frac{\sin A}{a} = \frac{\sin B}{b} = \frac{\sin C}{c}$$

$$c^2 = a^2 + b^2 - 2ab \cos C$$

Exterior angle  $D = A + C$



### Mathematical Signs and Symbols

= equals

≈ equals approximately

~ is the order of magnitude of

≠ is not equal to

≡ is identical to, is defined as

> is greater than ( $\gg$  is much greater than)

< is less than ( $\ll$  is much less than)

≥ is greater than or equal to (or, is no less than)

≤ is less than or equal to (or, is no more than)

± plus or minus

∝ is proportional to

$\Sigma$  the sum of

$\langle x \rangle$  the average value of  $x$

### Trigonometric Identities

$$\sin(90^\circ - \theta) = \cos \theta$$

$$\cos(90^\circ - \theta) = \sin \theta$$

$$\sin \theta / \cos \theta = \tan \theta$$

$$\sin^2 \theta + \cos^2 \theta = 1$$

$$\sec^2 \theta - \tan^2 \theta = 1$$

$$\csc^2 \theta - \cot^2 \theta = 1$$

$$\sin 2\theta = 2 \sin \theta \cos \theta$$

$$\cos 2\theta = \cos^2 \theta - \sin^2 \theta = 2 \cos^2 \theta - 1 = 1 - 2 \sin^2 \theta$$

$$\sin(\alpha \pm \beta) = \sin \alpha \cos \beta \pm \cos \alpha \sin \beta$$

$$\cos(\alpha \pm \beta) = \cos \alpha \cos \beta \mp \sin \alpha \sin \beta$$

$$\tan(\alpha \pm \beta) = \frac{\tan \alpha \pm \tan \beta}{1 \mp \tan \alpha \tan \beta}$$

$$\sin \alpha \pm \sin \beta = 2 \sin \frac{1}{2}(\alpha \pm \beta) \cos \frac{1}{2}(\alpha \mp \beta)$$

$$\cos \alpha + \cos \beta = 2 \cos \frac{1}{2}(\alpha + \beta) \cos \frac{1}{2}(\alpha - \beta)$$

$$\cos \alpha - \cos \beta = -2 \sin \frac{1}{2}(\alpha + \beta) \sin \frac{1}{2}(\alpha - \beta)$$

### Binomial Theorem

$$(1 + x)^n = 1 + \frac{nx}{1!} + \frac{n(n-1)x^2}{2!} + \dots \quad (x^2 < 1)$$

### Exponential Expansion

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots$$

### Logarithmic Expansion

$$\ln(1 + x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \dots \quad (|x| < 1)$$

### Trigonometric Expansions ( $\theta$ in radians)

$$\sin \theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \dots$$

$$\cos \theta = 1 - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} - \dots$$

$$\tan \theta = \theta + \frac{\theta^3}{3} + \frac{2\theta^5}{15} + \dots$$



### Cramer's Rule

Two simultaneous equations in unknowns  $x$  and  $y$ ,

$$a_1x + b_1y = c_1 \quad \text{and} \quad a_2x + b_2y = c_2,$$

have the solutions

$$x = \frac{\begin{vmatrix} c_1 & b_1 \\ c_2 & b_2 \end{vmatrix}}{\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}} = \frac{c_1b_2 - c_2b_1}{a_1b_2 - a_2b_1}$$

and

$$y = \frac{\begin{vmatrix} a_1 & c_1 \\ a_2 & c_2 \end{vmatrix}}{\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}} = \frac{a_1c_2 - a_2c_1}{a_1b_2 - a_2b_1}.$$

### Products of Vectors

Let  $\hat{i}$ ,  $\hat{j}$ , and  $\hat{k}$  be unit vectors in the  $x$ ,  $y$ , and  $z$  directions. Then

$$\hat{i} \cdot \hat{i} = \hat{j} \cdot \hat{j} = \hat{k} \cdot \hat{k} = 1, \quad \hat{i} \cdot \hat{j} = \hat{j} \cdot \hat{k} = \hat{k} \cdot \hat{i} = 0,$$

$$\hat{i} \times \hat{i} = \hat{j} \times \hat{j} = \hat{k} \times \hat{k} = 0,$$

$$\hat{i} \times \hat{j} = \hat{k}, \quad \hat{j} \times \hat{k} = \hat{i}, \quad \hat{k} \times \hat{i} = \hat{j}.$$

Any vector  $\vec{a}$  with components  $a_x$ ,  $a_y$ , and  $a_z$  along the  $x$ ,  $y$ , and  $z$  axes can be written as

$$\vec{a} = a_x\hat{i} + a_y\hat{j} + a_z\hat{k}.$$

Let  $\vec{a}$ ,  $\vec{b}$ , and  $\vec{c}$  be arbitrary vectors with magnitudes  $a$ ,  $b$ , and  $c$ . Then

$$\vec{a} \times (\vec{b} + \vec{c}) = (\vec{a} \times \vec{b}) + (\vec{a} \times \vec{c})$$

$$(s\vec{a}) \times \vec{b} = \vec{a} \times (s\vec{b}) = s(\vec{a} \times \vec{b}) \quad (s = \text{a scalar}).$$

Let  $\theta$  be the smaller of the two angles between  $\vec{a}$  and  $\vec{b}$ . Then

$$\vec{a} \cdot \vec{b} = \vec{b} \cdot \vec{a} = a_xb_x + a_yb_y + a_zb_z = ab \cos \theta$$

$$\begin{aligned} \vec{a} \times \vec{b} &= -\vec{b} \times \vec{a} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ a_x & a_y & a_z \\ b_x & b_y & b_z \end{vmatrix} \\ &= \hat{i} \begin{vmatrix} a_y & a_z \\ b_y & b_z \end{vmatrix} - \hat{j} \begin{vmatrix} a_x & a_z \\ b_x & b_z \end{vmatrix} + \hat{k} \begin{vmatrix} a_x & a_y \\ b_x & b_y \end{vmatrix} \\ &= (a_yb_z - b_ya_z)\hat{i} + (a_zb_x - b_za_x)\hat{j} + (a_xb_y - b_xa_y)\hat{k} \\ |\vec{a} \times \vec{b}| &= ab \sin \theta \end{aligned}$$

$$\vec{a} \cdot (\vec{b} \times \vec{c}) = \vec{b} \cdot (\vec{c} \times \vec{a}) = \vec{c} \cdot (\vec{a} \times \vec{b})$$

$$\vec{a} \times (\vec{b} \times \vec{c}) = (\vec{a} \cdot \vec{c})\vec{b} - (\vec{a} \cdot \vec{b})\vec{c}$$

### Derivatives and Integrals

In what follows, the letters  $u$  and  $v$  stand for any functions of  $x$ , and  $a$  and  $m$  are constants. To each of the indefinite integrals should be added an arbitrary constant of integration. The *Handbook of Chemistry and Physics* (CRC Press Inc.) gives a more extensive tabulation.

#### Derivatives

$$1. \quad \frac{dx}{dx} = 1$$

$$2. \quad \frac{d}{dx}(au) = a \frac{du}{dx}$$

$$3. \quad \frac{d}{dx}(u + v) = \frac{du}{dx} + \frac{dv}{dx}$$

$$4. \quad \frac{d}{dx}x^m = mx^{m-1}$$

$$5. \quad \frac{d}{dx} \ln x = \frac{1}{x}$$

$$6. \quad \frac{d}{dx}(uv) = u \frac{dv}{dx} + v \frac{du}{dx}$$

$$7. \quad \frac{d}{dx}e^x = e^x$$

$$8. \quad \frac{d}{dx} \sin x = \cos x$$

$$9. \quad \frac{d}{dx} \cos x = -\sin x$$

$$10. \quad \frac{d}{dx} \tan x = \sec^2 x$$

$$11. \quad \frac{d}{dx} \cot x = -\csc^2 x$$

$$12. \quad \frac{d}{dx} \sec x = \tan x \sec x$$

$$13. \quad \frac{d}{dx} \csc x = -\cot x \csc x$$

$$14. \quad \frac{d}{dx} e^u = e^u \frac{du}{dx}$$

$$15. \quad \frac{d}{dx} \sin u = \cos u \frac{du}{dx}$$

$$16. \quad \frac{d}{dx} \cos u = -\sin u \frac{du}{dx}$$

**Integrals**

$$1. \int dx = x$$

$$2. \int au \, dx = a \int u \, dx$$

$$3. \int (u + v) \, dx = \int u \, dx + \int v \, dx$$

$$4. \int x^m \, dx = \frac{x^{m+1}}{m+1} \quad (m \neq -1)$$

$$5. \int \frac{dx}{x} = \ln |x|$$

$$6. \int u \frac{dv}{dx} \, dx = uv - \int v \frac{du}{dx} \, dx$$

$$7. \int e^x \, dx = e^x$$

$$8. \int \sin x \, dx = -\cos x$$

$$9. \int \cos x \, dx = \sin x$$

$$10. \int \tan x \, dx = \ln |\sec x|$$

$$11. \int \sin^2 x \, dx = \frac{1}{2}x - \frac{1}{4}\sin 2x$$

$$12. \int e^{-ax} \, dx = -\frac{1}{a} e^{-ax}$$

$$13. \int x e^{-ax} \, dx = -\frac{1}{a^2} (ax + 1) e^{-ax}$$

$$14. \int x^2 e^{-ax} \, dx = -\frac{1}{a^3} (a^2 x^2 + 2ax + 2) e^{-ax}$$

$$15. \int_0^\infty x^n e^{-ax} \, dx = \frac{n!}{a^{n+1}}$$

$$16. \int_0^\infty x^{2n} e^{-ax^2} \, dx = \frac{1 \cdot 3 \cdot 5 \cdots (2n-1)}{2^{n+1} a^n} \sqrt{\frac{\pi}{a}}$$

$$17. \int \frac{dx}{\sqrt{x^2 + a^2}} = \ln(x + \sqrt{x^2 + a^2})$$

$$18. \int \frac{x \, dx}{(x^2 + a^2)^{3/2}} = -\frac{1}{(x^2 + a^2)^{1/2}}$$

$$19. \int \frac{dx}{(x^2 + a^2)^{3/2}} = \frac{x}{a^2(x^2 + a^2)^{1/2}}$$

$$20. \int_0^\infty x^{2n+1} e^{-ax^2} \, dx = \frac{n!}{2a^{n+1}} \quad (a > 0)$$

$$21. \int \frac{x \, dx}{x + d} = x - d \ln(x + d)$$

# APPENDIX F

## Properties of Common Elements

All physical properties are for a pressure of 1 atm unless otherwise specified.

Element	Symbol	Atomic Number Z	Molar Mass, g/mol	Density, g/cm <sup>3</sup> at 20°C	Melting Point, °C	Boiling Point, °C	Specific Heat, J/(g·°C) at 25°C
Aluminum	Al	13	26.9815	2.699	660	2450	0.900
Antimony	Sb	51	121.75	6.691	630.5	1380	0.205
Argon	Ar	18	39.948	$1.6626 \times 10^{-3}$	−189.4	−185.8	0.523
Arsenic	As	33	74.9216	5.78	817 (28 atm)	613	0.331
Barium	Ba	56	137.34	3.594	729	1640	0.205
Beryllium	Be	4	9.0122	1.848	1287	2770	1.83
Bismuth	Bi	83	208.980	9.747	271.37	1560	0.122
Boron	B	5	10.811	2.34	2030	—	1.11
Bromine	Br	35	79.909	3.12 (liquid)	−7.2	58	0.293
Cadmium	Cd	48	112.40	8.65	321.03	765	0.226
Calcium	Ca	20	40.08	1.55	838	1440	0.624
Carbon	C	6	12.01115	2.26	3727	4830	0.691
Cesium	Cs	55	132.905	1.873	28.40	690	0.243
Chlorine	Cl	17	35.453	$3.214 \times 10^{-3}$ (0°C)	−101	−34.7	0.486
Chromium	Cr	24	51.996	7.19	1857	2665	0.448
Cobalt	Co	27	58.9332	8.85	1495	2900	0.423
Copper	Cu	29	63.54	8.96	1083.40	2595	0.385
Fluorine	F	9	18.9984	$1.696 \times 10^{-3}$ (0°C)	−219.6	−188.2	0.753
Gadolinium	Gd	64	157.25	7.90	1312	2730	0.234
Gallium	Ga	31	69.72	5.907	29.75	2237	0.377
Germanium	Ge	32	72.59	5.323	937.25	2830	0.322
Gold	Au	79	196.967	19.32	1064.43	2970	0.131
Hafnium	Hf	72	178.49	13.31	2227	5400	0.144
Helium	He	2	4.0026	$0.1664 \times 10^{-3}$	−269.7	−268.9	5.23
Hydrogen	H	1	1.00797	$0.08375 \times 10^{-3}$	−259.19	−252.7	14.4
Indium	In	49	114.82	7.31	156.634	2000	0.233
Iodine	I	53	126.9044	4.93	113.7	183	0.218
Iridium	Ir	77	192.2	22.5	2447	(5300)	0.130
Iron	Fe	26	55.847	7.874	1536.5	3000	0.447
Krypton	Kr	36	83.80	$3.488 \times 10^{-3}$	−157.37	−152	0.247
Lanthanum	La	57	138.91	6.189	920	3470	0.195
Lead	Pb	82	207.19	11.35	327.45	1725	0.129
Lithium	Li	3	6.939	0.534	180.55	1300	3.58
Magnesium	Mg	12	24.312	1.738	650	1107	1.03
Manganese	Mn	25	54.9380	7.44	1244	2150	0.481
Mercury	Hg	80	200.59	13.55	−38.87	357	0.138
Molybdenum	Mo	42	95.94	10.22	2617	5560	0.251
Neodymium	Nd	60	144.24	7.007	1016	3180	0.188

Element	Symbol	Atomic Number Z	Molar Mass, g/mol	Density, g/cm <sup>3</sup> at 20°C	Melting Point, °C	Boiling Point, °C	Specific Heat, J/(g·°C) at 25°C
Neon	Ne	10	20.183	$0.8387 \times 10^{-3}$	−248.597	−246.0	1.03
Nickel	Ni	28	58.71	8.902	1453	2730	0.444
Niobium	Nb	41	92.906	8.57	2468	4927	0.264
Nitrogen	N	7	14.0067	$1.1649 \times 10^{-3}$	−210	−195.8	1.03
Osmium	Os	76	190.2	22.59	3027	5500	0.130
Oxygen	O	8	15.9994	$1.3318 \times 10^{-3}$	−218.80	−183.0	0.913
Palladium	Pd	46	106.4	12.02	1552	3980	0.243
Phosphorus	P	15	30.9738	1.83	44.25	280	0.741
Platinum	Pt	78	195.09	21.45	1769	4530	0.134
Plutonium	Pu	94	(244)	19.8	640	3235	0.130
Polonium	Po	84	(210)	9.32	254	—	—
Potassium	K	19	39.102	0.862	63.20	760	0.758
Radium	Ra	88	(226)	5.0	700	—	—
Radon	Rn	86	(222)	$9.96 \times 10^{-3}$ (0°C)	(−71)	−61.8	0.092
Rhenium	Re	75	186.2	21.02	3180	5900	0.134
Rubidium	Rb	37	85.47	1.532	39.49	688	0.364
Scandium	Sc	21	44.956	2.99	1539	2730	0.569
Selenium	Se	34	78.96	4.79	221	685	0.318
Silicon	Si	14	28.086	2.33	1412	2680	0.712
Silver	Ag	47	107.870	10.49	960.8	2210	0.234
Sodium	Na	11	22.9898	0.9712	97.85	892	1.23
Strontium	Sr	38	87.62	2.54	768	1380	0.737
Sulfur	S	16	32.064	2.07	119.0	444.6	0.707
Tantalum	Ta	73	180.948	16.6	3014	5425	0.138
Tellurium	Te	52	127.60	6.24	449.5	990	0.201
Thallium	Tl	81	204.37	11.85	304	1457	0.130
Thorium	Th	90	(232)	11.72	1755	(3850)	0.117
Tin	Sn	50	118.69	7.2984	231.868	2270	0.226
Titanium	Ti	22	47.90	4.54	1670	3260	0.523
Tungsten	W	74	183.85	19.3	3380	5930	0.134
Uranium	U	92	(238)	18.95	1132	3818	0.117
Vanadium	V	23	50.942	6.11	1902	3400	0.490
Xenon	Xe	54	131.30	$5.495 \times 10^{-3}$	−111.79	−108	0.159
Ytterbium	Yb	70	173.04	6.965	824	1530	0.155
Yttrium	Y	39	88.905	4.469	1526	3030	0.297
Zinc	Zn	30	65.37	7.133	419.58	906	0.389
Zirconium	Zr	40	91.22	6.506	1852	3580	0.276

The values in parentheses in the column of molar masses are the mass numbers of the longest-lived isotopes of those elements that are radioactive. Melting points and boiling points in parentheses are uncertain. The data for gases are valid only when these are in their usual molecular state, such as H<sub>2</sub>, He, O<sub>2</sub>, Ne, etc. The specific heats of the gases are the values at constant pressure. *Primary source:* Adapted from J. Emsley, *The Elements*, 3rd ed., 1998, Clarendon Press, Oxford ([www.webelements.com](http://www.webelements.com)). Data on newest elements are current.

# APPENDIX G

## Periodic Table of the Elements




# Answers to Reading Exercises and Odd-Numbered Problems

(Answers that involve a proof, graph, or otherwise lengthy solution are not included.)

## Chapter 1

**RE 1-1:** Examples include second or hour, meter or inch, and gram or kilogram.

**RE 1-2:** A 12-inch ruler would more likely change less over time than your foot, especially if you are still growing.

**RE 1-3:** The length of one day or the time it takes for the earth to rotate  $360^\circ$  about its own axis is not constant, because the speed of the earth's rotation is slowly decreasing with time.

**RE 1-4:** (a) Since 24 h of time occurs for each  $360^\circ$  of rotation or 4 min for each degree of longitude or 240 s for each degree of longitude, 20 min and 13 s will relate to a rotation or longitude change of  $(1213 \text{ s})/(240 \text{ s/deg}) = 5.05$  degrees of longitude change. (b) If the clock is off by 2 min or 120 s, the longitude will be off by  $(120 \text{ s})/(240 \text{ s/degree}) = 0.5$  degrees of longitude. (c)  $360^\circ$  or one revolution relates to one circumference of length. Therefore  $0.5^\circ/360^\circ = x/(24\,000 \text{ nautical miles})$ , or  $x = 33.3$  nautical miles off course. Sailor beware!

**RE 1-5:** (a) If your watches are synchronized, you should measure the same time for the flash. For the same duration of time between the flash and thunder you both should have accurate watches and be located close to one another. (b) No, the 12 h (smaller) clock shows a time of 7:44 or a total elapsed time of 464 min since 12 o'clock. This is  $464 \text{ min}/(1440 \text{ min/day}) = .322$  day elapsed. The 10 h (larger) clock shows a time of 8.23 hours elapsed since 10 o'clock (12 o'clock on the other scale) or  $8.23/(20 \text{ hr/day}) = .412$  day elapsed.

**RE 1-6:** One of many possible procedures would be to use the balance to determine the amount of clay equal to 1 kg. Divide the clay into 1000 equal volume pieces. Assuming the density of the clay is uniform, each clay piece now has a mass of 1 gram. Use these pieces with the balance and the object whose mass is to be determined to find its mass.

**RE 1-7:** (a) It is correct to write  $1 \text{ min}/60 \text{ s} = 1$  because 1 minute and 60 seconds are the same *length* of time. It is meaningless to say  $1/60 = 1$  when no units are specified. These numbers are not the same in the absence of the context of the units. (b) In terms of conversion factors and chain-link conversions, the number of minutes in a day is given by

$$1 \text{ d} = (1 \text{ d}) \left( \frac{24 \text{ h}}{1 \text{ d}} \right) \left( \frac{60 \text{ min}}{1 \text{ h}} \right) = 1440 \text{ min.}$$

**RE 1-8:** (a) 2. (b) Exact, if the cows were counted. (c) 6. Remember that the leading zeros don't count. (d) 7. Trailing zeros do count. (e) Exact, by definition.

**RE 1-9:** (a) 11. (b) Probably 3, we can't be sure. (c)  $2.09 \times 10^{10} \text{ ft.}$  (d)  $10^{10} \text{ ft}$  (ten to the tenth feet).

**RE 1-10:** (a) You should keep all digits for intermediate results; thus you should use  $A = 1.96 \text{ cm}^2$  for calculating  $V$ . (b)  $2.7 \text{ cm}^3$ ; in this situation the answer can be to no more significant figures than the original data. (c)  $2.8 \text{ cm}^3$ .

**RE 1-11:** (a) 27; (b) 198.0; (c) 0.6; (d) 0.9986, see *Evaluating Functions* in Appendix A, Section 5. (e) Since five is an exact number, the four significant numbers in the average length limits the answer to 10.67 m.

**RE 1-12:** (a) 0.01 s; (b) .01 s out of 1.78 s or  $.01/1.78 = 0.00562$ , or about 0.6%.

## Problems

**1.** (a) 0.98 ft/ns; (b) 0.30 mm/ps. **3.** C, D, A, B, E; the important criterion is the constancy of the daily variation, not its magnitude. **5.** 0.12 AU/min **7.** 2.1 h. **9.**  $1.21 \times 10^{12} \mu\text{s}$ . **11.** (a) 160 rods; (b) 40 chains. **13.** (a)  $4.00 \times 10^4 \text{ km}$ ; (b)  $5.10 \times 10^8 \text{ km}^2$ ; (c)  $1.08 \times 10^{12} \text{ km}^3$ . **15.**  $1.9 \times 10^{22} \text{ cm}^3$ . **17.**  $1.1 \times 10^3$  acre-feet. **19.**  $9.0 \times 10^{49}$ . **21.** (a)  $10^3 \text{ kg}$ ; (b) 158 kg/s. **23.** (a)  $1.18 \times 10^{-29} \text{ m}^3$ . **25.** 3.8 mg/s. **27.**  $8 \times 10^2 \text{ km}$ . **29.**  $6.0 \times 10^{26}$ . **31.** (a) 60.8 W; (b) 43.3 Z. **33.** 89 km. **35.**  $\approx 1 \times 10^{36}$ . **37.** 700 to 1500. **39.** (a) 293 U.S. bushels; (b)  $3.81 \times 10^3$  U.S. bushels. **41.**  $9.4 \times 10^{-3}$ . **43.** 5.95 km. **45.**  $1.9 \times 10^5 \text{ kg}$ . **47.**  $2 \times 10^4$  to  $4 \times 10^4$ . **49.** 10.7. **59.** (a) 13 597 kg; (b) 4917 L; (c) 6172 kg; (d) 20 075 L; (e) 45%

## Chapter 2

**RE 2-1:** (b), (c), and (d).

**RE 2-2:** Correct order: (c), (b), and (a).

**RE 2-3:** Yes, the displacement can be positive as long as the particle moves to a less negative position.

**RE 2-4:** (a) Average velocity is the displacement divided by the total time  $\langle v_x \rangle = 10 \text{ mi}/30 \text{ min} = 0.33 \text{ mi/min}$  due east. (b) Average speed is the total distance traveled divided by the total time  $\langle s \rangle = 30 \text{ mi}/30 \text{ min} = 1 \text{ mi/min}$ . (c) The answers are different because the displacement is different from the total distance traveled in the 30 minute time period.

**RE 2-5:** Instantaneous speed. The speedometer only tells you the speed at which you are currently driving, not your acceleration or direction.

## Ans-2 Answers to Reading Exercises and Odd-Numbered Problems

**RE 2-6:** (a) Remember that the velocity is the time derivative of the position equation. The velocity will be constant if it has no time dependence. Position equations 1 and 4 give a constant velocity. (b) The velocity is negative in equations 2 and 3.

**RE 2-7:** In returning to  $x_1$  the total displacement  $\Delta x = x_1 - x_1$  is zero. Since  $\langle v_x \rangle = \Delta x / \Delta t$ , the average velocity is also zero.

**RE 2-8:** (a) +, (b) -, (c) -, (d) +; remember that  $\vec{a}$  will have the same direction as  $\Delta \vec{v}$  or  $\vec{v}_2 - \vec{v}_1$ .

**RE 2-9:** The equations of Table 2-1 apply when  $a_x$  is constant. Take the second derivative of  $x$  with respect to  $t$  to find  $a_x$ . Only equations 1, 3 and 4 give a constant  $a_x$  ( $a_x = 0$  is a constant).

### Problems

**1.** 414 ms. **3.** (a) +40 km/h; (b) 40 km/h. **5.** (a) 73 km/h; (b) 68 km/h; (c) 70 km/h; (d) 0. **7.** (a) 0, -2, 0, 12 m; (b) +12 m; (c) +7 m/s. **9.** 1.4 m. **11.** (a) -6 m/s; (b) negative  $x$  direction; (c) 6 m/s; (d) first smaller, then zero, and then larger; (e) yes ( $t = 2$ s); (f) no. **13.** 100 m. **15.** (a) velocity squared; (b) acceleration; (c)  $\text{m}^2/\text{s}^2$ ,  $\text{m}/\text{s}^2$ . **17.** 20  $\text{m}/\text{s}^2$ , in the direction opposite to its initial velocity. **19.** (a)  $\text{m}/\text{s}^2$ ,  $\text{m}/\text{s}^3$ ; (b) 1.0 s; (c) 82 m; (d) -80 m; (e) 0, -12, -36, -72 m/s; (f) -6, -18, -30, -42  $\text{m}/\text{s}^2$ . **21.** 0.10 m. **23.** (a) 1.6 m/s; (b) 18 m/s. **25.** (a)  $3.1 \times 10^6$  s = 1.2 months; (b)  $4.6 \times 10^{13}$  m. **27.**  $1.62 \times 10^{15}$   $\text{m}/\text{s}^2$ . **29.** 2.5 s. **31.** (a) 3.56  $\text{m}/\text{s}^2$ ; (b) 8.43 m/s. **33.** (a) 5.00 m/s; (b) 1.67  $\text{m}/\text{s}^2$ ; (c) 7.50 m. **35.** (a) 0.74 s; (b) -6.2  $\text{m}/\text{s}^2$ . **37.** (a) 10.6 m; (b) 41.5 s. **39.** (a) 30 s; (b) 300 m. **41.** (a) 54 m, 18 m/s, -12  $\text{m}/\text{s}^2$ ; (b) 64 m at  $t = 4.0$  s; (c) 24 m/s at  $t = 2.0$  s; (d) -24  $\text{m}/\text{s}^2$ ; (e) 18 m/s. **49.** (a) 0.75 s; (b) 50 m. **57.** Since there is some latitude in what might be considered “the right answer” here, we have elected to mention some Web sites (current as of May 2002) where graphs for model rocket kinematics are shown: <http://www.rocket-roar.com/rap/alt.html>; <http://mks.nio-brara.com/altitude.html>; <http://www.boilerbay.com/rockets/>; **59.** 40 m.

### Chapter 3

**RE 3-1:** (a) The velocity of the cart on the carpet goes to zero at  $t = 1.1$  s. (b) The velocity of the cart on the track at  $t = 1.1$  s is approximately 0.65 m/s, so it still has (0.65 m/s/0.80 m/s) or 81% of its initial speed.

**RE 3-2:** (a) An elevator or car starting or stopping, or a merry-go-round moving at a constant speed. (b) The person feels heavy during startup and light during stopping. Objects, such as a marble, start to move with no apparent reason on the merry-go-round floor.

**RE 3-3:** (a) No acceleration: Sliding a block along a table with a small steady force or shoving on a huge object like a desk or car, etc., can result in either constant velocity motion or an inability to move the object (desk or car). (b) Acceleration: Pushing hard on a sliding block, pushing on a rolling ball, pushing or pulling someone on a vehicle with wheels, etc.

**RE 3-4:** You would attach one end of the rubber band to a post and hook the other end of the rubber band to a calibrated spring scale. Then you would record the unstretched length of the rubber band and the fact that the force on it is 0 N. Next you would pull on the rubber band with the spring scale until it reads 1 N and record the new length of the rubber band. Then you would repeat the process as the spring scale reads 2 N, 3 N, etc., recording the rubber-band length each time. In that way you can generate either a look-up table or a graph of force vs. rubber-band length. If greater precision is needed, you could take data for many more force-scale readings.

**RE 3-5:** (a)  $\vec{F} = (-26 \text{ N})\hat{i}$ ,  $\vec{a} = (-0.42 \text{ m}/\text{s}^2)\hat{i}$ ; (b)  $m = F/a = 62 \text{ kg}$ ; (c) 62 kg

**RE 3-6:** (a) The mass measurement in part (b) above uses the ratio of the force to acceleration and hence is the inertial mass. (b) We assumed that the student is on the surface of planet Earth and that the bathroom scale was calibrated for the same planet.

**RE 3-7:** In both cases (a) and (b) the acceleration is zero, therefore the net force must also be zero. This will require all three forces to add to zero as vectors. (a) This requires  $\vec{F}_C$  to point to the left in the diagram with a magnitude of 2 N so  $\vec{F}_C = (-2 \text{ N})\hat{i}$ . (b) Since the acceleration is also zero in this case, we still have  $\vec{F}_C = (-2 \text{ N})\hat{i}$ .

**RE 3-8:** (a) Bottom right cart has a net force of -5 N, top left has +4 N, top right has -1 N, and bottom left has a net force of zero. (b) Since the acceleration and net force are directly proportional, the accelerations rank in the same order.

**RE 3-9:** In the chosen coordinate system, all the accelerations in the  $v$  vs.  $t$  graphs shown in Fig. 3-2 are negative since the slopes are negative. (a) The box on carpet acceleration is about  $-3.9 \text{ m}/\text{s}^2$  as determined by calculating the slope of the  $v$  vs.  $t$  graph. Slope =  $(0.00 - 0.90)(\text{m}/\text{s}) / (0.23 - 0.00)(\text{s})$ . (b) The cart on track acceleration is about  $-0.15 \text{ m}/\text{s}^2$  as determined by calculating the slope of the  $v$  vs.  $t$  graph. Slope =  $(0.62 - 0.80)(\text{m}/\text{s}) / (1.2 - 0.0)(\text{s})$ .

**RE 3-10:** (a) There appear to be no other horizontal forces on the moving objects except friction. Thus, we can assume that the net force on each object is due to a friction force. This friction force seems to be constant since the acceleration is constant and we assume that  $F_x^{\text{net}} = ma_x$ . (b) Box on carpet  $F_x^{\text{fric}} = ma_x = 0.5 \text{ kg} \times (-3.9 \text{ m}/\text{s}^2) = -2 \text{ N}$ . It points to the left. (c) Cart on track  $F_x^{\text{fric}} = ma_x = 0.5 \text{ kg} \times (-0.15 \text{ m}/\text{s}^2) = -0.08 \text{ N}$ . It also points to the left.

**RE 3-11:** (a) A tossed object is changing its velocity at all times. Just before it reaches the top of its flight it has a positive velocity and just after it has a negative velocity. Since acceleration is rate of change of velocity over time, even the instantaneous acceleration doesn't go to zero over an infinitesimal time interval. (b) The Fig. 3-22 graph of velocity vs. time is linear with a constant negative slope. Since slope of a  $v_y$  vs.  $t$  graph represents the acceleration component  $a_y$ , then  $a_y = \text{constant}$  so  $\vec{a} = a_y\hat{j}$  is constant.

**RE 3-12:** Change every  $x$  in the two equations in Table 2-1 to a  $y$ . Then replace  $a_y$  (previously  $a_x$ ) with  $-g$ .

**RE 3-13:** (a) The unmagnetized paperclip will be attracted to the magnet and, in turn, the magnet will be attracted toward the paperclip. Newton's Third Law tells us that these attractive forces will be equal in magnitude to one another but opposite in direction; the force on the magnet will be to the left and the force on the paperclip will be to the right. (b) Newton's Third Law applies to all forces of interaction of which this is just one example.

### Problems

**1.** 16 N. **3.** (a) 0.02  $\text{m}/\text{s}^2$ ; (b)  $8 \times 10^4 \text{ km}$ ; (c)  $2 \times 10^3 \text{ m}/\text{s}$ . **5.**  $1.2 \times 10^5 \text{ N}$ . **7.** (a)  $4.9 \times 10^5 \text{ N}$ ; (b)  $1.5 \times 10^6 \text{ N}$ . **9.** (a) 245  $\text{m}/\text{s}^2$ ; (b) 20.4 kN. **11.** (a) 8.0 m/s; (b) + $x$  direction. **13.** 8.0  $\text{cm}/\text{s}^2$ . **15.**  $1.8 \times 10^4 \text{ N}$ . **17.** (a) 31.3 kN; (b) 24.4 kN. **19.**  $2Ma/(a + g)$ . **21.** 2.4 N. **23.** (a) 1.23 N; (b) 2.46 N; (c) 3.69 N; (d) 4.92 N; (e) 6.15 N; (f) 0.25 N. **25.** (a) 3.2 s; (b) 1.3 s. **27.** (a) 3.70 m/s; (b) 1.74 m/s; (c) 0.154 m. **29.**

4.0 m/s. **31.** 22 cm and 89 cm below the nozzle. **33.** (a) 5.4 s; (b) 41 m/s. **35.** (a) 1.23 cm; (b) 4 times, 9 times, 16 times, 25 times. **37.** (a) 29.4 m; (b) 2.45 s. **39.** (a) 3260 N (b)  $2.7 \times 10^3$  kg; (c) 1.2 m/s. **41.** (a) 17 s; (b) 290 m. **43.** (a) 11 N; (b) 2.2 kg; (c) 0; (d) 2.2 kg. **45.** (a) 494 N, up; (b) 494 N, down. **47.** (a) 1.1 N. **49.** 5.1 m/s. **51.** (a) 466 N; (b) 527 N.

## Chapter 4

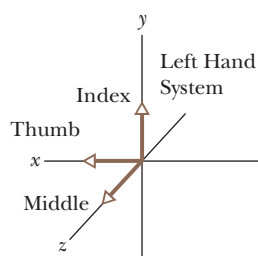
**RE 4-1:** Displacement (1) is identical as the ball ends up going a net distance of 6 meters north and 3 meters west. Displacement (2) is different. It actually has an equal magnitude but the ball has moved in the opposite direction. *Note:* Displacement does not depend on where something starts or ends, but only on how much and in what direction its position has changed relative to where it started.

**RE 4-2:** (a) The maximum magnitude occurs when the two vectors point in the same direction. This gives a magnitude for vector  $\vec{c}$  of  $3 \text{ m} + 4 \text{ m} = 7 \text{ m}$ . (This answer is not correct without a unit attached.) (b) The minimum magnitude occurs when the two vectors point in the opposite directions. This gives a magnitude for vector  $\vec{c}$  of  $4 \text{ m} - 3 \text{ m} = 1 \text{ m}$ .

**RE 4-3:** Methods (c), (d), and (f) work since the parallelogram methods (c) and (d) show that the same correct resultant can be obtained regardless of the order in which components are added. Method (f) shows an equivalent construction using components. All the other vectors point in the wrong directions.

**RE 4-4:** The vectors in figures (b) and (d) have the same components as the standard vector.

**RE 4-5:** Compare Figs 4-12 and 4-13.



**RE 4-6:** (a & b). The  $x$ - and  $y$ -components of  $\vec{d}_1$  are both positive. The  $x$ -component of  $\vec{d}_2$  is positive but the  $y$ -component points down in a negative direction. (c) Using the parallelogram method to get the vector sum of  $\vec{d}_1$  and  $\vec{d}_2$  results in a vector that has both  $x$ - and  $y$ -components that are positive.

**RE 4-7:** This is a kind of artificial question since units of force and acceleration are different as are units of displacement and velocity. However, if the scalars (mass and time respectively) act as compressors or stretchers, then the simplistic answers would be (a) The force vector would point in the same direction as the acceleration vector but be three times as long. (b) The velocity vector would point off in the same direction as the displacement vector and be twice as long since the displacement was divided by 0.5 s.

**RE 4-8:**

$$(a) \vec{F} = m\vec{a} = 3.0 \text{ kg}[(1.8 \text{ m/s}^2)\hat{i} + (1.0 \text{ m/s}^2)\hat{j}] = (5.4 \text{ N})\hat{i} + (3.0 \text{ N})\hat{j}.$$

$$(b) \langle \vec{v} \rangle = \frac{\Delta \vec{r}}{\Delta t} = \frac{(3.2 \text{ m})\hat{i} + (-0.8 \text{ m})\hat{j}}{0.5 \text{ s}} = (6.4 \text{ m/s})\hat{i} + (-1.6 \text{ m/s})\hat{j}.$$

## Problems

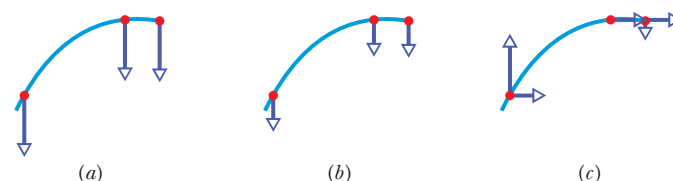
**1.** The displacements should be (a) parallel, (b) antiparallel, (c) perpendicular. **3.** (a) 5; (b) 1; (c) 7. **5.** (a)  $-2.5 \text{ m}$ ; (b)  $-6.9 \text{ m}$ . **7.** (a) 47.2 m; (b)  $122^\circ$ . **9.** (a) 168 cm; (b)  $32.5^\circ$  above the floor. **11.** (a) 6.42 m; (b) no; (c) yes; (d) yes; (e) a possible answer:  $(4.30 \text{ m})\hat{i} + (3.70 \text{ m})\hat{j} + (3.00 \text{ m})\hat{k}$ ; (f) 7.96 m. **13.** (a) 370 m; (b)  $36^\circ$  north of east; (c) 425 m; (d) the distance. **15.** (a)  $(-9 \text{ m})\hat{i} + (10 \text{ m})\hat{j}$ ; (b) 13 m; (c)  $+132^\circ$ . **17.** (a) 4.2 m; (b)  $40^\circ$  east of north; (c) 8.0 m; (d)  $24^\circ$  north of west. **19.** (a)  $(3.0 \text{ m})\hat{i} - (2.0 \text{ m})\hat{j} + (5.0 \text{ m})\hat{k}$ ; (b)  $(5.0 \text{ m})\hat{i} - (4.0 \text{ m})\hat{j} - (3.0 \text{ m})\hat{k}$ ; (c)  $(-5.0 \text{ m})\hat{i} + (4.0 \text{ m})\hat{j} + (3.0 \text{ m})\hat{k}$ . **21.** (a) 38 m; (b)  $320^\circ$ ; (c) 130 m; (d)  $1.2^\circ$ ; (e) 62 m; (f)  $130^\circ$ . **23.** (a) 1.59 m; (b) 12.1 m; (c) 12.2 m; (d)  $82.5^\circ$ . **29.** (a) Put axes along cube edges, with the origin at one corner. Diagonals are  $\vec{a}_i + \vec{a}_j + \vec{a}_k$ ,  $\vec{a}_i + \vec{a}_j - \vec{a}_k$ ,  $\vec{a}_i - \vec{a}_j - \vec{a}_k$ ; (b)  $54.7^\circ$ ; (c)  $\sqrt{3} a$ . **31.** **4.1.** **33.** (a) 103 km; (b)  $60.9^\circ$  north of due west. **35.** (a) 15 m; (b) south; (c) 6.0 m; (d) north. **37.** 5.0 km,  $4.3^\circ$  south of due west. **39.** 5.39 m at  $21.8^\circ$  left of forward. **41.** (a) 4.28 m; (b) 11.7 m. **43.** (a)  $-80 \text{ m}$ ; (b) 110 m; (c) 143 m; (d)  $+168^\circ$  (counterclockwise). **45.** 3.6 m. **47.** (a) 1.84 m; (b)  $69^\circ$  north of east. **49.** (a) 9.51 m; (b) 14.1 m; (c) 13.4 m; (d) 10.5 m. **51.** (a)  $9.19\hat{i} + 7.71\hat{j}$ ; (b)  $14.0\hat{i} + 3.41\hat{j}$

## Chapter 5

**RE 5-1:** (a) No, because in Fig. 5-5 the vertical positions of the ball on the right are the same as those of the ball on the left. (b) No. The horizontal positions of the ball on the right are equally spaced, indicating that horizontal velocity of the ball is constant and unaffected by the falling.

**RE 5-2:** The skateboarder's vertical motion is independent of his horizontal velocity. This is why the skateboarder lands back on his skateboard after his jump.

**RE 5-3:** (a) At each of the three points, the force vector points straight down and has a constant magnitude and (b) the same is true for the three acceleration vectors. (c) The horizontal component of each of the three velocity vectors points to the right and has a constant size. The vertical component of the velocity at the left point is directed straight upward and is slightly larger than the common size of the horizontal velocity components. The vertical component of the velocity at the center point is zero, while at the right point it is directed downward and is smaller in size than the horizontal velocity component.



**RE 5-4:** (a) The  $x$ -component of velocity is not changing and is the slope of Fig. 5-9. From the data in the figures, the slope is about 2.3 m/s. The initial  $y$ -component of velocity is the initial slope of Fig 5-10, which is about 3.5 m/s. The launch angle will be the inverse tangent of  $3.5/2.3$  or about  $57^\circ$ . (b) Using a protractor about  $57^\circ$ , too.

