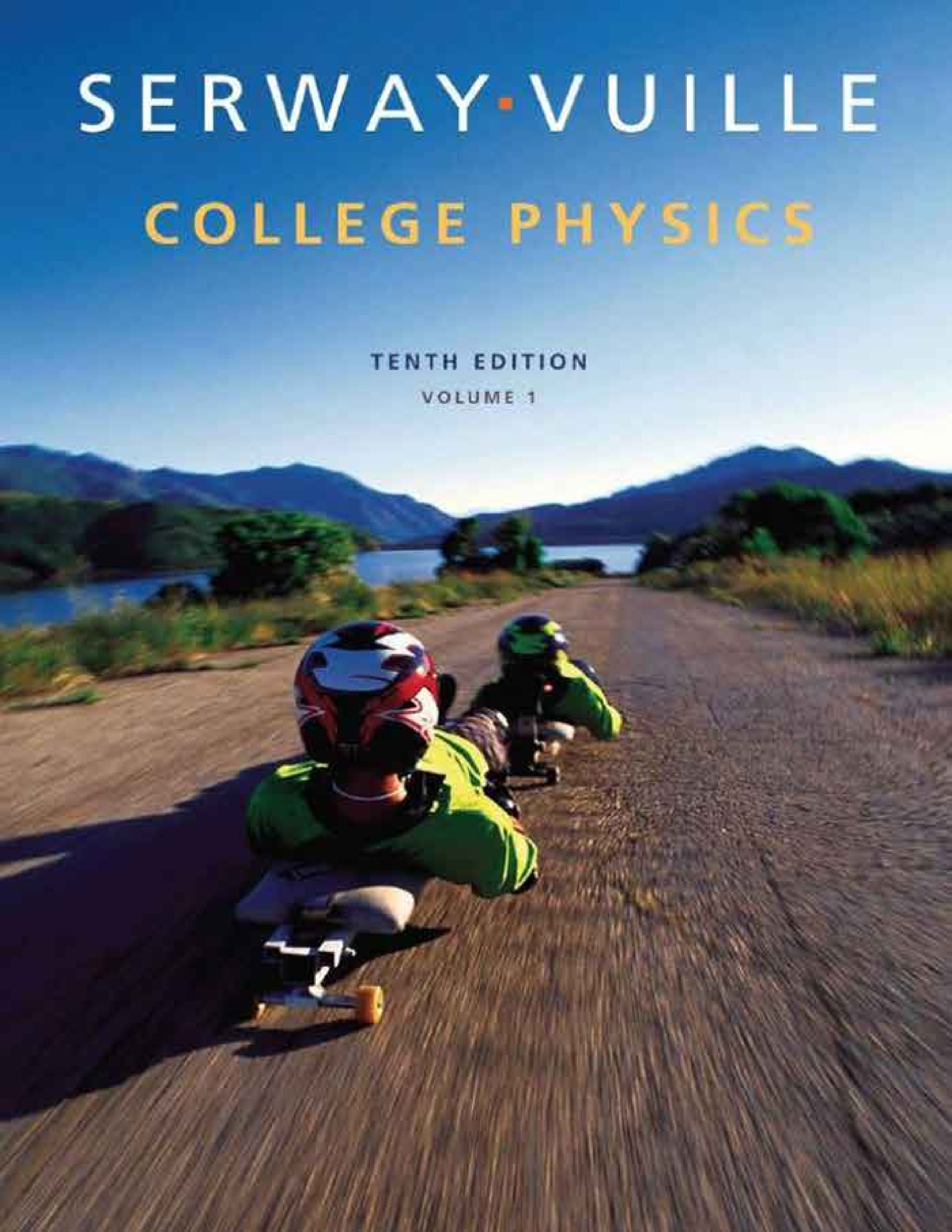
SERWAY · VUILLE

COLLEGE PHYSICS

TENTH EDITION

VOLUME 1



Pedagogical color chart

Mechanics and Thermodynamics

- Displacement and position vectors
- Displacement and position component vectors
- Linear ($\vec{\mathbf{v}}$) and angular ($\vec{\boldsymbol{\omega}}$) velocity vectors
- Velocity component vectors
- Force vectors ($\vec{\mathbf{F}}$)
- Force component vectors
- Acceleration vectors ($\vec{\mathbf{a}}$)
- Acceleration component vectors
- Energy transfer arrows (W_{eng}, Q_c, Q_h)
- Process arrow
- Linear ($\vec{\mathbf{p}}$) and angular ($\vec{\mathbf{L}}$) momentum vectors
- Linear and angular momentum component vectors
- Torque vectors ($\vec{\boldsymbol{\tau}}$)
- Torque component vectors
- Schematic linear or rotational motion directions
- Dimensional rotational arrow
- Enlargement arrow
- Springs
- Pulleys

Electricity and Magnetism

- Electric fields
- Electric field vectors
- Electric field component vectors
- Magnetic fields
- Magnetic field vectors
- Magnetic field component vectors
- Positive charges (+)
- Negative charges (−)
- Resistors
- Batteries and other DC power supplies (+, −)
- Switches
- Capacitors
- Inductors (coils)
- Voltmeters (V)
- Ammeters (A)
- AC Sources
- Lightbulbs
- Ground symbol
- Current

Light and Optics

- Light ray
- Focal light ray
- Central light ray
- Converging lens
- Diverging lens
- Mirror
- Curved mirror
- Objects
- Images

Conversion Factors

Length

1 m = 39.37 in. = 3.281 ft

1 in. = 2.54 cm (exact)

1 km = 0.621 mi

1 mi = 5 280 ft = 1.609 km

1 lightyear (ly) = 9.461×10^{15} m

1 angstrom (Å) = 10^{-10} m

Mass

1 kg = 10^3 g = 6.85×10^{-2} slug

1 slug = 14.59 kg

1 u = 1.66×10^{-27} kg = 931.5 MeV/c^2

Time

1 min = 60 s

1 h = 3 600 s

1 day = 24 h = 1.44×10^3 min = 8.64×10^4 s

1 yr = 365.242 days = 3.156×10^7 s

Volume

1 L = 1 000 cm^3 = 0.035 3 ft^3

1 ft^3 = 2.832×10^{-2} m^3

1 gal = 3.786 L = 231 in.^{3}

Angle

180° = π rad

1 rad = 57.30°

1° = 60 min = 1.745×10^{-2} rad

Speed

1 km/h = 0.278 m/s = 0.621 mi/h

1 m/s = 2.237 mi/h = 3.281 ft/s

1 mi/h = 1.61 km/h = 0.447 m/s = 1.47 ft/s

Force

1 N = 0.224 8 lb = 10^5 dynes

1 lb = 4.448 N

1 dyne = 10^{-5} N = 2.248×10^{-6} lb

Work and energy

1 J = 10^7 erg = 0.738 ft · lb = 0.239 cal

1 cal = 4.186 J

1 ft · lb = 1.356 J

1 Btu = 1.054×10^3 J = 252 cal

1 J = 6.24×10^{18} eV

1 eV = 1.602×10^{-19} J

1 kWh = 3.60×10^6 J

Pressure

1 atm = 1.013×10^5 N/m^2 (or Pa) = 14.70 lb/in.^{2}

1 Pa = 1 N/m^2 = 1.45×10^{-4} lb/in.^{2}

1 lb/in.^{2} = 6.895×10^3 N/m^2

Power

1 hp = 550 ft · lb/s = 0.746 kW

1 W = 1 J/s = 0.738 ft · lb/s

1 Btu/h = 0.293 W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Tenth Edition

College Physics

Volume 1

Raymond A. Serway | *Emeritus, James Madison University*

Chris Vuille | *Embry-Riddle Aeronautical University*

With contributions from John Hughes | *Embry-Riddle Aeronautical University*

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Volume 1
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200 First Stamford Place, 4th Floor
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We dedicate this book to our wives, children, grandchildren, relatives, and friends who have provided so much love, support, and understanding through the years, and to the students for whom this book was written.

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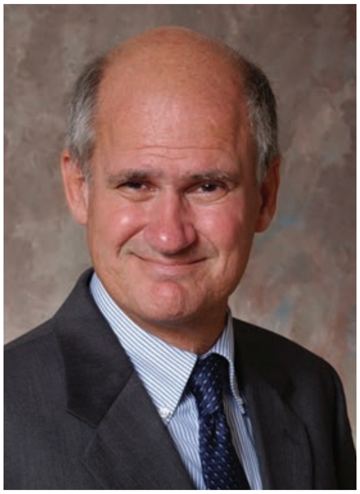
About the Authors

Raymond A. Serway received his doctorate at Illinois Institute of Technology and is Professor Emeritus at James Madison University. In 2011, he was awarded with an honorary doctorate degree from his alma mater, Utica College. He received the 1990 Madison Scholar Award at James Madison University, where he taught for 17 years. Dr. Serway began his teaching career at Clarkson University, where he conducted research and taught from 1967 to 1980. He was the recipient of the Distinguished Teaching Award at Clarkson University in 1977 and the Alumni Achievement Award from Utica College in 1985. As Guest Scientist at the IBM Research Laboratory in Zurich, Switzerland, he worked with K. Alex Müller, 1987 Nobel Prize recipient. Dr. Serway was also a visiting scientist at Argonne National Laboratory, where he collaborated with his mentor and friend, the late Sam Marshall. Early in his career, he was employed as a research scientist at Rome Air Development Center from 1961 to 1963 and at IIT Research Institute from 1963 to 1967. Dr. Serway is also the coauthor of *Physics for Scientists and Engineers*, ninth edition; *Principles of Physics: A Calculus-Based Text*, fifth edition; *Essentials of College Physics*, *Modern Physics*, third edition; and the high school textbook *Physics*, published by Holt, Rinehart and Winston. In addition, Dr. Serway has published more than 40 research papers in the field of condensed matter physics and has given more than 60 presentations at professional meetings. Dr. Serway and his wife Elizabeth enjoy traveling, playing golf, fishing, gardening, singing in the church choir, and especially spending quality time with their four children, nine grandchildren, and a recent great grandson.



Chris Vuille is an associate professor of physics at Embry-Riddle Aeronautical University (ERAU), Daytona Beach, Florida, the world's premier institution for aviation higher education. He received his doctorate in physics from the University of Florida in 1989 and moved to Daytona after a year at ERAU's Prescott, Arizona, campus. Although he has taught courses at all levels, including postgraduate, his primary interest has been instruction at the level of introductory physics. He has received several awards for teaching excellence, including the Senior Class Appreciation Award (three times). He conducts research in general relativity and quantum theory and was a participant in the JOVE program, a special three-year NASA grant program during which he studied neutron stars. His work has appeared in a number of scientific journals, and he has been a featured science writer in Analog Science Fiction/Science Fact magazine. In addition to this textbook, he is coauthor of *Essentials of College Physics*. Dr. Vuille enjoys tennis, swimming, and playing classical piano, and he is a former chess champion of St. Petersburg and Atlanta. In his spare time he writes fiction and goes to the beach. His wife, Dianne Kowing, is Chief of Optometry for a local Veterans' Administration clinic. They have a daughter, Kira, and two sons, Christopher and James.

Preface

College Physics is written for a one-year course in introductory physics usually taken by students majoring in biology, the health professions, or other disciplines, including environmental, earth, and social sciences, and technical fields such as architecture. The mathematical techniques used in this book include algebra, geometry, and trigonometry, but not calculus. Drawing on positive feedback from users of the ninth edition, analytics gathered from both professors and students who use Enhanced WebAssign, as well as reviewers' suggestions, we have refined the text to better meet the needs of students and teachers.

This textbook, which covers the standard topics in classical physics and twentieth-century physics, is divided into six parts. Part 1 (Chapters 1–9) deals with Newtonian mechanics and the physics of fluids; Part 2 (Chapters 10–12) is concerned with heat and thermodynamics; Part 3 (Chapters 13 and 14) covers wave motion and sound; Part 4 (Chapters 15–21) develops the concepts of electricity and magnetism; Part 5 (Chapters 22–25) treats the properties of light and the field of geometric and wave optics; and Part 6 (Chapters 26–30) provides an introduction to special relativity, quantum physics, atomic physics, and nuclear physics.

Objectives

The main objectives of this introductory textbook are twofold: to provide the student with a clear and logical presentation of the basic concepts and principles of physics and to strengthen an understanding of those concepts and principles through a broad range of interesting, real-world applications. To meet those objectives, we have emphasized sound physical arguments and problem-solving methodology. At the same time we have attempted to motivate the student through practical examples that demonstrate the role of physics in other disciplines.

Changes to the Tenth Edition

Several changes and improvements have been made in preparing the tenth edition of this text. Some of the new features are based on our experiences and on current trends in science education. Other changes have been incorporated in response to comments and suggestions offered by users of the ninth edition. The features listed here represent the major changes made for the tenth edition.

New Learning Objectives Added for Every Section

In response to a growing trend across the discipline (and the request of many users), we have added learning objectives for every section of the tenth edition. The learning objectives identify the major concepts in a given section and also identify the specific skills/outcomes students should be able to demonstrate once they have a solid understanding of those concepts. It is hoped that these learning objectives will assist those professors who are transitioning their course to a more outcomes-based approach.

New Online Tutorials

The new online tutorials (available via Enhanced WebAssign) offer students another training tool to assist them in understanding how to apply certain key concepts presented in a given chapter. The tutorials first present a brief review of the necessary concepts from the text, together with advice on how to solve problems involving them. The student can then attempt to solve one or two such problems, guided by questions presented in the tutorial. The tutorial automatically scores student responses and presents correct solutions together with discussion. Students can then practice on several additional problems of a similar level, and in some cases go to higher level or related problems, depending on the concepts covered in the tutorial.

New Warm-Up Exercises in Every Chapter

Warm-up exercises (over 320 are included in the full book) appear at the beginning of each chapter's problems set, and were inspired by one of the author's (Vuille) classroom experiences. The idea behind warm-up exercises is to review mathematical and physical concepts that are prerequisites for a given chapter's problems set, and also to provide students with a general preview of the new physics concepts covered in a given chapter. By doing the warm-up exercises first, students will have an easier time getting comfortable with the new concepts of a chapter before tackling harder problems.

New Algorithmic Solutions in Enhanced WebAssign

All quantitative end-of-chapter problems in Enhanced WebAssign now feature *algorithmic solutions*. Fully worked out solutions are available to students with quantitative parameters exactly matching the version of the problem assigned to individual students. As always for all "Hints" features, Enhanced WebAssign offers great flexibility to instructors regarding when to enable algorithmic solutions.

Chapter-by-Chapter Changes

The text has been carefully edited to improve clarity of presentation and precision of language. We hope that the result is a book both accurate and enjoyable to read. Although the overall content and organization of the textbook are similar to the ninth edition, a few changes were implemented. The list below highlights some of the major changes for the tenth edition.

Chapter 1 Introduction

- Nine new warm-up exercises have been added.
- A new tutorial (*Unit conversions*) has been added in Enhanced WebAssign.