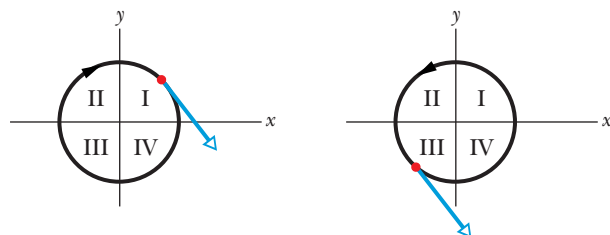
**RE 5-5:** (a) The horizontal component of velocity remains constant. (b) The vertical component of velocity is changing constantly as there is a vertical acceleration. (c) The horizontal component of its acceleration is zero. The only force (gravity) acting is in the vertical direction. (d) The vertical component of its acceleration is constant ( $9.8 \text{ m/s}^2$  downward).



## Ans-4 Answers to Reading Exercises and Odd-Numbered Problems

**RE 5-6:** (a) Using Eq. 5-15 and noting that  $\Delta x = 8 \text{ m}$  and  $\Delta y = -6 \text{ m}$  gives a displacement of  $\Delta \vec{r} = (8 \text{ m})\hat{i} + (-6 \text{ m})\hat{j}$ . (b) No, since it has components along both axes.

**RE 5-7:** (a) When traveling clockwise, the  $x$ -component of the particle's velocity is positive when it is in the I and II quadrant, and its  $y$ -component is negative in the I quadrant, so the particle is now in the I quadrant. (b) When traveling counterclockwise, the  $x$ -component of the particle's velocity is positive when it is in the III and IV quadrant, and its  $y$ -component is negative in the III quadrant, so the particle is then in the III quadrant.



(a) Quadrant I

(b) Quadrant II

**RE 5-8:** Remember that the  $x$ -component of acceleration will be in the direction of the change in the  $x$ -component of velocity and the  $y$ -component of acceleration will be in the direction of the change in the  $y$ -component of velocity. Just knowing the trajectory or path of the particle does not give you the direction of the acceleration. You also need to know how the velocity is changing as the particle travels along its trajectory. Therefore, if the change in the velocity vector is in the direction of the path of the particle,  $\vec{a}$  will be tangent to the trajectory. However, you will study other situations (Section 5-7) where  $\vec{a}$  is actually perpendicular to the trajectory, that is, the change in the velocity is perpendicular to the trajectory.

**RE 5-9:** The centripetal force is always inward toward the center of the curve. According to Newton's First Law, the passenger wants to travel in a straight line unless acted upon by a force. The centripetal force acts on the passenger through the friction between the passenger and the car seat. If that frictional force is not strong enough, the passenger tends to travel in a straight line and slides to the outside edge of the seat, where both the seat and the side of the car can provide the centripetal force needed to move your body in a curved path.

### Problems

**1.** (a) 62 ms; (b) 480 m/s. **3.** (a) 0.205 s; (b) 0.205 s; (c) 20.5 cm; (d) 61.5 cm. **5.** (a) 2.00 ns; (b) 2.00 mm; (c)  $1.00 \times 10^7 \text{ m/s}$ ; (d)  $2.00 \times 10^6 \text{ m/s}$ . **7.** (a) 16.9 m; (b) 8.21 m; (c) 27.6 m; (d) 7.26 m; (e) 40.2 m; (f) 0. **9.** 4.8 cm. **13.** (a) 11 m; (b) 23 m; (c) 17 m/s; (d)  $63^\circ$  below the horizontal. **15.** (a) 24 m/s; (b)  $65^\circ$  above the horizontal. **17.** (a) 10 s; (b) 897 m. **19.** the third. **21.** (a) 202 m/s; (b) 806 m; (c) 161 m/s; (d)  $-171 \text{ m/s}$ . **23.** (a) yes; (b) 2.56 m. **25.** between the angles  $31^\circ$  and  $63^\circ$  above the horizontal. **27.** (a)  $(-5.0 \text{ m})\hat{i} + (8.0 \text{ m})\hat{j}$ ; (b) 9.4 m; (c)  $122^\circ$ ; (e)  $(8 \text{ m})\hat{i} + (-8 \text{ m})\hat{j}$ ; (f) 11 m; (g)  $-45^\circ$ . **29.** (a)  $(-7.0 \text{ m})\hat{i} + (12 \text{ m})\hat{j}$ ; (b)  $x$  axis. **31.** 8.43 m at  $-129^\circ$ . **33.** 7.59 km/h,  $22.5^\circ$  east of north; **35.** (a)  $(3.00 \text{ m/s})\hat{i} + (-8.00 \text{ m/s})\hat{j}$ ; (b)  $(3.00 \text{ m/s})\hat{i} + (-16.00 \text{ m/s})\hat{j}$ ; (c) 16.3 m/s; (d)  $-79.4^\circ$ . **37.** 0.421 m/s at  $3.1^\circ$  west of due north. **39.** (a)  $(6.00 \text{ m})\hat{i} + (-106 \text{ m})\hat{j}$ ; (b)  $(19.0 \text{ m/s})\hat{i} + (-224 \text{ m/s})\hat{j}$ ; (c)  $(24.0 \text{ m/s}^2)\hat{i} + (-336 \text{ m/s}^2)\hat{j}$ ; (d)  $-85.2^\circ$  to  $+x$ . **41.** (a)  $(-1.5 \text{ m/s})\hat{j}$ ; (b)  $(4.5 \text{ m})\hat{i} + (-2.25 \text{ m})\hat{j}$ . **43.** (a). 45 m; (b) 22 m/s. **45.** (a)  $(8 \text{ m/s}^2)\hat{i}\hat{j}$ ; (b)  $(8 \text{ m/s}^2)\hat{j}\hat{i}$ . **47.** (a) 22 m; (b) 15 s. **49.**

(a) 7.49 km/s; (b) 8.00 m/s<sup>2</sup>. **51.** (a) 19 m/s; (b) 35 rev/min; (c) 1.7 s. **53.** (a) 0.034 m/s<sup>2</sup>; (b) 84 min. **55.** (a) 12 s; (b) 4.1 m/s<sup>2</sup>, down; (c) 4.1 m/s<sup>2</sup>, up. **57.** 160 m/s<sup>2</sup>. **59.** (4.00 m, 6.00 m)

### Chapter 6

**RE 6-1:** If you gather the tails of the three vectors shown in the helicopter diagram, you get the free-body diagram shown in (c).

**RE 6-2:** Use the balance in Fig. 3-9 and place one object on the left pan and the other object on the right pan. If the two objects have the same mass they will balance one another. They would have the same weight if they both gave the same reading on the spring scale. Also you could realize that if they have the same mass, they have the same weight since  $W = mg$  and  $g$  is a constant. The weight and mass are not the same. The weight is a force, and the mass is mass. Yes, since the weight and mass are proportional, the ratios are the same.

**RE 6-3:** It's true that the planet is yanking down on the patient but this is a force equal to his weight. However, since the normal force from the floor is equal and opposite, there is no net force and hence no acceleration.

**RE 6-4:** (a) In this case, at constant speed  $a$  equals zero and thus the net force must equal zero, requiring  $\vec{N}$  and  $\vec{F}^{\text{grav}}$  to be equal in magnitude and opposite in direction. (b) Since the only two forces acting on the block are  $\vec{N}$  and  $\vec{F}^{\text{grav}}$ , to have an upward acceleration we must have a net upward force, meaning that the magnitude of  $\vec{N}$  is now larger than that of  $\vec{F}^{\text{grav}}$ . (c) Slowing down means an acceleration or net force in the downward direction, requiring the magnitude of  $\vec{F}^{\text{grav}}$  to be larger than that of  $\vec{N}$ . What do you think would happen to  $\vec{N}$  if the elevator cable broke and the block fell freely with  $a = g$ ?

**RE 6-5:** In both answers to follow we are assuming the only forces acting on the block in the horizontal direction are the friction force and the pull of the cord, which is what the force sensor is measuring. Since in both cases there is no acceleration, these two forces must be equal and opposite, allowing us to equate the force sensor reading to the frictional force. (a) From the graph it looks like the block breaks free when the force is about 9.5 N. The total mass is 0.7956 kg, and the normal force that equals the weight is  $mg$ ; therefore using Eq. 6-11, we find  $\mu^{\text{stat}} = 9.5/(0.7956 \times 9.8) = 1.22$ . Notice that the coefficient of friction has no units. (b) From the graph, the force needed to keep the block moving at a constant speed is about 3.0 N. Using Eq. 6-10,  $\mu^{\text{kin}} = 3.0/(0.7956 \times 9.8) = 0.38$ .

**RE 6-6:** (a) Zero; (b) 5 N; (c) No; (d) Yes, there is now a net force of 2 N on the block causing it to accelerate; (e) 8 N.

**RE 6-7:** It is true that friction has both a bad side and a good side. Friction always tries to retard motion. If you desire that motion then friction is bad—for example, the pistons in your car engine—and we do everything we can (lubricants) to eliminate it. However, there are other times when we don't want motion (slippage) to occur, as when we are walking or riding a bike, and the force of friction allows us to do these activities.

**RE 6-8:** Think of the cord as an object with a mass you are trying to accelerate with only two forces—the one at one end from the hand and the other at the other end from the block. We will assume that the length of the cord hanging down on each side is the same so we can ignore the force of gravity on the cord. (a) If the cord is not accelerating then the magnitudes of the two forces are equal and can-

cel. (b) If the block is accelerating then so is the cord and the force of the hand on the cord is greater than that of the block. (c). In this case the acceleration is opposite to b and the pull force of the hand is less than the pull force due to the block.

**RE 6-9:** Look at Eq. 6-25. The only things in this equation that will change with the size of the drops are the mass,  $m$ , and the cross-sectional area  $A$ . So for this exercise  $v_t^2$  is proportional to  $m/A$ . How will this ratio change with the size of the drops?  $A$  changes as  $r^2$  and  $m$  changes as  $(\rho_{\text{water}})(\text{volume})$  and since volume goes as  $r^3$ , we finally determine that  $m/A$  and hence  $v_t^2$  goes as  $r$ . Therefore, large drops have greater speeds than small drops.

### Problems

**1.** (a)  $F_x = 1.88 \text{ N}$ ; (b)  $F_y = 0.684 \text{ N}$ ; (c)  $(1.88 \text{ N})\hat{i} + (0.684 \text{ N})\hat{j}$ .  
**3.**  $2.9 \text{ m/s}^2$ . **5.**  $(3 \text{ N})\hat{i} + (-11 \text{ N})\hat{j}$ . **7.** (a)  $(-32 \text{ N})\hat{i} + (-21 \text{ N})\hat{j}$ ; (b)  $38 \text{ N}$ ; (c)  $213^\circ$  from  $+x$ . **9.** (a)  $108 \text{ N}$ ; (b)  $108 \text{ N}$ ; (c)  $108 \text{ N}$ . **11.** (a)  $200 \text{ N}$ ; (b)  $120 \text{ N}$ . **13.**  $0.61$ . **15.** (a)  $190 \text{ N}$ ; (b)  $0.56 \text{ m/s}^2$ . **17.** (a)  $0.13 \text{ N}$ ; (b)  $0.12$ . **19.** (a) no; (b)  $(-12 \text{ N})\hat{i} + (5 \text{ N})\hat{j}$ . **23.** (a)  $300 \text{ N}$ ; (b)  $1.3 \text{ m/s}^2$ .  
**25.** (a)  $66 \text{ N}$ ; (b)  $2.3 \text{ m/s}^2$ . **27.** (b)  $3.0 \times 10^7 \text{ N}$ . **29.**  $100 \text{ N}$ .  
**31.** (a)  $0$ ; (b)  $3.9 \text{ m/s}^2$  down the incline; (c)  $1.0 \text{ m/s}^2$  down the incline.  
**33.** (a)  $3.5 \text{ m/s}^2$ ; (b)  $0.21 \text{ N}$ ; (c) blocks move independently. **35.**  $490 \text{ N}$ .  
**37.** (a)  $6.1 \text{ m/s}^2$ , leftward; (b)  $0.98 \text{ m/s}^2$ , leftward. **39.**  $g(\sin \theta - \sqrt{2}\mu^{\text{kin}} \cos \theta)$ . **41.**  $9.9 \text{ s}$ . **43.**  $6200 \text{ N}$ . **45.**  $2.3$ . **47.**  $1.5 \text{ mm}$ . **49.** (a)  $68 \text{ N}$  (b)  $73 \text{ N}$ . **51.** (a)  $2.2 \times 10^{-3} \text{ N}$ ; (b)  $3.7 \times 10^{-3} \text{ N}$ . **53.** (a)  $4.6 \times 10^3 \text{ N}$  for each bolt; (b)  $5.8 \times 10^3 \text{ N}$ . **55.** (a)  $180 \text{ N}$ ; (b)  $640 \text{ N}$ . **57.** (a)  $3.1 \text{ N}$ ; (b)  $14.7 \text{ N}$ . **59.** (a)  $6.8 \times 10^3 \text{ N}$  (b)  $-21^\circ$  or  $159^\circ$ . **61.** (b)  $F/(m + M)$ ; (c)  $MF/(m + M)$ ; (d)  $F(m + 2M)/2(m + M)$ . **63.**  $1.8 \times 10^4 \text{ N}$ .  
**65.** about  $48 \text{ km/h}$ . **67.**  $21 \text{ m}$ . **69.**  $\sqrt{Mg/r/m}$ . **71.** (a) light; (b)  $778 \text{ N}$ ; (c)  $223 \text{ N}$ . **73.**  $2.2 \text{ km}$ . **75.** (b)  $8.74 \text{ N}$ ; (c)  $37.9 \text{ N}$ , radially inward; (d)  $6.45 \text{ m/s}$ . **77.** (a)  $\sqrt{Rg \tan(\theta + \tan^{-1}(\mu^{\text{stat}}))}$ ; (b) graph; (c)  $41.3 \text{ m/s}$ ; (d)  $21.2 \text{ m/s}$ . **81.** (a)  $3.0 \text{ N}$ , up the incline; (b)  $3.0 \text{ N}$ , up the incline; (c)  $1.6 \text{ N}$ , up the incline; (d)  $4.4 \text{ N}$ , up the incline; (e)  $1.0 \text{ N}$ , down the incline. **83.**  $0.54$

### Chapter 7

**RE 7-1:** (a) The 60 s encounter between the *Titanic* and an iceberg was a collision. (b) A tennis ball encountering a racket for 2 s is not a collision.

**RE 7-2:** (a)  $|\vec{F}_1| > |\vec{F}_3| > |\vec{F}_2| = |\vec{F}_4| = 0$ . Since the slopes represent  $\Delta\vec{p}/\Delta t$  the magnitude is greatest where the slope is steepest. Thus, ranking is by steepness of slope. (b) Since the momentum is initially positive, the particle speeds up in region 1, drifts in region 2, and slows down in region 3, where its momentum is becoming less positive (and hence more negative).

**RE 7-3:** The change in the egg's momentum is  $m\vec{v}_2 - m\vec{v}_1$ , and since  $\vec{v}_2$  is zero the change is just  $m\vec{v}_1$ . The time you take in catching the egg does not affect the momentum change since the initial and final velocities are still the same. However the time taken in the catch will affect the average force the egg experiences. Since the change in momentum equals the impulse, which equals the average force times the time the force acts, making the time of the catch longer makes the average force on the egg less and hence a greater likelihood of a successful catch. In order to make  $\Delta t$  as large as possible, you move your hands and body backwards once the catch is made in order to bring the egg to zero speed over the largest time interval possible.

**RE 7-4:** (a)  $p_{1x}$  is to the right and  $+$ ,  $p_{2x}$  is to the left and  $-$ , therefore  $\Delta p_x$  is  $-$ . Remember that  $\Delta$  is always final minus initial, and here we have a negative number minus a positive number giving a negative re-

sult. (b)  $\Delta p_y$  is zero since the  $y$  component of the momentum does not change in the bounce. (c) The direction of  $\Delta\vec{p}$  is left. To see this, draw the two momentum vectors and subtract the initial from the final. Remember: To subtract vectors add the negative of the second to the first.

**RE 7-5:** (1) Assuming the carts are frictionless, the system consisting of the firecracker and the two carts is an isolated system and momentum should be conserved. In fact, if the firecracker is initially at rest and explodes symmetrically, then the carts should move off at the same speed in opposite directions. (2) Assuming the carts are not frictionless, then the track and the table and the Earth become part of the system. We might not see the carts come off with the same speeds in opposite directions. Instead the Earth might move (imperceptibly) to make up the difference. However, momentum is always conserved, so it should be so for our new system.

**RE 7-6:** (a) Zero, since no external forces are acting and hence the total momentum is conserved. (b) No, since the  $y$ -component of momentum must also be conserved. (c) The second piece must be moving in the negative direction on the  $x$  axis so that the total momentum after the explosion is zero.

**RE 7-7:** We need a mass for the grapefruit—let's say  $1.0 \text{ kg}$ . The grapefruit's momentum starts at zero and goes to  $(1 \text{ kg})(2 \text{ m/s}) = 2 \text{ kg} \cdot \text{m/s}$ , therefore  $\Delta p = 2 \text{ kg} \cdot \text{m/s}$ . The change in the Earth's momentum will be equal and opposite, therefore the change in the Earth's speed will be  $2 \text{ kg} \cdot \text{m/s}$  divided by the mass of the Earth. If you look at the inside front cover of this text, you find  $m_{\text{Earth}} = 5.98 \times 10^{24} \text{ kg}$ . Dividing, you get  $v_{\text{Earth}} = 3.3 \times 10^{-25} \text{ m/s}$ . Did you feel the Earth move?

### Problems

**1.**  $24 \text{ km/h}$ . **3.** (a)  $(-4.0 \times 10^4 \text{ kg} \cdot \text{m/s})\hat{i}$ ; (b) west. **5.** (a)  $30^\circ$ ; (b)  $(-0.572 \text{ kg} \cdot \text{m/s})\hat{j}$ . **7.**  $2.5 \text{ m/s}$ . **9.**  $3000 \text{ N}$ . **11.**  $67 \text{ m/s}$ , in opposite direction. **13.** (a)  $42 \text{ N} \cdot \text{s}$ ; (b)  $2100 \text{ N}$ . **15.** (a)  $(7.4 \times 10^3 \text{ N} \cdot \text{s})\hat{i} + (-7.4 \times 10^3 \text{ N} \cdot \text{s})\hat{j}$ ; (b)  $(-7.4 \times 10^3 \text{ N} \cdot \text{s})\hat{i}$ ; (c)  $2.3 \times 10^3 \text{ N}$ ; (d)  $2.1 \times 10^4 \text{ N}$ ; (e)  $-45^\circ$ . **17.**  $10 \text{ m/s}$ . **19.** (a)  $1.0 \text{ kg} \cdot \text{m/s}$ ; (b)  $10 \text{ N}$ ; (c)  $1700 \text{ N}$ ; (d) the answer for (b) includes time between pellet collisions. **21.**  $41.7 \text{ cm/s}$ . **23.** (a)  $46 \text{ N}$ ; (b) none. **25.**  $\approx 2 \text{ mm/y}$ . **27.**  $3.0 \text{ mm/s}$ , away from the stone. **29.** (a)  $4.6 \text{ m/s}$ ; (b)  $3.9 \text{ m/s}$ ; (c)  $7.5 \text{ m/s}$ . **31.** increases by  $4.4 \text{ m/s}$ . **33.**  $190 \text{ m/s}$ . **35.** (a)  $\{m_A/(m_A + m_B)\}v_{A1}$ . **37.** (a)  $7290 \text{ m/s}$ ; (b)  $8200 \text{ m/s}$ . **39.**  $4400 \text{ km/h}$ . **41.**  $8.1 \text{ m/s}$  at  $38^\circ$  south of east. **43.** (a)  $11.4 \text{ m/s}$ ; (b)  $95.1^\circ$  clockwise from  $+x$ . **45.** (a)  $61.7 \text{ km/h}$ ; (b)  $63.4^\circ$  south of west. **47.** (a)  $2.5 \text{ m/s}$ . **49.**  $1.0 \text{ m/s}$  north. **51.** (a)  $1.4 \times 10^{-22} \text{ kg} \cdot \text{m/s}$ ; (b)  $150^\circ$ ; (c)  $120^\circ$ . **53.**  $14 \text{ m/s}$ ,  $135^\circ$  from the other pieces. **55.**  $3.0 \text{ m/s}$ . **57.**  $120^\circ$ . **59.** (a)  $4.15 \times 10^5 \text{ m/s}$ ; (b)  $4.84 \times 10^5 \text{ m/s}$ . **61.** (a)  $41^\circ$ ; (b)  $4.76 \text{ m/s}$ ; (c) no. **63.**  $2.0 \text{ m/s}$ ,  $-x$  direction. **65.**  $108 \text{ m/s}$ . **67.** (a)  $1.57 \times 10^6 \text{ N}$ ; (b)  $1.35 \times 10^5 \text{ kg}$ ; (c)  $2.08 \text{ km/s}$ . **69.**  $2.2 \times 10^{-3}$

### Chapter 8

**RE 8-1:** (a) At the center; (b) in the lower right quadrant; (c) on the negative  $y$  axis; (d) at the center; (e) in the lower left quadrant; (f) at the center

**RE 8-2:** (a) The spacing between successive halfway points is the same, which suggests that the velocity represented by these points is constant.

(b)  $v = |\Delta\vec{r}/\Delta t = 0.41 \text{ m}/[(12/15)\text{s}] = 0.51 \text{ m/s}$

**RE 8-3:** Since there are no outside forces on the system, the center of mass of the system will not change. Thus, the skaters will end up meeting at the origin of the original coordinate system in all three sit-



## Ans-6 Answers to Reading Exercises and Odd-Numbered Problems

uations (a), (b), and (c). The only difference is that in case (a) Ethel will be holding one end of the “massless” pole at the end, in case (b) Fred will be holding an end of the “massless” pole, and in case (c) one-third of the “massless” pole will be sticking out behind Fred and two-thirds will be sticking out behind Ethel.

### Problems

1. (a)  $-4.5$  m; (b)  $-5.5$  m. **3.** (a) 4600 km; (b)  $0.73R_e$ . **5.** (a) 1.1 m; (b) 1.3 m; (c) shifts toward topmost particle. **7.** (a)  $-0.25$  m; (b) 0. **9.**  $6.8 \times 10^{-12}$  m from the nitrogen atom, along axis of symmetry. **11.** (a)  $H/2$ ; (b)  $H/2$ ; (c) descends to lowest point and then ascends to  $H/2$ ; (d)  $\frac{HM}{m} \left( \sqrt{1 + \frac{m}{M}} - 1 \right)$ . **13.**  $x_{\text{com}} = B/2$  and  $y_{\text{com}} = H/3$ . **15.**  $x_{\text{com}} = B/2$  and  $y_{\text{com}} = 4R/(3\pi)$ . **17.** (a) 0,0; (b) 0. **19.**  $(-1.50$  m,  $-1.43$  m). **21.** 29 m. **23.** 72 km/h. **25.** (a) 28 cm; (b) 2.3 m/s. **27.** 53 m. **29.** (a) halfway between the containers; (b) 26 mm toward the heavier container; (c) down; (d)  $-1.6 \times 10^{-2}$  m/s<sup>2</sup>. **31.** 4.2 m. **33.** 1.2 m/s, 132° counterclockwise from east. **37.** (a) 33 m/s; (b) 8.7 m/s. **39.** (a) 540 m/s; (b) 40.4°. **41.** (a)  $0.2000v^{\text{rel}}$ ; (b)  $0.2103v^{\text{rel}}$ ; (c)  $0.2095v^{\text{rel}}$ . **43.** (a) 1.0 m/s north; (b) 3 m north

### Chapter 9

**RE 9-1:** (a) Decreases. (b) Remains the same. Remember that the kinetic energy is a scalar and depends on the velocity squared, so  $-2$  m/s and  $2$  m/s give the same kinetic energy. (c) Negative for situation (a) and zero for situation (b). Situation (b) is interesting. How can the net work done be zero? Try breaking the velocity change into two changes: first from  $-2$  m/s to zero, then from zero to  $2$  m/s. For the first change the work is negative and for the second change the work is positive. When we add the two works together, we get zero for the total.

**RE 9-2:**  $c > a > b = d$

**RE 9-3:** Use Eq. 9-19: (a) positive; (b) negative; (c) zero. Think through your calculated answers. Do they make sense? For example, in (a) as the block moves from  $-3$  cm to the origin, the spring force and displacement are in the same direction giving a positive work; from the origin to  $2$  cm the spring force and displacement are in opposite directions giving a negative work, but the positive work is larger because the displacement is larger giving a net positive work.

**RE 9-4:**  $d > c > b > a$

**RE 9-5:** The power is zero at all times since  $\vec{F}$  and  $\vec{v}$  are always perpendicular in uniform circular motion.

### Problems

1.  $1.2 \times 10^6$  m/s. **3.** (a) 3610 J; (b) 1900 J; (c)  $1.1 \times 10^{10}$  J. **5.** (a)  $2.9 \times 10^7$  m/s; (b)  $2.1 \times 10^{-13}$  J. **7.** (a)  $7.5 \times 10^4$  J; (b)  $3.8 \times 10^4$  kg · m/s; (c) 38° south of east. **9.**  $1.18 \times 10^4$  kg. **11.** (a) 3.7 m/s; (b) 1.3 N · s; (c)  $1.8 \times 10^2$  N. **13.** (a) 42 J; (b) 30 J; (c) 12 J; (d) 6.48 m/s, positive direction of  $x$  axis; (e) 5.48 m/s, positive direction of  $x$  axis; (f) 3.46 m/s, positive direction of  $x$  axis. **15.**  $AB$ : +,  $BC$ : 0,  $CD$ : −,  $DE$ : +. **17.** (a) 170 N; (b) 340 m; (c)  $-5.8 \times 10^4$  J; (d) 340 N; (e) 170 m; (f)  $-5.8 \times 10^4$  J. **19.** 800 J. **21.** (a) 98 N; (b) 4.0 cm; (c) 3.9 J; (d)  $-3.9$  J. **23.** 0, by both methods. **25.** (a)  $-0.043$  J; (b)  $-0.13$  J. **27.** (a) 6.0 N; (b)  $-2.5$  N; (c) 15 N. **29.** 15.3 J. **31.** (a) 590 J; (b) 0; (c) 0; (d) 590 J. **33.** 6.8 J. **35.** (a) 1.20 J; (b) 1.10 m/s. **37.** (a) 1.50 J; (b) increases. **39.** (a)  $1.2 \times 10^4$  J; (b)  $-1.1 \times 10^4$  J; (c) 1100 J; (d) 5.4 m/s. **41.** (a)  $-3Mgd/4$ ; (b)  $Mgd$ ; (c)  $Mgd/4$ ; (d)  $\sqrt{gd/2}$ . **43.** 20 J. **45.** (a)  $8.84 \times 10^3$ ; (b)  $7.84 \times 10^3$  J; (c)  $6.84 \times 10^3$  J. **47.** (a) 2.3 J; (b) 2.6 J. **49.** 490 W. **51.** (a) 0.83 J; (b) 2.5 J; (c) 4.2 J; (d) 5.0 W. **53.** 740 W. **55.** 68 kW. **57.** (a)  $1.8 \times 10^5$  ft · lb; (b)

- 0.55 hp. **59.** (a) 8.8 m/s; (b) 2600 J; (c) 1.6 kW. **61.** 24 W. **63.** (a)  $2.1 \times 10^6$  kg; (b)  $\sqrt{100 + 1.5t}$  m/s; (c)  $(1.5 \times 10^6)/\sqrt{100 + 1.5t}$  N; (d) 6.7 km. **65.** (a)  $\approx 1 \times 10^5$  megatons; (b)  $\approx$  ten million bombs

### Chapter 10

**RE 10-1:** No, for the force to be conservative the work done in going between two points must not depend on the path taken. Also, if you go from 2 to 1 instead of 1 to 2 the work will change sign. Therefore, for the force in the exercise to be conservative the work for the bottom path should have a negative sign.

**RE 10-2:** A Hot Wheels® car that traverses path  $b$  should lose more kinetic energy than one that traverses path  $a$ . This is because path  $b$  is longer so the friction forces have more distance to act on path  $b$ .

**RE 10-3:** The kinetic energy of the barbell is zero before the lift and zero after the lift, as evidenced by the fact that  $y$  vs.  $t$  is a constant at  $t = 0.0$  s and at  $t = 2.0$  s. Since the kinetic energy change  $\Delta K = 0.0$  J, then the net work on the barbells should be zero. An examination of graph 10-10b shows that the positive work is approximately given by the area under the  $F^{\text{net}}$  vs.  $y$  curve.  $W^+ =$  area under the positive portion of the curve  $= (0.5)(116 \text{ N})(.15 \text{ m}) = +8.7$  J and  $W^- =$  area under the negative portion of the curve  $(0.5)(58 \text{ J})(.45 - .15) \text{ m} = -8.7$  J. So  $W^{\text{net}} = W^+ + W^- = 0.0$  J.

**RE 10-4:** Use Eq. 10-13. Note that the change in the potential energy is the negative of the area under the curves in the figure. The most positive will be (3) and the least positive (2).

**RE 10-5:** Without friction, the decrease in the potential energy will equal the increase in the kinetic energy. (a) Therefore, since all four blocks are losing the same amount of potential energy, they will all have the same kinetic energy at point  $B$ . (b) Since the kinetic energies are the same, the speeds are the same.

**RE 10-6:** Use the equation  $F_x^{\text{int}}(x) = -dU(x)/dx$ . The force is the negative of the slope of the  $U$  vs.  $x$  curve. (a) Ranking *magnitudes* with the greatest first:  $CD$ ,  $AB$ ,  $BC$ . (b) The slope is negative, hence the force is in the positive  $x$  direction.

**RE 10-7:**  $b > a > c$  as determined by the equation  $\Delta E^{\text{thermal}} = f_x^{\text{kin}} \Delta x$ .

**RE 10-8:** (a) 4 kg · m/s; (b) 8 kg · m/s; (c) assuming an elastic collision, 3 J.

**RE 10-9:** (a) 2 kg · m/s. (b) Since the initial  $y$ -component is zero, the final must be zero. Therefore, the final  $y$ -component of momentum for the target is 3 kg · m/s.

### Problems

1. 89 N/cm. **3.** (a) 4.31 mJ; (b)  $-4.31$  mJ; (c) 4.31 mJ; (d)  $-4.31$  mJ; (e) all increase. **5.** (a)  $mgL$ ; (b)  $-mgL$ ; (c) 0; (d)  $-mgL$ ; (e)  $mgL$ ; (f) 0; (g) same. **7.** (a) 184 J; (b)  $-184$  J; (c)  $-184$  J. **9.**  $-320$  J. **11.** (a) 2.08 m/s; (b) 2.08 m/s; (c) increase. **13.** (a)  $\sqrt{2gL}$ ; (b)  $2\sqrt{gL}$ ; (c)  $\sqrt{2gL}$ ; (d) all the same. **15.** (a) 260 m; (b) same; (c) decrease. **17.** (a) 21.0 m/s; (b) 21.0 m/s; (c) 21.0 m/s. **19.** (a) 0.98 J; (b)  $-0.98$  J; (c) 3.1 N/cm. **21.** (a) 39.2 J; (b) 39.2 J; (c) 4.00 m. **23.** (a) 35 cm; (b) 1.7 m/s. **25.** 10 cm. **27.** 1.25 cm. **31.** (a)  $2\sqrt{gL}$ ; (b)  $5mg$ ; (c) 71°. **33.**  $mgL/32$ . **37.** (a)  $1.12(A/B)^{1/6}$ ; (b) repulsive; (c) attractive. **39.** (a)  $-3.7$  J; (c) 1.29 m; (d) 9.12 m; (e) 2.16 J; (f) 4.0 m; (g)  $(4 - x)e^{-x/4}$  N; (h) 4 m. **41.** (a) 30.1 J; (b) 30.1 J; (c) 0.22. **43.** (a) 5.6 J; (b) 3.5 J. **45.** 11 kJ. **47.** 20 ft · lb. **49.** (a) 1.5 MJ; (b) 0.51 MJ; (c) 1.0 MJ; (d) 63 m/s. **51.** (a) 67 J;

(b) 67 J; (c) 46 cm. **53.** (a) 31.0 J; (b) 5.35 m/s; (c) conservative. **55.** (a) 44 m/s; (b) 0.036. **57.** (a)  $-0.90$  J; (b) 0.46 J; (c) 1.0 m/s. **59.** 1.2 m. **63.** in the center of the flat part. **65.** (a) 216 J; (b) 1180 N; (c) 432 J; (d) motor also supplies thermal energy to crate and belt. **67.** (a) 0.2 to 0.3 MJ; (b) same amount. **69.** (a) 860 N; (b) 2.4 m/s. **71.** (a)  $mR(\sqrt{2gh} + gt)$ ; (b) 5.06 kg. **73.** (a)  $mv_1/(m + M)$ ; (b)  $M/(m + M)$ . **75.** 25 cm. **79.** (a)  $41^\circ$ ; (b) 4.76 m/s; (c) no. **81.** (a) 6.9 m/s,  $30^\circ$  to  $+x$  direction; (b) 6.9 m/s,  $-30^\circ$  to  $+x$  direction; (c) 2.0 m/s,  $-x$  direction. **83.** (a) 99 g; (b) 1.9 m/s; (c) 0.93 m/s. **85.** 7.8%. **87.** (a) 1.2 kg; (b) 2.5 m/s. **89.** (a) 100 g; (b) 1.0 m/s. **91.** (a) 1.9 m/s, to the right; (b) yes; (c) no, total kinetic energy would have increased. **93.** (a)  $1/3$ ; (b)  $4h$ . **95.** 1.0 kg. **97.** (c) 11%; (d) 10%; (e) 79%

## Chapter 11

**RE 11-1:** (a) Positive, since  $\theta$  is increasing. (b) Negative, since  $\theta$  is decreasing.

**RE 11-2:** (a) Positive; (b) negative; (c) negative; (d) positive

**RE 11-3:** Find the angular acceleration,  $\alpha$ , by taking the second derivative of  $\theta$  with respect to  $t$ . The accelerations for (a) and (d) do not depend on  $t$  and are therefore constant, and hence the equations of Table 11-1 apply.

**RE 11-4:** Since the speeds are being squared,  $v^2$  and  $\omega^2$  will always be positive quantities.

**RE 11-5:** (a) Yes, the centripetal acceleration; (b) no, since  $\alpha$  is zero; (c) yes; (d) yes, since  $\alpha$  is no longer zero.

**RE 11-6:** Calculate  $mr^2$  for each, and you'll find they are all the same.

**RE 11-7:** (1)  $>$  (2)  $>$  (4)  $>$  (3). Remember that  $I$  depends not only on the mass but also on how far that mass is from the chosen axis.

**RE 11-8:**  $I_a = I_d = mr^2$ ,  $I_b = \frac{1}{2}mr^2$ ,  $I_c = \frac{5}{8}mr^2$ , so  $a = d > c > b$ .

**RE 11-9:**  $A = C > D > B = E = \text{zero}$ . For  $A$  and  $C$ ,  $\phi$  is  $90^\circ$ ; for  $D$ ,  $\phi$  is between zero and  $90^\circ$ ; for  $E$ ,  $\phi$  is zero; and for  $C$ ,  $r$  is zero.

**RE 11-10:** (a) Same direction. (b) Less.

## Problems

**1.** (a)  $a + 3bt^2 - 4ct^3$ ; (b)  $6bt - 12ct^2$ . **3.** (a)  $5.5 \times 10^{15}$  s; (b) 26. **5.** (a) 2 rad; (b) 0; (c) 130 rad/s; (d) 32 rad/s<sup>2</sup>; (e) no. **7.** 11 rad/s. **9.** (a)  $-67$  rev/min<sup>2</sup>; (b) 8.3 rev. **11.** 200 rev/min. **13.** 8.0 s. **15.** (a) 44 rad; (b) 5.5 s, 32 s; (c)  $-2.1$  s, 40 s. **17.** (a) 340 s; (b)  $-4.5 \times 10^{-3}$  rad/s<sup>2</sup>; (c) 98 s. **19.** 1.8 m/s<sup>2</sup>, toward the center. **21.** 0.13 rad/s. **23.** (a) 3.0 rad/s; (b) 30 m/s; (c) 6.0 m/s<sup>2</sup>; (d) 90 m/s<sup>2</sup>. **25.** (a)  $3.8 \times 10^3$  rad/s; (b) 190 m/s. **27.** (a)  $7.3 \times 10^{-5}$  rad/s; (b) 350 m/s; (c)  $7.3 \times 10^{-5}$  rad/s; (d) 460 m/s. **29.** 16 s. **31.** (a)  $-2.3 \times 10^{-9}$  rad/s<sup>2</sup>; (b) 2600 y; (c) 24 ms. **33.** 12.3 kg  $\cdot$  m<sup>2</sup>. **35.** (a) 1100 J; (b) 9700 J. **37.** (a)  $5md^2 + 8/3Md^2$ ; (b)  $(5/2m + 4/3M)d^2\omega^2$ . **39.** 0.097 kg  $\cdot$  m<sup>2</sup>. **41.**  $\frac{1}{3}M(a^2 + b^2)$ . **45.** 4.6 N  $\cdot$  m. **47.** (a)  $r_1F_A \sin \theta_1 - r_2F_B \sin \theta_2$ ; (b)  $-3.8$  N  $\cdot$  m. **49.** (a) 28.2 rad/s<sup>2</sup>; (b) 338 N  $\cdot$  m. **51.** (a) 155 kg  $\cdot$  m<sup>2</sup>; (b) 64.4 kg. **53.** 130 N. **55.** (a) 6.00 cm/s<sup>2</sup>; (b) 4.87 N; (c) 4.54 N; (d) 1.20 rad/s<sup>2</sup>; (e) 0.0138 kg  $\cdot$  m<sup>2</sup>. **57.** (a) 1.73 m/s<sup>2</sup>; (b) 6.92 m/s<sup>2</sup>. **59.** 396 N  $\cdot$  m. **61.** (a)  $mL^2\omega^2/6$ ; (b)  $L^2\omega^2/6g$ . **63.** 5.42 m/s. **65.**  $\frac{3}{2}\sqrt{\frac{g}{L}}$ . **67.** (a)  $[(3g/H)(1 - \cos \theta)]^{0.5}$ ; (b)  $3g(1 - \cos \theta)$ ; (c)  $3/2g \sin \theta$ ; (d)  $41.8^\circ$ . **69.** (a)  $0.083519ML^2 \approx 0.084ML^2$ ; (b) low by (only) 0.22%

## Chapter 12

**RE 12-1:** (a) When is the sin of the angle between the vectors zero? Sin is zero for  $0^\circ$  and  $180^\circ$ . (b) Here the sin needs to equal  $\pm 1$ . This occurs at  $90^\circ$  and  $270^\circ$ . (c) Here  $|\vec{c}||\vec{d}| \sin \phi = 3 \cdot 4 \sin \phi = 6$  so  $\phi = \sin^{-1}(6/12)$  so  $\phi = 30^\circ$  or  $150^\circ$ .

**RE 12-2:** The time rate of change of the rotational momentum is equal to the net torque.  $3 > 1 > 2 = 4 = \text{zero}$ .

**RE 12-3:** (a)  $1 = 3 > 2 = 4 > 5 = \text{zero}$ , since  $r_\perp$  is 4 m for both 1 and 3 and 2 m for both 2 and 4 and zero for 5. (b) Particles 2 and 3 have negative rotational momentum about  $o$ , since  $\vec{\ell} = \vec{r} \times \vec{p}$  points into the page for each of them.

**RE 12-4:** (a) Since the rate of change of the rotational momentum is equal to the applied torque, which is the same for all three cases, all three objects increase their rotational momentum at the same rate; and assuming all three started from rest, they will all have the same rotational momentum at any given time. (b) Look at Table 11-2 (Some Rotational Inertias). Note that  $I_{\text{hoop}} > I_{\text{disk}} > I_{\text{sphere}}$ . Since  $L = I\omega$  and they all have the same  $L$ , the object with the biggest  $I$  will have the smallest  $\omega$ ;  $\omega_{\text{sphere}} > \omega_{\text{disk}} > \omega_{\text{hoop}}$ .

**RE 12-5:** (a) Decrease, since although the total mass of the system has not changed, it is distributed closer to the axis of rotation. (b) Remain the same, since there is no net external torque. (c) If  $I$  decreases and  $L$  is constant, then  $\omega$  must increase.