Chapter 2 Motion in One Dimension

- Seven new warm-up exercises have been added.
- A new tutorial (*One-dimensional motion at constant acceleration*) has been added in Enhanced WebAssign.

Chapter 3 Vectors and Two-Dimensional Motion

- Nine new warm-up exercises have been added.
- Two new tutorials (*Applying the kinematics equations of two-dimensional motion* and *Applying the concept of relative velocity*) have been added in Enhanced WebAssign.

Chapter 4 The Laws of Motion

- Thirteen new warm-up exercises have been added.
- Five new tutorials (*Normal forces, Applying the second law to objects in equilibrium, Applying the second law to accelerating objects, Applying the static and kinetic friction forces in the second law,* and *Applying the system approach*) have been added in Enhanced WebAssign.

Chapter 5 Energy

- Ten new warm-up exercises have been added.
- Five new tutorials (*Calculating work, Applying the work-energy theorem, Applying conservation of mechanical energy, Applying the work-energy theorem with the potential energies of gravity and springs,* and *Applying average and instantaneous power*) have been added in Enhanced WebAssign.

Chapter 6 Momentum and Collisions

- Eleven new warm-up exercises have been added.
- Two new tutorials (*Collisions in one dimension* and *Inelastic collisions in two dimensions*) have been added in Enhanced WebAssign.

Chapter 7 Rotational Motion and the Law of Gravity

- Example 7.1 has been revised.
- Fifteen new warm-up exercises have been added.

- Two new tutorials (*Applying the second law to objects in uniform circular motion* and *Applying gravitational potential energy*) have been added in Enhanced WebAssign.

Chapter 8 Rotational Equilibrium and Rotational Dynamics

- Fourteen new warm-up exercises have been added.
- Four new tutorials (*Applying the conditions of mechanical equilibrium to rigid bodies, Applying the rotational second law, Applying the work-energy theorem including rotational kinetic energy,* and *Applying conservation of angular momentum*) have been added in Enhanced WebAssign.

Chapter 9 Solids and Fluids

- Eleven new warm-up exercises have been added.
- Two new tutorials (*Applying Archimedes' principle* and *Applying Bernoulli's equation*) have been added in Enhanced WebAssign.

Chapter 10 Thermal Physics

- Ten new warm-up exercises have been added.
- A new tutorial (*Applying the ideal gas law*) has been added in Enhanced WebAssign.

Chapter 11 Energy in Thermal Processes

- Example 11.11 ("Planet of Alpha Centauri B") is completely new to this edition.
- Nine new warm-up exercises have been added.
- A new tutorial (*Calorimetry*) has been added in Enhanced WebAssign.

Chapter 12 The Laws of Thermodynamics

- Fourteen new warm-up exercises have been added.
- Two new tutorials (*Thermal processes* and *Calculating changes in entropy*) have been added in Enhanced WebAssign.

Chapter 13 Vibrations and Waves

- Eleven new warm-up exercises have been added.
- A new tutorial (*Investigating simple harmonic oscillations*) has been added in Enhanced WebAssign.

Chapter 14 Sound

- Fourteen new warm-up exercises have been added.
- Two new tutorials (*Sound intensity, decibel level, and their variation with distance* and *Calculating the Doppler effect*) have been added in Enhanced WebAssign.

Textbook Features

Most instructors would agree that the textbook assigned in a course should be the student's primary guide for understanding and learning the subject matter. Further, the textbook should be easily accessible and written in a style that facilitates instruction and learning. With that in mind, we have included many pedagogical features that are intended to enhance the textbook's usefulness to both students and instructors. The following features are included.

Examples For this tenth edition we have reviewed all the worked examples and made numerous improvements. Every effort has been made to ensure the collection of examples, as a whole, is comprehensive in covering all the physical concepts, physics problem types, and required mathematical techniques. The Questions usually require a conceptual response or determination, but they also include estimates requiring knowledge of the relationships between concepts. The answers for the Questions can be found at the back of the book. The examples are in a two-column format for a pedagogic purpose: students can study the example, then cover up the right column and attempt to solve the problem using the cues in the left column. Once successful in that exercise, the student can cover up both solution columns and attempt to solve the problem using only the strategy statement, and finally just the problem statement. Here is a sample of an in-text worked example, with an explanation of each of the example's main parts:

The **Goal** describes the physical concepts being explored within the worked example.

The **Problem** statement presents the problem itself.

The **Strategy** section helps students analyze the problem and create a framework for working out the solution.

The **Solution** section uses a two-column format that gives the explanation for each step of the solution in the left-hand column, while giving each accompanying mathematical step in the right-hand column. This layout facilitates matching the idea with its execution and helps students learn how to organize their work. Another benefit: students can easily use this format as a training tool, covering up the solution on the right and solving the problem using the comments on the left as a guide.

EXAMPLE 13.7 Measuring the Value of g

GOAL Determine g from pendulum motion.

PROBLEM Using a small pendulum of length 0.171 m, a geophysicist counts 72.0 complete swings in a time of 60.0 s. What is the value of g in this location?

STRATEGY First calculate the period of the pendulum by dividing the total time by the number of complete swings. Solve Equation 13.15 for g and substitute values.

SOLUTION

Calculate the period by dividing the total elapsed time by the number of complete oscillations:

$$T = \frac{\text{time}}{\text{\# of oscillations}} = \frac{60.0\text{ s}}{72.0} = 0.833\text{ s}$$

Solve Equation 13.15 for g and substitute values:

$$T = 2\pi\sqrt{\frac{L}{g}} \quad\rightarrow\quad T^2 = 4\pi^2\frac{L}{g}$$

$$g = \frac{4\pi^2 L}{T^2} = \frac{(39.5)(0.171\text{ m})}{(0.833\text{ s})^2} = 9.73\text{ m/s}^2$$

REMARKS Measuring such a vibration is a good way of determining the local value of the acceleration of gravity.

QUESTION 13.7 True or False: A simple pendulum of length 0.50 m has a larger frequency of vibration than a simple pendulum of length 1.0 m.

EXERCISE 13.7 What would be the period of the 0.171-m pendulum on the Moon, where the acceleration of gravity is 1.62 m/s^2?

ANSWER 2.04 s

Remarks follow each Solution and highlight some of the underlying concepts and methodology used in arriving at a correct solution. In addition, the remarks are often used to put the problem into a larger, real-world context.

Question Each worked example features a conceptual question that promotes student understanding of the underlying concepts contained in the example.

Exercise/Answer Every Question is followed immediately by an exercise with an answer. These exercises allow students to reinforce their understanding by working a similar or related problem, with the answers giving them instant feedback. At the option of the instructor, the exercises can also be assigned as homework. Students who work through these exercises on a regular basis will find the end-of-chapter problems less intimidating.

Many Worked Examples are also available to be assigned in the Enhanced WebAssign homework management system (visit **www.cengage.com/physics/serway** for more details).

Integration with Enhanced WebAssign The textbook's tight integration with Enhanced WebAssign content facilitates an online learning environment that helps students improve their problem-solving skills and gives them a variety of tools to meet their individual learning styles. Extensive user data gathered by WebAssign were used to ensure that the problems most often assigned were retained for this new edition. In each chapter's problems set, the top quartile of problems that were assigned in WebAssign have cyan-shaded problem numbers for easy identification, allowing professors to quickly and easily find the most popular problems that were assigned in Enhanced WebAssign. Master It tutorials help students solve problems by having them work through a stepped-out solution. Problems with Master It tutorials are indicated in each chapter's problem set with a **M** icon. In addition, Watch It solution videos (indicated by a **W** icon) explain fundamental problem-solving strategies to help students step through selected problems. The problems most often assigned in Enhanced WebAssign (shaded in blue) have feedback to address student misconceptions, helping students avoid common pitfalls.

Artwork Every piece of artwork in the tenth edition is in a modern style that helps express the physics principles at work in a clearer and more precise fashion. Every piece of art is also drawn to make certain that the physical situations presented correspond exactly to the text discussion at hand.

Guidance labels are included with many figures in the text; these point out important features of the figure and guide students through figures without having to go back and forth from the figure legend to the figure itself. This format also helps those students who are visual learners. An example of this kind of figure appears below.

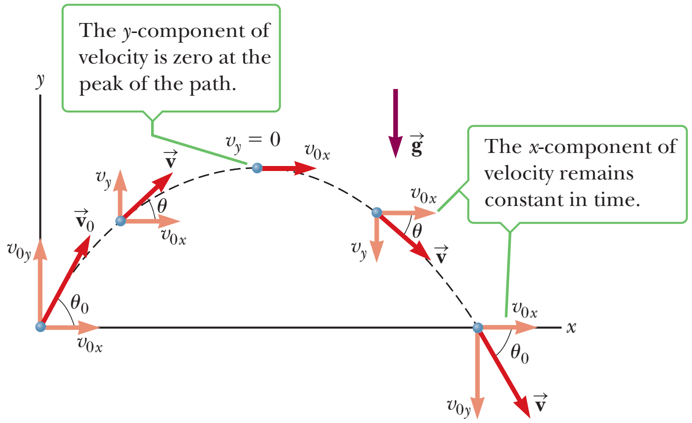


figure 3.14
The parabolic trajectory of a particle that leaves the origin with a velocity of $\vec{\mathbf{v}}_0$. Note that $\vec{\mathbf{v}}$ changes with time. However, the x-component of the velocity, v_x, remains constant in time, equal to its initial velocity, v_{0x}. Also, $v_y = 0$ at the peak of the trajectory, but the acceleration is always equal to the free-fall acceleration and acts vertically downward.

Warm-Up Exercises As discussed earlier, these new exercises (over 320 are included in the full book) were inspired by one of the author's (Vuille) classroom experiences. Warm-up exercises review mathematical and physical concepts that are prerequisites for a given chapter's problems set and also provide students with a general preview of the new physics concepts covered in a given chapter. By doing the warm-up exercises first, students will have an easier time getting comfortable with the new concepts of a chapter before tackling harder problems. Answers to odd-numbered warm-up exercises are included in the Answers section at the end of the book. Answers to all warm-up exercises are in the *Instructor's Solutions Manual.*

Conceptual Questions At the end of each chapter are approximately a dozen conceptual questions. The Applying Physics examples presented in the text serve as models for students when conceptual questions are assigned and show how the concepts can be applied to understanding the physical world. The conceptual questions provide the student with a means of self-testing the concepts presented in the chapter. Some conceptual questions are appropriate for initiating classroom discussions. Answers to odd-numbered conceptual questions are included in the Answers section at the end of the book. Answers to all conceptual questions are in the *Instructor's Solutions Manual.*

Problems All questions and problems for this revision were carefully reviewed to improve their variety, interest, and pedagogical value while maintaining their clarity and quality. An extensive set of problems is included at the end of each chapter (in all, more than 2 000 problems are provided in the tenth edition). Answers to odd-numbered problems are given at the end of the book. For the convenience of both the student and instructor, about two-thirds of the problems are keyed to specific sections of the chapter. The remaining problems, labeled "Additional Problems," are not keyed to specific sections. The three levels of problems are graded according to their difficulty. Straightforward problems are numbered in **black**, intermediate level problems are numbered in **blue**, and the most challenging problems are numbered in **red**. The BIO icon identifies problems dealing with applications to the life sciences and medicine. Solutions to approximately 12 problems in each chapter are in the *Student Solutions Manual and Study Guide*.

There are three other types of problems we think instructors and students will find interesting as they work through the text:

- **S** **Symbolic problems** require the student to obtain an answer in terms of symbols. In general, some guidance is built into the problem statement. The goal is to better train the student to deal with mathematics at a level appropriate to this course. Most students at this level are uncomfortable with symbolic equations, which is unfortunate because symbolic equations are the most efficient vehicle for presenting relationships between physics concepts. Once students understand the physical concepts, their ability to solve problems is greatly enhanced. As soon as the numbers are substituted into an equation, however, all the concepts and their relationships to one another are lost, melded together in the student's calculator. Symbolic problems train the student to postpone substitution of values, facilitating their ability to think conceptually using the equations. An example of a symbolic problem is provided here:

  14. S An object of mass m is dropped from the roof of a building of height h. While the object is falling, a wind blowing parallel to the face of the building exerts a constant horizontal force F on the object. (a) How long does it take the object to strike the ground? Express the time t in terms of g and h. (b) Find an expression in terms of m and F for the acceleration a_x of the object in the horizontal direction (taken as the positive x-direction). (c) How far is the object displaced horizontally before hitting the ground? Answer in terms of m, g, F, and h. (d) Find the magnitude of the object's acceleration while it is falling, using the variables F, m, and g.

- **Q|C** **Quantitative/conceptual problems** encourage the student to think conceptually about a given physics problem rather than rely solely on computational skills. Research in physics education suggests that standard physics problems requiring calculations may not be entirely adequate in training students to think conceptually. Students learn to substitute numbers for symbols in the equations without fully understanding what they are doing or what the symbols mean. Quantitative/conceptual problems combat this tendency by asking for answers that require something other than a number or a calculation. An example of a quantitative/conceptual problem is provided here:

  5. Q|C Starting from rest, a 5.00-kg block slides 2.50 m down a rough 30.0° incline. The coefficient of kinetic friction between the block and the incline is μ_k = 0.436. Determine (a) the work done by the force of gravity, (b) the work done by the friction force between block and incline, and (c) the work done by the normal force. (d) Qualitatively, how would the answers change if a shorter ramp at a steeper angle were used to span the same vertical height?

- **GP** **Guided problems** help students break problems into steps**.** A physics problem typically asks for one physical quantity in a given context. Often, however, several concepts must be used and a number of calculations are required to get that final answer. Many students are not accustomed to this level of complexity and often don't know where to start. A guided problem breaks a problem into smaller steps, enabling students to grasp all the concepts and strategies required to arrive at a correct solution. Unlike standard physics problems, guidance is often built into the problem statement. For example, the problem might say "Find the speed using conservation of energy" rather than asking only for the speed. In any given chapter there are usually two or three problem types that are particularly suited to this problem form. The problem must have a certain level of complexity, with a similar problem-solving strategy involved each time it appears. Guided problems are reminiscent of how a student might interact with a professor in an office visit. These problems help train students to break down complex problems into a series of simpler problems, an essential problem-solving skill. An example of a guided problem is provided here:

32. GP Two blocks of masses m_1 and m_2 ($m_1 > m_2$) are placed on a frictionless table in contact with each other. A horizontal force of magnitude F is applied to the block of mass m_1 in Figure P4.32. (a) If P is the magnitude of the contact force between the blocks, draw the free-body diagrams for each block. (b) What is the net force on the system consisting of both blocks? (c) What is the net force acting on m_1? (d) What is the net force acting on m_2? (e) Write the x-component of Newton's second law for each block. (f) Solve the resulting system of two equations and two unknowns, expressing the acceleration a and contact force P in terms of the masses and force. (g) How would the answers change if the force had been applied to m_2 instead? (*Hint:* Use symmetry; don't calculate!) Is the contact force larger, smaller, or the same in this case? Why?