## Problems

**1.** (a) 59.3 rad/s; (b) 9.31 rad/s<sup>2</sup>; (c) 70.7 m. **3.**  $-3.15$  J. **5.**  $1/50$  **7.** (a)  $8.0^\circ$ ; (b) more. **9.** (a) 13 cm/s<sup>2</sup>; (b) 4.4 s; (c) 55 cm/s; (d)  $1.8 \times 10^{-2}$  J; (e) 1.4 J; (f) 27 rev/s. **11.** (a) 10 s; (b) 897 m. **13.** the third. **17.** (a) 10 N  $\cdot$  m, parallel to  $yz$  plane, at  $53^\circ$  to  $+y$ ; (b) 22 N  $\cdot$  m,  $-x$ . **19.** (a)  $(50 \text{ N} \cdot \text{m})\hat{k}$ ; (b)  $90^\circ$ . **21.** (a)  $(-170 \text{ kg} \cdot \text{m}^2/\text{s})\hat{k}$ ; (b)  $(+56 \text{ N} \cdot \text{m})\hat{k}$ ; (c)  $(+56 \text{ kg} \cdot \text{m}^2/\text{s}^2)\hat{k}$ . **23.** (a) 0; (b)  $8t$  N  $\cdot$  m, in  $-z$  direction; (c)  $2/\sqrt{t}$  N  $\cdot$  m,  $-z$ ; (d)  $8/t^3$  N  $\cdot$  m,  $+z$ . **25.** 9.8 kg  $\cdot$  m<sup>2</sup>/s. **27.** (a) 0; (b)  $(8.0 \text{ N} \cdot \text{m})\hat{i} + (8.0 \text{ N} \cdot \text{m})\hat{k}$ . **29.** (a)  $mvd$ ; (b) no; (c) 0, yes. **31.** (a)  $-1.47$  N  $\cdot$  m; (b) 20.4 rad; (c)  $-29.9$  J; (d) 19.9 W. **33.** (a)  $14md^2$ ; (b)  $4md^2\omega$ ; (c)  $14md^2\omega$ . **35.**  $\omega_1 R_A R_B I_A / (I_A R_B^2 + I_B R_A^2)$ . **37.** (a) 3.6 rev/s; (b) 3.0; (c) in moving the bricks in, the forces on them from the man transferred energy from internal energy of the man to kinetic energy. **39.** (a) 267 rev/min; (b)  $2/3$ . **41.** (a) 149 kg  $\cdot$  m<sup>2</sup>; (b) 158 kg  $\cdot$  m<sup>2</sup>/s; (c) 0.746 rad/s. **43.**  $\frac{m}{M+m} \left( \frac{v}{R} \right)$ . **45.** (a)  $(mRv - I\omega_1)/(I + mR^2)$ ; (b) no, energy transferred to internal energy of cockroach. **47.** 3.4 rad/s. **49.** (a) 0.148 rad/s; (b) 0.0123; (c)  $181^\circ$ . **51.** The day would be longer by about 0.8 s. **53.** (a) 18 rad/s; (b) 0.92. **55.** (a) 0.24 kg  $\cdot$  m<sup>2</sup>; (b) 1800 m/s. **57.**  $\theta = \cos^{-1} \left[ 1 - \frac{6m^2h}{d(2m+M)(3m+M)} \right]$ . **59.** 11.0 m/s. **61.** (a) 0.180 m; (b) clockwise

## Chapter 13

**RE 13-1:** Situations (c), (e), and (f) can yield static equilibrium, since in each case both the net force and the net torque can be zero. In (a), (b), and (d) the net force can be zero but the net torque cannot.

**RE 13-2:** The apple's center of gravity will end up directly below the rod, since only in that position is the net torque on the apple *stably* zero. The net torque on the apple is also zero when the apple's center of gravity is directly *above* the rod, but this is an *unstable* equilibrium point and the slightest rotation will cause the apple to rotate away from this position.

## Ans-8 Answers to Reading Exercises and Odd-Numbered Problems

**RE 13-3:** You are better off if there is no friction between the ladder and the wall. With no friction between the ladder and the ground, the ground cannot exert any *horizontal* force to counter the horizontal force that the wall must exert on the ladder to keep it in place.

**RE 13-4:** In each of these three cases, the net horizontal force is zero independent of the magnitudes of the three unknown forces. This leaves only two independent equations for equilibrium—namely, net vertical force equals zero and net torque equals zero. But we have three unknowns to solve for. Since we can't do this, each of these three situations is indeterminate.

**RE 13-5:** Equation 13-29 tells us that, for elastic stretching, Young's modulus is just the stress ( $F/A$ ) divided by the strain ( $\Delta L/L$ ). Relative to rod 1, rod 2 has the same stress and twice the strain, and so its Young's modulus is half that of rod 1. By the same reasoning, rod 3 also has half the Young's modulus of rod 1, and rod 4 has a Young's modulus that is four times larger than that of rod 1. So, from higher to lower Young's modulus, rod 4 is the largest, rod 1 is next, and rods 2 and 3 tie for smallest.

**RE 13-6:** During bending, the particles on the inside of the bend are pushed closer together while those on the outside of the bend are pulled farther apart. During a shear deformation, adjacent planes of particles shift laterally with respect to one another. While the planes remain the same distance from one another, the "springs" (bonds) between adjacent planes are each stretched by the same amount.

### Problems

1. (a) 2; (b) 7 **3.** (a)  $(-27 \text{ N})\hat{i} + (2 \text{ N})\hat{j}$ ; (b)  $176^\circ$  counterclockwise from  $+x$  direction **5.** 7920 N **7.** (a)  $(mg/L) \sqrt{L^2 + r^2}$ ; (b)  $mgr/L$  **9.** (a) 1160 N, down; (b) 1740 N, up; (c) left; (d) right **11.** 74 g **13.** (a) 280 N; (b) 880 N,  $71^\circ$  above the horizontal **15.** (a) 8010 N; (b) 3.65 kN; (c) 5.66 kN **17.** 71.7 N **19.** (a) 5.0 N; (b) 30 N; (c) 1.3 m **21.**  $mg\sqrt{\frac{2rh - h^2}{r - h}}$  **23.** (a) 192 N; (b) 96.1 N; (c) 55.5 N **25.** (a) 6630 N; (b) 5740 N; (c) 5960 N **27.** 2.20 m **29.** 0.34 **31.** (a) 211 N; (b) 534 N; (c) 320 N **33.** (a) 445 N; (b) 0.50; (c) 315 N **35.** (a) slides at  $31^\circ$ ; (b) tips at  $34^\circ$  **37.** (a)  $6.5 \times 10^6 \text{ N/m}^2$ ; (b)  $1.1 \times 10^{-5} \text{ m}$  **39.** (a) 867 N; (b) 143 N; (c) 0.165 **41.** 44 N

### Chapter 14

**RE 14-1:** The ratio (relative amount) of the magnitudes of these two forces depends only on the square of the ratio of the two center-to-center distances between the Earth and the other mass.

**RE 14-2:** Equation 14-2 tells us that  $g$  (the acceleration of a freely falling body) is just  $(Gm_{\text{Earth}}/r^2)$  where  $r$  is the distance to the center of the Earth to the point where  $g$  is measured. This is consistent with the model that assumes that the Moon stays in its orbit simply because it is in free fall. Although the observations are consistent with this model, this does not "prove" that the model is "true." It only establishes that this model is "good enough" to account for the data at hand.

**RE 14-3:** Since the location of the particle lies outside each of the spheres at the same distance from the center of the sphere in each case, each of the spheres will exert exactly the *same* magnitude force on the particle.

**RE 14-4:**  $\vec{F}_{\text{grav}}$  due to the Earth *always* points directly toward the center of the Earth. However, the object's apparent weight associated with  $\vec{N}$ , (the "normal" force exerted on an object "at rest" on the surface of the rotating Earth), is *not* always directed exactly *away* from the center of the Earth! In fact,  $\vec{N}$  points directly away from the center of the Earth only at the Earth's poles and at its equator. Why?

**RE 14-5:** In each case the direction of  $\vec{F}_{\text{grav}}$  would be toward the center of the Earth. Case A: The magnitude of  $\vec{F}_{\text{grav}}$  would decrease as  $1/r^2$  where  $r$  is the distance to the center of the Earth. Case B: The magnitude of  $\vec{F}_{\text{grav}}$  would be proportional to  $r$ , and *hence decrease*. Case C: Because of the considerably higher density of the Earth's core compared with its surface crust, the magnitude of  $\vec{F}_{\text{grav}}$  would increase at first but then decrease to zero as we moved toward the center of the Earth.

**RE 14-6:** (a) The gravitational potential energy of the ball–sphere system increases. (b) The gravitational force between the ball and the sphere is attractive (inward), and the displacement is outward. Since the force and displacement are in opposite directions, the work done by the gravitational force is negative.

### Problems

1. 19 m **3.** 29 pN **5.**  $1/2$  **7.**  $2.60 \times 10^5 \text{ km}$  **9.** 0.017 N, toward the 300 kg sphere **11.**  $3.2 \times 10^{-7} \text{ N}$  **13.**  $\frac{GmM}{d^2} \left[ 1 - \frac{1}{8(1 - R/2d)^2} \right]$  **15.**  $2.6 \times 10^6 \text{ m}$  **17.** (b) 1.9 h **21.** (a)  $0.414R$ ; (b)  $0.5R$  **23.** (a)  $(3.0 \times 10^{-7} \text{ N/kg})m$ ; (b)  $(3.3 \times 10^{-7} \text{ N/kg})m$ ; (c)  $(6.7 \times 10^{-7} \text{ N/kg}\cdot\text{m})mr$  **25.** (a)  $9.83 \text{ m/s}^2$ ; (b)  $9.84 \text{ m/s}^2$ ; (c)  $9.79 \text{ m/s}^2$  **27.** (a)  $-1.3 \times 10^{-4} \text{ J}$ ; (b) less; (c) positive; (d) negative **29.** (a) 0.74; (b)  $3.7 \text{ m/s}^2$ ; (c) 5.0 km/s **31.** (a)  $5.0 \times 10^{-11} \text{ J}$ ; (b)  $-5.0 \times 10^{-11} \text{ J}$  **35.** (a) 1700 m/s; (b) 250 km; (c) 1400 m/s **37.** (a) 82 km/s; (b)  $1.8 \times 10^4 \text{ km/s}$  **39.**  $2.5 \times 10^4 \text{ km}$

### Chapter 15

**RE 15-1:** Half the weight of the woman,  $(125 \text{ lb}/2)(9.8 \text{ N}/2.2 \text{ lb}) \approx 300 \text{ N}$ , is supported by her two spike heels. Let's say that each heel makes contact with  $1 \text{ cm}^2 = 10^{-4} \text{ m}^2$  of the floor. Then the pressure of her heels on the floor is  $P = F/A = (300 \text{ N}/10^{-4} \text{ m}^2) = 3 \times 10^6 \text{ Pa}$ . This estimate is close to that presented in the table. This pressure is high because of the small contact area over which this otherwise modest force is applied. An automobile has a much larger contact area.

**RE 15-2:** If air and water are made up of molecules that are about the same size and mass, then the average distance between the molecules in air at sea level must be about  $1000^{1/3} = 10$  times larger than those of the water. This suggests that there is significantly more empty space around each air molecule, allowing them to be compressed closer together by quite a bit before they fill all of the available volume.

**RE 15-3:** The force the air exerts on the book is about  $(10^5 \text{ N/m}^2)(2.54 \times 10^{-2} \text{ m/in})^2 (2.2 \text{ lb}/9.8 \text{ N}) (8 \text{ in})(10 \text{ in}) \approx 1200 \text{ lb}$ . The close fit and the flexibility of the rubber mat prevents air from leaking into the space between the mat and the smooth tabletop, holding the mat down against the table with close to the full 1200 lb of force the air exerts on the top surface of the mat. The rougher surface of the book, as well as its rigidity, let air readily leak into the space between the book and the table when you start to pick up the book. This "equalizes" the pressure on each side of the book, reducing the net force that the air exerts on the book to a negligible amount.



**RE 15-4:** The density of air is only about one-thousandth that of water.

**RE 15-5:** The pressure at a depth  $\Delta y$  is the *same* in each container of oil. The shape of the container does not matter.

**RE 15-6:** Compressible fluids, like compressible springs, can “absorb” work and store it as elastic potential energy. Increasing the pressure of the compressible fluid in the hydraulic jack will thus store some of the work done on the fluid as elastic potential energy and slightly reduce the amount of work that the fluid does on the output by that amount.

**RE 15-7:** The pressure at the bottom of this container is determined solely by the depth of the fluid above the bottom and the pressure that the air exerts on the surface of that fluid. In particular, the weight of the “extra” fluid that lies outside the central column is *not* carried by the horizontal bottom of the container and does *not* increase the pressure there.

**RE 15-8:** (a) Since the penguin floats in each of the three fluids, each fluid supplies a buoyant force exactly equal to the penguin’s weight, so each fluid supplies the *same* buoyant force ( $A = B = C$ ). (b) The penguin must displace the amount of fluid that matches her weight. Thus she *displaces* more of the least dense fluid  $B$  than of  $A$ , and even less of the most dense fluid  $C$  ( $B > A > C$ ).

**RE 15-9:** You need to make sure that the weight of the canoe and its load is less than that of the water it displaces before the water starts coming in over the top edge of the hull. Although a chunk of concrete cannot displace its weight with water, a thin concrete canoe and its riders can.

**RE 15-10:** The net flow into (+) and out of (−) the entire system must be zero. So:  $+x + (4 + 8 + 4 - 6 + 5 - 2) \text{ cm}^3/\text{s} = 0 \text{ cm}^3/\text{s}$  or  $x = -13 \text{ cm}^3/\text{s}$ , so fluid flows out of the unlabeled pipe at a rate of  $13 \text{ cm}^3/\text{s}$ .

**RE 15-11:** (a) The area of face 1 is  $4.0 \text{ cm}^2 = 4.0 \times 10^{-4} \text{ m}^2$ . Face 2 has an area of  $5.7 \text{ cm}^2 = 5.7 \times 10^{-4} \text{ m}^2$ . Face 3 has an area of  $8.0 \text{ cm}^2 = 8.0 \times 10^{-4} \text{ m}^2$ . (b) The total surface area of all 6 faces is  $69.7 \text{ cm}^2 = 69.7 \times 10^{-4} \text{ m}^2$ .

**RE 15-12:** (a) The flux through any face is  $v \Delta A \cos(\theta)$ . Thus the flux through face 1 is  $(0.5 \text{ m/s})(4.0 \times 10^{-4} \text{ m}^2)(\cos(0)) = +2.0 \times 10^{-4} \text{ m}^3/\text{s}$ . The flux through face 2 is  $(0.5 \text{ m/s})(5.7 \times 10^{-4} \text{ m}^2)(\cos(45^\circ)) = +2.0 \times 10^{-4} \text{ m}^3/\text{s}$ . The flux through face 3 is  $(0.5 \text{ m/s})(8.0 \times 10^{-4} \text{ m}^2)(\cos(180^\circ)) = -4.0 \times 10^{-4} \text{ m}^3/\text{s}$ . (b) The flux through the front, back, and bottom faces is zero because  $\theta = 90^\circ$  for each of these faces and so the  $\cos(\theta)$  term in the expression for the flux is zero. (c) Adding the contributions from all six faces yields zero net flux through this closed surface, as expected.

**RE 15-13:** (a) The volume flow rate is the *same* through each of the four sections. (b) The flow speed is largest in section 1, followed by section 2 and section 3, where it will be the same, and finally section 4 has the smallest flow speed. Recall that the flow speed is inversely proportional to the local cross-sectional area of the pipe. (c) The pressure will be greatest in section 4, less in section 3, still less in section 2, and least in section 1. The pressure difference between sections 2 and 3 is due to their difference in altitude. The pressure differences between sections at the same altitude are due to differences in the flow speed.

## Problems

1.  $1.1 \times 10^5 \text{ Pa}$  or  $1.1 \text{ atm}$  3.  $2.9 \times 10^4 \text{ N}$  5.  $0.074$  7. (b)  $26 \text{ kN}$   
9.  $5.4 \times 10^4 \text{ Pa}$  11. (a)  $5.3 \times 10^6 \text{ N}$ ; (b)  $2.8 \times 10^5 \text{ N}$ ; (c)  $7.4 \times 10^5 \text{ N}$ ;  
(d) no 13.  $7.2 \times 10^5 \text{ N}$  15.  $\frac{1}{4} \rho g A (h_2 - h_1)^2$  17.  $1.7 \text{ km}$  19. (a)  
 $\rho g W D^2/2$ ; (b)  $\rho g W D^3/6$ ; (c)  $D/3$  21. (a)  $7.9 \text{ km}$ ; (b)  $16 \text{ km}$  23.  $4.4 \text{ mm}$   
25. (a)  $2.04 \times 10^{-2} \text{ m}^3$ ; (b)  $1570 \text{ N}$  27. (a)  $670 \text{ kg/m}^3$ ; (b)  $740 \text{ kg/m}^3$   
29. (a)  $1.2 \text{ kg}$ ; (b)  $1300 \text{ kg/m}^3$  31.  $57.3 \text{ cm}$  33.  $0.126 \text{ m}^3$  35. (a)  $45 \text{ m}^2$ ;  
(b) car should be over center of slab if slab is to be level 37. (a)  $9.4 \text{ N}$ ;  
(b)  $1.6 \text{ N}$  39.  $8.1 \text{ m/s}$  41.  $66 \text{ W}$  43. (a)  $2.5 \text{ m/s}$ ; (b)  $2.6 \times 10^5 \text{ Pa}$   
45. (a)  $3.9 \text{ m/s}$ ; (b)  $88 \text{ kPa}$  47. (a)  $1.6 \times 10^{-3} \text{ m}^3/\text{s}$ ; (b)  $0.90 \text{ m}$   
49.  $116 \text{ m/s}$  51. (a)  $6.4 \text{ m}^3$ ; (b)  $5.4 \text{ m/s}$ ; (c)  $9.8 \times 10^4 \text{ Pa}$  53. (a)  $74 \text{ N}$ ;  
(b)  $150 \text{ m}^3$  55. (b)  $2.0 \times 10^{-2} \text{ m}^3/\text{s}$  57. (b)  $63.3 \text{ m/s}$

## Chapter 16

**RE 16-1:** The amplitude and the angular frequency will stay the same. The initial phase will differ from  $\phi_0$  by  $90^\circ$  or  $\pi/2$  since you can think of a cosine as a sine that has been shifted  $90^\circ$  to the left.

**RE 16-2:** (a) When  $t = 2.00 T$  the particle will have moved through two full oscillations and will be back where it started from—namely, at  $x = -X$ . (b) When  $t = 3.50 T$  the particle will have moved through three full oscillations and an additional half oscillation and so will be at  $x = +X$ . (c) When  $t = 5.25 T$  the particle will have moved through five full oscillations and an additional quarter oscillation and so will be at  $x = 0$ .

**RE 16-3:** Equation 16-12 tells us that the period of a mass on a given spring increases as the amount of oscillating mass increases. The fact that the mass of the spring itself oscillates along with the mass on its end suggests that some of the spring’s mass should be included in the mass that appears in Eq. 16-12. Since the spring oscillates with a progressively smaller amplitude as we go from its moving end to its fixed end, only some fraction of the spring’s mass needs to be included in this corrected total oscillating mass.

**RE 16-4:** Only (a) implies simple harmonic motion. Although (b) is a restoring type of force, it is quadratic, not linear in  $x$ . Force (c) is repulsive rather than attractive, driving the particle away from  $x = 0$  rather than back toward it. Force (d) is both repulsive and nonlinear.

**RE 16-5:** The particle’s velocity component is zero at  $t = t_2$  and  $t_4$ . The particle is moving to the left at its greatest speed at  $t = t_1$  and it is moving to the right at its greatest speed at  $t = t_3$ . Considering  $v_x$  as a mathematical function of  $t$ , we can indeed say that  $v_x$  is a minimum at  $t_1$  and a maximum at  $t_3$ , but do remember that it is actually moving at its fastest speed when the velocity component is both a minimum and a maximum.

**RE 16-6:** The vertical component  $a_x$  of the acceleration is *increasing* in regions 1 and 2 and it is *decreasing* in regions 3 and 4. Note, however, that the *magnitude* of this acceleration is actually *decreasing* in regions 1 and 3 while the magnitude is *increasing* in regions 2 and 4. Pause and reflect on this!

**RE 16-7:** In each of these cases, the net force acting on the pendulum mass is proportional to the mass itself. Since Newton’s Second Law tells us that acceleration is net force divided by mass, the mass cancels out here and so acceleration will be independent of the mass in these cases.

**RE 16-8:** “Same shape and size” for these three pendula means that the rotational inertia of each is simply proportional to its mass

## Ans-10 Answers to Reading Exercises and Odd-Numbered Problems

with the same constant of proportionality in each case. “Suspended at the same point” means the same distance from the point of suspension to the center of mass in each case. Since  $I/m$  and  $h$  are the same for each of the three, Eq. 16-26 tells us that each will have the same period.

**RE 16-9:** Since  $K = 3 \text{ J}$  and  $U = 2 \text{ J}$  at a given point, then the total mechanical energy of this system is  $E = K + U = 5 \text{ J}$  at every point in its motion. Conservation of mechanical energy rules! (a) In particular, when the block is at  $x = 0$ , the system’s potential energy is zero and so its kinetic energy must be  $5 \text{ J}$ . (b) At  $x = -X$ , the system’s kinetic energy is zero so then  $U = 5 \text{ J}$ .

**RE 16-10:** From Eq. 16-39 the time it takes for the mechanical energy of a damped oscillator to fall to one-fourth (or to any given fraction, for that matter) of its initial value is proportional to  $m/b$ . The ratio of  $m/b$  for set 2 is  $4/6 = 2/3$  that of set 1, and for set 3 it is  $1/3$  of that for set 1. Thus set 1 takes the longest time to lose one-fourth of its mechanical energy, followed by set 2, then by set 3. (set 1 > set 2 > set 3)

### Problems

**1.** (a)  $0.50 \text{ s}$ ; (b)  $2.0 \text{ Hz}$ ; (c)  $18 \text{ cm}$  **3.** (a)  $0.500 \text{ s}$ ; (b)  $2.00 \text{ Hz}$ ; (c)  $12.6 \text{ rad/s}$ ; (d)  $79.0 \text{ N/m}$ ; (e)  $4.40 \text{ m/s}$ ; (f)  $27.6 \text{ N}$  **5.**  $f > 500 \text{ Hz}$  **7.** (a)  $6.28 \times 10^5 \text{ rad/s}$ ; (b)  $1.59 \text{ mm}$  **9.** (a)  $1.0 \text{ mm}$ ; (b)  $0.75 \text{ m/s}$ ; (c)  $570 \text{ m/s}^2$  **11.** (a)  $1.29 \times 10^5 \text{ N/m}$ ; (b)  $2.68 \text{ Hz}$  **13.**  $7.2 \text{ m/s}$  **15.**  $2.08 \text{ h}$  **17.**  $3.1 \text{ cm}$  **19.** (a)  $5.58 \text{ Hz}$ ; (b)  $0.325 \text{ kg}$ ; (c)  $0.400 \text{ m}$  **21.** (a)  $2.2 \text{ Hz}$ ; (b)  $56 \text{ cm/s}$ ; (c)  $0.10 \text{ kg}$ ; (d)  $20.0 \text{ cm}$  below  $y_i$  **23.** (a)  $0.183 \text{ A}$ ; (b) same direction **29.** (a)  $(n+1)k/n$ ; (b)  $(n+1)k$ ; (c)  $\sqrt{(n+1)/nf}$ ; (d)  $\sqrt{n+1}f$  **31.** (a)  $39.5 \text{ rad/s}$ ; (b)  $34.2 \text{ rad/s}$ ; (c)  $124 \text{ rad/s}^2$  **33.**  $99 \text{ cm}$  **35.**  $5.6 \text{ cm}$  **37.** (a)  $2\pi\sqrt{\frac{L^2 + 12d^2}{12gd}}$ ; (b) increases for  $d < L/\sqrt{12}$ , decreases for  $d > L/\sqrt{12}$ ; (c) increases; (d) no change **39.** (a)  $0.205 \text{ kg} \cdot \text{m}^2$ ; (b)  $47.7 \text{ cm}$ ; (c)  $1.50 \text{ s}$  **41.**  $2\pi\sqrt{m/3k}$  **43.** (a)  $0.35 \text{ Hz}$ ; (b)  $0.39 \text{ Hz}$ ; (c)  $0$  **45.** (b) smaller **47.** (a)  $(r/R)\sqrt{k/m}$ ; (b)  $\sqrt{k/m}$ ; (c) no oscillation **49.**  $37 \text{ mJ}$  **51.** (a)  $2.25 \text{ Hz}$ ; (b)  $125 \text{ J}$ ; (c)  $250 \text{ J}$ ; (d)  $86.6 \text{ cm}$  **53.** (a)  $\frac{3}{4}$ ; (b)  $\frac{1}{4}$ ; (c)  $x^{\max}/\sqrt{2}$  **55.** (a)  $16.7 \text{ cm}$ ; (b)  $1.23\%$  **57.**  $0.39$  **59.** (a)  $14.3 \text{ s}$ ; (b)  $5.27$  **61.** (a)  $F^{\max}/b\omega$ ; (b)  $F^{\max}/b$

### Chapter 17

**RE 17-1:** (a) None of these graphs correctly shows the displacement of the rope versus position along the rope at  $t = 0 \text{ s}$ . Graph (b) is the closest to correct of the four but fails to show the considerable length of undisturbed rope that lies between  $x = 0$  and the trailing (left) edge of the pulse at  $t = 0 \text{ s}$ . (b) Graph (a) correctly shows the displacement of the rope versus time at  $x = x_1$  as the pulse passes by.

**RE 17-2:** Realizing that each of these phase expressions is of the form  $(kx - \omega t)$  and that the wavelength  $\lambda = 2\pi/k$ , we see that wave 1 has the smallest wavelength and thus the largest  $k$  so it must correspond to case (c). Wave 2 has the smallest  $k$  and so must go with case (a), and wave 3 has the middle value of  $k$  and so matches case (b).

**RE 17-3:** The velocity  $v_y^{\text{string}}$  describes the up and down (transverse) motion of a particular small segment of the string as the wave passes by that location. Typically the velocity varies rapidly between positive and negative values as the wave goes by. The magnitude of the maximum of this velocity increases with increasing amplitude of passing wave having the same wavelength and frequency. The other velocity,  $v_x^{\text{wave}}$  tells us how fast and in what direction any given crest of the wave itself moves along the rope. For a uniform rope its time does not

vary at all and it does not depend on the amplitude of the wave. In the derivation in this section,  $v_x^{\text{wave}}$  is used to obtain the mass of the segment of string under study and  $v_y^{\text{string}}$  is used to obtain the momentum change of the segment.

**RE 17-4:** If you increase the frequency of the oscillations driving waves in a string, holding the tension constant, then (a) the speed of the waves remains the same and (b) the wavelength decreases. If you instead increase the tension keeping the driving frequency constant, then (c) the wave speed increases and (d) the wavelength also increases.

**RE 17-5:** (a) Equation (1) represents the interference of a pair of waves traveling in the positive  $x$  direction. (b) Equation (3) represents the interference of a pair of waves traveling in the negative  $x$  direction. (c) Equation (2) represents the interference of a pair of waves traveling in opposite directions.

**RE 17-6:** (a) The missing frequency is  $75 \text{ Hz}$ . (b) The seventh harmonic has a frequency of  $7 \times 75 \text{ Hz} = 525 \text{ Hz}$ .

### Problems

**1.** (a)  $3.49 \text{ m}^{-1}$ ; (b)  $31.5 \text{ m/s}$  **3.** (a)  $0.68 \text{ s}$ ; (b)  $1.47 \text{ Hz}$ ; (c)  $2.06 \text{ m/s}$  **7.** (a)  $y(x, t) = 2.0 \sin 2\pi(0.10x - 400t)$ , with  $x$  and  $y$  in cm and  $t$  in s; (b)  $50 \text{ m/s}$ ; (c)  $40 \text{ m/s}$  **9.** (a)  $11.7 \text{ cm}$ ; (b)  $\pi \text{ rad}$  **11.**  $129 \text{ m/s}$  **13.** (a)  $15 \text{ m/s}$ ; (b)  $0.036 \text{ N}$  **15.**  $y(x, t) = 0.12 \sin(141x + 628t)$ , with  $y$  in mm,  $x$  in m, and  $t$  in s **17.** (a)  $2\pi y^{\max}/\lambda$ ; (b) no **19.** (a)  $5.0 \text{ cm}$ ; (b)  $40 \text{ cm}$ ; (c)  $12 \text{ m/s}$ ; (d)  $0.033 \text{ s}$ ; (e)  $9.4 \text{ m/s}$ ; (f)  $5.0 \sin(16x + 190t + 0.93)$ , with  $x$  in m,  $y$  in cm, and  $t$  in s **21.**  $2.63 \text{ m}$  from the end of the wire from which the later pulse originates **25.**  $1.4y^{\max}$  **27.** (a)  $0.31 \text{ m}$ ; (b)  $1.64 \text{ rad}$ ; (c)  $2.2 \text{ mm}$  **29.** (a)  $140 \text{ m/s}$ ; (b)  $60 \text{ cm}$ ; (c)  $240 \text{ Hz}$  **31.** (a)  $82.0 \text{ m/s}$ ; (b)  $16.8 \text{ m}$ ; (c)  $4.88 \text{ Hz}$  **33.**  $7.91 \text{ Hz}$ ,  $15.8 \text{ Hz}$ ,  $23.7 \text{ Hz}$  **35.** (a)  $105 \text{ Hz}$ ; (b)  $158 \text{ m/s}$  **37.** (a)  $0.25 \text{ cm}$ ; (b)  $120 \text{ cm/s}$ ; (c)  $3.0 \text{ cm}$ ; (d) zero **39.** (a)  $50 \text{ Hz}$ ; (b)  $y = 0.50 \sin[\pi(x \pm 100t)]$ , with  $x$  in m,  $y$  in cm, and  $t$  in s **41.** (a)  $1.3 \text{ m}$ ; (b)  $y = 0.002 \sin(9.4x) \cos(3800t)$ , with  $x$  and  $y$  in m and  $t$  in s **43.** (a)  $2.0 \text{ Hz}$ ; (b)  $200 \text{ cm}$ ; (c)  $400 \text{ cm/s}$ ; (d)  $50 \text{ cm}$ ,  $150 \text{ cm}$ ,  $250 \text{ cm}$ , etc.; (e)  $0$ ,  $100 \text{ cm}$ ,  $200 \text{ cm}$ , etc. **47.** (a)  $323 \text{ Hz}$ ; (b) eight **49.**  $5.0 \text{ cm}$

### Chapter 18

**RE 18-1:** We express units in terms of very basic elements of length  $[L]$ , mass  $[M]$  and time  $[T]$ . Since  $B$  is a force per unit area, its units are  $B \sim \frac{[M][L]/[T^2]}{[L^2]} = [M]/[L][T^2]$ .  $\rho$  is a mass per unit volume so  $\rho \sim [M]/[L^3]$ .  $B/\rho \sim [L^2]/[T^2]$  and  $\sqrt{B/\rho} \sim [L]/[T]$  or a “velocity” given by  $[m]/[s]$  in SI units.

**RE 18-2:** The measured wave speed for the round trip is  $v^{\text{wave}} = (2)(2.4 \text{ m})/(.0133 - .0002)\text{s} = 366 \text{ m/s}$ , which is in reasonable agreement with the stated  $343 \text{ m/s}$  in room-temperature air.

**RE 18-3:** Since energy per unit time passing through a surface that faces a source of sound is just the product of the sound intensity there and the area of the surface, and since sound intensity falls off with distance from the source, (a) the intensity of the sound is the same at surfaces 1 and 2 and is smaller at surface 3, and (b) the areas of surfaces 1 and 2 are equal while that of surface 3 is larger.

**RE 18-4:** The second harmonic of the longer pipe B has the same frequency as the first harmonic of the shorter pipe A.

**RE 18-5:** (a) and (e) have greater detected frequency than emitted frequency. (b) and (f) have reduced detected frequencies. (c) and (d) are indeterminate.

**Problems**

1. divide the time by 3 **3.** (a) 79 m, 41 m; (b) 89 m **5.** 1900 km **7.** 40.7 m  
**9.** (a) 0.0762 mm; (b) 0.333 mm **11.** (a) 343 (1 + 2*m*) Hz, with *m* being an integer from 0 to 28; (b) 686*m* Hz, with *m* being an integer from 1 to 29 **13.** (a) 143 Hz, 429 Hz, 715 Hz; (b) 286 Hz, 572 Hz, 858 Hz **15.** 17.5 cm **17.** 15.0 mW **19.** (a) 1000; (b) 32 **21.** (a) 59.7; (b)  $2.81 \times 10^{-4}$  **23.** (a) 5000; (b) 71; (c) 71 **25.** (a) 5200 Hz; (b) amplitude<sub>SAD</sub>/amplitude<sub>SBD</sub> = 2 **27.** (a) 57.2 cm; (b) 42.9 cm **29.** (a) 405 m/s; (b) 596 N; (c) 44.0 cm; (d) 37.3 cm **31.** (a) 1129, 1506, and 1882 Hz **33.** 12.4 m **35.** (a) node; (c) 22 s **37.** 45.3 N **39.** 387 Hz **41.** 0.02 **43.** 17.5 kHz **45.** (a) 526 Hz; (b) 555 Hz **47.** (a) 1.02 kHz; (b) 1.04 kHz **49.** 155 Hz **51.** (a) 485.8 Hz; (b) 500.0 Hz; (c) 486.2 Hz; (d) 500.0 Hz **53.** (a) 598 Hz; (b) 608 Hz; (c) 589 Hz **55.** (a) 42°; (b) 11 s

**Chapter 19**

**RE 19-1:** Some properties that are measurable include mass, volume, hardness, elasticity, and breaking strength. Flavor and color, for example, are less easily quantified.

**RE 19-2:** For comfort we often want to maintain the temperature inside our homes significantly higher (in winter) or lower (in summer) than that of the environment outside. Thermal insulation inside the walls of our homes reduces the amount of heat energy that would otherwise flow out of the house in winter or into the house in summer, reducing the expenditure of energy needed to maintain a comfortable interior temperature.

**RE 19-3:** Equation 19-5 tells us that, for the same amount of heat energy added to the same mass, the temperature increase is inversely proportional to the specific heat of the material being heated. Thus object A has a greater specific heat than object B.

**RE 19-4:** The good news for the firefighter is that each kilogram of water sprayed on the fire can remove a relatively large amount of heat from the burning object. The bad news is that this heat can easily be transferred to the firefighter's body if the steam condenses on her skin. One gram of steam at 100 °C condensing on one gram of (water-like) flesh at 37 °C will yield two grams of water-like material at a temperature of  $(100\text{ °C} + 37\text{ °C})/2 = 69\text{ °C}$ .

**RE 19-5:** For the net work done by the gas on its environment to be positive, the top curve must go from left (lower pressure) to right (higher pressure.) For maximum positive work each cycle that area on the *P-V* diagram enclosed by the cycle must be as large as possible. So curves *c* and *e* yield the maximum possible positive work here.

**RE 19-6:** (a) The change in the internal energy of the gas is the same in each case. (b) The work done by the gas is greatest for path 4, then path 3, path 2, and finally path 1. (c) The thermal energy added to the gas is also greatest for path 4, then path 3, path 2, and finally path 1.

**RE 19-7:** (a) For any cyclic process,  $Q - W = 0$  or  $Q = W$ . (b) Because the net work that the gas does on its environment is negative here, that means that the net thermal energy  $Q$  transfer to the system is also negative and has the same value as the work. Thus thermal energy equal in magnitude to the work done by the system must be transferred from the gas to the environment each cycle.

**RE 19-8:** (a) Plates 2 and 3 will be tied for the largest increase in their vertical heights, followed by plate 1 and then plate 4. (b) Plate 3 will have the greatest increase in area, followed by plate 2, with plates 1 and 4 tied for last place.

**RE 19-9:** The hole gets larger as the plate's temperature increases, as would a circle drawn on the plate.

**RE 19-10:** The pressure at the base of the rod decreases, since the weight of the rod remains constant while the area of the base supporting that weight increases a bit.

**RE 19-11:** The greater the thermal conductivity, the smaller is the temperature difference between the two faces of samples of the same thickness. Since the temperature differences here, going from left to right, are 10 °C, 5 °C, 15 °C, and 5 °C, slabs b and d tie for greatest thermal conductivity, followed by slab a, with slab c having the smallest thermal conductivity.

**Problems**

1. (a) 320 °F; (b) -12.3 °F **3.** (a) Dimensions are inverse time. **5.** (a) 523 J/kg·K; (b) 26.2 J/mol·K; (c) 0.600 mole **7.** 42.7 kJ **9.** 1.9 times as great **11.** (a) 33.9 Btu; (b) 172 F° **13.** 160 s **15.** 2.8 days **17.** 742 kJ **19.** 73 kW **21.** 33 g **23.** (a) 0°C; (b) 2.5°C **25.** A: 120 J, B: 75 J, C: 30 J **27.** -30 J **29.** (a) 6.0 cal; (b) -43 cal; (c) 40 cal; (d) 18 cal, 18 cal **31.** 348 K **33.** (a) -40°; (b) 575°; (c) Celsius and Kelvin cannot give the same reading **35.** 960 μm **37.** 2.731 cm **39.** 29 cm³ **41.** 0.26 cm³ **43.** 360°C **47.** 0.68 s/h, fast **49.** 7.5 cm **51.** (a) 0.13 m; (b) 2.3 km **53.** 1660 J/s **55.** (a) 16 J/s; (b) 0.048 g/s **57.** 0.50 min **59.** (a) 17 kW/m²; (b) 18 W/m² **61.** 0.40 cm/h

**Chapter 20**

**RE 20-1:** Processes (a), (b), (d), and (e) start and end on the same isotherm because each has  $PV = 12$  units.

**RE 20-2:** (a) The average translational kinetic energy doubles when the temperature in kelvins of the gas doubles. (b) The average translational kinetic energy would be zero if the temperature of the gas were 0 K. However, all real gases condense into liquids before reaching 0 K.

**RE 20-3:** (a) The average kinetic energy of each of the three types of molecules is the same. (b) Since that is true, the rms speed of each is inversely related to its molecular mass, so type 3 has the greatest rms speed, followed by type 2, with type 1 the smallest.

**RE 20-4:** Since the internal energy of an ideal gas depends only on its temperature, path 5 has the greatest change in  $E^{\text{int}}$ , followed by the other four paths, all of which tie for second place.

**Problems**

1. 0.933 kg **3.** 6560 **5.** (a)  $5.47 \times 10^{-8}$  mol; (b)  $3.29 \times 10^{16}$  **7.** (a) 0.0388 mol; (b) 220°C **9.** (a) 106; (b) 0.892 m³ **11.**  $A(T_2 - T_1) - B(T_2^2 - T_1^2)$  **13.** 5600 J **15.** 100 cm³ **17.**  $2.0 \times 10^5$  Pa **19.** 180 m/s **21.**  $9.53 \times 10^6$  m/s **23.** 1.9 kPa **25.**  $3.3 \times 10^{-20}$  J **27.** (a)  $6.75 \times 10^{-20}$  J; (b) 10.7 **31.** (a)  $6 \times 10^9$  km **33.** 15 cm **35.** (a)  $3.27 \times 10^{10}$ ; (b) 172 m **37.** (a) 6.5 km/s; (b) 7.1 km/s **39.** (a)  $1.0 \times 10^4$  K; (b)  $1.6 \times 10^5$  K; (c) 440 K, 7000 K; (d) hydrogen, no; oxygen, yes **41.** (a) 7.0 km/s; (b)  $2.0 \times 10^{-8}$  cm; (c)  $3.5 \times 10^{10}$  collisions/s **43.** (a)  $\frac{2}{3}v_0$ ; (b)  $N/3$ ; (c)  $122v_0$ ; (d)  $1.31v_0$  **45.**  $RT \ln(V_f/V_i)$  **47.**  $(n_1C_1 + n_2C_2 + n_3C_3)/(n_1 + n_2 + n_3)$  **49.** (a)  $6.6 \times 10^{-26}$  kg; (b) 40 g/mol **51.** 8000 J **53.** (a) 6980 J; (b) 4990 J; (c) 1990 J; (d) 2990 J **55.** (a) 14 atm; (b) 620 K **59.** 1.40 **61.** (a) In joules, in the order  $Q, \Delta E^{\text{int}}, W$ : 1 → 2: 3740, 3740, 0; 2 → 3: 0, -1810, 1810; 3 → 1: -3220, -1930, -1290; cycle: 520, 0, 520; (b)  $V_2 = 0.0246\text{ m}^3$ ,  $p_2 = 2.00\text{ atm}$ ,  $V_3 = 0.0373\text{ m}^3$ ,  $p_3 = 1.00\text{ atm}$



## Chapter 21

**RE 21-1:** As the putty falls to the floor, gravitational potential energy is converted into translational kinetic energy. When the putty hits the floor it looks at first as if all the mechanical energy is somehow destroyed. But a closer look at the putty after the fall reveals that the putty and the floor beneath it have warmed up a bit. How so? As the putty collides with the floor, the floor does work on the putty. Since the putty doesn't bounce back, the work done on the putty system serves to raise its internal energy. Now the putty's temperature rises and it begins transferring microscopic thermal energy to its surroundings (air and floor) until thermal equilibrium is achieved. Even more careful observations show, in fact, that all of the mechanical energy present in the system before the fall is still there after the putty hits the floor, just in other forms, primarily as thermal energy.

**RE 21-2:** Driving a nail into a board, letting your hot coffee cool, and saying hello to your friend are all examples of irreversible processes in the sense that if you saw a movie of them running backward you would know something was wrong.

**RE 21-3:** Process (c) and (b) involve the same amount of heat energy transfer to the water, while (a) adds twice as much heat to the water. Process (a) also happens at the lowest average temperature, so it involves the greatest entropy change of the water, followed by (b) and then (c).

**RE 21-4:** Equation 21-11 relates the efficiency of a Carnot engine to the two thermodynamic temperatures between which it operates. Applying this to these three cases yields Carnot efficiencies of (a) 0.20, (b) 0.25, and (c) 0.33, so ranking the efficiencies, greatest first, yields (c), then (b), then (a).