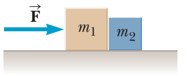


Figure P4.32

Quick Quizzes All the Quick Quizzes (see example below) are cast in an objective format, including multiple-choice, true–false, matching, and ranking questions. Quick Quizzes provide students with opportunities to test their understanding of the physical concepts presented. The questions require students to make decisions on the basis of sound reasoning, and some have been written to help students overcome common misconceptions. Answers to all Quick Quiz questions are found at the end of the textbook, and answers with detailed explanations are provided in the *Instructor's Solutions Manual*. Many instructors choose to use Quick Quiz questions in a "peer instruction" teaching style.

■ *Quick Quiz*

4.4 A small sports car collides head-on with a massive truck. The greater impact force (in magnitude) acts on (a) the car, (b) the truck, (c) neither, the force is the same on both. Which vehicle undergoes the greater magnitude acceleration? (d) the car, (e) the truck, (f) the accelerations are the same.

Problem-Solving Strategies A general problem-solving strategy to be followed by the student is outlined at the end of Chapter 1. This strategy provides students with a structured process for solving problems. In most chapters, more specific strategies and suggestions (see example below) are included for solving the types of problems featured in both the worked examples and the end-of-chapter problems. This feature helps students identify the essential steps in solving problems and increases their skills as problem solvers.

■ **PROBLEM-SOLVING STRATEGY**

Newton's Second Law

Problems involving Newton's second law can be very complex. The following protocol breaks the solution process down into smaller, intermediate goals:

1. **Read** the problem carefully at least once.
2. **Draw** a picture of the system, identify the object of primary interest, and indicate forces with arrows.
3. **Label** each force in the picture in a way that will bring to mind what physical quantity the label stands for (e.g., T for tension).
4. **Draw** a free-body diagram of the object of interest, based on the labeled picture. If additional objects are involved, draw separate free-body diagrams for them. Choose convenient coordinates for each object.
5. **Apply Newton's second law.** The x- and y-components of Newton's second law should be taken from the vector equation and written individually. This usually results in two equations and two unknowns.
6. **Solve** for the desired unknown quantity, and substitute the numbers.

Biomedical Applications For biology and pre-med students, BIO icons point the way to various practical and interesting applications of physical principles to biology and medicine.

MCAT Skill Builder Study Guide The tenth edition of *College Physics* has a special skill-building Appendix (Appendix E) available via CengageCompose to help pre-med students prepare for the MCAT exam. The appendix contains examples written by the text authors that help students build conceptual and quantitative skills. These skill-building examples are followed by MCAT-style questions written by test prep experts to make sure students are ready to ace the exam.

MCAT Test Preparation Guide Located at the front of the book, this guide outlines the six content categories related to physics on the new MCAT exam that will be administered starting in 2015. Students can use the guide to prepare for the MCAT exam, class tests, or homework assignments.

Applying Physics The Applying Physics features provide students with an additional means of reviewing concepts presented in that section. Some Applying Physics examples demonstrate the connection between the concepts presented in that chapter and other scientific disciplines. These examples also serve as models for students when assigned the task of responding to the Conceptual Questions presented at the end of each chapter. For examples of Applying Physics boxes, see Applying Physics 9.5 (Home Plumbing) on page 313 and Applying Physics 13.1 (Bungee Jumping) on page 456.

Tips Placed in the margins of the text, Tips address common student misconceptions and situations in which students often follow unproductive paths (see example at the right). More than 95 Tips are provided in this edition to help students avoid common mistakes and misunderstandings.

Tip 4.3 Newton's Second Law Is a *Vector* Equation

In applying Newton's second law, add all of the forces on the object as vectors and then find the resultant vector acceleration by dividing by *m*. Don't find the individual magnitudes of the forces and add them like scalars.

Marginal Notes Comments and notes appearing in the margin (see example at the right) can be used to locate important statements, equations, and concepts in the text.

◀ Newton's third law

Applications Although physics is relevant to so much in our modern lives, it may not be obvious to students in an introductory course. Application margin notes (see example to the right) make the relevance of physics to everyday life more obvious by pointing out specific applications in the text. Some of these applications pertain to the life sciences and are marked with a BIO icon. A list of the Applications in Volume 1 appears after this Preface.

BIO **APPLICATION**

Diet Versus Exercise in Weight-loss Programs

Style To facilitate rapid comprehension, we have attempted to write the book in a style that is clear, logical, relaxed, and engaging. The somewhat informal and relaxed writing style is designed to connect better with students and enhance their reading enjoyment. New terms are carefully defined, and we have tried to avoid the use of jargon.

Introductions All chapters begin with a brief preview that includes a discussion of the chapter's objectives and content.

Units The international system of units (SI) is used throughout the text. The U.S. customary system of units is used only to a limited extent in the chapters on mechanics and thermodynamics.

Pedagogical Use of Color Readers should consult the pedagogical color chart (inside the front cover) for a listing of the color-coded symbols used in the text diagrams. This system is followed consistently throughout the text.

Important Statements and Equations Most important statements and definitions are set in **boldface** type or are highlighted with a background screen for added emphasis and ease of review. Similarly, important equations are highlighted with a tan background screen to facilitate location.

Illustrations and Tables The readability and effectiveness of the text material, worked examples, and end-of-chapter conceptual questions and problems are enhanced by the large number of figures, diagrams, photographs, and tables. Full color adds clarity to the artwork and makes illustrations as realistic as possible. Three-dimensional effects are rendered with the use of shaded and lightened areas where appropriate. Vectors are color coded, and curves in graphs are drawn in color. Color photographs have been carefully selected, and their accompanying captions have been written to serve as an added instructional tool. A complete description of the pedagogical use of color appears on the inside front cover.

Summary The end-of-chapter Summary is organized by individual section heading for ease of reference. Most chapter summaries also feature key figures from the chapter.

Significant Figures Significant figures in both worked examples and end-of-chapter problems have been handled with care. Most numerical examples and problems are worked out to either two or three significant figures, depending on the accuracy of the data provided. Intermediate results presented in the examples are rounded to the proper number of significant figures, and only those digits are carried forward.

Appendices and Endpapers Several appendices are provided at the end of the textbook. Most of the appendix material (Appendix A) represents a review of mathematical concepts and techniques used in the text, including scientific notation, algebra, geometry, and trigonometry. Reference to these appendices is made as needed throughout the text. Most of the mathematical review sections include worked examples and exercises with answers. In addition to the mathematical review, some appendices contain useful tables that supplement textual information. For easy reference, the front endpapers contain a chart explaining the use of color throughout the book and a list of frequently used conversion factors.

Teaching Options

This book contains more than enough material for a one-year course in introductory physics, which serves two purposes. First, it gives the instructor more flexibility in choosing topics for a specific course. Second, the book becomes more useful as a resource for students. On average, it should be possible to cover about one chapter each week for a class that meets three hours per week. Those sections, examples, and end-of-chapter problems dealing with applications of physics to life sciences are identified with the BIO icon. We offer the following suggestions for shorter courses for those instructors who choose to move at a slower pace through the year.

> ***Option A:*** If you choose to place more emphasis on contemporary topics in physics, you could omit all or parts of Chapter 8 (Rotational Equilibrium and Rotational Dynamics), Chapter 21 (Alternating-Current Circuits and Electromagnetic Waves), and Chapter 25 (Optical Instruments).
>
> ***Option B:*** If you choose to place more emphasis on classical physics, you could omit all or parts of Part 6 of the textbook, which deals with special relativity and other topics in twentieth-century physics.

The *Instructor's Solutions Manual* offers additional suggestions for specific sections and topics that may be omitted without loss of continuity if time presses.

Cengage Compose

CengageCompose Options for *College Physics*

Would you like to easily create your own personalized text, selecting the elements that meet your specific learning objectives?

CengageCompose puts the power of the vast Cengage Learning library of learning content at your fingertips to create exactly the text you need. The all-new, Web-based CengageCompose site lets you quickly scan content and review materials to pick what you need for your text. Site tools let you easily assemble the modular learning units into the order you want and immediately provide you with an online copy for review. Add enrichment content like case studies, exercises, and lab materials to further build your ideal learning materials. Even choose from hundreds of vivid, art-rich, customizable, full-color covers.

Cengage Learning offers the fastest and easiest way to create unique customized learning materials delivered the way you want. For more information about custom publishing options, visit **www.cengage.com/custom** or contact your local Cengage Learning representative.

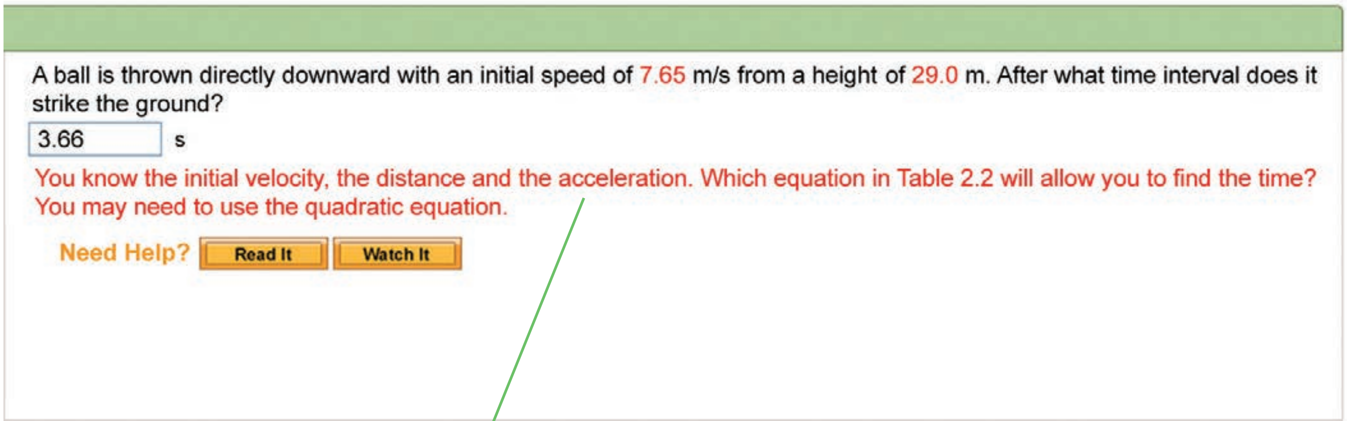
Course Solutions That Fit Your Teaching Goals and Your Students' Learning Needs

Recent advances in educational technology have made homework management systems and audience response systems powerful and affordable tools to enhance the way you teach your course. Whether you offer a more traditional text-based course, are interested in using or are currently using an online homework management system such as Enhanced WebAssign, or are ready to turn your lecture into an interactive learning environment with JoinIn™, you can be confident that the text's proven content provides the foundation for each and every component of our technology and ancillary package.

Homework Management Systems

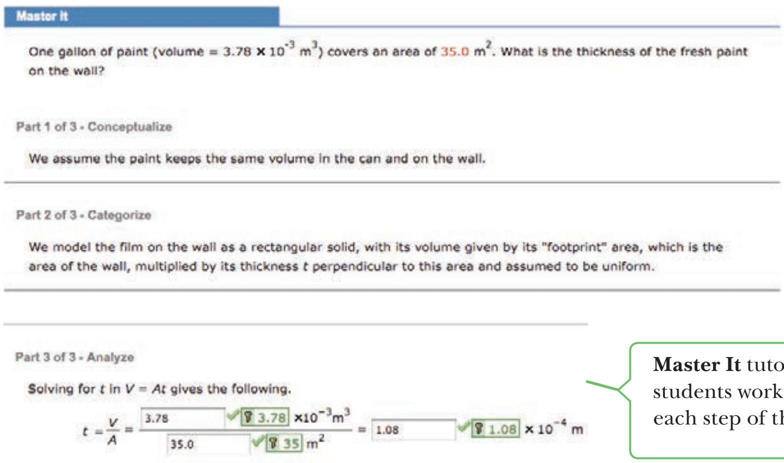
Enhanced WebAssign for *College Physics*, Tenth Edition. Exclusively from Cengage Learning, Enhanced WebAssign offers an extensive online program for physics to encourage the practice that's so critical for concept mastery. The meticulously crafted pedagogy and exercises in our proven texts become even more effective in Enhanced WebAssign. Enhanced WebAssign includes the Cengage YouBook, a highly customizable, interactive eBook. WebAssign includes:

- **All of the quantitative end-of-chapter problems, now including worked out solutions, matching the algorithmic version of the question assigned to each student.**
- **Selected problems enhanced with targeted feedback.** An example of targeted feedback appears below:



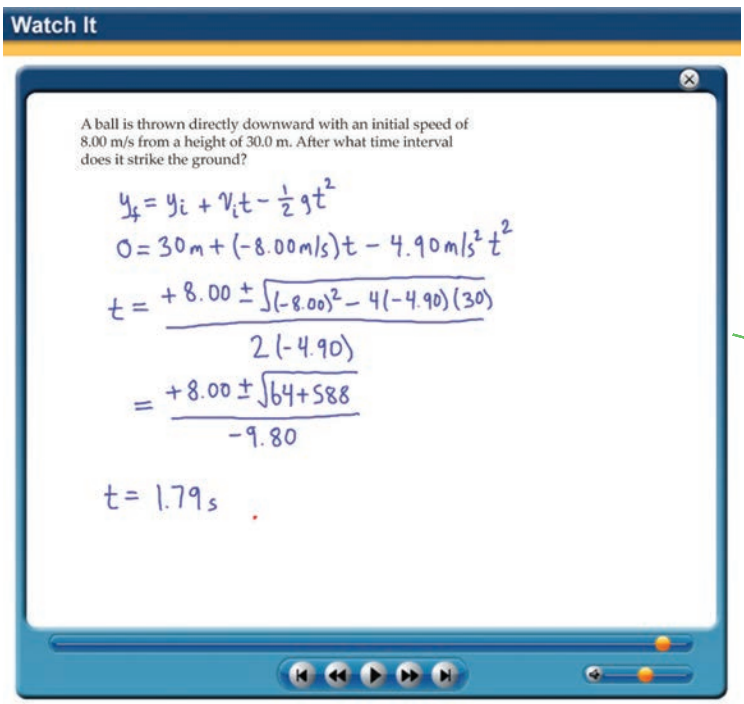
Selected problems include feedback to address common mistakes that students make. This feedback was developed by professors with years of classroom experience.

- **Master It tutorials** (indicated in the text by an M icon), to help students work through the problem one step at a time. An example of a Master It tutorial appears below:



Master It tutorials help students work through each step of the problem.

- **Watch It solution videos** (indicated in the text by a W icon) that explain fundamental problem-solving strategies, to help students step through the problem. In addition, instructors can choose to include video hints of problem-solving strategies. A screen shot from a Watch It solution video appears below:



Watch It solution videos help students visualize the steps needed to solve a problem.