**RE 21-5:** (a) Raising the lower temperature  $T_L$  by  $(\delta T)$  increases the numerator of Eq. 21-14 by  $(\delta T)$  and simultaneously decreases the denominator by the same amount. This yields the *greatest increase* in the coefficient of performance of the refrigerator. (b) Lowering the lower temperature  $T_L$  by  $(\delta T)$  decreases the numerator of Eq. 21-14 by  $(\delta T)$  and simultaneously decreases the denominator by the same amount. This yields the *greatest decrease* in the coefficient of performance of the refrigerator. (c) Increasing the higher temperature  $T_H$  by  $(\delta T)$  makes the denominator bigger by  $(\delta T)$  with no change in the numerator, decreasing the coefficient of performance of the refrigerator, but not as much as in (b). (d) Decreasing the higher temperature  $T_H$  by  $(\delta T)$  makes the denominator smaller by  $(\delta T)$  with no change in the numerator, increasing the coefficient of performance of the refrigerator, but not as much as in (a). So, from greatest to least, the changes in the coefficient of performance of the refrigerator are (a), (d), (c), and finally (b).

**RE 21-6:** If we had, say, 6 molecules, then the number of microstates corresponding to 3 molecules in each half of the box would be  $6!/(3!)^2 = 20$ . Generalizing Eq. 21-18 to three bins in the box with 2 molecules in each bin would have  $6!/(2!)^3 = 90$ . In this case a greater number of microstates is associated with dividing the box up into a larger number of equally populated equal subvolumes. This remains true as the number of molecules is increased, so (b) has more microstates than (a).

## Problems

**1.** 14.4 J/K **3.** (a) 9220 J; (b) 23.0 J/K; (c) 0 **5.** (a)  $5.79 \times 10^4$  J; (b) 173 J/K **7.** (a) 14.6 J/K; (b) 30.2 J/K **9.** (a) 57.0°C; (b) -22.1 J/K; (c) +24.9

J/K; (d) +2.8 J/K **13.** (a) 320 K; (b) 0; (c) +1.72 J/K **15.** +0.75 J/K **17.** (a) -943 J/K; (b) +943 J/K; (c) yes **19.** (a)  $3p_0V_0$ ; (b)  $\Delta E^{\text{int}} = 6RT_0$ ,  $\Delta S = \frac{3}{2}R \ln 2$ ; (c) both are zero **21.** (a) 31%; (b) 16 kJ **23.** (a) 23.6%; (b)  $1.49 \times 10^4$  J **25.** 266 K and 341 K **27.** (a) 1470 J; (b) 554 J; (c) 918 J; (d) 62.4% **29.** (a) 2270 J; (b) 14800 J; (c) 15.4% (d) 75.0%, greater **31.** (a) 78%; (b) 81 kg/s **33.** (a)  $T_2 = 3T_1$ ,  $T_3 = 3T_1/4^{1-\gamma}$ ,  $T_4 = T_1/4^{1-\gamma}$ ,  $p_2 = 3p_1$ ,  $p_3 = 3p_1/4^\gamma$ ,  $p_4 = p_1/4^\gamma$ ; (b)  $1 - 4^{1-\gamma}$  **35.** 21 J **37.** 440 W **39.** 0.25 hp **41.**  $[1 - (T_2/T_1)]/[1 - (T_4/T_3)]$  **45.** (a)  $W = N!/(n_1!n_2!n_3!)$ ; (b)  $[(N/2)! (N/2)!]/[(N/3)! (N/3)! (N/3)!]$ ; (c)  $4.2 \times 10^{16}$

## Chapter 22

**RE 22-1:** Electric stove, microwave, lights, car starter motor, toothbrush, computer, tape recorder, CD player, FM radio, amplifier, etc.

**RE 22-2:** (a) Since the two tapes have identical histories, they should have like charges and repel. (b) The observations were consistent with my predictions. The two tapes repelled each other.

**RE 22-3:** (a) If woodolin was a new type of charge then two wooden rods charged with linen would repel each other. A wooden rod would have to attract *both* the charged amber (or plastic) rod *and* the charged glass rod. (b) According to the text statements, this observation has never been made. It has always been the case that a suspected new type of charge (such as woodolin) always repels either a charged amber rod or a charged glass rod and attracts the other type rod. This makes it the same as one of the existing charges.

**RE 22-4:** A very simple explanation is that in a solid, all parts are stiff. But since one can melt ice into water and then boil water into a gas (water vapor) the atomic explanation seems quite plausible.

**RE 22-5:** I would discharge one of the spheres by touching it. Then I would allow the two spheres to touch each other. They should share the charge  $q$  equally so each sphere has charge  $q/2$ . If I repeat the process, then each sphere will have charge  $(q/2)/2 = q/4$ .

**RE 22-6:** (a) If the paper bits are uncharged, then there is no mutual attraction or repulsion. (b) "Induction" always causes the neutral object to be *attracted* toward the charged object, independent of the sign of the charge on the charged object. So, no, you can't tell the sign of the charge on the charged object in this way.

**RE 22-7:** (1)  $A$ ,  $B$  is attractive (unlike charges), (2)  $A$ ,  $A$  is repulsive (like charges), (3)  $B$ ,  $B$  is repulsive (like charges), (4)  $B$ ,  $C$  attract (by induction), (5)  $C$ ,  $C$  nonexistent forces (both neutral), and (6)  $C$ ,  $A$  attract (by induction).

**RE 22-8:** (a) Scotch tape acts like an insulator since charge doesn't draw away as you handle the tape at its ends. (b) A balloon behaves like an insulator, because when you charge it, it can stick by induction to a wall rather than touch and pull away.

**RE 22-9:** (a) No, since charges on it are not mobile. (b) If we start with a positively charged glass plate as the bottom plate in Fig. 22-10 and perform all the same steps, the aluminum pie plate will be negatively charged.

**RE 22-10:** All of these assertions are inconsistent with the experimental results in the text.

**RE 22-11:** (a) The central proton is attracted toward the electron, so this force is to the left. (b) The central proton is repelled by the other proton, so this force is also to the left. (c) Thus the net force on the central proton is to the left. (d) There are no locations along the line connecting the charges where the force on the former central

proton can be zero. Since the magnitudes of the charges on the proton and electron are the same, the only location where the force magnitudes on the other proton are zero is halfway between the first two, but we know the forces don't cancel there.

### Problems

1.  $-1.32 \times 10^{13}$  C **3.**  $6.3 \times 10^{11}$  **5.** 122 mA **7.** (a) positron; (b) electron  
**9.** 1.38 m **11.** (a)  $4.9 \times 10^{-7}$  kg; (b)  $7.1 \times 10^{-11}$  C **13.** (a) 0.17 N; (b)  $-0.046$  N **15.** either  $-1.00 \mu\text{C}$  and  $+3.00 \mu\text{C}$  or  $+1.00 \mu\text{C}$  and  $-3.00 \mu\text{C}$  **17.** (a) charge  $-4q/9$  must be located on the line joining the two positive charges, a distance  $L/3$  from charge  $+q$ . **19.**  $q = Q/2$   
**21.** (a)  $3.2 \times 10^{-19}$  C; (b) two **23.** (a) 0; (b)  $1.9 \times 10^{-9}$  N **25.** (a) 6.05 cm; (b) 6.05 cm from central bead **27.**  $+13e$  **29.** (a) positive; (b)  $+9$   
**31.** 9.0 kN **33.** 1.72a, directly rightward **35.**  $-11.1 \mu\text{C}$  **37.**  $q = 0.71Q$   
**39.** (b)  $1e$ , 0.654 rad;  $2e$ , 0.889 rad;  $3e$ , 0.988 rad;  $4e$ , 1.047 rad;  $5e$ , 1.088 rad **41.** (a) Let  $J = qQ/4\pi\epsilon_0 d^2$ . For  $\alpha < 0$ ,  $F = -J[\alpha^{-2} + (1 + |\alpha|)^{-2}]$ ; for  $0 < \alpha < 1$ ,  $F = J[\alpha^{-2} - (1 - \alpha)^{-2}]$ ; for  $1 < \alpha$ ,  $F = J[\alpha^{-2} + (\alpha - 1)^{-2}]$   
**43.** (a)  $5.7 \times 10^{13}$  C, no; (b)  $6.0 \times 10^5$  kg **45.** (b)  $\pm 2.4 \times 10^{-8}$  C  
**47.** (a)  $\frac{L}{2} \left( 1 + \frac{1}{4\pi\epsilon_0} \frac{qQ}{Wh^2} \right)$ ; (b)  $\sqrt{3qQ/4\pi\epsilon_0 W}$

### Chapter 23

**RE 23-1:**  $F^{\text{elec}} \propto 1/r^2$ . Thus at 4 cm,  $F^{\text{elec}}$  would be  $(1/2)^2 = 1/4$  of its value at 2 cm, or 9 mm. At 6 cm,  $F^{\text{elec}}$  would be  $(1/3)^2 = 1/9$  of its value at 2 cm, or 4 mm.

**RE 23-2:** Since the force on the test object to the sources,  $\vec{F}_{s \rightarrow t}$ , varies from point to point in space, the test object must be small enough spatially to test the “local” value rather than the average value over too large a volume of space.

**RE 23-3:** The type of test charge makes no difference! For a negative test charge we would still use Eq. 23-9 to determine the electric field vector. But, the new  $(\vec{F}^{\text{elec}})' = -\vec{F}^{\text{elec}}$  and the new negative charge  $q'_i = -q_i$ . So  $\vec{E}'_i$  will equal  $\vec{E}_i$  (no charge).

**RE 23-4:** (a) Rightward, (b) leftward, (c) leftward, (d) rightward (p and e have the same charge magnitude and p is farther).

**RE 23-5:** (a) To the left, (b) to the left in a parabolic path, (c) its speed decreases at first, then increases. It will move in a straight line first rightward, then leftward.

**RE 23-6:** All four experience the same magnitude torque.

**RE 23-7:** Near a positive charge,  $\vec{E}$  points always away from the charge; near a negative charge,  $\vec{E}$  points always toward the charge.

**RE 23-8:** Just as for the two equidistant point charges in Fig. 23-10, we can “pair up” equal patches of charge equidistant from the point at which we are calculating  $\vec{E}$  for all such patches of charge on the sheet, canceling the contributions to  $\vec{E}$  parallel to the sheet.

### Problems

1. 56 pC **3.**  $3.07 \times 10^{21}$  N/C, radially outward **5.** 50 cm from  $q_A$  and 100 cm from  $q_B$  **7.** 0 **9.**  $1.02 \times 10^5$  N/C, upward **11.** (a) 47 N/C; (b) 27 N/C **13.**  $4kQ/3d^2$  or  $Q/3\pi\epsilon_0 d^2$  **15.**  $1.38 \times 10^{-10}$  N/C,  $180^\circ$  from  $+x$  **17.**  $6.88 \times 10^{-28}$  C  $\cdot$  m **23.**  $q/\pi^2\epsilon_0 r^2$ , vertically downward **25.** (a)  $-q/L$ ; (b)  $q/4\pi\epsilon_0 a(L + a)$  **29.** (a)  $-1.72 \times 10^{-15}$  C/m; (b)  $-3.82 \times 10^{-14}$  C/m<sup>2</sup>; (c)  $-9.56 \times 10^{-15}$  C/m<sup>2</sup>; (d)  $-1.43 \times 10^{-12}$  C/m<sup>3</sup> **31.**  $E = 2k|Q|(\sin \theta/2)/\theta R^2$  **33.**  $217^\circ$  **35.**  $3.51 \times 10^{15}$  m/s<sup>2</sup> **37.**  $6.6 \times 10^{-15}$  N **39.** (a)  $1.5 \times 10^3$  N/C; (b)  $2.4 \times 10^{-16}$  N, up; (c)  $1.6 \times 10^{-26}$  N; (d)  $1.5 \times 10^{10}$  **41.** (a)  $1.92 \times 10^{12}$  m/s<sup>2</sup>; (b)  $1.96 \times 10^5$  m/s **43.** (a)  $2.7 \times 10^6$  m/s; (b) 1000 N/C

- 45.**  $27 \mu\text{m}$  **47.** (a) yes; (b) upper plate, 2.73 cm **49.** (a) 27 km/s; (b) 50  $\mu\text{m}$  **51.** 5.2 cm **53.** (a) 0; (b)  $8.5 \times 10^{-22}$  N  $\cdot$  m; (c) 0 **55.**  $(1/2\pi)\sqrt{pE/I}$  **57.**  $1.92 \times 10^{-21}$  J **59.** (a)  $6.4 \times 10^{-18}$  N; (b) 20 N/C **63.** (a) to the right in the figure; (b)  $(2kqQ \cos 60^\circ)/a^2$

### Chapter 24

**RE 24-1:** (a)  $\phi = \vec{v} \cdot \Delta\vec{A} = (3 \text{ m/s})(2 \times 10^{-4} \text{ m}^2) \cos 60^\circ = (3 \times 10^{-4} \text{ m}^3/\text{s})$ . Whatever fluid that is represented by this vector velocity field is flowing through this surface area  $dA$ . (b)  $\phi = \vec{E} \cdot \Delta\vec{A} = (3 \text{ N/C})(2 \times 10^{-4} \text{ m}^2) \cos 60^\circ = 3 \times 10^{-4} \text{ N} \cdot \text{m}^2/\text{C}$ . Nothing is flowing through the small area. Instead, the flux represents the product of the  $E$ -field component normal to the area.

**RE 24-2:** To find the answers we simply sum the flux through all six faces. We get  $\phi_{\text{cube } 1}^{\text{net}} = 0 \text{ N} \cdot \text{m}^2/\text{C}$ ,  $\phi_{\text{cube } 2}^{\text{net}} = +5 \text{ N} \cdot \text{m}^2/\text{C}$ , and  $\phi_{\text{cube } 3}^{\text{net}} = -3 \text{ N} \cdot \text{m}^2/\text{C}$ . (a) Cube 2, (b) cube 3, and (c) cube 1.

**RE 24-3:** The central charge always acts along the central line. For each noncentral charge (for example, the one to the left) that acts at a point on this central line, there is a conjugate charge (in this example, the one to the right of center) that is exactly the same distance from the point as the original point. The  $E$ -field vectors have the same magnitude. The  $E$ -components perpendicular to the plane act in the same direction and add vectorially. The parallel components act in opposite directions and cancel.

**RE 24-4:** Since Gauss' law states that  $\phi^{\text{net}} = q^{\text{enc}}/\epsilon_0$  as long as the same charge is enclosed by the new Gaussian surfaces,  $\phi^{\text{net}}$  is unchanged.

**RE 24-5:** Negative charges would be induced on the inside surface of the cavity so that  $q^{\text{enc}} = q^{\text{induced}} + q^{\text{center}} = 0$ . Thus, the net flux at the cavity's Gaussian surface would be zero.

### Problems

1. (a) 0; (b)  $-3.92 \text{ N} \cdot \text{m}^2/\text{C}$ ; (c) 0; (d) 0 for each field **3.**  $2.0 \times 10^5 \text{ N} \cdot \text{m}^2/\text{C}$  **5.** (a)  $8.23 \text{ N} \cdot \text{m}^2/\text{C}$ ; (b)  $8.23 \text{ N} \cdot \text{m}^2/\text{C}$ ; (c) 72.8 pC in each case **7.**  $3.54 \mu\text{C}$  **9.** 0 through each of the three faces meeting at  $q$ ,  $q/24\epsilon_0$  through each of the other faces **11.**  $-7.5 \text{ nC}$  **15.**  $-1.04 \text{ nC}$  **19.** (a)  $E = (q/4\pi\epsilon_0 a^3)r$ ; (b)  $E = q/4\pi\epsilon_0 r^2$ ; (c) 0; (d) 0; (e) inner,  $-q$ ; outer, 0 **21.**  $q/2\pi a^2$  **23.**  $6K\epsilon_0 r^3$  **25.**  $5.0 \mu\text{C}/\text{m}$  **27.** (a)  $E = q/2\pi\epsilon_0 LR$ , radially inward; (b)  $-q$  on both inner and outer surfaces; (c)  $E = q/2\mu\epsilon_0 Lr$ , radially outward **29.** (a)  $2.3 \times 10^6$  N/C, radially out; (b)  $4.5 \times 10^5$  N/C, radially in **31.** (b)  $\rho R^2/2\epsilon_0 r$  **33.** (a)  $5.3 \times 10^7$  N/C; (b) 60 N/C **35.**  $5.0 \text{ nC}/\text{m}^2$  **37.** 0.44 mm **39.**  $2.0 \mu\text{C}/\text{m}^2$  **41.** (a)  $37 \mu\text{C}$ ; (b)  $4.1 \times 10^6 \text{ N} \cdot \text{m}^2/\text{C}$

### Chapter 25

**RE 25-1:** Question 1: Because charges that are infinitely far apart exert no forces on each other. Question 2: Zero separation between particles would involve infinite attractive or repulsive forces.

**RE 25-2:** (a) If we assume the  $E$ -field does not change as a result of the reconfiguration of the charge then the positive charge displacement is opposite to the direction of the  $E$ -field, so the  $E$ -field does negative work. (b) It takes external work to move the charge against the field so  $\Delta U$  increases, and (c) because we are interested in the change of electric potential between points 1 and 2.

**RE 25-3:** (a) The external force does positive work. (b) The proton moves to a higher potential so  $V_2 > V_1$ .

**RE 25-4:** (a) The  $E$ -field acts from left to right. (b) Positive external work is done on the electron in paths 1, 2, 3, and 5. Negative work is done on Path 4. (c)  $\Delta V_3 > \Delta V_1 = \Delta V_2 = \Delta V_5 > \Delta V_4$ .

## Ans-14 Answers to Reading Exercises and Odd-Numbered Problems

**RE 25-5:** Given the charge distribution, we can simply add the contribution to the potential at a point  $P$  due to each of the charges, taken separately, using Eq. 25-25. If all we know is  $\vec{E}(\vec{r})$  then we must calculate  $V(\vec{r})$  using Eq. 25-17.

**RE 25-6:**  $V$  at  $P$  is the same for all three of these configurations. The potential at  $P$  due to each proton only depends on how far away that proton is from  $P$  and not on the direction.

**RE 25-7:** Using Eq. 25-29 for case (a)  $\theta = 0$  and so  $\cos\theta = +1$ , for case (b)  $\theta = 180^\circ$  and  $\cos\theta = -1$ , and for case (c)  $\theta = 90^\circ$  so  $\cos\theta = 0$ . All other terms remain constant, so ranked from most to least positive,  $V_a > V_c > V_b$ .

**RE 25-8:** (a)  $E_2 > E_1 = E_3$ , (b) Pair 3. (c) It accelerates leftward.

**RE 25-9:** Since potential energy is a scalar quantity, its superposition involves only scalar addition while the superposition of electric fields requires adding vectors.

**RE 25-10:** (a) A is wrong since it originates on  $-$  and terminates on  $+$ . B is wrong since it is not perpendicular to the plate near the plate. C is wrong since it has a kink. D is wrong for the same reason as A. E is wrong since it both originates and terminates on a  $+$  charge. F is ok. (b) A correct drawing would have curves like A, D, and F but with arrows pointing toward the negatively-charged sphere.

**RE 25-11:** Because her skin is a conductor and thus an equipotential surface. Charges will redistribute so they have a higher density near the top of her head, which has more curvature than the sides of her head. The strength of the electric field is higher where the charges bunch so the equipotential surfaces are closer together than they were.

### Problems

**1.** (a)  $3.0 \times 10^5$  C; (b)  $3.6 \times 10^6$  J **3.** (a)  $3.0 \times 10^{10}$  J; (b) 7.7 km/s; (c)  $9.0 \times 10^4$  kg **5.** 8.8 mm **7.** (a) 136 MV/m; (b) 8.82 kV/m **9.** (b) because  $V = 0$  point is chosen differently; (c)  $q/(8\pi\epsilon_0 R)$ ; (d) potential differences are independent of the choice for the  $V = 0$  point

**11.** (a)  $Q/4\pi\epsilon_0 r$ ; (b)  $\frac{\rho}{3\epsilon_0} \left( \frac{3}{2} r_2^2 - \frac{1}{2} r^2 - \frac{r_1^3}{r} \right)$ ,  $\rho = \frac{4\pi Q}{3(r_2^3 - r_1^3)}$ ;

(c)  $\frac{\rho}{2\epsilon_0} (r_2^2 - r_1^2)$ , with  $\rho$  as in (b); (d) yes **13.** (a)  $-4.5$  kV; (b)  $-4.5$  kV

**15.**  $x = d/4$  and  $x = -d/2$  **17.** (a) 0.54 mm; (b) 790 V **19.**  $6.4 \times 10^8$  V **21.**  $2.5q/4\pi\epsilon_0 d$  **23.**  $-0.21q^2/\epsilon_0 a$  **25.** (a)  $+6.0 \times 10^4$  V; (b)  $-7.8 \times 10^5$  V; (c) 2.5 J; (d) increase; (e) same; (f) same

**27.**  $W = \frac{qQ}{8\pi\epsilon_0} \left( \frac{1}{r_1} - \frac{1}{r_2} \right)$  **29.** 2.5 km/s **31.** (a) 0.225 J; (b) A, 45.0

m/s<sup>2</sup>; B, 22.5 m/s<sup>2</sup>; (c) A, 7.75 m/s, B, 3.87 m/s **33.** 0.32 km/s **35.**  $1.6 \times 10^{-9}$  m **39.**  $(c/4\pi\epsilon_0)[L - d \ln(1 + L/d)]$  **41.** 17 V/m at  $135^\circ$  counter-

clockwise from  $+x$  **45.** (a)  $\frac{Q}{4\pi\epsilon_0 d(d+L)}$ , leftward; (b) 0 **47.** 2.5  $\times$

$10^{-8}$  C **49.** (a)  $-180$  V; (b) 2700 V,  $-8900$  V **51.** (a)  $-0.12$  V; (b)  $1.8 \times 10^{-8}$  N/C, radially inward

### Chapter 26

**RE 26-1:** Volta probably felt a tingling sensation or perhaps a shock or jolt that would cause him to let go of the terminals.

**RE 26-2:** "Circuit" means a full round trip around some route. This is just what the electric charge does.

**RE 26-3:** (a) If the overall circuit had  $q^{\text{net}} = 0$  before the switch was closed, it will remain charge neutral after the switch is closed since the circuit is a closed system and charge is neither created nor destroyed, but merely flows around the circuit. (b) Individual wires in the circuit can and do acquire a (small) net positive or negative charge, but this charge must come from other parts of the circuit.

**RE 26-4:** Electrical current *is* the net transport of charge past a given point in a circuit in a given time. If equal amounts of positive charge moving, say, right, and negative charge moving right go past the same point, there is no net transport of charge past that point, so  $i = 0$  A.

**RE 26-5:** Let's assume that the unknown current  $i$  flows from right to left. Then the net current flowing into (+) or out of ( $-$ ) the *middle* node is  $(+2 + 3 + 4 - 1 + 2 - 2 + i)$  A. But currents must all add to zero at this node. Thus  $i = -8$  A, meaning our assumption was wrong and that  $i = 8$  A flowing from left to right.

**RE 26-6:** A voltmeter is attached *across* a circuit element because it is designed to measure the potential difference *between* the ends of the circuit. An ammeter is inserted in a branch of a circuit because it is designed to measure the current *through* that part of the circuit. In a series circuit where there are no branches or alternate paths for current to flow, it doesn't matter whether the ammeter is placed before or after a series circuit element.

**RE 26-7:** Device 1 is ohmic since  $(\Delta V/i) = 2.25 \Omega = \text{constant}$  and  $i = 0$  A when  $\Delta V = 0$  V. Device 2 is nonohmic since  $(\Delta V/i) \neq \text{constant}$ . Device 3 is nonohmic. Although a plot of  $\Delta V$  vs.  $i$  is a straight line,  $i$  is nonzero at  $\Delta V = 0$ , so  $i$  is not proportional to  $\Delta V$ .

**RE 26-8:** If the cross-sectional area of the Nichrome wire is cut in half, its resistance will double, so the slope of the  $i$  vs.  $\Delta V$  graph which is  $1/R$  will be cut in half.

**RE 26-9:** (a)  $R \propto 1/r^2$  for most wires, suggesting the current flows through the whole cross-sectional area of the wire, not just on its surface as indicated in Eq. 26-8. (b) If the current flowed only in a thin layer near the surface then I'd expect  $R \propto 1/r$  since the circumference is  $2\pi r$  for a wire with a circular cross section.

**RE 26-10:** Since  $R = \rho L/A$ , (a) = (c)  $>$  (b).

**RE 26-11:** (a) = (b)  $>$  (d)  $>$  (c).

**RE 26-12:** Only the cross-sectional area  $A$  matters in comparing current densities, so (a) = (d)  $>$  (b) = (c).

**RE 26-13:** Since the current density is  $(I/A) = (\Delta V/(RA))$  and  $RA = \rho L$ , we see here that the current density is just inversely proportional to the length of each wire. So (b) = (d)  $>$  (a) = (c).

### Problems

**1.** (a) 1200 C; (b)  $7.5 \times 10^{21}$  **3.** 5.6 ms **5.** 100 V **7.**  $2.0 \times 10^{-8} \Omega \cdot \text{m}$  **9.** 2.4  $\Omega$  **11.** 54  $\Omega$  **13.** 3.0 **15.** (a) 0.43%, 0.0017%, 0.0034% **17.** 560 W **19.** (a) 1.0 kW; (b) 25  $\mu$  **21.** 0.135 W **23.** (a) 10.9 A; (b) 10.6  $\Omega$ ; (c) 4.5 MJ **25.** 660 W **27.** (a)  $3.1 \times 10^{11}$ ; (b) 25  $\mu$ A; (c) 1300 W, 25 MW **29.** (a) 17 mV/m; (b) 243 J **31.** (a) 6.4 A/m<sup>2</sup>, north; (b) no, cross-sectional area **33.** 0.38 mm **35.** (a)  $2 \times 10^{12}$ ; (b) 5000; (c) 10 MV **37.** 13 min **39.**  $8.2 \times 10^{-4} \Omega \cdot \text{m}$  **41.** (a) 0.67A; (b) toward the negative terminal **43.** (a) 1.73 cm/s; (b) 3.24 pA/m<sup>2</sup>



**Chapter 27**

**RE 27-1:**  $R = \rho L/A$ ;  $A = \pi r^2 = \frac{1}{4} \pi d^2$

$$\rho_{\text{Cu}} = 1.7 \times 10^{-8} \Omega \cdot \text{m}; d = 2.4 \times 10^{-4} \text{ m}; L = 0.30 \text{ m}$$

$$\therefore R = (1.7 \times 10^{-8} \Omega \cdot \text{m})(0.30 \text{ m}) / (\frac{1}{4} \pi (2.4 \times 10^{-4} \text{ m})^2) \\ = 0.113 \Omega.$$

**RE 27-2:** (a) If all the current were “used up” in the first bulb, the second and third bulbs would be dark. (b) If most of the current were “used up” in the first bulb, the second bulb would glow more dimly than the first and the third bulb would glow more dimly than the second. (c) If only a small amount were “used up” in the first bulb, the third would be dimmer than the second, and the second would be a bit dimmer than the first.

**RE 27-3:**  $i_a = i_b = i_c$  and  $V_b > V_c > V_a$ .

**RE 27-4:** (a)  $i_1 = i_2 = i_3$ . (b)  $\Delta V_1 > \Delta V_2 > \Delta V_3$ .

**RE 27-5:** Since the ammeter is wired *in series* with the resistors, its resistance *adds* to theirs. (a) With no ammeter, the current will be largest. (b) with  $R_A \ll R_1 + R_2$  the current will be reduced, but only a little. (c) With  $R_A = R_1 + R_2$  the current would be cut in half. Thus a good ammeter should have as *small* a resistance as possible.

**RE 27-6:** (a)  $R_1 = R_2$  in series so  $i_1 = i_2$  and  $\Delta V_1 = \Delta V_2 = \frac{1}{2} \Delta V_B$  and so  $i = i_1 = i_2 = \Delta V_B / (R_1 + R_2)$ . (b)  $R_1 = R_2$  in parallel so  $i_1 = i_2$  and  $\Delta V_1 = \Delta V_2 = \Delta V_B$  so now  $i = i_1 + i_2 = 2 \Delta V_B / R_1 = 2 \Delta V_B / R_2$ .

**RE 27-7:** Note that  $R_V$  is in parallel with  $R_1$ . Thus if  $R_V \ll R_1$ , the effective resistance between  $d$  and  $e$  in Fig. 27-7 would be dramatically decreased from  $R_1$  to less than  $R_V$ . This would “pull down”  $\Delta V_{de}$  to a smaller value that it had before I installed the voltmeter. However, if  $R_V \gg R_1$ , then the effective resistance between  $d$  and  $e$  remains just about  $R_1$  and the value of  $\Delta V_{de}$  is about what it was without the meter present. Thus  $R_V \gg R$  gives more accurate measurements of potential differences.

**RE 27-8:** Since the bulbs are identical and wired in parallel,  $i_1 = i_2 = i_3$ . If only one bulb were connected to the battery its brightness would be the same as before, since the potential difference across it is still  $\Delta V_B$ .

**Problems**

**1.** (a) 30  $\Omega$ ; (b) clockwise; (c) A **3.** (a) 45  $\Omega$ ; (b) 0.33 A each; (c) 0.33 A **5.**  $V_1 = 3.5 \text{ V}$ ;  $V_2 = 4.3 \text{ V}$ ;  $V_3 = 7.2 \text{ V}$  **7.** 8.0  $\Omega$  **9.** (a) 0; (b) 1.25 A, downward **11.** (a) 120  $\Omega$ ; (b)  $i_1 = 51 \text{ mA}$ ,  $i_2 = i_3 = 19 \text{ mA}$ ,  $i_4 = 13 \text{ mA}$  **13.** 20  $\Omega$  **15.** (a) bulb 2; (b) bulb 1 **17.** 0.45 A **19.**  $i_1 = -50 \text{ mA}$ ,  $i_2 = 60 \text{ mA}$ ,  $V_{ab} = 9.0 \text{ V}$  **21.** (a) Cu: 1.11 A, Al: 0.893 A; (b) 126 m **23.** 5.56 A **25.** 3d **29.** nine **31.** providing energy, 360 W **33.** (a) 3.0 A, downward; (b) 1.6 A, downward; (c) 6.4 W, supplying; (d) 55.2 W, supplying **35.** (a) 12 eV ( $1.9 \times 10^{-18} \text{ J}$ ); (b) 6.5 W **39.** (a) 7.50 A, leftward; (b) 10.0 A, leftward; (c) 87.5 W, supplied **41.** (a) 0.33 A, rightward; (b) 720 J **43.** (a) \$320; (b) 4.8 cents **45.** 14 h 24 min **47.** (a) 0.50 A; (b)  $P_1 = 1.0 \text{ W}$ ,  $P_2 = 2.0 \text{ W}$ ; (c)  $P_1 = 6.0 \text{ W}$  supplied,  $P_2 = 3.0 \text{ W}$  absorbed **49.** (a)  $V_T = -ir + \mathcal{E}$ ; (b) 13.6 V; (c) 0.060  $\Omega$  **51.** (a) 14 V; (b) 100 W; (c) 600 W; (d) 10 V, 100 W **53.** (a) 50 V; (b) 48 V; (c) B is connected to the negative terminal **55.** (a)  $r_1 - r_2$ ; (b) battery with  $r_1$  **59.** (a)  $R = r/2$ ; (b)  $P^{\text{max}} = \mathcal{E}^2/2r$  **61.** (a) 0.346 W; (b) 0.050 W; (c) 0.709 W; (d) 1.26 W; (e) -0.158 W **63.** (a) battery 1, 0.67 A down; battery 2, 0.33 A up; battery 3, 0.33 A up; (b) 3.3 V

**Chapter 28**

**RE 28-1:** The capacitance of a capacitor remains the same, whatever the amount of excess charge on its plates and whatever potential difference is applied across it. Doubling  $|q|$  doubles  $\Delta V_c$  while tripling  $\Delta V_c$  triples  $|q|$ .

**RE 28-2:** Each of these three types of capacitors becomes electrically isolated when removed from a battery so the excess charge on each of the “plates” does not change.

**RE 28-3:** In these cases  $\Delta V$  is constant and  $C$  and hence  $|q|$  must change when spacings change, so  $|q|$  (a) decreases, (b) increases, and (c) decreases.

**RE 28-4:** Each capacitor initially has the same  $|q|$  and the same  $|\Delta V|$ . (a) Wiring them in parallel, positive plate to positive and negative to negative, leaves  $|q|$  and  $|\Delta V|$  on each unchanged. Wiring them in parallel, positive to negative, makes  $|\Delta V| = 0$  and so  $|q| = 0$  on each. (b) Wiring them in series leaves these quantities unchanged.

**RE 28-5:** (a) Since  $i_0 = |\Delta V_B|/R$ ,  $(i_0)_1 > (i_0)_2 > (i_0)_4 > (i_0)_3$ . (b) Since  $t_{(1/2)}$  is proportional to  $\tau = RC$ ,  $(t_{(1/2)})_4 > (t_{(1/2)})_1 = (t_{(1/2)})_2 > (t_{(1/2)})_3$ .

**Problems**

**1.** 7.5 pC **3.** 3.0 mC **5.** (a) 140 pF; (b) 17 nC **7.**  $5.04 \pi \epsilon_0 R$  **11.** 9090 **13.** 3.16  $\mu\text{F}$  **17.** 43 pF **19.** (a) 50 V; (b)  $5.0 \times 10^{-5} \text{ C}$ ; (c)  $1.5 \times 10^{-4} \text{ C}$

$$\mathbf{21.} \quad q_1 = \frac{C_1 C_2 + C_1 C_3}{C_1 C_2 + C_1 C_3 + C_2 C_3} C_1 \Delta V_0, \\ q_2 = q_3 = \frac{C_2 C_3}{C_1 C_2 + C_1 C_3 + C_2 C_3} C_1 \Delta V_0$$

**23.** 72 F **25.** 0.27 J **27.** (a) 2.0 J **29.** (a) 2  $\Delta V$ ; (b)  $U_i = \epsilon_0 A \Delta V^2 / 2d$ ,  $U_f = 2U_i$ ; (c)  $\epsilon_0 A \Delta V^2 / 2d$  **35.** Pyrex **37.** 81 pF/m **39.** 0.63 m<sup>2</sup> **43.** (a) 10 kV/m; (b) 5.0 nC; (c) 4.1 nC

$$\mathbf{45.} \quad (a) C = 4 \pi \epsilon_0 \kappa \left( \frac{ab}{b-a} \right); \quad (b) q = 4 \pi \epsilon_0 \kappa \Delta V \left( \frac{ab}{b-a} \right);$$

(c)  $q' = q(1 - 1/\kappa)$  **47.** 4.6  $\mu\text{s}$ ; (b) 161 pF **51.** (a) 2.17 s; (b) 39.6 mV **53.** (a)  $1.0 \times 10^{-3} \text{ C}$ ; (b)  $1.0 \times 10^{-3} \text{ A}$ ; (c)  $\Delta V_C = 1.0 \times 10^3 \text{ e}^{-t} \text{ V}$ ,  $\Delta V_R = 1.0 \times 10^3 \text{ e}^{-t} \text{ V}$ ; (d)  $P = \text{e}^{-2t} \text{ W}$

**Chapter 29**

**RE 29-1:** (a)  $z$  axis, (b)  $-x$  axis, (c) no direction since  $\vec{F} = 0 \text{ N}$ .

**RE 29-2:** (a) The electron, because it's less massive and “bends” more easily in the presence of a perpendicular force, (b) the electron travels clockwise.

**RE 29-3:**  $\vec{F}_{\text{net}} = \vec{F}_{\text{elec}} + \vec{F}_{\text{mag}}$ . The force exerted on the charge by the  $E$ -field is the same in all 4 cases and points out of the page. In cases 1 and 3,  $\vec{B}$  and  $\vec{v}$  are parallel so there is no magnetic force on the charged particle. In cases 2 and 4,  $\vec{B}$  and  $\vec{v}$  are perpendicular with magnetic forces out of and into the page respectively. (a) In terms of force magnitude  $|\vec{F}_{\text{net}}| > |\vec{F}_{\text{net}}| = |\vec{F}_{\text{net}}|$ .  $|\vec{F}_{\text{net}}|$  can take on any value from zero to larger than  $|\vec{F}_{\text{net}}|$  and so can not be ranked. (b) A zero net force is only possible for case 4.

**RE 29-4:** The equation  $|\vec{F}_{\text{mag}}| = |i\vec{L} \times \vec{B}|$  is a maximum for a given  $|\vec{B}|$  when  $\vec{B}$  is perpendicular to both  $\vec{F}_{\text{mag}}$  and  $\vec{L}$ . This is true whenever  $\vec{B} = \pm |\vec{B}| \hat{j}$ . Trying each direction, the right-hand rule yields  $\vec{B}$  pointing along the  $-y$  axis.

**RE 29-5:** (a)  $\tau = |\vec{\mu}| |\vec{B}| \sin \phi$  where  $\phi = \theta$  for cases 2 and 3 and  $\phi = \pi - \theta$  for cases 1 and 4. But  $\sin \theta = \sin(\pi - \theta)$  so  $\tau$  is the same for all 4 cases. (b)  $U(\phi) = -\vec{\mu} \cdot \vec{B} = -|\vec{\mu}| |\vec{B}| \cos \phi$ . Now for cases 2

## Ans-16 Answers to Reading Exercises and Odd-Numbered Problems

and 3,  $\phi = \theta < \pi/2$  so  $\cos \theta > 0$ , and for cases 1 and 4  $\phi = \pi - \theta > \pi/2$  so  $\cos \phi = -\cos \theta < 0$ , thus  $U_1 = U_4 > U_3 = U_2$ .

### Problems

**1.** (a)  $6.2 \times 10^{-18}$  N; (b)  $9.5 \times 10^8$  m/s<sup>2</sup>; (c) remains equal to 550 m/s **3.** (a) 400 km/s; (b) 835 eV **5.** (a) east; (b)  $6.28 \times 10^{14}$  m/s<sup>2</sup>; (c) 2.98 mm **7.** 21  $\mu$ T **9.** (a)  $2.05 \times 10^7$  m/s; (b) 467  $\mu$ T; (c) 13.1 MHz; (d) 76.3 ns **11.** (a) 0.978 MHz; (b) 96.4 cm **15.** (a) 1.0 MeV; (b) 0.5 MeV **17.** (a) 495 mT; (b) 22.7 mA; (c) 8.17 MJ **19.** (a) 0.36 ns; (b) 0.17 nm; (c) 1.5 mm **21.** (a)  $3.4 \times 10^{-4}$  T, horizontal and to the left as viewed along  $\vec{v}_1$ ; (b) yes, if its velocity is the same as the electron's velocity **23.** 0.27 mT **25.** 680 kV/m **27.** (b)  $2.84 \times 10^{-3}$  **29.** 38.2 cm/s **31.** 28.2 N, horizontally west **33.** 467 mA, from left to right **35.** 0.10 T, at  $31^\circ$  from the vertical **37.**  $4.3 \times 10^{-3}$  N·m, negative y **41.**  $2\pi aiB \sin \theta$ , normal to the plane of the loop (up) **43.** 2.45 A **45.** (a) 12.7 A; (b) 0.0805 N·m **47.** (a) 0.30 J/T; (b) 0.024 N·m **49.** (a)  $2.86 \text{ A} \cdot \text{m}^2$ ; (b)  $1.10 \text{ A} \cdot \text{m}^2$  **51.** (a)  $(8.0 \times 10^{-4} \text{ N} \cdot \text{m})(-1.2\hat{i} - 0.90\hat{j} + 1.0\hat{k})$ ; (b)  $-6.0 \times 10^{-4}$  J

### Chapter 30

**RE 30-1:** (a)  $\vec{B}$  is to the left at point 1, (b)  $\vec{B}$  is up at point 2, (c)  $\vec{B}$  is to the right at point 1, (d)  $\vec{B}$  is down at point 2.

**RE 30-2:** (a) If  $\vec{B}_{\text{net}} = 0$  at point 1 then the current in the wire is coming out of the page. (b) Since  $\vec{B}_{\text{net}} = \vec{B}_{\text{ext}} + \vec{B}_{\text{wire}}$ , and since  $\vec{B}_{\text{wire}}$  at point 2 points straight down and has the same magnitude as  $\vec{B}_{\text{ext}}$ ,  $\vec{B}_{\text{net}}$  is directed 45 degrees down and toward the right at point 2 and its magnitude is  $\sqrt{2} B_{\text{ext}}$ .

**RE 30-3:**  $F_b > F_c > F_a$ .

**RE 30-4:**  $\oint \vec{B} \cdot d\vec{s} = \mu_0 i^{\text{enc}}$  where  $i^{\text{enc}}$  is the net current flowing

through the loop. Therefore,  $\left| \frac{1}{\mu_0} \oint \vec{B} \cdot d\vec{s} \right| = i$  for case (a)

= 0 for case (b)  
=  $i$  for case (c)  
=  $2i$  for case (d).

(d) > (a) = (c) > (b).

**RE 30-5:** For  $z \gg R$ ,  $|\vec{B}|$  due to any one loop is proportional to  $|\vec{\mu}| = iA$ . Since all the  $i$ 's are equal,  $|\vec{B}| \propto A$  for each loop. Taking the directions of the currents into account and calling  $B_1$  the magnetic field magnitude for one small loop, and  $B_2 = 4B_1$ , the magnetic field magnitude for one large loop,  $B_a = 2B_1$ ;  $B_b = 0$ ;  $B_c = 0$ ;  $B_d = 2B_1 + B_2 = 2B_1 + 4B_1$ .  $\therefore |\vec{B}_d| > |\vec{B}_a| > |\vec{B}_b| = |\vec{B}_c| = 0$ .

### Problems

**1.** (a) 3.3  $\mu$ T; (b) yes **3.** (a) 16 A; (b) west to east **5.**  $\mu_0 qvi/2\pi d$ , antiparallel to  $i$ ; (b) same magnitude, parallel to  $i$  **7.** 2 rad

**9.**  $\frac{\mu_0 i \theta}{4\pi} \left( \frac{1}{b} - \frac{1}{a} \right)$ , out of page. **19.**  $(\mu_0 i/2\pi w) \ln(1 + w/d)$ , up

**21.** 256 nT **23.** (a) it is impossible to have other than  $B = 0$  midway between them; (b) 30 A **25.** 4.3 A, out of page **27.** 80  $\mu$ T, up the page **29.**  $0.791\mu_0 i^2/\pi a$ ,  $162^\circ$  counterclockwise from the horizontal **31.** 3.2 mN, toward the wire **33.** (a)  $(-2.0 \text{ A})\mu_0$ ; (b) 0 **37.**  $\mu_0 J_0 r^2/3a$  **43.** 0.30 mT **45.** (a) 533  $\mu$ T; (b) 400  $\mu$ T **49.** (a) 4.77 cm; (b) 35.5  $\mu$ T **51.**  $0.47 \text{ A} \cdot \text{m}^2$  **53.** (a)  $2.4 \text{ A} \cdot \text{m}^2$ ; (b) 46 cm **59.** (a) 79  $\mu$ T; (b)  $1.1 \times 10^{-6} \text{ N} \cdot \text{m}$

### Chapter 31

**RE 31-1:** They were trying to relate induction to the presence of a magnetic field rather than to a changing field.

**RE 31-2:** Since the magnetic field is uniform, the left and right segments are polarized symmetrically as shown in the diagram. There is no favored direction in which current can flow.

**RE 31-3:** This case is similar to the one shown in Fig. 31-7. However, now the polarization will always be stronger on the right side of the coil than it is on the left side, so the current will flow continuously in a counter clockwise direction.

**RE 31-4:** Yes, since observations show that the  $\vec{v}$  in the magnetic force law ( $\vec{F} = q\vec{v} \times \vec{B}$ ) turns out to be the relative velocity between the object producing the  $B$ -field and the charge.

**RE 31-5:** The magnet is accelerating downward as it falls at  $\vec{a} = (-9.8 \text{ m/s}^2)\hat{j}$ . By the time its rear end is passing through the area subtended by the loop, it is traveling faster than the front pole was as it passed by, so the rate of change of the  $B$ -field is greater at  $t = 0.20$  s than it was at  $t = 0.10$  s and the amount of induced current is also greater.

**RE 31-6:** (a)  $b > d = e > a = c$ . (b) The magnitude  $|dB/dt|$  determines that the amount of induced emf is greatest when the slope is greatest.

**RE 31-7:** (a) into the page to add to the decreasing field, (b) out of the page to subtract from the decreasing field.

**RE 31-8:** In each semicircular area  $|d\Phi^{\text{mag}}/dt|$  is identical. The only issue is the "sense" of the induced emf contributed by each semicircle. Using Lenz's law, loop (a) has a nonzero, clockwise (CW) induced current. Loop (b) has a counterclockwise (CCW) current in both the upper and lower halves, so  $|i_a| = |i_b|$ . In loop (c), the induced emfs in the upper and lower half circles cancel one another out so  $|i_c| = 0$  so  $|i_a| = |i_b| > |i_c|$ .

**RE 31-9:** As each loop enters or leaves the region where  $B \neq 0$ ,  $|\mathcal{E}| = |d\Phi^{\text{mag}}/dt| \propto (h)(v)$  where  $h$  = height of the loop and  $v$  is its speed. Since  $v$  = constant for each,  $|\mathcal{E}_c| = |\mathcal{E}_d| = 2|\mathcal{E}_a| = 2|\mathcal{E}_b|$ .

**RE 31-10:** (a) Out (given), (b) out since path 3 has  $|\mathcal{E}| = 3(\text{mag})$ , (c) out since path 3 has  $|\mathcal{E}| = 3(\text{mag})$ , (e) in, since path 4 has  $|\mathcal{E}| = 0$ , (d) in since path 2 has  $|\mathcal{E}| = 2(\text{mag})$ .

**RE 31-11:** When we pointed a right thumb in the direction of the current our fingers wrapped around the wire in the direction of the magnetic field. This is consistent with the direction of the magnetic field shown in Fig. 31-24.

**RE 31-12:** The quantity  $i^{\text{dis}} = \mathcal{E}_0 d\Phi^{\text{elec}}/dt$  has the units of current. We can use the right hand rule to find the direction of  $\vec{B}$  and we can use it to find the magnitude of  $\vec{B}$  induced by a capacitor.

**RE 31-13:** (a)  $|\Phi_d| > |\Phi_b| > |\Phi_c| > |\Phi_a|$ . Since  $\oint \vec{B} \cdot d\vec{A} = 0$  (Eq. 31-49),

$$\Phi_{\text{net}} = \oint_{\text{ends}} \vec{B} \cdot d\vec{A} + \oint_{\text{curve}} \vec{B} \cdot d\vec{A} \text{ so } \Phi_{\text{curve}} = -\oint_{\text{ends}} \vec{B} \cdot d\vec{A}.$$

**RE 31-14:** They both involve the integration of a field vector over a closed Gaussian surface. Each integral determines a net flux at the closed surface that is proportional to the net electric or magnetic charge enclosed by the surface. The major difference between the electric and magnetic situation is that the net magnetic charge enclosed is always zero (that is, north and south poles always appear together), and the net electric charge enclosed can be positive, negative, or zero.

**RE 31-15:** A statement of Faraday's law is that a changing magnetic field produces an electric field. The Ampère-Maxwell law states that a changing electric field produces a magnetic field. So there is a mathematical symmetry between the two fields.

### Problems

**1.** 1.5 mV **3.** (a) 31 mV; (b) right to left **5.** (a)  $1.1 \times 10^{-3} \Omega$ ; (b) 1.4 T/s **7.** 30 mA **9.** 2.9 mV **11.** (a)  $\mu_0 i R^2 \pi r^2 / 2x^3$ ; (b)  $3\mu_0 i \pi R^2 r^2 v / 2x^4$ ; (c) in the same direction as the current in the large loop **13.** (b) no **15.** 29.5 mC **17.** (a) 21.7 V; (b) counterclockwise **19.** (b) design it so that  $Nab = (5/2\pi) m^2$  **21.** 5.50 kV **23.** 80  $\mu$ V, clockwise **25.** (a) 13  $\mu$ Wb/m; (b) 17%; (c) 0 **27.** 3.66  $\mu$ W **29.** (a) 48.1 mV; (b) 2.67 mA; (c) 0.128 mW **31.** (a) 600 mV, up the page; (b) 1.5 A, clockwise; (c) 0.90 W; (d) 0.18 N; (e) same as (c) **33.** (a) 240  $\mu$ V; (b) 0.600 mA; (c) 0.144  $\mu$ W; (d)  $2.88 \times 10^{-8}$  N; (e) same as (c) **35.** (a) 71.5  $\mu$ V/m; (b) 143  $\mu$ V/m **39.**  $2.4 \times 10^{13}$  V/m  $\cdot$  s **41.** (a)  $1.18 \times 10^{-19}$  T; (b)  $1.06 \times 10^{-19}$  T **43.** (a)  $5.01 \times 10^{-22}$  T; (b)  $4.51 \times 10^{-22}$  T **45.** 52 nT  $\cdot$  m **51.** (a) 0.63  $\mu$ T; (b)  $2.3 \times 10^{12}$  V/m  $\cdot$  s **53.** (a) 710 mA; (b) 0; (c) 1.1 A **55.** (A) 2.0 A; (b)  $2.3 \times 10^{11}$  V/m  $\cdot$  s; (c) 0.50 A; (d) 0.63  $\mu$ T  $\cdot$  m **57.** (a) 75.4 nT; (b) 67.9 nT **59.** (a) 27.9 nT; (b) 15.1 nT **61.** (b) sign is minus; (c) no, there is compensating positive flux through open end near magnet **63.** 47.4  $\mu$ Wb, inward

### Chapter 32

**RE 32-1:** Combine Eqs. 32-1 and 32-2 to get  $L = \mu_0 A n^2 l$ . (a) If  $n$  doubles  $L \rightarrow 4L$ . (b) If  $l$  doubles  $A \rightarrow 2A$ .

**RE 32-2:** (d) decreasing rightward or (e) increasing and leftward.

**RE 32-3:** (a)  $R_{eq} = (N_p/N_s)^2 R$  we want  $R_{eq}$  seen by the generator to be smaller. So  $N_s$  must be greater than  $N_p$ . (b) This would be a step up transformer.

**RE 32-4:** A refrigerator magnet is ferromagnetic; a standard paper clip is also ferromagnetic, since it is made of steel, a ferromagnetic material; a silver wire is diamagnetic (the book says so).

**RE 32-5:** (a) Spin down or (2). (b) Since the proton has the opposite sign of charge, spin up or (1).

**RE 32-6:** A ferromagnetic material must have well more than 50% of its domains aligned with each other to act like a strong magnet. If no one alignment of the domains dominates, then it is not a permanent magnet.

**RE 32-7:** Hysteresis is a lack of retracability of a magnetization curve. It occurs because the reorientation of domains are not completely reversible.

**RE 32-8:** (a)  $\vec{F}_{mag}$  is directed *toward* the magnet. (b) The dipole moments are also directed *toward*. (c) The force on sphere 1 is *less*.

**RE 32-9:** (a)  $\vec{F}_{mag}$  is directed *away* from the magnet. (b) The dipole moments are also directed *away*. (c) The force on sphere 1 is *less*.

**RE 32-10:** The Earth's  $B$ -field has a different declination and inclination at different locations at any one time. But, it also varies in time. Currently the geographic poles are moving daily. They can also reverse themselves in time periods on the scale of 1000 years.

### Problems

**1.** 0.10  $\mu$ Wb **5.** let the current change at 5.0 A/s **7.** (b) so that the changing magnetic field of one does not induce current in the other; (c)  $L_{eq} = \sum_{j=1}^N L_j$  **9.** 12 A/s **11.** (a) 0.60 mH; (b) 120 **13.** (a) 1.67 mH;

(b) 6.00 mWb **15.** (b) have the turns of the two solenoids wrapped in opposite directions **17.** magnetic field exists only within the cross section of solenoid 1 **19.** (a)  $\frac{\mu_0 N l}{2\pi} \ln \left( 1 + \frac{b}{a} \right)$ ; (b) 13  $\mu$ H **21.**  $6.91 \tau_L$

**23.** 46  $\Omega$  **25.** (a) 8.45 ns; (b) 7.37 mA **27.** 10.6 A/s **29.** (a)  $i_1 = i_2 = 3.33$  A; (b)  $i_1 = 4.55$  A;  $i_2 = 2.73$  A; (c)  $i_1 = 0$ ,  $i_2 = 1.82$  A (reversed); (d)  $i_1 = i_2 = 0$  **31.** (a) 3.28 ms; (b) 6.45 ms; (c) infinite time; (d) for  $R = 6.0 \Omega$ , the current of the 2.00 A is the equilibrium current, given by  $\mathcal{E}/R = (12 \text{ V})/(6.0 \Omega)$ ; it takes an infinite time to reach. For  $R = 5.00 \Omega$ , the current of 2.00 A is less than the equilibrium current and requires a finite time to reach. (e) 0; (f) 3 ms **33.** 81.1  $\mu$ s **35.** (a) 2.4 V; (b) 3.2 mA, 0.16 A **37.** 10 **39.** (a)  $-9.3 \times 10^{-24}$  J/T; (b)  $1.9 \times 10^{-23}$  J/T **41.** (a) 0; (b) 0; (c) 0; (d)  $\pm 3.2 \times 10^{-25}$  J; (e)  $-3.2 \times 10^{-34}$  J  $\cdot$  s,  $2.8 \times 10^{-23}$  J/T,  $+9.7 \times 10^{-25}$  J,  $\pm 3.2 \times 10^{-25}$  J **43.** (a) nine; (b) 4  $\mu_B = 3.71 \times 10^{-23}$  J/T; (c)  $+9.27 \times 10^{-24}$  J; (d)  $-9.27 \times 10^{-24}$  J **45.**  $5.15 \times 10^{-24}$  A  $\cdot$  m<sup>2</sup> **47.** (a) 180 km; (b)  $2.3 \times 10^{-5}$  **49.**  $\Delta\mu = e^2 r^2 B / 4m$  **51.** 20.8 mJ/T **53.** yes **55.** (b)  $K_i/B$ , opposite to the field; (c) 310 A/m **57.** 55  $\mu$ T **59.** (a) 31.0  $\mu$ T,  $0^\circ$ ; (b) 55.9  $\mu$ T,  $73.9^\circ$ ; (c) 62.0  $\mu$ T,  $90^\circ$

### Chapter 33

**RE 33-1:** Using Eq. 33-6,  $a = b > c$ . (Note that coil area doesn't matter here.)

**RE 33-2:** At  $t = 0$  s,  $U^{elec} = \max$  and  $U^{mag} = 0$ .  $T = \text{period} = 1/f$ . (a)  $|q(t)|$  is a maximum again at  $t = T/2$ . (b)  $\Delta v_C$  is next the same at  $t = T$ . (c)  $U^{elec}$  is next a maximum at  $t = T/2$ . (d)  $i$  is next a maximum at  $t = T/4$ .

**RE 33-3:** The unit for  $\omega$  is [rad/s]. Since  $L = \mathcal{E}_L / (di/dt)$ , we get  $[H] = [V/(A/s)]$ . Since  $C = q/\Delta V$  we get  $[F] = [Q/V]$ .  $\omega = 1/\sqrt{LC}$  and the units of  $1/\sqrt{LC}$  are  $[1/(V \cdot s/A)(Q/V)]^{1/2}$  but  $[A] = [Q/s]$  so  $[1/s^2]^{1/2}$  or  $[1/s]$ . This matches the  $\omega$  unit of [rad/s].

**RE 33-4:** (a) According to the loop rule,  $\Delta v_C + \Delta v_L = 0$ . Since  $\mathcal{E}_L = \Delta v_L$ ,  $\mathcal{E}_L = -5$  V. (b)  $U^{mag} = U - U^{elec} = 160 \mu\text{J} - 10 \mu\text{J} = 150 \mu\text{J}$ .

**RE 33-5:** (a)  $C > B > A$ . (b) 1 & A, 2 & B, 3 & S, 4 & C. (c) A.

**RE 33-6:** (a) (1) lags, (2) leads, (3) in phase. (b) (3) ( $\omega^{dr} = \omega$  when  $X_L = X_C$ ).

**RE 33-7:** (a) Increase since the circuit is mainly capacitive; increase  $C$  to decrease  $X_C$  to be closer to resonance for maximum  $\langle P \rangle$ . (b) Closer.

### Problems

**1.** 25.6 ms **3.** (a) 97.9 H; (b) 0.196 mJ **7.** (a) 34.2 J/m<sup>3</sup>; (b) 49.4 mJ **9.**  $1.5 \times 10^8$  V/m **11.** (a) 1.0 J/m<sup>3</sup>; (b)  $4.8 \times 10^{-15}$  J/m<sup>3</sup> **13.** 9.14 nF **15.** (a) 1.17  $\mu$ J; (b) 5.58 mA **17.** with  $n$  a positive integer: (a)  $t = n(5.00 \mu\text{s})$ ; (b)  $t = (2n - 1)(2.50 \mu\text{s})$ ; (c)  $t = (2n - 1)(1.25 \mu\text{s})$  **19.** (a) 1.25 kg; (b) 372 N/m; (c)  $1.75 \times 10^{-4}$  m; (d) 3.02 mm/s **21.**  $7.0 \times 10^{-4}$  s **23.** (a) 3.0 nC; (b) 1.7 mA; (c) 4.5 nJ **25.** (a) 275 Hz; (b) 364 mA **27.** (a) 6.0:1; (b) 36 pF, 0.22 mH **29.** (a) 1.98  $\mu$ J; (b) 5.56  $\mu$ C; (c) 12.6 mA; (d)  $-46.9^\circ$ ; (e)  $+46.9^\circ$  **31.** (a) 0.180 mC; (b)  $T/8$ ; (c) 66.7 W **33.** (a) 356  $\mu$ s; (b) 2.50 mH; (c) 3.20 mJ **35.** Let  $T_2$  ( $= 0.596$  s) be the period of the inductor plus the 900  $\mu$ F capacitor and let  $T_1$  ( $= 0.199$  s) be the period of the inductor plus the 100  $\mu$ F capacitor. Close  $S_2$ , wait  $T_2/4$ ; quickly close  $S_1$ , then open  $S_2$ ; wait  $T_1/4$  and then open  $S_1$ . **37.** 8.66 m $\Omega$  **39.**  $(L/R) \ln 2$  **43.** (a) 0.0955 A; (b) 0.0119 A **45.** (a) 0.65 kHz; (b) 24  $\Omega$  **47.** (a) 6.73 ms; (b) 11.2 ms; (c) inductor; (d) 138 mH **49.** (a)  $X_C = 0$ ,  $X_L = 86.7 \Omega$ ,  $Z = 218 \Omega$ ,  $I = 165$  mA,  $\phi = 23.4^\circ$  **51.** (a)  $X_C = 37.9 \Omega$ ,  $X_L = 86.7 \Omega$ ,  $Z = 206 \Omega$ ,  $I = 175$  mA,  $\phi = 13.7^\circ$  **53.** 1000 V **55.** 89  $\Omega$  **57.** (a) 224 rad/s; (b) 6.00 A; (c)



## Ans-18 Answers to Reading Exercises and Odd-Numbered Problems

228 rad/s, 219 rad/s; (d) 0.040 **61.** 1.84 A **63.** 141 V **65.** 0, 9.00 W, 2.73 W, 1.82 W **67.** (a) 12.1  $\Omega$ ; (b) 1.19 kW **69.** (a) 0.743; (b) leads; (c) capacitive; (d) no; (e) yes, no, yes; (f) 33.4 W **71.** (a) 117  $\mu\text{F}$ ; (b) 0; (c) 90.0 W, 0; (d)  $0^\circ$ ,  $90^\circ$ ; (e) 1, 0 **73.** (a) 2.59 A; (b) 38.8 V, 159 V, 224 V, 64.2 V, 75.0 V; (c) 100 W for R, 0 for L and C.

### Chapter 34

**RE 34-1:** (a) Since the induced emf around the dotted loop must oppose the increase in  $\vec{B}$ ,  $\vec{E}$  on the right of the rectangle points down in the negative  $y$  direction.  $\vec{E} + d\vec{E}$  on the left has a greater magnitude and points in the same direction. (b) Since  $\vec{E} \times \vec{B}$  must be in the positive  $x$  direction,  $\vec{B}$  on the right points into the paper in the negative  $z$  direction.  $\vec{B} + d\vec{B}$  on the left points in the same direction as  $\vec{B}$  but has a greater magnitude.

**RE 34-2:** In the positive  $x$  direction.

**RE 34-3:** For total absorption,  $P_r = I/c$  independent of area, but  $F_r = P_r/A$  so it decreases as the area decreases.

### Problems

**1.**  $5.0 \times 10^{-21}$  H **3.**  $B_x = 0$ ,  $B_y = -6.7 \times 10^{-9} \cos[\pi \times 10^{15}(t - x/c)]$ ,  $B_z = 0$  in SI units **5.** 0.10 MJ **7.**  $8.88 \times 10^4 \text{ m}^2$  **9.** (a) 16.7 nT; (b) 33.1 mW/m<sup>2</sup> **11.** (a) 6.7 nT; (b) 5.3 mW/m<sup>2</sup>; (c) 6.7 W **13.** (a) 87 mV/m; (b) 0.30 nT; (c) 13 kW **15.**  $3.44 \times 10^6 \text{ T/s}$  **17.** (a)  $z$  axis; (b)  $7.5 \times 10^{14} \text{ Hz}$ ; (c) 1.9 kW/m<sup>2</sup> **19.** 89 cm **21.** (a)  $3.5 \mu\text{W/m}^2$ ; (b) 0.078  $\mu\text{W}$ ; (c)  $1.5 \times 10^{-17} \text{ W/m}^2$ ; (d) 110 nV/m; (e) 0.25 fT **23.**  $1.0 \times 10^7 \text{ Pa}$  **25.**  $5.9 \times 10^{-8} \text{ Pa}$  **27.** (a) 100 MHz; (b) 1.0  $\mu\text{T}$  along the  $z$  axis; (c)  $2.1 \text{ m}^{-1}$ ,  $6.3 \times 10^8 \text{ rad/s}$ ; (d) 120 W/m<sup>2</sup>; (e)  $8.0 \times 10^{-7} \text{ N}$ ,  $4.0 \times 10^{-7} \text{ Pa}$  **31.** 1.9 mm/s **33.** (b) 580 nm **35.** (a)  $4.68 \times 10^{11} \text{ W}$ ; (b) any chance disturbance could move the sphere from being directly above the source, and then the two force vectors would no longer be along the same axis **37.** (a) 1.9 V/m; (b)  $1.7 \times 10^{-11} \text{ Pa}$  **39.** 3.1% **41.** 4.4 W/m<sup>2</sup> **43.** 2/3 **45.** (a) 2 sheets; (b) 5 sheets **47.** 0.21 **49.**  $35^\circ$  **51.** 0.031 **53.**  $19.6^\circ$  or  $70.4^\circ$  ( $= 90^\circ - 19.6^\circ$ ) **55.** (a) 0.50 ms; (b) 8.4 min; (c) 2.4 h; (d) 5500 B.C. **57.** (a) 515 nm, 610 nm; (b) 555 nm,  $5.41 \times 10^{14} \text{ Hz}$ ,  $1.85 \times 10^{-15} \text{ s}$  **59.** it would steadily increase; (b) the summed discrepancies between the apparent time of eclipse and those observed from  $x$ ; the radius of Earth's orbit

### Chapter 35

**RE 35-1:** a

**RE 35-2:** 0.2d, 1.8d, 2.2d.

**RE 35-3:** When you look into a flat mirror, you see the portion of light scattering off your face that bounces off the mirror and travels straight back into your eyes. But you assume that the light entering your eyes has traveled in a straight line to reach you, so you see an image of your face behind the mirror. The image of your face is right side up. The light from your hair hits the mirror at a slight angle and then bounces into your eyes from above which is why you see your hair on top. Left and right are a different story. If you are standing face to face with another person and your right ear points toward the east, her left ear will point toward the east. If, instead, you face a flat mirror, the light from your right ear will bounce off the mirror and enter your eyes from the east. Even though your east ear is the east ear of the image, your right ear has become the left ear of the image.

**RE 35-4:** Ray 1: A ray that is initially parallel to the central axis reflects as if it came originally from the focal point *behind* the mirror. Ray 2: A ray that comes from the object and is traveling toward the

focal point behind the mirror emerges parallel to the central axis. Ray 3: A ray that comes from the object and is traveling toward the center of curvature  $C$  of the mirror returns along itself. Ray 4: A ray that comes from the object and reflects from the mirror at its intersection  $c$  from the central axis is reflected symmetrically from the central axis.

**RE 35-5:** (a) Real; (b) inverted; (c) same.

**RE 35-6:** (a) e; (b) virtual, same.

### Problems

**1.** 1.48 **3.** 1.26 **5.** 1.07 m **11.** 1.22 **13.** (a)  $49^\circ$ ; (b)  $29^\circ$  **15.** (a) cover the center of each face with an opaque disk of radius 4.5 mm; (b) about 0.63 **17.** (a)  $\sqrt{1 + \sin^2 \theta}$ ; (b)  $\sqrt{2}$ ; (c) light emerges at the right; (d) no light emerges at the right **19.**  $49.0^\circ$  **21.** 40 cm **23.** (a) 3 **27.** new illumination is 10/9 of the old **29.** 10.5 cm **33.** (a) 2.00; (b) none **37.**  $i = -12 \text{ cm}$  **39.** 45 mm, 90 mm **43.** 22 cm **47.** same orientation, virtual, 30 cm to the left of the second lens;  $m = 1$  **53.** (a) 13.0 cm; (b) 5.23 cm; (c)  $-3.25$ ; (d) 3.13; (e)  $-10.2$  **55.** (a) 2.35 cm; (b) decrease **57.** (a) 5.3 cm; (b) 3.0 mm

### Chapter 36

**RE 36-1:**  $b$  (least  $n$ ),  $c$ ,  $a$ .

**RE 36-2:** (a)  $3\lambda$ , 3; (b)  $2.5\lambda$ , 2.5.

### Problems

**1.** (a)  $5.09 \times 10^{14} \text{ Hz}$ ; (b) 388 nm; (c)  $1.97 \times 10^8 \text{ m/s}$  **3.** 1.56 **5.**  $22^\circ$ , refraction reduces  $\theta$  **7.** (a) 3.60  $\mu\text{m}$ ; (b) intermediate, closer to fully constructive interference **9.** (a) 0.833; (b) intermediate, closer to fully constructive interference **11.** (a) 0.216 rad; (b)  $12.4^\circ$  **13.** 2.25 mm **15.** 648 nm **17.** 16 **19.** 0.072 mm **21.** 6.64  $\mu\text{m}$  **23.** 2.65 **25.**  $y = 27 \sin(\omega t + 8.5^\circ)$  **27.** (a) 1.17 m, 3.00 m, 7.50 m; (b) no **29.**  $I = \frac{1}{9} I_m [1 + 8 \cos^2(\pi d \sin \theta / \lambda)]$ ,  $I_m$  = intensity of central maximum **31.** Fully constructively **33.** 0.117  $\mu\text{m}$ , 0.352  $\mu\text{m}$  **35.** 70.0 nm **37.** 120 nm **39.** (a) 552 nm; (b) 442 nm **43.** 140 **45.** 1.89  $\mu\text{m}$  **47.** 2.4  $\mu\text{m}$  **49.**  $\sqrt{(m + \frac{1}{2})\lambda R}$ , for  $m = 0, 1, 2, \dots$  **51.** 1.00 m **53.**  $x = (D/2a)(m + \frac{1}{2})\lambda$ , for  $m = 0, 1, 2, \dots$  **55.** 588 nm **57.** 1.00030

### Chapter 37

**RE 37-1:** (a) expand, (b) expand

**RE 37-2:** (a) second side maximum, (b) 2.5

**RE 37-3:** (a) red, (b) violet

**RE 37-4:** Diminish

**RE 37-5:** (a) left, (b) less.

### Problems

**1.** 60.4  $\mu\text{m}$  **3.** (a)  $\lambda_a = 2\lambda_b$ ; (b) coincidences occur when  $m_b = 2m_a$  **5.** (a) 70 cm; (b) 1.0 mm **7.** 1.77 mm **11.** (d)  $53^\circ$ ,  $10^\circ$ ,  $5.1^\circ$  **13.** (b) 0 rad, 4.493 rad, etc.; (c)  $-0.50$ , 0.93, etc. **15.** (a)  $1.3 \times 10^{-4} \text{ rad}$ ; (b) 10 km **17.** 50 m **19.** (a)  $1.1 \times 10^4 \text{ km}$ ; (b) 11 km **21.** 27 cm **23.** (a)  $0.347^\circ$ ; (b)  $0.97^\circ$  **25.** (a)  $8.7 \times 10^{-7} \text{ rad}$ ; (b)  $8.4 \times 10^7 \text{ km}$ ; (c) 0.025 mm **27.** five **29.** (a) 4; (b) every fourth bright fringe is missing **31.** (a) nine; (b) 0.255 **33.** (a) 3.33  $\mu\text{m}$ ; (b)  $0.0^\circ$ ,  $\pm 10.2^\circ$ ,  $\pm 20.7^\circ$ ,  $\pm 32.0^\circ$ ,  $\pm 45.0^\circ$ ,  $\pm 62.2^\circ$  **35.** three **37.** (a) 6.0  $\mu\text{m}$ ; (b) 1.5  $\mu\text{m}$ ; (c)  $m = 0, 1, 2, 3, 5, 6, 7, 9$ , **39.** 1100 **47.** 3650 **53.** 0.26 nm **55.** 39.8 pm **59.** (a)  $a_0/\sqrt{2}$ ,  $a_0/\sqrt{5}$ ,  $a_0/\sqrt{10}$ ,  $a_0/\sqrt{13}$ ,  $a_0/\sqrt{17}$  **61.**  $30.6^\circ$ ,  $15.3^\circ$  (clockwise);  $3.08^\circ$ ,  $37.8^\circ$  (counterclockwise)

**Chapter 38**

**RE 38-1:** We observe that the second train is moving with respect to our train. The “slight vibration” we feel is evidence that our own train is moving along the tracks, but this does not tell us either the speed or the direction of that motion. Without this information on our own motion, we cannot determine whether or not the second train is at rest with respect to the tracks.

**RE 38-2:** (a) Our measured value of the speed of light is equal to its value measured by the rider. (b) With respect to our frame, it takes some time for the light to move from one end of the boxcar to the other. During that time the boxcar moves in a direction opposite to that of the light. As a result, we measure the distance between emission and absorption of the light to be smaller than the length of the boxcar. (c) Part (b) shows that the distance between emission and absorption is shorter in our frame than in the frame of the rider on the boxcar. The speed of light is the same for both of us. Therefore, the time between emission and detection is shorter as measured in our frame is shorter than the time measured in the boxcar frame. (You should revisit this analysis after reading Section 38-12 Lorentz Contraction. Will this re-analysis lead to the same conclusion or a different one?)

**RE 38-3:** These questions concern individual impressions, so there are no objective answers. Here are mine: Halfway through the performance I would experience it as a whole series of events: hard parts, easy parts, mistakes! Those who printed the program probably listed the Minute Waltz as one event in the concert. Looking back ten years later, I will probably (but not necessarily) remember it as a single event.

**RE 38-4:** (a) Recall that, in general, distance = velocity\*time. We know the velocity ( $c$ ) and the distance (30 meters) of the returning light pulse. Therefore the time taken for this return is  $(30 \text{ m})/(3 \times 10^8 \text{ m/s}) = 10^{-7} \text{ second} = 0.1 \text{ microsecond}$ . Therefore the pulse arrived at detector B  $0.225 - 0.1 = 0.125 \text{ microsecond}$  after it passed us at detector A. (b) The proton pulse left detector A at  $t = 0$  and, according to part (a) arrived at detector B at  $t = 0.125 \text{ microseconds}$ . Therefore its speed from A to B is  $(30 \text{ m})/(0.125 \times 10^{-6} \text{ s}) = 2.4 \times 10^8 \text{ m/sec}$ , or  $2.4/3 = 0.8$  of the speed of light.

**RE 38-5:** Decay reduces the remaining number of pions by a factor of two for every 25 meters of distance they travel (at that particular speed, whatever it is). So there will be one-quarter remaining after 50 meters of travel and one-eighth at a distance of 75 meters from the target.

**RE 38-6:** All the clocks will run at the rate of every other clock. If this were not so, you could use the difference between rates of different clocks to detect which inertial reference frame you are in, contrary to the principle of relativity.

**RE 38-7:** Rearrange Eq. 38-3 to read  $\Delta\tau/\Delta t = \sqrt{1 - v^2/c^2}$ . Square both sides of this equation, solve for  $v^2/c^2$ , and substitute the values given in the statement of the exercise,  $v^2/c^2 = 1 - \Delta\tau/\Delta t = 1 - 1/1.01 = 0.0099$ . Take the square root of both sides to obtain approximately  $v/c = 0.1$ . This is a rough-and-ready criterion for the speed above which relativistic effects become significant in reasonably accurate experiments.

**RE 38-8:** The time a light pulse takes to travel one way from Earth’s surface to the moon’s surface is  $3.76 \times 10^8 \text{ m}/3.00 \times 10^8 \text{ m/s} = 1.25 \text{ second}$ . The two firecrackers, one on each surface explode one second apart in the earth-moon frame. Nothing, not even light can

travel from the first explosion to the second explosion. Therefore one explosion cannot have caused the other one.

**RE 38-9:** Music has been emitted from the tape player. There are vibrations in the air. This is a fact that must be true in both frames of reference. (For example, it might be arranged to have the noise set off a firecracker, whose explosion must be acknowledged by all.) Air currents and distance permitting, Sam on the ground will be able to hear the music sometime (with what distortions we do not bother to analyze here). When Sam and Susan meet over coffee, they will both verify that some tape has been wound from one spool to the other in the tape recorder.

**RE 38-10:** Rearrange Eq. 38-17 to read  $E/mc^2 = (1 - v^2/c^2)^{-1/2}$ . Take the reciprocal of both sides, then square both sides and substitute values for the ratio of energy to rest energy given in the statement of the exercise. The result is  $(mc^2/E)^2 = 1/4 = 1 - v^2/c^2$ . Rearrange and take a square root to obtain  $v = \sqrt{3/4} c = 0.866c$ .

**RE 38-11:** The algebraic equations for this solution are essentially identical to those for the solution to the preceding reading exercise 38-10. Rearrange Eq. 38-28 to read  $\Delta x'/\Delta x = (1 - v^2/c^2)^{-1/2}$ . Take the reciprocal of both sides, then square both sides and substitute values for the ratio of measured lengths given in the statement of the exercise. The result is  $(\Delta x'/\Delta x)^2 = 1/4 = 1 - v^2/c^2$ . Rearrange and take a square root to obtain  $v = \sqrt{3/4} c = 0.866c$ .

**RE 38-12:** The light flash will move with speed  $c$  in our frame; this is a basic assumption of special relativity (Section 38-3). Verify this result by substituting the values  $u' = c$  and  $v^{\text{rel}} = 0.9c$  into Eq. 38-31.

$$u = \frac{c + v^{\text{rel}}}{1 + cv^{\text{rel}}/c^2} = \frac{c + 0.9c}{1 + 0.9c^2/c^2} = \frac{1.9c}{1.9} = c \text{ as we predicted.}$$

**RE 38-13:** Square both sides of Eq. 38-33 and multiply through by the resulting denominator:  $(f/f_0)^2(1 + v^{\text{rel}}/c) = (1 - v^{\text{rel}}/c)$ . Solve for  $v^{\text{rel}}$

$$v^{\text{rel}} = \frac{1 - (f/f_0)^2}{1 + (f/f_0)^2} c = \frac{1 - 0.81}{1 + 0.81} c = 0.1c.$$

**Problems**

**1.** (a)  $v/c = 3.16 \times 10^{-18}$  (b)  $v/c = 9.26 \times 10^{-8}$  (c)  $v/c = 2.87 \times 10^{-6}$  (d)  $v/c = 10^{-4}$  **3.** EACH of the identical experiments should give the same result in the uniformly moving train as in the closed freight container. **5.**  $v/c = 0.990$  or  $v = 2.97 \times 10^8 \text{ m/s}$  **7.** You set your clock to the time  $2 \times 10^{-4} \text{ s}$ . **9.**  $\Delta\tau = 4.7 \times 10^{-8} \text{ s}$  and  $\Delta t = 17 \times 10^{-8} \text{ s}$ . Therefore  $\Delta t/\Delta\tau = 3.6$  **11.** (a) 26.3 y (b) 52.3 y (c) 3.71 y **13.** (a)  $v/c = 0.995$  (b)  $4.8 \times 10^3 \text{ m}$  (c) 480 m (d) 48 km (e)  $9.8 \times 10^4$  particles will survive. **15.** (a)  $v/c = 0.9999995$  (b) one year (c) It does not matter as long as the acceleration is small. **17.** (1, 2) timelike, yes; (1, 3) spacelike, no; (2,3) lightlike, yes **21.**  $3.51 \times 10^{-8} \text{ kg/y}$  or about 35 micrograms/year **23.**  $1.4467 \times 10^{-29} \text{ kg}$ , or 8.127 MeV **25.** (a)  $1.04 \times 10^{10} \text{ J}$  (b) 0.116 mg **27.** (a)  $v/c = [N(N+2)]^{1/2}/(N+1)$  (b)  $p = [N(N+2)]^{1/2} mc$  **29.** (a)  $m[p^2/(2K)] - [K/(2c^2)]$ . For slow particle speed this reduces to the first term, which becomes  $m$ , as expected. (b)  $m/m_e = 206$  **31.** (a) The lowest total energy after the collision (equal to the total energy before the collision) leaves the products at rest. (b) Kinetic energy of each incident proton is equal to the rest energy (the mass) of one proton. (c) This incident kinetic energy is equal to 1 GeV, which is reasonable since in the zero-total-momentum frame all the incident kinetic energy goes into the creation of mass, provided that the products remain at rest. **33.**  $v_x = v^{\text{rel}}$  and  $v_y = v_y'[1 - (v^{\text{rel}})^2/c^2]^{1/2}$  **35.** (a)  $\cos\phi = [\cos\phi' + v^{\text{rel}}/c]/[1 +$

## Ans-20 Answers to Reading Exercises and Odd-Numbered Problems

$(v^{\text{rel}}/c) \cos \phi']$  (b)  $\cos \phi_o = v^{\text{rel}}/c$  (c)  $\phi_o = 8.1^\circ$  **37.** (a)  $v = 2.6 \times 10^8$  m/s (b)  $L = 50$  m. **39.** (a) Yes, at an appropriate speed, proper time between two timelike events can be made as small as desired. (b)  $v = 0.999\,999\,15c$  **41.** velocity with respect to the rocket  $= -0.82c$  **43.** Minimum and maximum values occur when daughter particles move along direction of relative motion.  $u_+ = 0.990\,c$  and  $u_- = 0.282\,c$  **45.**  $f = 22.9$  MHz **47.**  $v^{\text{rel}} = 0.96\,c$  **49.** (a) She does not age at all. (b) Both earth and Zircon age 100 y. (c) 350 y (d) 1200 y on earth **51.** 31.6 s **55.** (a) 0.511 MeV (b)  $M_{\text{sys}} = m + 2m_e$  (c) Mass of the system is  $2m_e$  both before and after the collision. **57.**  $E_M = (M^2 + m^2)c^2/(2m)$  **61.** Partial answer: Let  $T$  be the time lapse between the instant we see the sun explode and the instant we see Venus change color. Then we have time  $T/3$  to escape earth after we see Venus change color. This assumes that the alien ship moves faster than the pulse emitted by the sun.

# Photo Credits

**Dedication** Photo courtesy Jean Arons.

**Introduction** Opener: Courtesy of the Archives, California Institute of Technology. Reproduced with permission of the Estate of Richard Feynman. Figure I-1: FOXTROT ©1999 Bill Amend. Reprinted with permission of UNIVERSAL PRESS SYNDICATE. All rights reserved.

**Preface** Figures P-1, P-2 and P-3: Courtesy Priscilla Laws.

**Chapter 1** Opener: Larry Bray/Taxi/Getty Images. Figure 1-2: Detlev van Ravenswaay/Photo Researchers. Figure 1-3: Courtesy Randall Feenstra, Carnegie Mellon University. Figure 1-4: ©Steven Pitkin. Figure 1-5: Courtesy National Institute of Standards and Technology. Figure 1-7: Courtesy Bureau International des Poids et Mesures, France. Figure 1-8: Courtesy Fisher Scientific. Figures 1-9, 1-10 and 1-11 (left): Courtesy Vernier Software and Technology. Figure 1-11 (right): Courtesy Pasco Scientific. Figure 1-12: Courtesy Ron Thornton. Figures 1-13 and 1-14: Courtesy Priscilla Laws. Figure 1-15: Getty Images News and Sport Services. Figure 1-20: Worldscapes/Age Fotostock America, Inc. Figure 1-21: Lynda Richardson/Corbis Images. Figure 1-22: Corbis Digital Stock.

**Chapter 2** Opener: Niagara Gazette/Corbis Sygma. Figures 2-6, 2-7 and 2-9: Courtesy Pat Cooney. Figure 2-10: Courtesy Priscilla Laws. Figure 2-13: Courtesy U.S. Air Force. Figure 2-16: Courtesy Ron Thornton. Figures 2-18, 2-19, 2-20 and 2-21b: Courtesy Priscilla Laws. Figure 2-30: Courtesy Vernier Software and Technology. Figure 2-42: Courtesy Priscilla Laws.

**Chapter 3** Opener: Nicole Duplaix/Corbis Images. Figure 3-1: American Institute

of Physics/Photo Researchers. Figures 3-2, 3-3 and 3-5: Courtesy Priscilla Laws. Figure 3-8: Courtesy Vernier Software and Technology. Figure 3-10: Courtesy Ohaus Corporation. Figures 3-12 and 3-13: Courtesy Priscilla Laws. Page 67: ©AP/Wide World Photos. Figure 3-19a: Courtesy Priscilla Laws. Figure 3-20: James A. Sugar/Corbis Images. Figures 3-22 and 3-28: Courtesy Priscilla Laws. Figure 3-34: Clive Newton/Corbis Images. Figures 3-45, 3-55 and 3-56: Courtesy Priscilla Laws.

**Chapter 4** Opener: Courtesy David des Marais, Cave Research Foundation. Figure 4-2: FOXTROT ©1999 Bill Amend. Reprinted with permission of UNIVERSAL PRESS SYNDICATE. All rights reserved.