- **Concept Checks**
- **PhET simulations**
- **Most worked examples**, enhanced with hints and feedback, to help strengthen students' problem-solving skills
- **Every Quick Quiz**, giving your students ample opportunity to test their conceptual understanding

- **Personalized Study Plan.** The Personal Study Plan in Enhanced WebAssign provides chapter and section assessments that show students what material they know and what areas require more work. For items that they answer incorrectly, students can click on links to related study resources such as videos, tutorials, or reading materials. Color-coded progress indicators let them see how well they are doing on different topics. You decide what chapters and sections to include—and whether to include the plan as part of the final grade or as a study guide with no scoring involved.
- **The Cengage YouBook.** WebAssign has a customizable and interactive eBook, the Cengage YouBook, that lets you tailor the textbook to fit your course and connect with your students. You can remove and rearrange chapters in the table of contents and tailor assigned readings that match your syllabus exactly. Powerful editing tools let you change as much as you'd like—or leave it just like it is. You can highlight key passages or add sticky notes to pages to comment on a concept in the reading, and then share any of these individual notes and highlights with your students, or keep them personal. You can also edit narrative content in the textbook by adding a text box or striking out text. With a handy link tool, you can drop in an icon at any point in the eBook that lets you link to your own lecture notes, audio summaries, video lectures, or other files on a personal Web site or anywhere on the Web. A simple YouTube widget lets you easily find and embed videos from YouTube directly into eBook pages. The Cengage YouBook helps students go beyond just reading the textbook. Students can also highlight the text and add their own notes or bookmarks. Animations play right on the page at the point of learning so that they're not speed bumps to reading but true enhancements. Please visit **www.webassign.net/brookscole** to view an interactive demonstration of Enhanced WebAssign.
- Offered exclusively in WebAssign, **Quick Prep** for physics is algebra and trigonometry math remediation within the context of physics applications and principles. Quick Prep helps students succeed by using narratives illustrated throughout with video examples. The Master It tutorial problems allow students to assess and retune their understanding of the material. The Practice Problems that go along with each tutorial allow both the student and the instructor to test the student's understanding of the material.

Quick Prep includes the following features:

- 67 interactive tutorials
- 67 additional practice problems
- A thorough overview of each topic, including video examples
- Can be taken before the semester begins or during the first few weeks of the course
- Can also be assigned alongside each chapter for "just in time" remediation

Topics include units, scientific notation, and significant figures; the motion of objects along a line; functions; approximation and graphing; probability and error; vectors, displacement, and velocity; spheres; and force and vector projections.

MindTap™: The Personal Learning Experience

MindTap™

MindTap for Serway and Vuille *College Physics* is a personalized, fully online digital learning platform of authoritative textbook content, WebAssign assignments, and services that engages your students with interactivity while also offering choices in the configuration of coursework and enhancement of the curriculum via complimentary Web apps known as MindApps. MindApps range from WebAssign, ReadSpeaker (which reads the text out loud to students), to Kaltura (allowing you to insert inline video and audio into your curriculum), to ConnectYard (allowing you to create digital "yards" through social media—all without "friending" your students). MindTap is well beyond an eBook, a homework solution or digital supplement, a resource center Web site, a course delivery platform, or a Learning Management System. It is the first in a new category—the Personal Learning Experience.

CengageBrain.com

On **CengageBrain.com** students will be able to save up to 60% on their course materials through our full spectrum of options. Students will have the option to rent their textbooks or purchase print textbooks, e-textbooks, or individual e-chapters and audio books all for substantial savings over average retail prices. **CengageBrain.com** also includes access to Cengage Learning's broad range of homework and study tools and features a selection of free content.

Lecture Presentation Resources

Instructor's Companion Site for *College Physics*, Tenth Edition. Bringing physics principles and concepts to life in your lectures has never been easier! The full-featured Instructor's Companion Site provides everything you need for *College Physics*, tenth edition. Key content includes the *Instructor's Solutions Manual*, art and images from the text, premade chapter-specific PowerPoint lectures, Cengage Learning Testing Powered by Cognero with pre-loaded test questions, JoinIn response-system "clickers," Active Figures animations, a physics movie library, and more.

Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to author, edit, and manage test bank content, create multiple test versions in an instant, and deliver tests from your LMS, your classroom, or wherever you want. No special installs or downloads needed, you can create tests from anywhere with internet access. Cognero brings simplicity at every step, with a desktop-inspired interface, a full-featured test generator, and cross-platform compatibility.

JoinIn. *Assessing to Learn in the Classroom* questions developed at the University of Massachusetts Amherst. This collection of 250 advanced conceptual questions has been tested in the classroom for more than ten years and takes peer learning to a new level. JoinIn helps you turn your lectures into an interactive learning environment that promotes conceptual understanding. Available exclusively for higher education from our partnership with Turning Technologies, JoinIn is the easiest way to turn your lecture hall into a personal, fully interactive experience for your students!

Assessment and Course Preparation Resources

A number of resources listed below will assist with your assessment and preparation processes.

Instructor's Solutions Manual This manual contains complete worked solutions to all end-of-chapter warm-up exercises, conceptual questions, and problems in the text, and full answers with explanations to the Quick Quizzes. Volume 1 contains Chapters 1 through 14, and Volume 2 contains Chapters 15 through 30. Electronic files of the *Instructor's Solutions Manual* are available on the Instructor's Companion Site.

Test Bank by Ed Oberhofer (University of North Carolina at Charlotte and Lake-Sumter Community College). The test bank is available on the Instructor's Companion Site. This two-volume test bank contains approximately 1 750 multiple-choice questions. Instructors may print and duplicate pages for distribution to students. The test bank is available in the Cognero test-generator, or in PDF, Word, WebCT, or Blackboard versions on the instructor's companion site at **www.CengageBrain.com**.

Supporting Materials for the Instructor

Supporting instructor materials are available to qualified adopters. Please consult your local Cengage Learning representative for details. Visit **www.CengageBrain.com** to

- request a desk copy
- locate your local representative
- download electronic files of select support materials

Student Resources

Visit the *College Physics* website at **www.CengageBrain.com** to see samples of select student supplements. Go to **CengageBrain.com** to purchase and access this product at Cengage Learning's preferred online store.

CENGAGE brain .com
buy. rent. access.

Student Solutions Manual and Study Guide Now offered in two volumes, the *Student Solutions Manual and Study Guide* features detailed solutions to approximately 12 problems per chapter. Boxed numbers identify those problems in the textbook for which complete solutions are found in the manual. The manual also features a skills section, important notes from key sections of the text, and a list of important equations and concepts. Volume 1 contains Chapters 1 through 14, and Volume 2 contains Chapters 15 through 30.

Physics Laboratory Manual, Third Edition by David Loyd (Angelo State University) supplements the learning of basic physical principles while introducing laboratory procedures and equipment. Each chapter includes a prelaboratory assignment, objectives, an equipment list, the theory behind the experiment, experimental procedures, graphing exercises, and questions. A laboratory report form is included with each experiment so that the student can record data, calculations, and experimental results. Students are encouraged to apply statistical analysis to their data. A complete *Instructor's Manual* is also available to facilitate use of this lab manual.

Physics Laboratory Experiments, Seventh Edition by Jerry D. Wilson (Lander College) and Cecilia A. Hernández (American River College). This market-leading manual for the first-year physics laboratory course offers a wide range of class-tested experiments designed specifically for use in small to midsize lab programs. A series of integrated experiments emphasizes the use of computerized instrumentation and includes a set of "computer-assisted experiments" to allow students and instructors to gain experience with modern equipment. This option also enables instructors to determine the appropriate balance between traditional and computer-based experiments for their courses. By analyzing data through two different methods, students gain a greater understanding of the concepts behind the experiments. The seventh edition is updated with the latest information and techniques involving state-of-the-art equipment and a new Guided Learning feature addresses the growing interest in guided-inquiry pedagogy. Fourteen additional experiments are also available through custom printing.