**Chapter 5** Opener: ©AP/Wide World Photos. Figure 5-1: Photo by Andrew Davidhazy/RIT. Figure 5-2: Bettmann/Corbis Images. Figure 5-4: Courtesy Priscilla Laws. Figure 5-5: Richard Megna/Fundamental Photographs. Figure 5-6: Courtesy Priscilla Laws. Figure 5-7: Jammie Budge/Gamma-Press, Inc. Figures 5-9 and 5-10: Courtesy Priscilla Laws. Figure 5-23: Adam Woolfitt/Corbis Images. Figure 5-30, Problem 6: Allsport/Getty Images.

**Chapter 6** Opener: © Natural History Photographic Agency. Page 145: ©2003 Tom Thaves. Reprinted with permission. Figure 6-14: Courtesy Priscilla Laws. Figure 6-16: Courtesy Pasco Scientific. Figure 6-17: Courtesy Priscilla Laws. Figure 6-26: Jean Y. Ruzsnewki/Stone/Getty Images. Figure 6-28: Joe McBride/Stone/Getty Images. Figure 6-29: Courtesy Priscilla Laws. Figure 6-41: Jerry Schad/Photo Researchers. Figure 6-47: Susan Copen Oken/Dot, Inc. Figure 6-73: Peter Turnley/Corbis Images. Figure 6-84: Courtesy Joe Redish. Figure 6-92a: Courtesy Priscilla Laws.

**Chapter 7** Opener: Terje Rakke/The Image Bank/Getty Images. Figure 7-1a: Charles and Josette Lenars/Corbis Images. Figure 7-1b: Science Photo Library/Photo Researchers. Figure 7-1c: Photo by Andrew Davidhazy/RIT. Figure 7-5: Courtesy Robert Teese. Figure 7-9: Courtesy Priscilla Laws. Figure 7-10: Courtesy PASCO scientific. Figures 7-11, 7-12, 7-13 and 7-14: Courtesy Priscilla Laws. Figure 7-17: Courtesy NASA. Page 198: FOXTROT ©2000 Bill Amend. Reprinted with permission of UNIVERSAL PRESS SYNDICATE.. All rights reserved. Figure 7-19: Courtesy NASA. Figure 7-21: George Long/Sports Illustrated/Time, Inc. Picture Collection. Figure 7-22: Superman #48, October 1990. ©D.C. Comics. All rights reserved. Reprinted with permission. Figures 7-33 and 7-38: Courtesy Priscilla Laws.

**Chapter 8** Opener: Lois Greenfield. Figure 8-1a: Richard Megna/Fundamental Photographs. Figures 8-6, 8-10, 8-11 and 8-12: Courtesy Priscilla Laws. Figure 8-23: Adam Crowley/PhotoDisc, Inc./Getty Images.

**Chapter 9** Opener and Figure 9-22: ©AP/Wide World Photos. Figure 9-21: ©Photri.

**Chapter 10** Opener: Malcolm S. Kirk/Peter Arnold, Inc. Figure 10-1: Dimitri Lundt/Corbis Images. Figure 10-7: Photo provided courtesy of Mattel, Inc. Figure 10-9a: ©AP/Wide World Photos. Figure 10-14: Courtesy Priscilla Laws. Figure 10-19: Courtesy Mercedes-Benz of North America.

**Chapter 11** Opener: Arthur Tilley/Stone/Getty Images. Figure 11-1a: Doug Pensinger/Getty Images News and Sport Services. Figure 11-1b: Duomo/Corbis Images. Figures 11-2: Courtesy PASCO scientific and Priscilla Laws. Figure 11-9: Cour-



## C-2 Photo Credits

tesy Priscilla Laws. Page 308: Calvin and Hobbes ©1990 Bill Watterson. Reprinted with permission of UNIVERSAL PRESS SYNDICATE. All rights reserved. Figure 11-13: Roger Ressmeyer/Corbis Images. Figure 11-16: Courtesy Test Devices, Inc. Figure 11-26: Courtesy Lick Observatory. Figure 11-34: Courtesy Lawrence Livermore Laboratory, University of California. Figure 11-50: Courtesy Mark Luetzelschwab.

**Chapter 12** Opener: Image courtesy Ringling Brothers and Barnum & Bailey®, THE GREATEST SHOW ON EARTH. Figure 12-1: Richard Megna/Fundamental Photographs. Figure 12-2: Courtesy PASCO Scientific. Figure 12-15: From *Shepp's World's Fair* Photographed by James W. Shepp and Daniel P. Shepp, Globe Publishing Co., Chicago and Philadelphia, 1893. Photo provided courtesy of Jeffery Howe.

**Chapter 13** Opener: Greg Epperson/Age Fotostock America, Inc. Page 363 (top): David Noton/Age Fotostock America, Inc. Page 363 (bottom): Andy Levin/Photo Researchers. Page 375 (right): Courtesy PASCO Scientific. Page 375 (bottom): Courtesy Vishay Micro-Measurements Group, Raleigh, NC. Page 378: Worldscapes/Age Fotostock America, Inc.

**Chapter 14** Opener: Courtesy NASA. Page 386: Courtesy Jon Lomberg. Page 394: Mark Simons, California Institute of Technology/Photo Researchers. Page 406 (center): Courtesy National Radio Astronomy Observatory. Page 406 (right): Courtesy NASA.

**Chapter 15** Opener: Peter Atkinson/The Image Bank/Getty Images. Page 419 (left): Courtesy Vernier Software and Technology. Page 419 (right): Courtesy PASCO Scientific. Page 425 (top and bottom): Corbis Sygma. Page 427: Courtesy Carol Everett. Page 428: Will McIntyre/Photo Researchers. Page 429 (left): Courtesy D. H. Peregrine, University of Bristol. Page 429 (right): Courtesy Volvo North America Corporation. Page 443: David Parker/Science Photo Library/Photo Researchers.

**Chapter 16** Opener: Owen Franken/Corbis Images. Page 445 (left): PhotoDisc, Inc./Getty Images. Page 445 (right): Digital Vision/Getty Images. Pages 451 and 456: Courtesy Priscilla Laws. Page 474: David Wall/Age Fotostock America, Inc.

**Chapter 17** Opener: John Visser/Bruce Coleman, Inc. Page 493: Courtesy Education Development Center. Page 500: Richard Megna/Fundamental Photographs. Page 501: Courtesy Thomas D. Rossing, Northern Illinois University.

**Chapter 18** Opener: Stephen Dalton/Animals Animals. Page 513 (top): Courtesy Virginia Jackson. Page 513 (bottom): Courtesy Kerry Browne. Page 514: Courtesy Sara Settlemyer. Page 521: Ben Rose/The Image Bank/Getty Images. Page 524 (top): Bob Gruen/Star File. Page 524 (bottom): Jaroslav Kubec/HAGA/The Image Works. Page 534: U.S. Navy photo by Ensign John Gay.

**Chapter 19** Opener: Courtesy Dr. Masato Ono, Tamagawa University. Page 541 (top): PhotoDisc, Inc./Getty Images. Page 541 (center): Adam Hart-Davis/Photo Researchers. Page 541 (bottom): Damien Lovegrove/Photo Researchers. Page 546: Courtesy Pat Cooney. Page 548: Courtesy Priscilla Laws. Page 563: ©AP/Wide World Photos. Page 568: Alfred Pasioka/Photo Researchers. Page 569: Courtesy Dr. Masato Ono, Tamagawa University.

**Chapter 20** Opener: Tom Branch/Photo Researchers.

**Chapter 21** Opener: Stephen Dalton/Photo Researchers. Page 619: Tim Wright/Corbis Images.

**Chapter 22** Opener: Fundamental Photographs. Page 634: Vaughan Fleming/Photo Researchers. Page 644: Johann Gabriel Doppelmayr, *Neuentdeckte Phaenomena von Bewunderswürdigen Wirkungen der Natur*, Nuremberg 1744. Page 645: Courtesy Priscilla Laws.

**Chapter 23** Opener: Courtesy Paula Brakke.

**Chapter 24** Opener: Peter Menzel.

**Chapter 25** Opener: Larry Lee/Corbis Images. Page 717: Courtesy PASCO scientific. Pages 738 (top) and 739: Courtesy NOAA. Page 738 (bottom): Courtesy Westinghouse Corporation.

**Chapter 26** Opener: Corbis-Bettmann. Page 752: Courtesy Priscilla Laws. Page 755: The Image Works. Page 758: Tim Flach/Stone/Getty Images. Page 767: Cour-

tesy Shoji Tonaka/International Superconductivity Technology Center, Tokyo, Japan.

**Chapter 27** Opener: George Grall/National Geographic Society.

**Chapter 28** Opener: Photo by Harold E. Edgerton. ©The Harold and Esther Edgerton Family Trust, courtesy of Palm Press, Inc. Page 800 (top): Lester V. Bergman/Corbis Images. Pages 800 (bottom) and 801: Courtesy Priscilla Laws. Page 806: Courtesy Timothy Settlemyer. Page 815: The Royal Institution, England/Bridgeman Art Library/NY.

**Chapter 29** Opener: EFDA-JET/Photo Researchers. Page 830: Jeremy Walker/Photo Researchers. Page 836: Lawrence Berkeley Laboratory/Photo Researchers. Page 837: Courtesy Dr. Richard Cannon, Southeast Missouri State University, Cape Girardeau. Page 840: Courtesy John Le P. Webb, Sussex University, England. Page 841: Courtesy EFDA-JET, [www.jet.efda.org](http://www.jet.efda.org).

**Chapter 30** Opener: NASDA/Gamma-Press, Inc. Page 863: Courtesy Education Development Center.

**Chapter 31** Opener: Copyright General Motors Corporation. Page 889: Science Photo Library/Photo Researchers. Pages 894 and 897 (top): Courtesy PASCO scientific. Page 897 (bottom): Joseph Sia/Archive Photos/Hulton Archive/Getty Images.

**Chapter 32** Opener: Courtesy Dr. Timothy St. Pierre, University of Western Australia. Page 923: The Royal Institution, England/Bridgeman Art Library/NY. Pages 936 and 943: Yoav Levy/Phototake. Page 941: Courtesy Ralph W. DeBlois. Page 945: Courtesy Andre Geim, University of Manchester, U.K. Page 946: Mehau Kulyk/Photo Researchers. Page 947 (top): Courtesy Greg Foss, Pittsburgh Supercomputing Center; research and data: Gary Glatzmaier, USC; Earth map provided by NOAA/NOS. Page 947 (bottom): Courtesy Dr. Timothy St. Pierre, University of Western Australia.

**Chapter 33** Opener: Photo by Rick Diaz, provided courtesy Haverfield Helicopter Co. Page 955 (top): Corbis Images. Page 955 (bottom): Bettmann/Corbis Images. Page 960: Courtesy Agilent Technologies.

**Chapter 34** Opener: Chris Madeley/Science Photo Library/Photo Researchers. Page 986: Baldwin H. Ward/Corbis Images. Page 1006: Diane Schiumo/Fundamental Photographs.

**Chapter 35** Opener: Courtesy Courtauld Institute Galleries, London. Page 1017: From *PSSC Physics*, 2nd edition; ©1975 D.C. Heath and Co. with Education Development Center, Newton, MA. Page 1020 (top): Courtesy Bausch & Lomb. Pages 1020 (bottom) and 1022: PhotoDisc, Inc./Getty Images. Page 1033: Dr. Paul A. Zahl/Photo Researchers. Page 1037: Courtesy Matthew J. Wheeler.

**Chapter 36** Opener: Gail Shumway/Taxi/Getty Images. Pages 1063 and 1081: From Michel Cagnet, Maurice Franzon, and Jean Claude Thierr, *Atlas of Optical Phenomena*, Springer-Verlag, New York, 1962. Reproduced with permission. Page 1073: Richard Megna/Fundamental Pho-

tographs. Page 1080: Courtesy Bausch & Lomb.

**Chapter 37** Opener: Georges Seurat, *A Sunday on La Grande Jatte*, 1884; oil on canvas,  $207.5 \times 308$  cm, Helen Birch Bartlett Memorial Collection; photograph ©2003, The Art Institute of Chicago. All rights reserved. Page 1084: Ken Kay/Fundamental Photographs. Pages 1085, 1092 (top) and 1095: From Michel Cagnet, Maurice Franzon, and Jean Claude Thierr, *Atlas of Optical Phenomena*, Springer-Verlag, New York, 1962. Reproduced with permission. Page 1093: P.M. Motta & S. Correr/Photo Researchers. Page 1099: Department of Physics, Imperial College/Science Photo Library/Photo Researchers. Page 1100: Steve Percival/Science Photo Library/Photo Researchers. Page 1106: Kjell B. Sandved/Bruce Coleman, Inc. Page 1107: Pekka Parvianen/Photo Researchers.

**Chapter 38** Opener: Courtesy Fermi National Accelerator Laboratory. Page 1112: Corbis Images.

### Data Credits

**Chapter 15** Page 417(top): Data obtained by David Vernier. Page 417 (bottom): Data obtained by Priscilla Laws.

**Chapter 16** Pages 446, 457, 464, and 465: Data obtained by Priscilla Laws.

**Chapter 18** Pages 516 and 517: Data obtained by Priscilla Laws. Pages 526-527: Data obtained by Priscilla Laws and David and Ginger Hildebrand.

**Chapter 19** Pages 544-545: Data obtained by Priscilla Laws.

**Chapter 33** Pages 645, 803, and 892: Courtesy Priscilla Laws.



*This page intentionally left blank*

# Index

Page references followed by italic *table* indicate material in tables.  
Page references followed by italic *n* indicate material in footnotes.

## A

- a* (gravitational acceleration constant), 73, 74, 392–393
  - various altitudes, 393*table*
- absolute pressure, 421
- absolute zero, 560, 561
- absorbed radiation, 1001
- acceleration. *See also* forces; velocity
  - average, 38
  - center of mass, 219
  - centripetal, 125–127, 129
  - constant, 41–45
  - constant force along line, 60–61
  - constant rotational acceleration, 306–307
  - corresponding relations for translation and rotation, 322*table*
  - and drag force, 160
  - free fall motion, 73–75
  - ideal projectile motion, 111–113
  - and kinetic friction force, 149–151
  - and mass measurement, 63–65
  - Newton's Second Law for multiple forces in straight line motion, 70–71
  - Newton's Second Law for single force in straight line motion, 65–66
  - Newton's Second Law in multiple dimensions, 141–142
  - of particles in mechanical waves, 487
  - rocket flight, 196–197
  - rotational, 304, 310
  - speeding up and slowing down, 39–40
  - standard force, 62–63
  - and static friction force, 151–152
  - and tension, 155–156
  - torque, 315–320
- acceleration amplitude, 455
- accelerometer, 64–65
- acetone, index of refraction, 1018*table*
- acoustic interferometers, 535–536
- AC 114 quasar, 406
- addition, vectors, 92
- adiabat, 599
- adiabatic compression, Carnot engine, 615–618
- adiabatic expansion, 598–601
- adiabatic processes, 556*table*, 556–557, 598, 615–618
- Advanced Hybrid Particulate Collector (AHPC), 659, 676
- air, 516*table*
  - density, 414*table*
  - dielectric properties, 816*table*
  - humidity and breakdown, 684
  - index of refraction, 1018*table*
  - mean free path at sea level, 587
  - molar specific heat at freezing point of water, 605
  - sound waves through, 514
  - thermal conductivity of dry, 567*table*
- air-filled pipe
  - longitudinal wave in, 513
  - standing sound waves in, 525
- Allegheny Observatory, 1107
- Alpha Centauri, 1122
- alpha particles, 682
  - velocity selector, 858
- alternating current circuits, 932, 955, 967, 978–980. *See also* transformers
- alternating current generator, electric dipole antenna, 990
- aluminum
  - coefficient of linear expansion, 564*table*
  - dopant in silicon, 767
  - elastic properties, 376*table*
  - paramagnetic material, 936
  - resistivities, 757*table*
  - specific heat, 549*table*
  - speed of sound in, 516*table*
  - thermal conductivity, 567*table*
- ammeters, 752, 777–778
- ammonia, permanent electric dipole moment, 741
- ammonium, molar specific heat at constant volume, 592*table*
- Ampère, André Marie, 831, 863, 870, 871, 872
- Ampère-Maxwell law, 907, 912*table*, 987
- Ampère's law, 871–875, 987
- ampere (unit), 748, 871
- Ampèrian loop, 872
- amplitude
  - AC emf, 967
  - interfering transverse waves, 496
  - mass-spring oscillating system, 451
  - sinusoidal oscillation, 448
  - waves, 478, 480, 483, 485, 499, 497*table*
- Amundsen-Scott South Pole Station, 300 F club, 574
- analog ammeters, 752, 777–778
- Anderson, Paul, 226, 248
- Andromeda galaxy, 386, 1135
- angle of incidence, 1017, 1057
- angle of minimum deviation, 1048
- angle of reflection, 1017
- angle of refraction, 1017, 1057
- angular amplitude, simple pendulum, 458
- angular displacement, 457, 465
- angular frequency
  - AC emf, 967, 968
  - and beats, 528
  - LC oscillator, 963–964
  - mass-spring oscillating system, 451, 452
  - sinusoidal oscillation, 448, 449
  - sound waves, 518
  - transverse waves, 484, 485
- angular magnification, 1042–1044
- angular velocity, gravitational pendulum, 457
- antennas, 990, 1004
- anti-matter ion cosmic rays, 859–860
- antinodes, 499–501
- aorta, 431
- apparent weight, 147–148
  - at equator, 395
  - in fluid, 426–428
- Archimedes' principle, 424–428
- arc of charge, field due to, 674–675
- Arecibo radio telescope, 1009
- Argo, Dominique, 1084
- argon
  - mean free path at room temperature, 603
  - molar specific heat at constant volume, 592*table*
- Aristotle, 37
- Arons, A. A., 443*n*, 1053
- asteroid impact, 403–404
- astrophysics, 406, 409
- atmosphere, 411
  - negative and positive ions in lower, 770
- atmosphere (atm; unit), 413, 563*n*
- atmospheric convection, 547
- atmospheric pressure, 414, 416–417
- atomic clocks, 8, 11, 13, 1118–1119
- atomic mass units, 13–14, 578–579
- atomic model, 637–638
- atomic nucleus. *See* nucleus
- atomic theory
  - conductors and insulators, 643
  - dielectrics, 817–818
  - and electrification, 637–641
  - magnetism, 937, 939
- aurora, 842
- automobiles, 466, 784, 795
  - car lift, 423–424
  - fluids required by, 411
  - tire pressure, 414*table*
- autotransformer, 951
- Avogadro, Amedeo, 578
- Avogadro's law (hypothesis), 603, 605
- Avogadro's number, 578–579
- axis of rotation, 301

## B

- Babinet's principle, 1105–1106
- back emf, 924
- bacteria, magnetic, 922, 947–948
- ballet dancer, physics of *grand jeté*, 16, 209, 218
- ballistic pendulum, 282
- Ballot, Buys, 529
- bar magnet, 935, 837, 851
- barometer, 419–420
- base quantities, 8–9
- base standards, 8–10
- base units, 9*table*
- bats, echo navigation, 512, 543
- batteries, 774–789
  - in circuit, 808–812
  - electric current, 745–751
  - as external force acting on charges, 717–718
  - in LC circuits, 958
  - power, 758–760
  - in RC circuits, 821
  - resistance of AA batteries, 771
  - in RL circuits, 929–930
  - symbol for, 751
- beams, 992–993, 1016

## I-2 Index

- beam splitter, 1076  
beats, 527–529  
Bell, Alexander Graham, 522  
benzene, index of refraction, 1049  
Bernoulli, Daniel, 435  
Bernoulli's equation, 434–437  
beta decay, 654  
Big Stone plant, Advanced Hybrid Particulate Collector, 659, 676  
Biot, Jean Baptiste, 864  
Biot-Savart law, 865, 870  
bismuth, diamagnetic material, 936  
black holes, 409, 414*table*  
blocks  
    accelerated by friction, 164–165  
    contact forces on surfaces, 146–152  
    floating, 443  
    pulling, 79–80, 157–158  
    sliding up ramp, 162–163, 276  
    static equilibrium, 363  
    three cords, 158–159  
block-spring systems, 263  
    electrical-mechanical analogy, 960–962  
    simple harmonic motion, 450  
blood, density, 414*table*  
body-mass measuring device (BMMD), 468  
body temperature, 542, 543*table*, 559  
Bohr magneton, 938  
Bohr radius, 710  
boiling point  
    sea level, 559  
    selected atoms and water, 551*table*  
    water, 543*table*  
Boltzmann, Ludwig, 568, 583, 626  
Boltzmann constant, 578, 580, 626  
Boltzmann's entropy equation, 626  
bone, 376*table*  
boron, 859  
boundary reflections, sinusoidal waves, 500  
Boyle, Robert, 577  
Bragg, W. L., 1104  
Bragg angle, 1104  
Bragg's law, 1104  
branches, connecting junctions in electric circuits, 778  
brass  
    coefficient of linear expansion, 564*table*  
    specific heat, 549*table*  
Brewster angle, 1023  
Brewster's law, 1023–1024  
bright bands, 1063  
bright fringes  
    double-slit interference, 1063–1065  
    single slit diffraction, 1085–1087  
British thermal unit (BTU), 546  
building materials, 564*table*, 567*table*  
bulb, 747–751  
    resistance in circuit, 753  
bulk modulus, 376  
    selected materials, 516*table*  
    and speed of sound, 515  
buoyant force, 424–428  
    and convection, 547  
  
**C**  
cadmium, visible emission lines, 1097  
Cajori, Florian, 389*n*  
Callisto, angle with Jupiter, 446, 453  
calorie (cal), 546  
cameras, 1033, 1041, 1056, 1079  
capacitance, 801–808  
capacitive reactance, 970  
capacitive time constant, 822–823  
capacitors, 800  
    charge ratios, 828  
    with dielectric, 815–817  
    displacement current, 908–910  
    energy density, 814  
    as energy storage device, 800–801  
    *LC* circuits, 958–965  
    in parallel, 808–809  
    phasor representation for ac capacitive load, 970–971  
    *RC* circuits, 821–824  
    *RLC* circuits, 965–967, 968, 972–977  
    in series, 810–812  
capillaries (blood vessels), 431  
carbon, phase diagram, 438  
carbon-12, 14, 579, 860  
carbon-13, 579  
carbon-14, 860  
carbon dioxide  
    molar specific heat at constant volume, 592*table*  
    root-mean-square speed at room temperature, 585*table*  
carbon disulfide, index of refraction, 1018*table*  
carbon resistors, 755, 781  
Cardoso, Maria Fernanda, 57  
Carnot, N. L. Sadi, 615  
Carnot cycle, 615  
Carnot engine, 615–623  
Carnot refrigerators, 620–623  
carrier charge density, 763–764  
carts  
    collision, 188–193, 281  
    flea pulling, 57, 66–67  
Casiani, Tom, 180  
cathode ray tube, 843  
cats, falls from high buildings, 139, 160–161  
cell membrane, 828  
Celsius, Anders, 542  
Celsius scale, 541–543, 561*table*  
Centaurus cluster of galaxies, 386  
center of curvature, mirrors, 1028, 1033  
center of gravity, 365–370  
center of mass, 211–217  
center of oscillation, physical pendulum, 460  
centigrade temperature, 542  
central diffraction maximum, 1084  
    full width at half-maximum (FWHM), 1105  
    half-width in diffraction gratings, 1098  
    single slit diffraction, 1089, 1090  
central forces, 651  
central interference maximum, 1065, 1067  
centripetal acceleration, 125–127, 129  
centripetal force, 124–125, 128–129  
ceramics  
    dielectric properties, 816*table*  
    superconductive, 767  
Ceres, escape speed, 403*table*  
cesium atomic frequency standard, 11  
cesium chloride, crystal structure, 654–655  
chain-link conversion, of units, 16–17  
change in entropy, 608–613, 617  
charge, 636–639. *See also* capacitors; Coulomb's law; Gauss' law  
    batteries, 745–746  
    conservation at circuit junctions, 749–750  
    contained inside closed surface, 696–698  
    field, 665–669, 671–674, 690  
    field lines for two positive charges, 680  
    magnetic force from moving, 831  
    motion of point charges in electric field, 675–677  
    oscillations in *LC* circuit, 963  
    potential due to group of point charges, 725–730  
    predicting forces on, 664–665  
charge carrier density, 767  
silicon and copper compared, 766*table*  
charge carriers  
    average speed, 763–764  
    drift speed measurement using Hall effect, 846  
charge-coupled devices (CCDs), 800  
charged arc, field due to, 674–675  
charge density, 671, 672*table*  
charge distribution, 671  
    cylindrical symmetry for uniform line, 702–703  
    determining from electric field patterns, 690  
    electric potential due to continuous, 732–733  
    net flux at closed surface, 692–694  
    nonspherical isolated conductor, 736–737  
    symmetry, 698–705  
charged ring, field due to, 671–675  
charge ratios, capacitors, 828  
charge separation, capacitors, 801  
charging. *See also* electrification  
    batteries, 747, 788  
    capacitors, 801, 821–822, 909–910  
    by induction, 643–644  
Charles, Jacques, 578  
Chemerkin, Andrey, 226, 248  
chokes, 923. *See also* inductors  
chromatic aberration, 1044, 1045  
chromatic dispersion, 1019–1020  
chronometers, 8  
circuit diagrams, 751–752  
circuit elements, 751, 773  
circuit junctions  
    charge conservation at, 749–750  
    multiloop circuits, 778–779  
circuit meters, 751–752  
circuits, 747. *See also* alternating current circuits; capacitance; current; potential difference; resistance  
    capacitors in, 800, 808–812  
    charge conservation at junctions, 749–750  
    and currents, 773  
    Kirchoff's law, 750, 775–776, 779  
    *LC* circuits, 958–965  
    multiloop, 775, 778–779  
    parallel, 749–750  
    power, 758–760  
    *RC* circuits, 821–824  
    resistors, 776–784  
    *RL* circuits, 929–932, 956–957  
    *RLC* circuits, 965–967, 968, 972–977  
    series, 749–750  
    single-loop, 774–776  
    symbols for basic elements, 751  
circuit sketch, 751  
circular aperture diffraction, 1092–1094  
circular motion, 116–129  
circular wave, 514  
classical mechanics, 81  
classical theories, 1112  
clocks, 1116–1119  
closed cycle processes, 556*table*  
closed surface charge distribution, 690, 692–694  
closed systems, 196, 218, 280  
    and entropy, 608, 610, 614  
coaxial cables, as capacitors, 800, 806  
cobalt, as ferromagnetic material, 936, 940  
coefficient of kinetic friction, 151  
coefficient of linear expansion, 563–564, 566  
coefficient of static friction, 152  
coefficient of volume expansion, 564–565  
coherent light, 1066  
coils  
    Helmholtz, 864  
    induced emf, 894  
    in long solenoid, 895–896  
    inductance, 923–928  
    magnetic field of current-carrying, 877–880  
    in transformers, 933–935  
collimator, 1098  
collision forces, 72, 78

- collisions, 181  
     bouncy, 190–191, 280  
     elastic and inelastic, 280–285  
     of gas molecules, 583–584  
     one-dimensional, 190–193, 282–285  
     sticky, 191–193, 281  
     system of particles, 217–218  
     two-dimensional, 193–195, 286
- combustion, 608
- comets, 985, 1003
- compass, 862–863, 946
- completely inelastic collisions, 280–281
- complex objects, 210–220. *See also* center of mass
- component notation, for vectors, 96
- component vectors, 94–96, 98–99
- composite slab, thermal conduction through, 567, 569
- compound microscope, 1043–1044
- compressible fluids, 414
- compressive forces, 372–375
- computer-assisted data acquisition and analysis (CADAA) system, 15*n*
- concave mirrors, 1028, 1029
- concert A, 529
- concrete  
     coefficient of linear expansion, 564*table*  
     compressive and tensile strength, 375, 376*table*
- conduction electrons, 638, 766–767
- conduction rate, 566
- conduction (thermal), 547, 566–569
- conductivity, 765
- conductors, 766–768  
     charged isolated, 706–708  
     current density, 760–761  
     defined, 642–645  
     moving through magnetic field, 890–891  
     Ohm's law, 754–755, 762
- cone, center of mass, 214
- configurations, of molecules, 624–627
- conservation of electric charge, 639, 749–750
- conservation of energy, 278–281, 608  
     and electric potential energy, 717–718
- conservation of mechanical energy, 270–272
- conservation of rotational momentum, 350–352
- conservation of translational momentum, 189–195
- conservative forces, 261–264, 715
- constant acceleration, 41–45
- constant-pressure processes  
     molar specific heat, 593–595  
     work done by ideal gas, 582
- constant rotational acceleration, 306–307
- constant-temperature processes  
     change in entropy, 610  
     work done by ideal gas, 581–582
- constant translational acceleration, 306
- constant-volume gas thermometer, 562
- constant-volume processes, 556*table*, 557  
     molar specific heat, 591–593  
     Stirling engine, 618  
     work done by ideal gas, 582
- constructive interference  
     light waves, 1057, 1071  
     sound waves, 519, 520  
     transverse waves, 497
- contact forces, 72. *See also* tension
- experimental verification for, 78
- Force component, 146–152
- idealized model of solids, 145–146
- continuous charge distribution, 671
- continuous wave, 477
- convection, 547
- conventional current, 760–761
- converging lens, 1036–1037, 1092–1094
- conversation, sound level, 523*table*
- conversion, of units, 16–17
- conversion factors, 16
- convex mirrors, 1028, 1029
- cooling, 545–548
- coordinate axis, 27, 28
- Coordinated Universal Time (CUT), 11
- copper  
     carrier charge density, 763–764  
     coefficient of linear expansion, 564*table*  
     diamagnetic material, 936  
     electrical properties, 766*table*  
     resistivities, 756, 757*table*  
     specific heat, 549*table*  
     thermal conductivity, 567*table*
- copper wire  
     in circuits, 755  
     electric field inside household wires, 664*table*
- cordierite, 1006
- core (Earth), 408, 414*table*  
     and Earth's magnetic field, 946
- core (Sun), 414*table*  
     speed distribution of protons in, 590
- cornea, 1052
- cornering forces, cars around curves, 128
- corona discharge, 738
- cosine  
     describing sinusoidal oscillation, 448  
     using to find vector components, 95
- cosine-squared rule (Malus' law), 1006
- cosmic rays, 859–860, 1141
- Coulomb, Charles Augustin, 638, 644
- Coulomb constant, 646–647
- Coulomb's law, 644–647  
     and Gauss' law, 705–706  
     problem solving using, 647–651
- coulomb (unit), 638
- $C_p$ , *See* molar specific heat at constant pressure
- Crab nebula, 1012
- Cramer's rule, 784
- crates  
     path dependence of work done on, 261  
     work done by crepe crate in storm, 234  
     work done pulling up ramp, 248–249
- critical angle, for total internal reflection, 1022
- critical damping, 465–466
- crossed fields, 843–844
- cross product, 100–101, 340–342
- crown glass, index of refraction, 1018*table*
- crust (Earth), 394, 408  
     density, 414*table*  
     and Earth's magnetic field, 946
- crystal defect, 655
- crystal planes, 1104
- crystals, x-ray diffraction by, 1103–1105
- Curie, P., 944
- Curie constant, 944
- Curie's law, 944
- Curie temperature, 941
- current, 745. *See also* circuits  
     and Ampère's law, 871–875  
     batteries, 746–751  
     in circuit, 776–784  
     defining, 748  
     ideal circuits, 773  
     from induction, 900  
     magnetic field, 862–869, 873, 874  
     magnetic force, 870–871  
     microscopic view, 762–766  
     multiloop circuits, 778–779  
     oscillations in  $LC$  circuit, 963  
     and parallel resistance, 779–784  
     *RC* circuits, 821  
     real emf battery, 787  
     *RLC* circuits, 973–975  
     *RL* circuits, 930–932  
     rms current in AC circuits, 978–979  
     and series resistance, 776–778  
     single-loop circuits, 774–776  
     solenoid, 875–877  
     toroid, 877
- current amplitude, alternating current, 973–975
- current density, 760–762
- current loop, torque on, 849–850
- current phase, alternating current, 973*table*
- curvature of space, 405–406
- $C_v$ , *See* molar specific heat at constant volume
- cycle, engines, 614, 615
- cycloid, 333
- cyclotron, 840, 852–853
- cylinder, rotational inertia, 313*table*
- cylindrical capacitors, 800, 806–807
- displacement current, 909–910
- cylindrical symmetry, uniform line charge distribution, 702–703

## D

- damped oscillations, in  $RLC$  circuits, 965–967
- damped simple harmonic motion, 463–466
- damping, 463–464
- dark fringes  
     double-slit interference, 1063–1065  
     single slit diffraction, 1085–1091
- Data Studio (PASCO scientific), 46
- da Vinci, Leonardo, 476
- Davy, Humphrey, 955
- DC motor, 850
- deceleration, 39–40
- decibel scale, 522–523
- decimal places, 17–18
- decomposing vectors, 94
- dees, cyclotron, 853
- deformation, 362, 371. *See also* elasticity
- degrees, temperature scales, 542, 561–562
- degrees of freedom, 595–597
- density  
     and floating, 426  
     fluids, 413–415  
     selected engineering materials, 376*table*  
     selected materials, 414*table*, 516*table*  
     and speed of sound in media, 515
- derived units, 9
- destructive interference  
     light waves, 1057, 1071  
     sound waves, 519–520  
     transverse waves, 497
- Dialog Concerning Two New Sciences* (Galileo), 108, 109
- diamagnetism, 936, 944–945
- diamond, 438  
     coefficient of linear expansion, 564*table*  
     index of refraction, 1018*table*
- diatomic gases, 592*table*, 595–597
- dielectric constant, 815, 816*table*
- dielectrics, 815–821
- dielectric strength, 815–817
- diffraction, 1084–1097  
     entropic halos, 1106  
     x-ray, 1103–1105  
     and Young's interference experiment, 1062–1066
- diffraction factor, 1096
- diffraction gratings, 1097–1102
- diffraction grating spectrometer, 1099
- diffraction patterns, 1084
- digital multimeter, 752
- digital temperature sensor, 548
- dipole, *See* electric dipole
- dipole axis, 945
- direct current, 955
- discrete charge distribution, 671

## I-4 Index

- disk
    - diffraction pattern, 1085
    - rotational inertia, 313*table*, 336*table*
  - dispersion
    - chromatic, 1019–1020
    - in diffraction gratings, 1100–1102
  - displacement. *See also* work
    - along line in straight line motion, 27–31
    - mass-spring oscillating system, 451
    - rotational, 302–303, 308–309
    - sinusoidal, 448, 481–484
    - standing waves, 499
    - two dimensions, 116–119
    - and velocity and speed, 33–35
  - displacement, of fluid by buoyant object, 425
  - displacement current, 908–910, 987
  - displacement node, 525
  - displacement vectors, 29–30, 90–91
  - dissociation, 598
  - diverging lens, 1036–1037
  - division, vectors by a scalar, 100–101
  - D* line, in sodium spectrum, 1108
  - Dog Star (Sirius), 1137–1138
  - domino, static equilibrium, 363
  - Doppler, Johann Christian, 529
  - Doppler effect, 529–533, 1135
  - Doppler shift, 1135–1136
  - dot product, 100, 101*n*, 339, 343–344
  - double pole double throw switch (DPDT), 751
  - double-slit diffraction, 1094–1097
  - double-slit interference
    - with diffraction, 1092–1093
    - intensity, 1066–1070
    - Young's experiment, 1062–1066
  - Douglas fir, elastic properties, 376*table*
  - DPDT (double pole double throw switch), 751
  - drag coefficient, 160
  - drag force, 159–161, 465
  - Drake, Frank D., 1009
  - drift speed, of charge carriers, 846
  - driven oscillations, 467, 968
  - driving angular frequency, 968
  - DuFay, Charles, 634
  - dyne (force unit), 62
  - dysprosium, as ferromagnetic material, 940
- E**
- $E^{\text{int}}$ , *See* internal energy
  - e*, charge on electron, 1113
  - Earth. *See also* gravitational force density, 414*table*
    - diameter determined from sunset measurements, 5, 12
    - electric field near surface, 740
    - equatorial bulge, 393–394
    - escape speed, 402, 403*table*
    - insolation, 1014
    - intensity of solar radiation reaching, 1010
    - interior, 408
    - interior temperature, 951
    - level of compensation, 439
    - magnetic dipole moment, 851*table*, 857, 951
    - magnetic field, 837*table*, 862–863, 885
    - magnetic latitude, 952
    - magnetism, 945–947
    - mean diameter, 408
    - mean radius, 393*table*
    - Michelson-Morley experiment, 1112–1113
    - negative and positive ions in lower atmosphere, 770
    - rotation, 394–395
    - uneven surface of, 393
    - Van Allen radiation belts, 842
  - Earth orbit, 128
  - earthquakes, 444, 467–468
    - S and P waves, 534
  - Easter Island, 25, 279
  - Echo* satellites, 406
  - eddy currents, 901
  - Edgerton, H., 799
  - Edison, Thomas, 955
  - Eiffel tower, as lightning rod, 714, 738–739
  - Einstein, A., 2, 13, 81, 912, 993, 1112–1113
    - principle of equivalence, 404–405
    - Principle of Relativity, 1113–1114
    - search for superforce, 167
  - Einstein ring, 406
  - Einstein's elevator, 156–157
  - Einstein's train paradox, 1126
  - elastic collisions, 280–285
  - elasticity, 371–377
  - elastic potential energy, 267
    - stretched string with traveling wave, 492
  - electrical-mechanical analogy, 960–961
  - electric cars, 888, 892–893
  - electric charge, *See* charge
  - electric circuits, *See* circuits
  - electric constant, 647
  - electric current, *See* current
  - electric dipole, 670–678
    - electric potential due to, 730–732
  - electric dipole antenna, 990–991
  - electric eel (*Electrophorus*), 772, 789–790
  - electric field, 660, 662–664
    - and aurora, 842
    - calculating from electric potential, 733–735
    - calculating potential from, 723–725
    - capacitors, 801, 804–805, 826–827
    - charge carrier speed, 763
    - charged isolated conductors, 707–708
    - crossed fields, 843–844
    - cylindrical symmetry for uniform line charge distribution, 702–703
    - due to arc of charge, 674–675
    - due to electric dipole, 670–671
    - due to multiple charges, 667–669
    - due to point charge, 665–667, 690
    - due to ring of charge, 671–675
    - electric dipole antenna, 990–991
    - electric dipole in, 677–678
    - and electric potential difference, 719–720
    - electromagnetic waves, 989–990, 992–997
    - energy stored in, 812–815
    - generating in absence of conductors, 986–987
    - induced, 901–908
    - magnitude of selected, 664*table*
    - motion of point charges in, 675–677
    - near Earth surface, 740
    - near nonconducting sheet, 679–680
    - polarized light, 1005
    - sheet of uniform charge, 703–704
    - spherical symmetry, 701–702
    - uniform, 680
    - vector representation, 667
  - electric field lines, 664, 678–680
  - electric field vector, 663–664, 667
  - electric flux, 434, 691–694
  - electricity, 634–636
  - electric motors, 849–850
  - electric potential. *See also* potential difference; voltage
    - calculating electric field from, 733–735
    - calculating from electric field, 723–725
    - charged isolated conductor, 735–739
    - defined, 718–721
    - due to continuous charge distribution, 732–733
    - due to electric dipole, 730–732
    - due to group of point charges, 727–730
    - due to point charge, 725–727
    - equipotential surfaces, 721–723
    - and induced electric field, 904–906
    - near proton, 727
  - electric potential difference, *See* potential difference
  - electric potential energy, 715–718
    - due to group of point charges, 727–730
    - stored in electric field, 812–815
  - electric quadrupole, 682
  - electric spark
    - electric field at breakdown in air, 664*table*
    - potential of spark from charge buildup in ungrounded gas can, 751
    - sound level, 523
  - electric wave component, of electromagnetic waves, 992
  - electrification, 635–642
  - electrocardiogram, 445
  - electrocution, 768
  - electromagnetic force, 72, 78, 167–168
  - electromagnetic induction, 641–644. *See also* inductors
    - by changing magnetic field, 891–893
    - energy transfer, 899–901
    - Faraday's law, 893–896
    - induced electric/magnetic fields, 901–908
    - Lenz's law, 896–898
    - by motion in magnetic field, 889–891
  - electromagnetic oscillations, 955
    - forced, 968
    - LC* oscillations, 958–960
    - phasor representation, 968–972
    - RLC* damped oscillations, 965–967
  - electromagnetic radiation, 547–548, 568–569, 988, 1007–1008
  - electromagnetic rail gun, 861, 871
  - electromagnetic spectrum, 1007–1009
  - electromagnetic wave pulse, 988–990
  - electromagnetic waves, 476, 986–1003
    - full-angle beam divergence, 1009
    - images, 1016
    - speed, 504
  - electromagnetism, 652
    - Maxwell's prediction, 986–988
  - electromagnets, 830, 836, 837*table*
  - electrometer, 824
  - electromotive force, 784–785
  - electron beams, 1041
  - electron gun, 839–840
  - electronic accelerometer, 64–65
  - electronic balance, 64, 144
  - electronic force sensor, 63, 152
  - electron mass, 13–14
  - electron microscope, 1093
  - electron-positron pair, 1142
  - electrons, 637–638. *See also* conduction electrons
    - avalanche in Geiger counter, 711
    - from beta decay, 654
    - charge, 637*table*
    - in conductors and insulators, 643
    - in crossed fields, 843–844
    - discovery, 844
    - and electrification, 635
    - magnetic dipole moment, 851*table*, 937–939
    - as point charges, 665
    - transferring in electrostatic interactions, 639
  - electron-volt (eV), 720–721
  - Electrophorus* (electric eel), 772, 789–790
  - electroplaques, 789
  - electroscope, 640–641
  - electrostatic discharge, 745–746. *See also* electric spark



electrostatic force, 634–636  
 and Coulomb's law, 644–651  
 dipole in electric field, 678  
 due to arc of charge, 674–675  
 due to multiple charges, 667–669  
 due to point charge, 665–667, 690  
 due to ring of charge, 671–675  
 gravitational force contrasted, 651–653  
 magnetic force contrasted, 830–831  
 motion of point charges in electric field, 675–677  
 path independent, 715  
 predicting forces on charges, 664–665  
 and quantity of charge, 639–640  
 electrostatic precipitation, 676  
 electrostatic stress, 826  
 electroweak force, 167  
 elementary charge, 637–638  
 E-measure systems, 15*n*  
 emf, 784–785  
 alternating current, 967–968  
 back, 924  
 devices, 785–787  
 induced, 892, 894, 898  
 emission lines, 1097  
 emissivity, 568  
 energy. *See also* kinetic energy; mechanical energy; potential energy  
 law of conservation of, 278–279  
 and special relativity, 1127–1130  
 stretched string with traveling wave, 492–493  
 transfer from batteries, 784–785  
 transfer in electromagnetic induction, 899–901  
 transformation of mass into, 1127–1129  
 transport by electromagnetic waves, 997–1001  
 energy density  
 capacitors, 814  
 electromagnetic waves, 997  
 engines, 614–623  
 entropic halos, 1106  
 entropy, 608–609, 613–627  
 epsilon sub zero (electric constant), 647  
 equation of continuity, fluids, 429–431, 434  
 equations of motion  
 constant acceleration, 44*table*  
 constant translation and rotational acceleration, 307*table*  
 equilibrium, 362–371  
 equilibrium point  
 electrostatic force on two charged particles, 650–651  
 potential energy curves, 275  
 equilibrium position, 450, 457–458  
 equilibrium value, of particle in sinusoidal oscillation, 448  
 equipartition of energy, 596

equipotential surfaces, 721–723  
 equivalent capacitor, 808, 811–812  
 escape speed, 402–404  
 ether, 1112, 1113  
 ethyl alcohol  
 dielectric properties, 816*table*  
 index of refraction, 1018*table*  
 physical properties, 571  
 specific heat, 549*table*  
 EV1 electric car, 888, 893  
 event horizon, black holes, 409  
 exchange coupling, 940–941  
 expansion slots, 563  
 exponent of ten, 9  
 extended objects, 26, 1026–1027  
 locating images with principal rays, 1038–1039  
 extended systems, *See* complex objects  
 external electric field, 677, 707–708, 737–738  
 external forces, 184, 218  
 and conservation of electric potential energy, 717–718  
 eye, *See* human eye  
 eyeglasses, 1016, 1033, 1041

## F

Fahrenheit, Gabriel, 542  
 Fahrenheit scale, 541–543, 561*table*  
 Faraday, Michael, 652, 679, 815, 889, 891–892, 893, 923, 925  
 Faraday cage, 708, 738  
 Faraday-Maxwell law, 986  
 Faraday's law of induction, 902–903, 893–896, 912*table*, 987  
 farad (F), 804  
 fast Fourier transform (FFT), 527  
 Fermi National Laboratory accelerator, 1111  
 ferromagnetic materials, 935, 936, 941–943  
 Feynman, R., 2  
 fiberglass, thermal conductivity, 567*table*  
 fibrillation, 654  
 field of view, 1028  
 fields, 660–662. *See also* electric field; gravitational field; magnetic field  
 figure skating, 195, 300  
 rotational inertia and spin speed, 333  
 final state, 553, 591, 610  
 first harmonic, 501, 525  
 first law of thermodynamics, 555–558  
 fixed axis, 301  
 flint glass, index of refraction, 1018*table*  
 floaters, 1084  
 floating, 425–426  
 fluids, 159, 411–437 638  
 flux, 431  
 focal length  
 spherical mirrors, 1029  
 thin lens, 1036  
 focal plane, 1065  
 focal point (focus)  
 compound microscope, 1043  
 magnifying lens, 1042  
 spherical mirrors, 1028–1029  
 thin lens, 1036–1037  
 fog  
 formation after opening carbonated drink, 576, 599–600  
 from jet plane's supersonic shock wave, 534  
 food calorie, 546  
 force at-a-distance, 72, 145, 830  
 forced oscillations, 466–468, 968  
 force fields, 660  
 forces, 58. *See also* contact forces; electrostatic force; friction force; gravitational force; kinetic energy; magnetic force; potential energy; tension; work  
 applying Newton's laws in problem solving, 161–162  
 attractive, 372  
 buoyant, 424–428  
 central, 651  
 centripetal, 124–125, 128–129  
 conservative, 261–264, 715  
 drag, 159–161  
 everyday, 140  
 fundamental forces of nature, 72, 166–167  
 ideal projectile motion, 111–113  
 and interaction, 71–72  
 internal and external, 184, 218  
 measurement, 61–63  
 net, 69–70, 140–142  
 and Newton's First Law, 58–69  
 Newton's Second Law for multiple in straight line motion, 70–71  
 Newton's Second Law for single in straight line motion, 65–67  
 and Newton's Third Law, 76–78  
 nonconservative, 261–262, 276–278  
 passive, 151  
 repulsive, 372  
 rocket thrust, 197, 199  
 rolling, 334–336  
 torque, 315–320  
 types of, 71–72  
 force sensor, 63  
 Fourier analysis, of musical sounds, 527  
 fractional half-width, resonance curve, 983  
 Francis Bittner National Magnet Laboratory, 916  
 Franklin, Benjamin, 638, 639, 644, 749  
 free-body diagrams, 68, 69, 140–141, 161–162  
 free charge, 819–820  
 free expansion, 556*table*, 557–558, 600–601, 609  
 free fall motion, 73–75

free oscillations, 467, 968  
 free space, 1008  
 freezing point  
 sea level, 559  
 water, 543*table*  
 French, A. P., 446  
 Fresnel, Augustin, 1084  
 Fresnel bright spot, 1084–1085  
 friction force, 72, 146, 148–149  
 kinetic, 149–151  
 object accelerated by, 164–165  
 path dependence of work done by, 261  
 static, 151–152  
 frictionless surface, 149  
 fuel consumption rate, of rockets, 197  
 fujara, 524  
 fulcrum, 377  
 full-angle beam divergence, 1009  
 full width at half-maximum (FWHM), 1105  
 fully constructive interference  
 light waves, 1057, 1071  
 sound waves, 519, 520  
 transverse waves, 497  
 fully destructive interference  
 light waves, 1057, 1071  
 sound waves, 519–520  
 transverse waves, 497  
 fundamental mode, 501, 525  
 fused quartz  
 coefficient of linear expansion, 564*table*  
 index of refraction, 1018*table*, 1049  
 index of refraction dependence on wavelength, 1019  
 resistivities, 757*table*  
 fusion power, 829

## G

*G* (gravitational constant), 388  
*g* (local gravitational strength), 40, 74–75, 144, 392, 393–394, 663  
 measuring with simple pendulum, 459  
 gadolinium, as ferromagnetic material, 940  
 Galilean transformation equations, 1132  
 Galileo, 37, 41, 73, 1132  
 Callisto observations, 446, 453  
 hypothesis about motion, 108–110  
 speed of light estimate, 1013  
 gamma rays, 988, 1142  
 bubble chamber tracks, 859  
 gas discharge tube, 770  
 gases. *See also* ideal gases; kinetic theory of gases  
 defined, 550  
 density, 414*table*  
 as fluids, 411  
 law of partial pressures, 602  
 macroscopic behavior, 577–580  
 root-mean-square speed of selected at room temperature, 585*table*



## I-6 Index

- gases (*Continued*)  
 speed of sound in selected, 516*table*  
 thermal conductivity of selected, 567*table*
- gas pressure sensors, 419
- gas thermometer, 558–559, 562–563, 572
- gauge number, wire, 768
- gauge pressure, 421, 602
- Gauss, Carl Friedrich, 690
- Gaussian form, thin-lens formula, 1051
- Gaussian pulse, 510
- Gaussian surface, 692–696, 701–705, 707
- Gauss' law, 389*n*, 694–708, 910–912*table*  
 dielectrics, 818–821
- Gay-Lussac, Joseph, 578
- Geiger counter, 711
- General Conference on Weights and Measures, 9
- general relativity, 404–405, 1113, 1121
- generators, 932, 955, 967–968
- geographic north pole, 945, 946
- geological prospecting, 513
- geomagnetic north/south poles, 838, 945
- geometrical optics, 1016, 1057, 1062, 1084
- germanium, dielectric properties, 816*table*
- Giant Shower Array detector, 1141
- Gibbs, William, 583
- glass  
 coefficient of linear expansion, 564*table*  
 elastic properties, 376*table*  
 index of refraction of various types, 1018*table*  
 resistivities, 757*table*  
 specific heat, 549*table*  
 thermal conductivity of window, 567*table*
- Glatzmaier, Gary, 947
- Glatzmaier/Roberts model, of Earth's magnetic field, 947
- Global Positioning System (GPS), and speed of light, 1013–1014
- gold, diamagnetic material, 936
- Goudsmit, S. A., 854
- grand unification theories (GUTs), 167
- granite  
 specific heat, 549*table*  
 speed of sound in, 516*table*
- Graphical Analysis (Vernier Software and Technology), 46
- grating spectroscopy, 1099
- gravitation, 386–398, 404–406
- gravitational acceleration constant (*a*), 73, 74, 392–393, 393*table*
- gravitational constant (*G*), 388
- gravitational field, 660, 662–663
- gravitational force, 72, 166, 386, 388  
 and center of gravity, 365–370  
 component for blocks on surfaces, 147  
 and Earth, 392–395  
 electrostatic force contrasted, 651–653  
 force field maps for near Earth forces, 660  
 and free fall motion, 73–75  
 and hydrostatic forces, 415–419  
 magnetic force contrasted, 830  
 path dependence test for, 260–261  
 and principle of superposition, 390–391  
 and weight, 143–145  
 work done by, 233–234  
 work done on flowing fluid, 436
- gravitational lensing, 385, 405–406
- gravitational mass, 63–64, 65
- gravitational pendulum, 456–460
- gravitational potential energy, 267, 398–404
- graviton, 406
- gravity, 72–75
- Great Attractor, 386
- Griffith, George, 397–398
- grounding, 643
- H**
- Hafele, J. C., 1118
- half-life, 1119
- half-width, of central diffraction maximum in diffraction gratings, 1098
- Hall, Edwin H., 844–845
- Hall effect, 844–847
- Hall potential difference, 845–847
- harmonic number, 501, 525
- harmonics, 501, 525–526
- Harrison, John, 8, 13
- hearing threshold, 523*table*
- heat, 540–541, 545–548. *See also* thermodynamics
- heat engines, 615
- heat of fusion, 551*table*
- heat of vaporization, 550–551*table*
- heat pumps, 620
- heats of transformation, 550–551*table*
- heat transfer, 547
- heavy water, 829
- Heimlich maneuver, 421
- helical path, of circulating charged particle in magnetic field, 841
- helium  
 atomic structure, 637, 638  
 degrees of freedom, 595, 597*table*  
 molar specific heat at constant volume, 592*table*  
 root-mean-square speed at room temperature, 585*table*  
 speed of sound in, 516*table*  
 thermal conductivity, 567*table*
- helium-neon laser, 1010
- Helmholtz coil, 864
- henry (H), 925
- Henry, Joseph, 889, 893, 925, 988, 989
- hertz (Hz), 447
- Hertz, Heinrich, 986, 988, 989, 1007
- higher temperature superconductors, 767
- high-speed electronic flash, 799, 813–814
- high speed tail, of Maxwell's speed distribution, 590
- Hindenburg*, 744, 757–758
- Hooke, Robert, 63, 234
- Hooke's law, 63, 234–235, 372, 374, 450
- hoop, rotational inertia, 313*table*, 336*table*
- horizontal oscillators, 450
- horseshoe bat, echo navigation, 512, 543
- house, thermogram, 568
- Hudson Bay, Canada, gravity low, 393
- Human cannonball, 107, 115–116
- human centrifuge, 311
- human eye, 1008, 1016, 1024, 1041, 1042, 1052
- laser surgery, 1014
- humidity  
 affects electrostatic interaction, 634, 635  
 and air breakdown, 684
- Huygens, Christian, 1057, 1084
- Huygens' principle, 1057–1058
- Huygens' wavelet, 1058
- Hydra cluster of galaxies, 386
- hydraulic compression, 376
- hydraulic jack, 423
- hydraulic lift, 422–423
- hydraulic stress, 374, 376–377
- hydroelectric generators, 932
- hydrogen  
 atomic structure, 637  
 effect of temperature on molar specific heat at constant volume, 598  
 electric field at Bohr radius, 710  
 electric field within, 664*table*  
 root-mean-square speed at room temperature, 585*table*  
 speed of sound in, 516*table*  
 thermal conductivity, 567*table*  
 visible emission lines, 1097
- hydrostatic pressures, 415–419
- hyperfine levels, 11
- hysteresis, 942–943
- hysteresis loop, 943
- I**
- ice  
 coefficient of linear expansion, 564*table*  
 density, 414*table*  
 specific heat, 549*table*  
 at triple point, 560
- iceberg, percentage visible when floating, 427
- ice/salt mixture temperature, 559
- ideal gases, 578–582, 591, 598–601. *See also* kinetic theory of gases
- ideal gas law, 577–580
- ideal gas temperature, 563
- ideal inductors, 925–926  
*RL* circuits, 929–932
- ideal transformers, 933–935
- image distance, 1026–1030, 1038–1040
- image height, 1027, 1028, 1030
- images, 1024–1027, 1031–1033, 1037–1038
- impulse, 184–186
- impulse-momentum theorem, 186, 227, 230
- incident beam, 1016–1017
- incoherent light, 1066
- incompressible flow, 428
- indeterminate problems, 370–371
- index of refraction, 1018–1020, 1059–1061  
 and reflection phase shifts, 1070
- indistinguishable molecules, 624, 626
- induced current, 892
- induced dipole moment, 731–732
- induced electric field, 901–906  
 electromagnetic waves, 993–995
- induced emf, 892, 894, 898
- induced magnetic field, 906–908  
 electromagnetic waves, 995–997
- inductance, 923–928
- induction, *See* electromagnetic induction
- induction motors, 955
- induction stove, 901
- inductive chargers, 923
- inductive reactance, 971
- inductive time constant, 930–931
- inductors  
 energy in, 956–958  
 ideal, 925–926  
 with iron cores, 942, 943  
*LC* circuits, 958–965  
 mutual inductance, 923, 926–928  
 phasor representation for ac inductive load, 971–972  
*RL* circuits, 929–932, 956–957  
*RLC* circuits, 965–967, 968, 972–977  
 self-inductance, 923–926
- inelastic collisions, 280–281
- inelastic deformation, 372
- inertial mass, 64–65
- inertial reference frames, 60, 1117
- infrared cameras, 1041
- infrared radiation, 547, 1008
- inner core (Earth), 946
- insolation, 1014
- insulation (thermal), 568
- insulators, 642–645  
 resistivities of selected at room temperature, 757*table*  
 semiconductors contrasted, 767

- intensity, of electromagnetic waves, 997, 998–999  
 diffraction gratings (line shapes), 1102  
 double-slit diffraction, 1095–1097  
 double-slit interference, 1066–1070  
 single-slit diffraction, 1088–1091  
 transmitted polarized light, 1005–1006  
 variation with distance, 999–1001
- intensity, of sound, 521–522
- interaction, and forces, 71–73
- interference. *See also* wave interference  
 applications, 1057  
 coherence, 1066  
 combining more than two waves, 1069  
 diffraction contrasted, 1096  
 diffraction gratings, 1097  
 double-slit, 1062–1070  
 light as wave, 1057–1062  
 Michelson interferometer, 1076–1077  
 thin films, 1070–1077
- interference factor, 1096
- interference pattern, 1063
- interfering waves, 496
- interferometer, 1076
- intermediate interference, transverse waves, 497
- internal combustion engine, 619
- internal energy, 540, 551, 555–557, 577, 591–595
- internal energy change, 597
- internal forces, 184, 218
- International Bureau of Weights and Measures, 13, 14
- International units. *See* SI units
- interplanar spacing, in crystals, 1104
- interstellar space  
 density, 414*table*  
 magnetic field, 837*table*, 981
- intrinsic magnetic moment, 836
- Invar, coefficient of linear expansion, 564*table*
- invariant intervals, 1121–1125
- inverting vectors, 93
- ions  
 measuring mass of heavy, 854  
 as point charges, 665
- iron  
 atomic nucleus, 652–653  
 cores for inductors and transformers, 942, 943  
 Curie temperature, 941  
 density of nucleus, 414*table*  
 dipole moment of atom, 951  
 as ferromagnetic material, 935, 936, 940  
 resistivities, 757*table*
- irreversible processes, 608  
 and second law of thermodynamics, 614
- irreversible reactions, 608
- irrotational flow, 435*n*
- isolated conductors, 706–708  
 electric potential, 735–739
- isolated spherical capacitors, capacitance calculation, 808
- isolated systems, 183, 280
- isotherm, 581
- isothermal compression, 581, 615–618
- isothermal expansion, 581, 610–611, 635–618. *See also* constant-temperature processes
- isotropic light source, 999–1000
- isotropic materials, current density, 762
- isotropic sound source, 522
- J**
- jet planes  
 fluids required by, 411  
 sound level, 523*table*
- Joint European Torus (JET) Tokamak, 841
- joule (J), 230, 546
- junctions  
 charge conservation at, 749–750  
 multiloop circuits, 778–779
- Jupiter, 446, 453  
 escape speed, 403*table*
- K**
- karate, breaking of boards, 180, 185, 189
- Keating, R. E., 1118
- Kelvin, Lord William Thompson, 542, 561
- Kelvin scale, 542, 561
- kelvins (unit), 558
- kettledrum, 501, 524
- kilometers, 17
- kinematic calculations, 43
- kinematic equations  
 constant acceleration, 41–44  
 free fall motions, 75  
 ideal projectile motion, 113*table*
- kinematics, 26
- kinetic energy, 229–230  
 conversion into thermal energy, 575  
 corresponding relations for translation and rotation, 322*table*  
 everyday speeds, 1129–1130  
 and law of conservation of energy, 278–279  
 mechanical energy component, 270  
 relativistic, 1129–1130  
 of rotation, 311–312  
 simple harmonic motion, 461  
 stretched string with traveling wave, 491–492  
 and thermodynamics, 540  
 translation with simple rotation, 334–337  
 work-kinetic energy theorem, 320–322
- kinetic friction force, 149–151
- kinetic theory of gases, 540, 577, 583–598  
 and law of partial pressures, 602
- Kirchhoff, Gustav Robert, 775
- Kirchhoff's law, 750, 775–779
- $K^0$  meson, 1131
- L**
- laboratory frame, 1117, 1132
- laboratory pressure, highest sustained, 414*table*
- laboratory vacuum, 414*table*, 602
- LabPro interface, 15
- laminar flow, 428, 432
- Land, Edwin, 1004
- Large Magellanic Cloud, 386
- laser beam, 992, 1002
- laser eye surgery, 1014
- lasers, 1066, 1002
- lateral magnification, 1030–1031, 1038, 1040, 1043
- lattice, 371
- latticework clock synchronization, 1116–1118
- launch angle, ideal projectile motion, 111
- lava currents, and Earth's magnetism, 946–947
- law of addition of velocities, 1134
- law of addition of velocities, in special relativity, 1134
- law of conservation of energy, 278–279
- law of conservation of rotational momentum, 350–352
- law of conservation of translational momentum, 189, 281
- law of inertia, 60
- law of partial pressures, 602
- law of reflection, 1017
- law of refraction (Snell's law), 1017–1019, 1058–1059
- Lawrence, E. O., 852
- LC circuits, 958
- LC oscillations, 958–965
- LC oscillators, 962–965  
 electric dipole antenna, 990  
 loudspeakers, 981
- lead  
 coefficient of linear expansion, 564*table*  
 diamagnetic material, 936  
 specific heat, 549*table*  
 thermal conductivity, 567*table*
- lead acid batteries, 784–785
- left-handed coordinate system, 98
- length, measurement, 6, 8, 12–13
- length contraction (Lorentz contraction), 1132–1133
- lenses, 1035–1041  
 magnesium fluoride coating, 1073–1074
- Lenz, Heinrich Friedrich, 896
- Lenz's law, 896–898  
 direction of self-induced emf, 925
- level of compensation, Earth, 439
- light, 1016. *See also* diffraction; images; reflection; refraction
- chromatic dispersion, 1019–1020
- Doppler shift, 532
- and Maxwell's equations, 986
- wave theory of, 1057–1062, 1084
- light gathering power, refracting telescope, 1044
- lightning, 634, 643, 658, 738–739
- line, motion along. *See* straight line motion
- linear charge density, 671, 672*table*
- cylindrical symmetry of uniform, 702–703
- electric potential due to continuous, 732–733
- linear device, 753, 754
- linear expansion, 563–564
- line integral, 723
- line of action, of torque, 316
- lines, diffraction gratings, 1097–1098
- line shapes, 1102
- lines of force, 679
- liquids  
 coefficient of volume expansion, 565  
 compressibility, 376  
 defined, 550  
 density, 414*table*  
 specific heats of selected, 549*table*  
 speed of sound in selected, 516*table*  
 thermal energy transfer to, 548–553
- liquid thermometer, 540, 558–559
- lithium, atomic structure, 637
- ln (natural logarithm), 197
- local gravitational field vector, 663
- local gravitational strength ( $g$ ), 40, 74–75, 144, 392–393  
 and gravitational field, 663  
 measuring with simple pendulum, 459
- Local Supercluster, 386
- lodestones, 652, 862, 935, 943
- longitude, quest to measure precisely, 8
- longitudinal magnification, 1050
- longitudinal waves, 477, 513. *See also* sound waves
- Lorentz contraction, 1132–1133
- Lorentz force law, 834
- Lorentz transformation, 1131–1132
- loudspeakers, 468, 522, 981
- Loverude, M. E., 443*n*
- M**
- Mach cone, 533, 534
- magnesium fluoride lens coating, 1073–1074
- magnetic bacteria, 922, 947–948
- magnetic bottle, 841
- magnetic dipole moment, 850–852  
 orbital, 937–939
- magnetic dipoles  
 characteristics, 936–937  
 current-carrying wire as, 877–880

## I-8 Index

- magnetic domains, 941, 943
- magnetic energy, 956–958
- magnetic field, 831–833
  - and Ampère's law, 871–875
  - charged particles trapped in Earth's, 842–843
  - crossed fields, 843–844
  - current-carrying coil, 877–880
  - cyclotron, 840, 852–853
  - displacement current, 908–910
  - due to current, 862–869
  - eddy currents, 901
  - electric dipole antenna, 990–991
  - electromagnetic waves, 989–990, 992–997
  - energy in, 956–958
  - and Faraday's law, 893–896
  - Gauss' law for, 910–912
  - generating in absence of conductors, 986–987
  - Hall effect, 844–847
  - induced, 901–910
  - and magnetic force, 833–839
  - selected situations, 837*table*
  - solenoid, 875–877
  - toroid, 877
- magnetic field lines, 837–838
- magnetic flux, 434, 893–898
- magnetic force, 652, 653, 830–843
  - current-carrying wire, 847–849
  - between parallel currents, 870–871
  - torque on current loop, 849–850
- magnetic latitude, 952
- magnetic potential energy, 851
- magnetic repulsive forces, 77–78
- magnetic resonance imaging (MRI), 951
- magnetic wave component, of electromagnetic waves, 992
- magnetism, 862, 937, 945–947
- magnetite, 652
- magnetization, 942–943
- magnetization curves, 941, 944
- magnetosomes, 947–948
- magnetotactic bacteria, 947–948
- magnets, 652, 836–838, 862. *See also* bar magnet; electromagnets
  - magnetic field near selected, 837*table*
  - velocity selector, 858
- magnification, 1040–1044
  - lateral, 1030–1031, 1038 longitudinal, 1050
- magnifying lens, 1041, 1042–1043
- magnitude, 28–30
- magnitude-angle notation, for vectors, 96
- Malus, Etienne, 1006
- Malus' law, 1006
- Mammoth-Flint Ridge cave system, 89
- Manganin, resistivities, 757*table*
- manometer, 420–421
- mantle (Earth), 408
  - and Earth's magnetic field, 946
- maritime radio, 1008
- Mars, mean diameter, 408
- mass, 7
  - corresponding relations for translation and rotation, 322*table*
  - and gravitational force, 73–75
  - measuring 7–8, 13–14, 63–65
  - transformation into energy, 1127–1129
  - weight contrasted, 144–145
- mass distribution, and rotational inertia, 312, 313*table*
- mass flow rate, 430
- Massis, John, 67
- mass spectrometer, 842–843, 859
- mass-spring systems
  - damped simple harmonic motion, 465
  - simple harmonic motion, 450–454
- maxima
  - diffraction patterns, 1084
  - interference patterns, 1063, 1067
- Maxwell, James Clerk, 583, 588, 596, 652, 872, 889, 986, 1001, 1007
- Maxwell's equations, 652, 912, 912*table*, 986
- Maxwell's law of induction, 906
- Maxwell's rainbow, 1007–1009
- Maxwell's speed distribution law, 588–590
- mean free path, 586–588, 603
- measurable property, 541
- measurement, 5–7
  - changing units, 16–17
  - fluid pressure, 419–421
  - force, 61–63
  - gravitational mass, 63–64, 65
  - international units (SI system), 8–10
  - length standards, 12–13
  - mass standards, 13–14
  - precision, 7–8
  - significant figures, 17–18
  - temperature, 540–543, 558–563
  - time standards, 11–12
  - tools for physics labs, 14–15
- mechanical energy, 270–272
  - battery energy transformed into, 747
  - and law of conservation of energy, 278–279
  - and nonconservative forces, 276–278
  - simple harmonic motion, 461
  - and thermodynamics, 540
- mechanical waves, 476, 487
- medium
  - electromagnetic waves, 993
  - light waves, 1112–1113
- Mehlhoff, C. J., 161*n*
- melting point, 550, 551*table*
- mercury
  - density of nucleus, 414*table*
  - specific heat, 549*table*
  - superconductivity at 4 K, 767
- mercury barometer, 419–420
- mercury manometer, 562
- Mercury-Redstone rocket, 198
- metallic conductors, 641–643, 766
  - resistivities of selected at room temperature, 757*table*
- metallic lattice, 371
- meter, 12–13, 1077
- methane
  - combustion, 608
  - degrees of freedom, 595, 597*table*
- metric equation, 1121–1123, 1128
- metric system, 9. *See also* SI units
- Mexico City earthquake of 1985, 444, 467–468
- MG1131+0456 (Einstein ring), 406
- mhos per meter (unit), 765
- mica, dielectric properties (ruby mica), 816*table*
- Michelson, A. A., 1076
- Michelson, Albert W., 1112
- Michelson interferometer, 1076–1077
- Michelson-Morley experiment, 1112–1113
- microcomputer based laboratory (MBL) system, 15*n*
- microfarad, 804
- microscopes, 1016, 1033, 1043–1044, 1093
- microstates, 624–627
- microwaves, 477
- Milky Way galaxy, 386
- Millikan, Robert, 638, 687
- millimeter of mercury (mmHg), 413
- minima
  - diffraction patterns, 1084, 1085–1087
  - interference patterns, 1063, 1067
- mirrors, 1016, 1026–1029
  - optical instruments, 1041–1042
- molar mass, 578, 579, 585*table*
- molar specific heat, 549*table*, 590–597
- molar specific heat, 549–550, 591–598, 597*table*
- molecular speed, of gases, 583–586, 588–590
- moles, 549, 578–580
- molten lava currents, and Earth's magnetism, 946–947
- moment of inertia, *See* rotational inertia
- momentum, 280. *See also* rotational momentum; translational momentum
  - and special relativity, 1127–1130
- monatomic gases, 591, 592*table*, 595–597
- Moon, 387, 390
  - diffraction by water drops, 1106–1107
  - escape speed, 403*table*
  - laser beam bounced off by Soviet-French team, 1107
- Morley, Edward W., 1112
- Morpho* butterfly, iridescent wings, 1056, 1073–1074
- motion, 26. *See also* acceleration; circular motion; equations of motion; projectile motion; rotation; straight line motion; vectors; velocity
  - basic measurements of, 6–7
- complex objects, 210
- displacement in two dimensions, 116–119
- free fall, 73–75
- representing in diagrams and graphs, 32–33
- motion data, 46
- motion diagrams, 32, 33
- Motte, Andrew, 389*n*
- Mount Everest, 392, 393*table*, 417
- Mount Palomar telescope, 1106
- MRI (magnetic resonance imaging), 951
- multiloop circuits, 775, 778–779
- multimeter, 752
- multiplication vectors, 100–101, 339–342
- multiplicity, of configurations, 624–627
- Munday, Dave, 25, 44
- muons, 1138
- mutual inductance, 923, 926–928

## N

- $\pi^+$  meson, 1119, 1131
- $\pi^-$  meson, 1131
- National Electric Code (U. S.), 769
- National Institute of Standards and Technology (NIST), 10, 11, 14
- natural angular frequency, 968
- negative flux, 434
- negatively charged objects, 636–637
- negative of a vector, 93
- neodymium-glass laser, 1009
- nerve cell membrane
  - electric field, 664*table*
  - modeling, 798
- net flux, 434
- net force, 69–70
  - as vector sum, 140–142
- net torque, 316–317
- net work-kinetic energy theorem, 229–230, 241, 246–248
  - corresponding relations for translation and rotation, 322*table*
  - flowing fluid, 436–437
  - rotation, 321–322
- net work per cycle, Carnot engine, 616
- neutral equilibrium, 275
- neutrons, 637–638, 665
- neutron stars, 352, 407
  - density, 414*table*
  - escape speed, 403*table*
  - magnetic field at surface, 837*table*
- New Hampshire, horizontal component of magnetic field, 952
- newton (force unit), 61–62, 64
- Newton, Isaac, 58, 387
- Newtonian form, thin-lens formula, 1051
- Newtonian mechanics, 81
- newton per square meter, 562*n*
- Newton's First Law, 58–60
- Newton's law of cooling, 570

- Newton's law of gravitation, 386–390
- Newton's laws  
   applying, 161–162  
   and momentum conservation, 189  
   system of particles, 217–218  
 newtons per coulomb, 664
- Newton's Second Law  
   corresponding relations for translation and rotation, 322*table*, 352*table*  
   multiple dimensions, 141–142  
   for multiple forces in straight line motion, 70–71  
   for rotation, 317–318  
   for single force in straight line motion, 65–67  
   for uniform circular motion, 124
- Newton's Third Law, 76–79  
   and law of gravitation, 389
- NGC 7319, 1141
- Niagara Falls, physics of plunge from, 25, 44–45
- Nichrome wire, 753, 754, 759
- nickel  
   as ferromagnetic material, 936, 940, 941  
   saturation magnetization, 951
- nitrogen  
   mean free path, 603  
   molar specific heat at constant volume, 592*table*  
   root-mean-square speed at room temperature, 585*table*
- NMR (nuclear magnetic resonance), 951
- nodes, 499–501
- nonconducting sheet, electric field near, 679–680
- nonconductors, 643. *See also* insulators
- nonconservative forces, 261–262  
   and mechanical energy, 276–278
- noncontact forces, 72, 73
- nonlaminar flow, 428
- nonlinear device, 753
- nonpolar dielectrics, 817–818
- nonrigid objects, 301
- nonsteady flow, 428
- nonuniform electric field, 693, 694
- nonuniform forces, fluid pressure, 413
- nonviscous flow, 428
- normal force, 146–148
- normal vector, 433, 691
- North America, average rate of energy conduction outward, 573
- North Anna nuclear power plant, 619
- north magnetic pole, 946
- north pole, magnets, 837–838, 862
- nuclear magnetic resonance (NMR), 951
- nuclear repulsion, 652–653
- nuclear weapons, 1127
- nucleus, 637–638  
   as point charges, 665
- null interval, 1125
- number density of charge carriers, 846
- numerical integration, 239–240
- O**
- object distance, 1026
- oblate spheroid, Earth's shape, 393–394
- ocean, 411  
   pressure at average depth of Pacific, 376  
   pressure in deepest trench, 414*table*
- Oersted, Hans Christian, 652, 831, 862–863, 870
- Ohm, George Simm, 754
- ohmic devices, 754  
   in ideal circuits, 773
- ohmmeter, 762
- ohm-meter (unit), 762
- Ohm's law, 754–755, 762–763
- ohm (unit), 754
- oil drop experiment (Millikan), 638, 687
- oil slicks, interference effects, 1056, 1070
- one-half rule, for intensity of transmitted polarized light, 1005
- Onnes, Kamerlingh, 767
- open-tube manometer, 420–421
- opposite charges, 637
- optical fibers, 1022
- optical instruments, 1016, 1041–1045
- optical path difference, 1060
- orbital magnetic dipole moment, 938–939
- orb web spiders, oscillations of web, 456
- order numbers, diffraction gratings, 1097–1098
- order of magnitude, 18
- oscillating term, 483, 485, 496, 499
- oscillation frequency, 449
- oscillation mode, 500
- oscillations, 445. *See also* electromagnetic oscillations; LC oscillations; simple harmonic motion; sinusoidal oscillations; waves  
   forced, and resonance, 466–468  
   and waves, 479–481
- oscilloscope trace, 960
- outer core (Earth), 946
- overdamping, 465–466
- oxygen  
   degrees of freedom, 595, 597*table*  
   Maxwell speed distribution at room temperature, 588  
   mean free path at room temperature, 588  
   molar specific heat at constant volume, 592*table*
- paramagnetism of liquid, 936, 943
- root-mean-square speed at room temperature, 585*table*
- P**
- pain threshold, sound level, 523*table*
- paper  
   dielectric properties, 816*table*  
   plastic comb attracts after rubbing fur, 633, 642
- parabola, projectile motion, 108–109
- parallel-axis theorem, 314
- parallel capacitors, 808–809
- parallel circuits, 749–750
- parallel components, of unpolarized light wave, 1023
- parallel-plate capacitors, 800, 801–803, 805–806  
   displacement current, 909–910
- parallel resistance, 779–784
- paramagnetic materials, 936, 943–944  
   and Curie temperature, 941
- particle accelerators, 1041, 1111, 1123
- particles, 476  
   interaction of two charged by Coulomb's law, 646–651
- particle systems, *See* complex objects
- Pascal, Blaise, 421
- pascal (Pa), 413, 515, 562*n*
- Pascal's principle, 421–424
- PASCO pressure sensors, 419
- passive forces, 151
- path dependence, 554
- path independence, 261–262  
   electrostatic force, 715  
   gravitational potential energy, 401–402
- path length difference  
   double-slit interference, 1064  
   interference, 1060–1061, 1069, 1070  
   Michelson interferometer, 1076–1077  
   single-slit diffraction, 1086, 1088  
   sound waves, 519
- Pauli exclusion principle, 939, 940
- pendulum, 271–272, 282, 450, 453, 456–460, 464, 465  
   two colliding, 285
- period  
   mass-spring oscillating system, 451, 452–453  
   simple pendulum, 458  
   sinusoidal oscillations, 447  
   sound waves, 518  
   transverse waves, 480, 484, 485  
   uniform circular motion, 127
- periodic motion, 445. *See also* simple harmonic motion
- period of revolution, 127
- permanent electric dipole moment, 731, 817
- permanent magnets, 836–837, 857
- permittivity constant, 647
- perpendicular components, of unpolarized light wave, 1023
- perpendicular distance, 308
- phase (matter), 550
- phase (waves), 483  
   AC emf, 967
- phase angle, 449  
   single slit diffraction, 1090
- phase changes (matter), 550–551
- phase constant, 483  
   alternating current, 973*table*  
   mass-spring oscillating system, 451  
   RLC circuits, 975  
   sinusoidal oscillation, 449
- phase difference  
   double-slit interference, 1067–1069  
   interference, 1060–1061  
   single-slit diffraction, 1085–1086, 1088–1089  
   sound waves, 519  
   thin-film interference, 1070  
   transverse waves, 496, 497*table*  
   two waves traveling on same string, 502
- phase-shifted  
   sound waves, 520  
   transverse waves, 496  
   two waves traveling on same string, 502
- phasor diagrams, 502–503  
   AC circuits, 968–972
- phasors, 502–504  
   double-slit interference, 1067  
   representation, 968–972  
   single-slit diffraction, 1088–1091
- phosphorus, dopant in silicon, 767
- photocopier, electric field near charged drum, 664*table*
- photons, 1142
- physics labs, measurement equipment, 14–15
- picofarad, 804
- pi-mesons, 1119
- pine boards, 180, 184–186, 189  
   thermal conductivity (white pine), 567*table*
- pinhole, diffraction from, 1084
- pions, 1119
- pipe organ, 524, 526
- pitot tube, 442
- Planck's constant, 1113
- plane mirrors, 1026–1027
- plane-polarized light, 1004
- planets, 403*table*, 407, 409
- plane waves, 514  
   electromagnetic waves, 991  
   Huygen's principle, 1056–1057
- plastic bag, electrification, 635, 636, 639
- plates, parallel-plate capacitors, 801
- platinum, resistivities, 757*table*
- plutonium-239, 681
- point charges  
   electric field due to, 665–667, 690  
   motion of in electric field, 675–677  
   potential due to group of, 727–730
- pointillism, 1083, 1093



## I-10 Index

- point image, 1026
- point-like objects, 26
- Poisson, S. D., 1084
- Poisson-Argo bright spot, 1084*n*
- polar coordinates, 96
  - displacement in two dimensions, 117–118
  - uniform circular motion, 129
- polar dielectrics, 817–818
- polarization, 641–642, 643, 1004–1007
  - by reflection, 1023–1024
- Polaroids (Polaroid filters), 1004
- Pole to Pole* (Griffith), 397–398
- polyatomic gases
  - degrees of freedom, 595–597
  - molar specific heats at constant volume, 592*table*
- polystyrene
  - dielectric properties, 816*table*
  - elastic properties, 376*table*
  - index of refraction, 1018*table*
- polyurethane foam, thermal conductivity, 567*table*
- porcelain, dielectric properties, 816*table*
- position vectors, 28–29
  - displacement in two dimensions, 116–119
- positive direction, 27
- positive flux, 434
- positively charged objects, 636–637
- positrons, from beta decay, 654
- potassium chromium sulfate, magnetization curve, 944
- potential, 719. *See also* electric potential
- potential difference, 719–720. *See also* current; resistance; voltage
  - batteries, 746
  - capacitors, 801, 805
  - in circuit with capacitors, 808–812
  - in circuit with series resistance, 776–778, 779–784
  - Hall, 845–847
  - ideal and real emf devices, 785–787
  - ideal inductors, 925–926
  - LC circuits, 958
  - linear and nonlinear devices, 753
  - measuring with voltmeter, 752
  - multiloop circuits, 778–779
  - and power in circuits, 758–759
  - RC circuit, 821
  - single-loop circuits, 774–776
- potential energy 265–275
  - and law of conservation of energy, 278–279
  - simple harmonic motion, 461
  - and thermodynamics, 540
- pound force, 62
- power, 249–251
  - alternating-current circuits, 978–980
  - batteries, 758–760, 788–789
  - circuits, 758–760
  - corresponding relations for translation and rotation, 322*table*
  - induction, 899–901
    - of light source, 1000
    - rotating body, 322
    - of sound source, 521, 522
    - stretched string with traveling wave, 493
  - power factor, 979
  - power transmission lines
    - repair, 954, 955*n*
    - role of transformers, 932–933
  - Poynting, John Henry, 999
  - Poynting vector, 999
  - prefixes, for SI units, 10, 10*table*
  - pressure, 414*table*. *See also* constant-pressure processes
    - of fluids, 411–413
      - as function of depth in water, 417
    - and gas macroscopic behavior, 577–578
    - gauge and absolute, 421
    - and ideal gas law, 578–580
    - and kinetic theory of gases, 583–586
    - law of partial pressures, 602
    - measurement in fluids, 419–421
    - and state of material, 550
    - work done on flowing fluid by pressure difference, 436–437
  - pressure amplitude, 517–518
  - pressure field, 660
  - pressure sensor, 412
  - Priestly, Joseph, 644
  - primary coil, transformers, 933–935
  - primary windings, transformers, 934
  - Principia* (Newton), 389
  - principle of equivalence, 404–405
  - Principle of Relativity, 1113–1114, 1119–1120, 1127
  - principle of superposition for forces, 70–71, 140
    - and electrostatic force, 647–648
    - and gravitational force, 390–391
    - torque, 316–317
  - principle of superposition for waves
    - sound, 529
    - transverse waves, 493–495
  - probability distribution function, 589
  - projectile motion, 109–119
  - Project Seafarer, 1012
  - proton-antiproton pair, 1139
  - proton beams, 1041
  - proton gun, 684
  - protons, 637–639
    - in cyclotron, 852–853
    - density in solar wind near Earth, 769
    - electric potential near, 727
    - magnetic dipole moment of small, 851*table*
    - as point charges, 665
  - Proxima Centauri, 1009
  - pulsating variable star, 536
  - P waves (seismic longitudinal wave), 534
  - Pyrex glass
    - coefficient of linear expansion, 564*table*
    - dielectric properties, 816*table*
    - Mt. Palomar Observatory telescope mirror, 572

**Q**

  - Q*, *See* thermal energy
  - quadruple somersault, 332, 354
  - quadrupole moment, 682
  - quantity, 541
  - quantization, 937, 638–639
  - quantum theory, 597–598, 653, 767
  - quartz, fused, *See* fused quartz
  - quartz clock, 11
  - quartzite, stress-strain curve, 381
  - quasars, 385, 406

**R**

  - R* (universal gas constant), 579–580
  - R*-value, 566–567
  - radar waves, 477
  - radial component, 310, 316
  - radian, 302, 309, 449, 484
  - radiant energy, 548
  - radiation, 547–548, 568–569, 988, 1007–1008
  - radiation pressure, 1001–1003
  - radio broadcasting, 986
  - radio telescopes, 1009, 1041
  - radio waves, 477, 988, 1008
  - radius of curvature, 1027, 1033
  - rail gun, electromagnetic, 861, 871
  - rain, speed distribution of water molecules, 590
  - randomly polarized waves, 1004
  - rate of energy transport per unit area, electromagnetic waves, 998, 999
  - ray diagram, 1032
  - Rayleigh, Lord, 428
  - Rayleigh's criterion, 1092, 1093
  - ray model, of light, 1016
  - rays, 514, 1016
  - razor blade, diffraction from edge, 1084
  - RC circuits, 821–824
  - rectangular components, of vectors, straight line motion, 94–96
  - rectangular coordinates
    - one dimensional motion, 94
    - two dimensional motion, 116–117
  - red blood cells, electron micrograph, 1093
  - red light, 1019, 1075, 1087
  - red shift, 1135
  - redshift factor, 1140
  - reference lines, 301, 302
  - reference point, 267
  - reflected light, 1017
  - reflecting planes, in x-ray diffraction, 1104
  - reflection, 1016–1017, 1021–1024
  - reflection phase shifts, 1070
  - refracting telescopes, 1044–1045
  - refraction, 1016–1020
    - law of (Snell's law), 1017–1019, 1058–1059
    - spherical refracting surfaces, 1033–1035, 1045–1046
  - relativity, 404–405, 1112–1113, 1121. *See also* special relativity
  - relativity of simultaneity, 1125–1127
  - relativity of velocities, 1133–1134
  - resistance
    - AA batteries, 771
    - ammeters, 778
    - charged isolated conductors, 706
    - defined, 753–754
    - internal, in batteries, 785–787
    - microscopic view, 762–766
    - ohmic devices, 754, 773
    - Ohm's law, 754–755, 762–763
    - parallel resistance, 779–784
    - and resistivity, 755–758
    - series resistance, 776–778
    - voltmeters, 781–782
  - resistive dissipation, 759
    - from induction, 899
  - resistivity
    - and current density, 761–762
    - microscopic view, 764–765
    - and resistance, 755–758
    - selected materials at room temperature, 757*table*
    - silicon and copper compared, 766*table*
    - temperature effect, 756–758
  - resistors, 755. *See also* LC oscillations
    - color code, 755*table*
    - multiloop circuits, 778–779
    - in parallel, 779–784
    - phasor representation for ac resistive load, 968–970
    - RC circuits, 821–824
    - RL circuits, 929–932, 956
    - RLC circuits, 965–967, 968, 972–977
    - in series, 776–778
    - single-loop circuits, 774–776
  - resolvability, in circular aperture diffraction, 1092–1093
  - resolving power, 1092–1093
    - diffraction gratings, 1100–1102
    - refracting telescope, 1044–1045
  - resolving vectors, 94–95
  - resonance, 466–468
    - RLC circuits, 975–977
    - and standing waves, 500–502
  - resonance condition, cyclotron, 853
  - resonance curves
    - fractional half-width, 983
    - RLC circuits, 976–977
  - resonant frequencies, 501
    - musical instruments, 524–525, 526
  - restoring force, 450
  - retina, 1024, 1042
  - reversible processes
    - change in entropy, 610–611
    - and second law of thermodynamics, 614



Rhodes, William, 410  
 right-handed coordinate system, 98  
 right-hand rule  
   Ampère's law, 872  
   rotational displacement/velocity, 303  
   vector product, 340  
 rigid bodies, 300–301, 362  
   rotational inertia, 313*table*  
 ring, rotational inertia, 313*table*  
 ring of charge, field due to, 671–675  
*RL* circuits, 929–932, 956–957  
*RLC* circuits, 965–968, 972–977  
 rms current, 978–979  
 Roberts, Paul, 947  
 Robertson, Gregory, 161  
 rock climbing, 361, 369–370, 379  
 rock concerts, sound level, 523*table*, 524  
 rocket frame, 1117, 1132  
 rockets  
   model rocket, 76  
   sound, 533  
   translational momentum, 196–199  
 rocket thrust, 197, 199  
 rock wool, thermal conductivity, 567*table*  
 rod, rotational inertia, 312, 313*table*  
 rollerboards, 382  
 roller coaster, acceleration, 40  
 rolling forces, 334–336  
 root-mean-square current, 978–979  
 root-mean-square speed, 585–587, 588, 589  
 root-mean-square value, of electric field in electromagnetic wave, 999  
 rotation, 300  
   complex/simple, 333–337  
   constant rotational acceleration, 306–307  
   Earth, 394–395  
   fastest possible rate of planets, 407  
   kinetic energy of, 311–312  
   Newton's Second Law for, 317–318, 344–345  
   power, 322  
   summary of relations compared to translation, 322*table*, 352*table*  
   torque, 315–320, 342–343  
   work-kinetic energy theorem, 321  
 rotational acceleration, 304, 310  
   corresponding relations for translation and rotation, 322*table*  
   vector, 339  
 rotational displacement, 302–303, 338  
 rotational equilibrium, 364  
 rotational inertia, 312–314, 333  
   corresponding relations for translation and rotation, 322*table*  
 rotational kinetic energy, 311–312, 334

rotational momentum, 344–352, 352*table*  
 rotational position, 301–302, 308–309, 322*table*  
 rotational simple harmonic motion, 454  
 rotational simple harmonic oscillator, 453–454  
 rotational speed, 304, 308, 309  
 rotational variables, 300–311  
   as vectors, 337–340  
 rotational velocity, 303–304  
   corresponding relations for translation and rotation, 322*table*  
   vector, 338–339  
 rotation axis, 301  
 rotor failure, 315  
 Rowland ring, 942  
 ruby mica, dielectric properties, 816*table*  
 Ruiping, Sun, 265  
 rulings, diffraction gratings, 1097–1098, 1100  
 Rutherford, Ernest, 710  
*R*-value, 566–567

## S

sapphire, index of refraction, 1018*table*  
 saturation magnetization, 942, 951  
 Savart, Félix, 864  
 scalar fields, 660  
 scalar product, 101*n*, 243, 339  
 scalars, 28  
   multiplying and dividing vectors by, 100–101  
 scattering, of light, 1016–1023  
   polarization by, 1006  
 scattering, of x-rays in diffraction, 1103–1104  
 Science Workshop 500 interface, 15  
 scientific laws, 2  
 scientific notation, 9–10  
 scientific theories, 6  
 scuba diving, hydrostatic pressure on diver, 410, 418  
 seawater  
   density, 414*table*  
   specific heat, 549*table*  
   speed of sound in, 516*table*  
 secondary coil, transformers, 933–935  
 secondary maxima  
   diffraction patterns, 1084  
   interference patterns, 1065  
 secondary minima  
   diffraction patterns, 1084  
   interference patterns, 1065  
 secondary windings, transformers, 934  
 second dark fringes, 1065  
 second harmonic, 501, 525  
 second law of thermodynamics, 613–614, 618  
 second-order fringes, 1065  
 seismic waves, 477  
   *S* and *P* waves, 534  
 self-inductance, 923–926  
 semiconductors, 766–767  
   Ohm's law, 754  
   resistivities of selected at room temperature, 757*table*  
 sensors, 15  
 serial computer, 1137  
 series capacitors, 810–812  
 series circuits, 749–750  
 series resistance, 776–778  
 series *RLC* circuits, 965–967, 972–977  
 SETI (Search for Extra-Terrestrial Intelligence), 1009  
 shearing stress, 374, 376  
 shear modulus, 376  
 sheet  
   electric field near nonconducting, 679–680  
   uniform charge, 703–705  
 shell of charge  
   isolated conductors, 707, 736  
   spherical metal shell, 709  
   spherical symmetry, 700  
 shell theorem, 388–389, 396  
 Shepard, Alan, 198  
 shock waves, 533–534  
 short wave, 477  
 side maxima, diffraction patterns, 1084  
 side minima, diffraction patterns, 1084  
 significant figures, 17–18  
 silicon  
   dielectric properties, 816*table*  
   electrical properties, 766*table*, 767  
   surfaces of crystal, 10  
 silicon, *n* type, resistivities, 757*table*  
 silicon, *p* type, resistivities, 757*table*  
 silver  
   diamagnetic material, 936  
   resistivities, 757*table*  
   specific heat, 549*table*  
   thermal conductivity, 567*table*  
 simple harmonic motion, 445, 450–466  
 simple harmonic oscillator, 450, 453–454  
 simple pendulum, 456–459  
 simultaneity, relativity of, 1125–1127  
 sine  
   describing sinusoidal oscillation, 448  
   using to find vector components, 95  
 single crystal, 941  
 single-loop circuits, 774–776  
   real emf battery, 785  
 single pole double throw switch (SPDT), 751  
 single-slit diffraction, 1085–1091  
 sinusoidal oscillations, 445–449.  
   *See also* simple harmonic motion  
   not all are simple harmonic motion, 453  
 sinusoidal waves, 481–485, 495–500  
   transverse, 478  
 Sirius B, escape speed, 403*table*

Sirius (Dog Star), 1137–1138  
 SI units, 8–16  
 slab  
   rotational inertia, 313*table*  
   *R*-value, 566  
   thermal conduction through composite, 567, 569  
 sliding surfaces, 150  
 slit, diffraction from, 1084  
 slope, position vs. time graphs, 33, 34  
 sloth, potential energy of, 269–270  
 slowing down, 45  
 Snell's law, 1017–1019, 1058–1059  
 sodium  
   *D* line, 1108  
   yellow light in air wavelength, 1077  
 sodium chloride  
   index of refraction, 1018*table*  
   x-ray diffraction, 1103–1105  
 solar cells, 784  
 solar energy, 547  
 solar flare, 842  
 solar water heater, 571  
 solar wind, 769, 985, 1003  
 solenoid  
   coil in long, 895–896  
   magnetic field, 875–877  
   self-inductance, 923–924  
 solid bodies, 214  
 solids, 550  
   coefficient of volume expansion, 565  
   compressibility, 376  
   defined, 550  
   deformation, 374  
   idealized model of, and contact forces, 145–146  
   specific heats of selected, 549*table*  
   speed of sound in selected, 516*table*  
   thermal energy transfer to, 548–553  
   thermal expansion, 564  
 sonar, 513  
 sonic boom, 534  
 sound  
   arrival delay, 518  
   beats, 527–529  
   intensity, 521–522  
   sources of musical, 524–527  
 sound barrier, 534  
 sound level, 522–524, 523*table*  
 sound waves, 477, 513–514, 519–520, 529–534  
 south pole, magnets, 837–838  
 spacecraft orientation, 351–352  
 space-dependent phase, *See* time- and space-dependent phase  
 Space Shuttle, electric potential, 740  
 Space Shuttle *Columbia*, tethered satellite experiment, 918  
 Space Shuttle *Discovery*, laser beam measurements, 1106  
 space-time, 1121  
 spacetime curvature, 405–406  
 spark, *See* electric spark

## I-12 Index

- SPDT (single pole double throw switch), 751
- special relativity, 81, 912, 993, 1112–1113
- and cause and effect, 1124–1125
  - and Doppler shift, 1135–1136
  - $E = mc^2$ , 1127–1129
  - event location with intelligent observer, 1114–1115
  - headlight effect, 1139
  - latticework clock synchronization, 1116–1118
  - Lorentz transformation, 1131–1133
  - metric equation, 1121–1123
  - momentum and energy, 1127–1130
  - Principle of Relativity, 1113–1114, 1119–1120, 1127
  - relativity of simultaneity, 1125–1127
  - relativity of velocities, 1133–1134
  - time stretching, 1118–1123
- specific heat, 548–549, 590. *See also* molar specific heat
- selected solids and liquids, 549*table*
- speed, 34–36
- base quantities, 8
  - rotational, 304, 308, 309
- speed of light, 1012–1014
- invariance, 1119
  - and meter standard, 13
  - as nature's speed limit, 1123, 1133
  - transmission speed of electromagnetic waves, 993, 1008
- speed of sound, 515–518, 1129
- and root-mean-square speed of gas, 585
  - and sonic boom, 534
- sphere
- center of mass, 214
  - rolling force, 336–337
  - rotational inertia, 313*table*, 336*table*
- spherical aberration, 1044, 1045
- spherical capacitors, capacitance calculation, 807–808
- spherically symmetric charge distribution, 701
- spherical mirrors, 1027–1035, 1045
- spherical shell, rotational inertia, 313*table*
- spherical shell of charge, 707, 736, 738
- spherical symmetry, 700–702
- spherical wave, 514
- spin magnetic dipole moment, 937–938
- spreadsheet graphing routine, 46
- spring constant, 235
- spring force, 234–236
- conservative force test for, 263–264
  - elastic potential energy, 267
  - and simple harmonic motion of mass-spring system, 452–453
- spring scales, 62, 63, 144
- stable equilibrium, 275
- stable static equilibrium, 363
- stainless steel, thermal conductivity, 567*table*
- standard kilogram, 13
- standard meter bar, 13, 1076
- standards, 8–10
- force, 61–63
  - length, 12–13
  - mass, 13–14
  - time, 11–12
- standing waves, 498–500
- musical instruments, 524–527
- and resonance, 500–502
  - sound, 529
- Stapp, J. P., 40
- stars. *See also* black holes; neutron stars; white dwarf stars
- density, 414*table*
  - pulsating variable, 536
- starting motor, 795
- state function, 611
- state properties, 609, 611–613
- static equilibrium, 362–365
- fluid pressure, 412–413, 416
- static friction force, 151–152
- statistical mechanics, 623–627
- steady flow, 428
- steady-state current, *RLC* circuits, 975
- steady-state process, 567
- steel
- bulk modulus, 376, 516*table*
  - coefficient of linear expansion, 564*table*
  - elastic properties, 376*table*
  - stress-strain curve, 375
  - thermal conductivity, 567*table*
- Stefan, Josef, 568
- Stefan-Boltzmann constant, 568
- step-down/step-up transformers, 934
- Stirling engine, 618–619
- Stirling's approximation, 626
- stop-action photography, of speeding bullet, 799, 813–814
- storage batteries, 758
- straight line motion, 26. *See also* translation
- acceleration, 37–40
  - combining forces along, 68–71
  - constant acceleration, 41–45
  - free fall motion, 73–75
  - and Newton's First Law, 58–60
  - and Newton's Second Law for multiple forces, 70–71
  - and Newton's Second Law for single force, 65–67
  - and Newton's Third Law, 76–79
  - position and displacement along line, 27–31
  - representing in diagrams and graphs, 32–33
  - single constant force and acceleration along, 60–61
  - velocity and speed, 31–36
  - velocity change, 37–40
  - work done by, 232–233
- strain, 374–375
- strain gage, 375
- Stratocaster guitar, 897
- stray capacitance, 808
- stream, volume flux in, 432
- stress, 374–377
- stress-strain curve, 375
- stress-strain equation, 374
- stress-strain test, 375
- stretched strings, waves on, 500–504
- energy and power transported by, 491–493
  - musical instruments, 524–527
  - pulses, 477–478
  - sinusoidal transverse waves, 482–485, 488
  - standing waves, 498–502
  - wave speed, 489–491
- stroboscopic photographs, 73, 108, 109, 500
- strong nuclear force, 72, 167
- strontium titanate, dielectric properties, 816*table*
- Styrofoam, 413, 414*table*
- electrification, 635, 636, 639
- subtraction, of vectors, 92–93
- sugar solutions, index of refraction, 1018*table*
- sulfur dioxide, root-mean-square speed at room temperature, 585*table*
- sulfuric acid, in lead acid battery, 784–785
- Sun, 562, 1008, 1141
- average wavelength, 1062–1063
  - density, 414*table*
  - escape speed, 403*table*
  - fire starting using thin lens, 1037
  - intensity of radiation reaching atmosphere of Earth, 1010
  - intensity of radiation reaching surface of Earth, 1013
  - partial coherence of sunlight, 1066
  - proton currents streaming from, 749
- sunspots, 1114
- superconductors, 706, 766, 767–768
- superelastic collisions, 280–281
- superforce, 167
- supernova, 403*table*
- superposition. *See* principle of superposition for forces; principle of superposition for waves
- supersonic speeds, 533–534
- superstring theories, 167
- supersymmetry theories, 167
- surface charge density, 672*table*
- S waves (seismic transverse wave), 534
- switches
- make-before-break, 931
  - SPDT and DPDT, 931
  - symbol for, 751
- symmetric charge distributions, 698–705
- synchronizing flash, 1117
- Système International, 9
- systems
- closed, 196, 218, 280, 608, 610, 614
  - defined, 544
  - isolated, 183, 280
- ## T
- Takahashi, D., 828
- tangent, using inverse to find vector angle, 96
- tangential component of torque, 316
- of translational acceleration, 310
- tantalum oxide, dielectric properties, 816*table*
- Teese, Robert, 184
- telescopes, 1033, 1041, 1044–1045
- television waves, 477, 1008
- temperature. *See also* constant-temperature processes
- and change in entropy, 610
  - effect on molar specific heat at constant volume, 597–598
  - effect on resistivity, 756–758
  - and gas macroscopic behavior, 577–578
  - and heating and cooling, 545–548
  - and ideal gas law, 578–580
  - and kinetic theory of gases, 583–586
  - and state of material, 550
  - variation of resistivity with, 756–758
- temperature coefficient of resistivity, 756–757
- temperature conversions, 542–543, 543*table*
- temperature field, 660
- temperature measurement, 540–543, 558–563
- temperature scales, 540–543
- tensile forces, 372–375
- tension, 72, 153–156, 166–167
- tensors, 348
- teraflop computer, 1137
- terminal speed, 160–161
- Tesla, Nikola, 955
- Thaw refracting telescope, 1107
- thermal conduction, 547
- composite wall, 567, 569
- thermal conductivity, 566
- selected metals, gases, and building materials, 567*table*
- thermal efficiency, 617–619, 622–623
- thermal energy, 278, 540
- battery energy transformed into, 747
  - conversion of kinetic energy into, 575
  - in thermodynamic processes, 556–557
  - and work, 553–554
- thermal energy transfer, 541, 546
- and first law of thermodynamics, 555–556

- mechanisms for, 547–548, 566–569  
to solids and liquids, 548–553  
thermal equilibrium, 544–545, 553  
thermal expansion, 541, 563–566  
thermal insulator, 567  
thermal interactions, 543–545  
thermal radiation, 548, 568–569  
thermal reservoir, 553–554, 614  
thermal resistance, 566–567  
thermodynamic processes, 553  
and first law of thermodynamics, 556–558  
thermodynamics, 540–548, 577, 583. *See also* entropy;  
kinetic theory of gases  
first law of, 555–558  
irreversible processes, 608–609  
second law of, 613–614, 618  
thermodynamic temperature scale, 561  
thermogram, 568  
thermometers, 540–542  
thermopile, 784  
thin films interference, 1070–1077  
thin lenses, 1035–1042  
thin-lens formulas, 1036, 1046–1047, 1051  
third harmonic, 501, 525  
third law force-pair, 78, 184  
Thomson, J. J., 843, 844  
threshold energy, for creating proton-antiproton pair, 1139  
time, 6–8  
arrow of, 607, 608  
standards of measurement, 11–12  
time- and space-dependent phase interfering waves, 496  
sinusoidal waves, 483, 485  
sound waves, 518  
time constant  
capacitive (*RC* circuits), 822–823  
inductive (*RL* circuits), 930–931  
time-dependent phase, sinusoidal oscillation, 448  
time dilation, 1120, 1122  
time stretching, 1118–1123  
titania ceramic, dielectric properties, 816*table*  
Tokomak reactor, 829, 841  
ton force, 62  
toroid, 877  
torpedo models, 440–441  
torque, 315–317, 342–345. *See also* rotational momentum  
on current loop, 849–850  
torr, 413, 562*n*  
Torricelli, Evangelista, 413  
torsion, 453–454  
total energy, 278  
total internal reflection, 1021–1023  
total mass, 218  
tracer flow studies, 428–429  
trajectory, *See* projectile motion  
transformer oil, dielectric properties, 816*table*  
transformers, 923, 932–935  
autotransformer, 951  
with iron cores, 943  
transient current, *RLC* circuits, 975  
translation, 300. *See also* straight line motion  
with simple rotation, 334–337  
summary of relations compared to rotation, 322*table*, 352*table*  
work-kinetic energy theorem, 320  
translational acceleration, 310  
translational equilibrium, 364  
translational kinetic energy, 229–230, 334  
ideal gases, 586, 595  
and net work, 246–248  
translational momentum  
conservation in one-dimensional collisions, 190–193  
conservation in two-dimensional collisions, 193–195  
conservation of, 189, 281  
corresponding relations for translation and rotation, 352*table*  
and impulse, 184–186  
particles, 181–184, 219–220  
rockets, 196–199  
translational position, 308–309  
translational speed, 308, 309  
translational variables, 300, 308–311  
transparent materials, 1017  
transverse waves, 513  
defined, 477–478  
electromagnetic wave pulse, 990, 991  
sinusoidal, 478  
*Treatise de Magnete* (Gilbert), 862  
triangular prism  
angle of minimum deviation, 1048  
chromatic dispersion, 1020  
total internal reflection, 1022–1023  
triple-point cell, 560, 563  
triple point of water, 541, 560  
tube length, compound microscope, 1043  
tube of flow, 430  
tubes  
open-tube manometer, 420–421  
pitot tube, 442  
sound in, 527  
U-tubes, pressure equilibrium in fluid filled, 418–419  
tungsten  
resistivities, 757*table*  
specific heat, 549*table*  
turbulence, 159–160  
turbulent flow, 428  
turning points, potential energy curves, 274–275  
TV cameras, 1041  
TV tubes, 684  
twin paradox, 1142–1143  
two-dimensional collisions, 193–195, 286  
two-dimensional motion, 116–122. *See also* circular motion  
two-lens systems, 1039–1040
- U**
- ultimate strength, 375, 376*table*  
ultrasonic motion detector, 15  
ultrasound, 513, 535  
ultraviolet light, 477, 1008, 1092  
underdamped pendulum, 464  
underwater pressure, 417–419  
unification, of forces of nature, 167  
uniform circular motion, 123–129  
and sinusoidal oscillation, 446  
uniform density, 214, 414  
uniform electric field, 680  
net flux, 693–694  
uniform external electric field, 677–678  
uniform forces, fluid pressure, 411–412  
uniform line charge distribution, cylindrical symmetry, 702–703  
uniform volume charge distribution, spherical symmetry, 701–702  
unit cell, 1103  
United States National Electric Code, 769  
units, 6. *See also* SI units  
converting, 16–17  
unit vectors, 28–29, 98  
universal gas constant (*R*), 579–580  
universe  
estimated mass of known, 13  
expansion and cooling, 562  
unlike charges, 637  
unpolarized light, 1004  
unpolarized waves, 1004  
unstable equilibrium, 275  
unstable static equilibrium, 363  
uranium  
density of nucleus, 414*table*  
electric field at surface of nucleus, 664*table*  
U-tubes, pressure equilibrium in fluid filled, 418–419
- V**
- vacuum, index of refraction, 1018*table*  
Van Allen radiation belts, 842  
Van de Graaff generator, 689, 708, 717–718  
vapor, 550, 560  
variable stars, pulsating, 536  
Vazquez, Miguel, 332  
vector fields, 660–662, 678  
vector product, 100–101, 340–343  
vectors, 90–102  
acceleration, 39, 62  
defined, 27–28  
force, 62, 65, 69–70  
normal vector, 433  
position, 27–30  
rotational variables, 337–340  
translational momentum, 182  
vector sum, 92  
vector sum of forces, 69  
Vega, 1137  
velocity. *See also* acceleration  
average, 33–34  
bouncy collisions, 190–191, 280  
changes in, 37–40  
corresponding relations for translation and rotation, 322*table*  
ideal projectile motion, 111–113  
instantaneous, 35–36  
of particles in mechanical waves, 487  
relativity of, 1133–1134  
rocket flight, 196–197  
rotational, 303–304  
sticky collisions, 191–193, 281  
in straight line motion, 31–36  
two-dimensional collisions, 194–195  
and work, 228–229  
velocity amplitude, 455  
velocity selector, 858  
velocity vector field, flow in stream, 432  
venturi meter, 441–442  
vernier calipers, 14  
Vernier pressure sensors, 419  
vertical motion, of projectiles, 112–113  
vertical oscillators, 450  
*Vespa mandarinia japonica*, 539, 569  
video capture and analysis tools, 14–16  
VideoPoint software, 645  
virtual focal point, 1029  
virtual image, 1025  
viscosity, 428  
viscous drag force, 428  
visible emission lines, 1097  
visible light, 476, 547, 988, 993, 1008–1009, 1016. *See also* diffraction; images; reflection; refraction  
visual system, 1024  
Volta, Alessandro, 745  
voltage, 715, 754–754. *See also* electric potential energy; potential difference  
voltmeters, 752, 781–782  
volt (unit), 720  
volume, 577–580. *See also* constant-volume processes  
and state of material, 550  
volume charge density, 672*table*  
spherical symmetry of uniform, 701–702  
volume expansion, 564  
volume flow rate, 430  
volume flux, 430, 431–434, 691

## I-14 Index

von Guericke, Otto, 438  
von Laue, Max, 1103  
*Voyager 2*, 352

### W

wall, thermal conduction through  
    composite, 569  
water, 543–551. *See also* seawater  
    bulk modulus, 376, 516*table*  
    coefficient of volume expansion, 565  
    density, 414*table*, 516*table*  
    diamagnetic material, 936  
    dielectric properties, 816*table*  
    diffraction by, 1062  
    as dipole, 677–678, 731  
    index of refraction, 1018*table*  
    root-mean-square speed at  
        room temperature (vapor), 585*table*  
    sound waves through, 514  
    speed of sound in, 516*table*  
    viscosity, 428  
water vapor  
    root-mean-square speed at  
        room temperature, 585*table*  
    at triple point, 560  
water waves, 477  
Watt, James, 250  
watt (W), 9, 250  
wave equation, 510  
wave form, 478, 483, 488  
wavefront, 514  
wave interference. *See also* interference  
    sound waves, 519–520, 529  
    transverse waves, 495–498  
wavelength  
    and index of refraction, 1059–1061  
    sound waves, 518  
transverse waves, 478, 480, 484, 491  
wave number  
    sound waves, 518  
    transverse waves, 484  
wave optics, 1057  
wave pulses, 477–481, 489, 493, 495  
waves, 476–481. *See also* sinusoidal waves; sound waves; stretched strings, waves on  
    non-sinusoidal, 486  
    phasors, 502–504  
    standing, 498–502  
wave speed  
    sound waves, 518  
    stretched strings, 489–491  
    transverse waves, 486  
wave velocity, transverse waves, 486–488  
weak nuclear force, 72, 167  
weighing, 144  
weight, 74. *See also* apparent weight  
    mass contrasted, 144–145  
weightlessness, 128, 404  
weight lifting, 226, 248, 260, 265–266  
Westinghouse, George, 955  
wheel, acceleration of, 318–319  
whirligig beetles, interference coloration, 1108  
white dwarf stars, 403*table*, 414*table*  
white light, 1019, 1087  
white pine, thermal conductivity, 567*table*  
Whitney, M. O., 161*n*  
Williams, Debbie, 161  
windings, transformers, 934  
window glass, thermal conductivity, 567*table*  
wind-tunnel tests, 429

wires  
    average charge carrier speed in, 763–764  
    electric field inside copper household wires, 664*table*  
    gauge number, 768  
    ideal conducting, 773  
    levitating, 848–849  
    magnetic field, 873–874  
    magnetic force on current-carrying, 847–849  
    multiloop circuits, 778–779  
    resistance in, 756  
    single-loop circuits, 774–776  
    symbol for, 751  
Wittmann, M., 510*n*  
wood, elastic properties, 376*table*  
work, 227–230. *See also* net work; kinetic energy theorem  
    Carnot engine, 616–617  
    corresponding relations for translation and rotation, 322*table*  
    as dot product, 243–244  
    and external forces acting on charges, 717–718  
    and first law of thermodynamics, 555–556  
    fluid flow, 436–437  
    force and, 234–242  
    gravitational force, 233–234  
    ideal gas, 581–582  
    internal resistance of battery, 787  
    nonconservative forces, 276–278  
    one-dimensional forces and motions along same line, 232–233  
    path dependence, 260–265  
    physical, 231–232  
    positive and negative, 232–233

potential energy as stored, 265–269  
scalar quantity, 233, 339  
and thermal energy, 553–557  
three-dimensional variable force, 241–242  
working substance, 614, 615

### X

x-component  
    of unit vector, 98  
    of vector projection on axis, 95  
x-ray diffraction, 1103–1105  
x-ray microscopes, 1041  
x-rays, 477, 988, 1103

### Y

y-component  
    of unit vector, 98  
    of vector projection on axis, 95  
Yenzer, Scott H., 955*n*  
yield strength, 375, 376*table*  
Young, Thomas, 1084  
    interference experiment, 1062–1063  
Young's modulus, 373–374, 375, 376*table*

### Z

Zacchini, Emanuel, human cannonball, 107, 115–116  
z-component  
    of unit vector, 98  
    of vector projection on axis, 95  
zero point, 27  
zero potential, 724  
zeroth law of thermodynamics, 545  
Zopf, Richard, 89

# Mathematical Formulas\*

## Quadratic Formula

If  $ax^2 + bx + c = 0$ , then  $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

## Binomial Theorem

$(1 + x)^n = 1 + \frac{nx}{1!} + \frac{n(n-1)x^2}{2!} + \dots \quad (x^2 < 1)$

## Products of Vectors

Let  $\theta$  be the smaller of the two angles between  $\vec{a}$  and  $\vec{b}$ . Then

$\vec{a} \cdot \vec{b} = \vec{b} \cdot \vec{a} = a_x b_x + a_y b_y + a_z b_z = |\vec{a}| |\vec{b}| \cos \theta$

$\vec{a} \times \vec{b} = -\vec{b} \times \vec{a} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ a_x & a_y & a_z \\ b_x & b_y & b_z \end{vmatrix}$

$= \hat{i} \begin{vmatrix} a_y & a_z \\ b_y & b_z \end{vmatrix} - \hat{j} \begin{vmatrix} a_x & a_z \\ b_x & b_z \end{vmatrix} + \hat{k} \begin{vmatrix} a_x & a_y \\ b_x & b_y \end{vmatrix}$

$= (a_y b_z - b_y a_z) \hat{i} + (a_z b_x - b_z a_x) \hat{j} + (a_x b_y - b_x a_y) \hat{k}$

$|\vec{a} \times \vec{b}| = |\vec{a}| |\vec{b}| \sin \theta$

## Trigonometric Identities

$\sin \alpha \pm \sin \beta = 2 \sin \frac{1}{2}(\alpha \pm \beta) \cos \frac{1}{2}(\alpha \mp \beta)$

$\cos \alpha + \cos \beta = 2 \cos \frac{1}{2}(\alpha + \beta) \cos \frac{1}{2}(\alpha - \beta)$

## Derivatives and Integrals

$\frac{d}{dx} \sin x = \cos x \quad \int \sin x \, dx = -\cos x$

$\frac{d}{dx} \cos x = -\sin x \quad \int \cos x \, dx = \sin x$

$\frac{d}{dx} e^x = e^x \quad \int e^x \, dx = e^x$

$\int \frac{dx}{\sqrt{x^2 + a^2}} = \ln(x + \sqrt{x^2 + a^2})$

$\int \frac{x \, dx}{(x^2 + a^2)^{3/2}} = -\frac{1}{(x^2 + a^2)^{1/2}}$

$\int \frac{dx}{(x^2 + a^2)^{3/2}} = \frac{x}{a^2(x^2 + a^2)^{1/2}}$

## Cramer's Rule

Two simultaneous equations in unknowns  $x$  and  $y$ ,

$a_1 x + b_1 y = c_1 \quad \text{and} \quad a_2 x + b_2 y = c_2,$

have the solutions

$x = \frac{\begin{vmatrix} c_1 & b_1 \\ c_2 & b_2 \end{vmatrix}}{\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}} = \frac{c_1 b_2 - c_2 b_1}{a_1 b_2 - a_2 b_1}$

and

$y = \frac{\begin{vmatrix} a_1 & c_1 \\ a_2 & c_2 \end{vmatrix}}{\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}} = \frac{a_1 c_2 - a_2 c_1}{a_1 b_2 - a_2 b_1}.$

\* See Appendix E for a more complete list.

## The Greek Alphabet

Alpha	A	$\alpha$	Iota	I	$\iota$	Rho	P	$\rho$
Beta	B	$\beta$	Kappa	K	$\kappa$	Sigma	$\Sigma$	$\sigma$
Gamma	$\Gamma$	$\gamma$	Lambda	$\Lambda$	$\lambda$	Tau	T	$\tau$
Delta	$\Delta$	$\delta$	Mu	M	$\mu$	Upsilon	$\Upsilon$	$\upsilon$
Epsilon	E	$\epsilon$	Nu	N	$\nu$	Phi	$\Phi$	$\phi, \varphi$
Zeta	Z	$\zeta$	Xi	$\Xi$	$\xi$	Chi	X	$\chi$
Eta	H	$\eta$	Omicron	O	$o$	Psi	$\Psi$	$\psi$
Theta	$\Theta$	$\theta$	Pi	$\Pi$	$\pi$	Omega	$\Omega$	$\omega$



## Some Physical Constants\*

Speed of light	$c$	$3.00 \times 10^8 \text{ m/s}$
Gravitational constant	$G$	$6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$
Avogadro constant	$N_A$	$6.02 \times 10^{23} \text{ mol}^{-1}$
Universal gas constant	$R$	$8.31 \text{ J/mol} \cdot \text{K}$
Mass-energy relation	$c^2$	$8.99 \times 10^{16} \text{ J/kg}$
		$931.5 \text{ MeV/u}$
Electric constant (permittivity)	$\epsilon_0$	$8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2$
Coulomb constant	$k = 1/4\pi\epsilon_0$	$8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$
Magnetic constant (permeability)	$\mu_0$	$1.26 \times 10^{-6} \text{ N/A}^2$
Planck constant	$h$	$6.63 \times 10^{-34} \text{ J} \cdot \text{s}$
		$4.14 \times 10^{-15} \text{ eV} \cdot \text{s}$
Stefan-Boltzmann	$\sigma$	$5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$
Boltzmann constant	$k_B$	$1.38 \times 10^{-23} \text{ J/K}$
		$8.62 \times 10^{-5} \text{ eV/K}$
Elementary charge	$e$	$1.60 \times 10^{-19} \text{ C}$
Electron mass	$m_e$	$9.11 \times 10^{-31} \text{ kg}$
Proton mass	$m_p$	$1.67 \times 10^{-27} \text{ kg}$
Neutron mass	$m_n$	$1.68 \times 10^{-27} \text{ kg}$
Deuteron mass	$m_d$	$3.34 \times 10^{-27} \text{ kg}$
Bohr radius	$r_B$	$5.29 \times 10^{-11} \text{ m}$
Bohr magneton	$\mu_B$	$9.27 \times 10^{-24} \text{ J/T}$
		$5.79 \times 10^{-5} \text{ eV/T}$
Rydberg constant	$R$	$0.01097 \text{ nm}^{-1}$

\* For a more complete list, showing also the best experimental values, see Appendix B.

## Some Conversion Factors\*

### Mass and Density

$$1 \text{ kg} = 1000 \text{ g} = 6.02 \times 10^{26} \text{ u}$$

$$1 \text{ slug} = 14.6 \text{ kg}$$

$$1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$$

$$1 \text{ kg/m}^3 = 10^{-3} \text{ g/cm}^3$$

### Length and Volume

$$1 \text{ m} = 100 \text{ cm} = 39.4 \text{ in.} = 3.28 \text{ ft}$$

$$1 \text{ mi} = 1.61 \text{ km} = 5280 \text{ ft}$$

$$1 \text{ in.} = 2.54 \text{ cm}$$

$$1 \text{ nm} = 10^{-9} \text{ m} = 10 \text{ \AA}$$

$$1 \text{ pm} = 10^{-12} \text{ m} = 1000 \text{ fm}$$

$$1 \text{ light-year} = 9.46 \times 10^{15} \text{ m}$$

$$1 \text{ m}^3 = 1000 \text{ L} = 35.3 \text{ ft}^3 = 264 \text{ gal}$$

### Time

$$1 \text{ d} = 86,400 \text{ s}$$

$$1 \text{ y} = 365\frac{1}{4} \text{ d} = 3.16 \times 10^7 \text{ s}$$

### Angular Measure

$$1 \text{ rad} = 57.3^\circ = 0.159 \text{ rev}$$

$$\pi \text{ rad} = 180^\circ = \frac{1}{2} \text{ rev}$$

### Speed

$$1 \text{ m/s} = 3.28 \text{ ft/s} = 2.24 \text{ mi/h}$$

$$1 \text{ km/h} = 0.621 \text{ mi/h} = 0.278 \text{ m/s}$$

### Force and Pressure

$$1 \text{ N} = 10^6 \text{ dyne} = 0.225 \text{ lb}$$

$$1 \text{ lb} = 4.45 \text{ N}$$

$$1 \text{ ton} = 2000 \text{ lb}$$

$$1 \text{ Pa} = 1 \text{ N/m}^2 = 10 \text{ dyne/cm}^2$$

$$= 1.45 \times 10^{-4} \text{ lb/in.}^2$$

$$1 \text{ atm} = 1.01 \times 10^5 \text{ Pa} = 14.7 \text{ lb/in.}^2$$

$$= 76 \text{ cm-Hg}$$

### Energy and Power

$$1 \text{ J} = 10^7 \text{ erg} = 0.239 \text{ cal} = 0.738 \text{ ft} \cdot \text{lb}$$

$$1 \text{ kW} \cdot \text{h} = 3.6 \times 10^6 \text{ J}$$

$$1 \text{ cal} = 4.19 \text{ J}$$

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

$$1 \text{ horsepower} = 746 \text{ W} = 550 \text{ ft} \cdot \text{lb/s}$$

### Magnetism

$$1 \text{ T} = 1 \text{ Wb/m}^2 = 10^4 \text{ gauss}$$

\* See Appendix D for a more complete list.

## Some Physical Properties

### Air (dry, at 20°C and 1 atm)

Density	1.21 kg/m <sup>3</sup>
Specific heat at constant pressure	1010 J/kg · K
Ratio of specific heats	1.40
Speed of sound	343 m/s
Electrical breakdown strength	$3 \times 10^6$ V/m
Effective molar mass	0.0289 kg/mol

### Water

Density	1000 kg/m <sup>3</sup>
Speed of sound	1460 m/s
Specific heat at constant pressure	4190 J/kg · K
Heat of fusion (0°C)	333 kJ/kg
Heat of vaporization (100°C)	2260 kJ/kg
Index of refraction ( $\lambda = 589$ nm)	1.33
Molar mass	0.0180 kg/mol

### Earth

Mass	$5.98 \times 10^{24}$ kg
Mean radius	$6.37 \times 10^6$ m
Free-fall acceleration at Earth's surface	9.8 m/s <sup>2</sup>
Standard atmosphere	$1.01 \times 10^5$ Pa
Period of satellite at 100 km altitude	86.3 min
Radius of the geosynchronous orbit	42,200 km
Escape speed	11.2 km/s
Magnetic dipole moment	$8.0 \times 10^{22}$ A · m <sup>2</sup>
Mean electric field at surface	150 V/m, down

### Distance to

Moon	$3.82 \times 10^8$ m
Sun	$1.50 \times 10^{11}$ m
Nearest star	$4.04 \times 10^{16}$ m
Galactic center	$2.2 \times 10^{20}$ m
Andromeda galaxy	$2.1 \times 10^{22}$ m
Edge of the observable universe	$\sim 10^{26}$ m

## SI Prefixes\*

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10 <sup>24</sup>	yotta	Y	10 <sup>-1</sup>	deci	d
10 <sup>21</sup>	zetta	Z	10 <sup>-2</sup>	centi	c
10 <sup>18</sup>	exa	E	10 <sup>-3</sup>	milli	m
10 <sup>15</sup>	peta	P	10 <sup>-6</sup>	micro	$\mu$
10 <sup>12</sup>	tera	T	10 <sup>-9</sup>	nano	n
10 <sup>9</sup>	giga	G	10 <sup>-12</sup>	pico	p
10 <sup>6</sup>	mega	M	10 <sup>-15</sup>	femto	f
10 <sup>3</sup>	kilo	k	10 <sup>-18</sup>	atto	a
10 <sup>2</sup>	hecto	h	10 <sup>-21</sup>	zepto	z
10 <sup>1</sup>	deka	da	10 <sup>-24</sup>	yocto	y

\*In all cases, the first syllable is accented, as in ná-no-mé-ter.