Acknowledgments

In preparing the tenth edition of this textbook, we have been guided by the expertise of many people who have reviewed manuscript or provided suggestions. Prior to our work on this revision, we conducted a survey of over 250 professors who teach the course; their collective feedback helped shape this revision, and we thank them. We also wish to acknowledge the following reviewers of recent editions, and express our sincere appreciation for their helpful suggestions, criticism, and encouragement.

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Gerd Kortemeyer and Randall Jones contributed several end-of-chapter problems, especially those of interest to the life sciences. Edward F. Redish of the University of Maryland graciously allowed us to list some of his problems from the Activity Based Physics Project.

Special thanks and recognition go to the professional staff at Cengage Learning—in particular, Mary Finch, Charlie Hartford, Ed Dodd, Andrew Coppola, Alison Eigel Zade, Janet del Mundo, Nicole Molica, Cate Barr, Chris Robinson, and Karolina Kiwak—for their fine work during the development, production, and promotion of this textbook. We recognize the skilled production service provided by the staff at Graphic World, Inc., and the dedicated photo research efforts of Vignesh Sadhasivam and Abbey Stebing at PreMediaGlobal.

Finally, we are deeply indebted to our wives and children for their love, support, and long-term sacrifices.

Raymond A. Serway
St. Petersburg, Florida

Chris Vuille
Daytona Beach, Florida

Engaging Applications

Although physics is relevant to so much in our lives, it may not be obvious to students in an introductory course. In this tenth edition of *College Physics,* we continue a design feature begun in the seventh edition. This feature makes the relevance of physics to everyday life more obvious by pointing out specific applications in the form of a marginal note. Some of these applications pertain to the life sciences and are marked with the BIO icon. The list below is not intended to be a complete listing of all the applications of the principles of physics found in this textbook. Many other applications are to be found within the text and especially in the worked examples, conceptual questions, and end-of-chapter problems.

To the Student

As a student, it's important that you understand how to use this book most effectively and how best to go about learning physics. Scanning through the Preface will acquaint you with the various features available, both in the book and online. Awareness of your educational resources and how to use them is essential. Although physics is challenging, it can be mastered with the correct approach.

How to Study

Students often ask how best to study physics and prepare for examinations. There is no simple answer to this question, but we'd like to offer some suggestions based on our own experiences in learning and teaching over the years.

First and foremost, maintain a positive attitude toward the subject matter. Like learning a language, physics takes time. Those who keep applying themselves on a *daily basis* can expect to reach understanding and succeed in the course. Keep in mind that physics is the most fundamental of all natural sciences. Other science courses that follow will use the same physical principles, so it is important that you understand and are able to apply the various concepts and theories discussed in the text. They're relevant!

Concepts and Principles

Students often try to do their homework without first studying the basic concepts. It is essential that you understand the basic concepts and principles *before* attempting to solve assigned problems. You can best accomplish this goal by carefully reading the textbook *before* you attend your lecture on the covered material. When reading the text, you should jot down those points that are not clear to you. Also be sure to make a diligent attempt at answering the questions in the Quick Quizzes as you come to them in your reading. We have worked hard to prepare questions that help you judge for yourself how well you understand the material. Pay careful attention to the many Tips throughout the text. They will help you avoid misconceptions, mistakes, and misunderstandings as well as maximize the efficiency of your time by minimizing adventures along fruitless paths. During class, take careful notes and ask questions about those ideas that are unclear to you. Keep in mind that few people are able to absorb the full meaning of scientific material after only one reading. Your lectures and laboratory work supplement your textbook and should clarify some of the more difficult material. You should minimize rote memorization of material. Successful memorization of passages from the text, equations, and derivations does not necessarily indicate that you understand the fundamental principles.

Your understanding will be enhanced through a combination of efficient study habits, discussions with other students and with instructors, and your ability to solve the problems presented in the textbook. Ask questions whenever you think clarification of a concept is necessary.

Study Schedule

It is important for you to set up a regular study schedule, preferably a daily one. Make sure you read the syllabus for the course and adhere to the schedule set by your instructor. As a general rule, you should devote about two hours of study time for every one hour you are in class. If you are having trouble with the course, seek the advice of the instructor or other students who have taken the course. You may find it necessary to seek further instruction from experienced students. Very often, instructors offer review sessions in addition to regular class periods. It is important that you avoid the practice of delaying study until a day or two before an exam. One hour of study a day for 14 days is far more effective than 14 hours the day before the exam. "Cramming" usually produces disastrous results, especially in science. Rather than attempting an all-night study session immediately before an exam, briefly review the basic concepts and equations and get a good night's rest. If you think you need additional help in understanding the concepts, in preparing for exams, or in problem solving, we suggest you acquire a copy of the *Student Solutions Manual and Study Guide* that accompanies this textbook; this manual should be available at your college bookstore.

Visit the *College Physics* website at **www.CengageBrain.com** to see samples of select student supplements. Go to **CengageBrain.com** to purchase and access this product at Cengage Learning's preferred online store.

Use the Features

You should make full use of the various features of the text discussed in the preface. For example, marginal notes are useful for locating and describing important equations and concepts, and **boldfaced** type indicates important statements and definitions. Many useful tables are contained in the appendices, but most tables are incorporated in the text where they are most often referenced. Appendix A is a convenient review of mathematical techniques.

Answers to all Quick Quizzes and Example Questions, as well as odd-numbered multiple-choice questions, conceptual questions, and problems, are given at the end of the textbook. Answers to selected end-of-chapter problems are provided in the *Student Solutions Manual and Study Guide.* Problem-Solving Strategies included in selected chapters throughout the text give you additional information about how you should solve problems. The contents provide an overview of the entire text, and the index enables you to locate specific material quickly. Footnotes sometimes are used to supplement the text or to cite other references on the subject discussed.

After reading a chapter, you should be able to define any new quantities introduced in that chapter and to discuss the principles and assumptions used to arrive at certain key relations. The chapter summaries and the review sections of the *Student Solutions Manual and Study Guide* should help you in this regard. In some cases, it may be necessary for you to refer to the index of the text to locate certain topics. You should be able to correctly associate with each physical quantity the symbol used to represent that quantity and the unit in which the quantity is specified. Further, you should be able to express each important relation in a concise and accurate prose statement.

Problem Solving

R. P. Feynman, Nobel laureate in physics, once said, "You do not know anything until you have practiced." In keeping with this statement, we strongly advise that you develop the skills necessary to solve a wide range of problems. Your ability to solve problems will be one of the main tests of your knowledge of physics, so you should try to solve as many problems as possible. It is essential that you understand basic concepts and principles before attempting to solve problems. It is good practice to try to find alternate solutions to the same problem. For example, you can solve problems in mechanics using Newton's laws, but very often an alternate method that draws on energy considerations is more direct. You should not deceive yourself into thinking you understand a problem merely because you have seen it solved in class. You must be able to solve the problem and similar problems on your own. We have cast the examples in this book in a special, two-column format to help you in this regard. After studying an example, see if you can cover up the right-hand side and do it yourself, using only the written descriptions on the left as hints. Once you succeed at that, try solving the example using only the strategy statement as a guide. Finally, try to solve the problem completely on your own. At this point you are ready to answer the associated question and solve the exercise. Once you have accomplished all these steps, you will have a good mastery of the problem, its concepts, and mathematical technique. After studying all the Example Problems in this way, you are ready to tackle the problems at the end of the chapter. Of those, the guided problems provide another aid to learning how to solve some of the more complex problems.

The approach to solving problems should be carefully planned. A systematic plan is especially important when a problem involves several concepts. First, read the problem several times until you are confident you understand what is being asked. Look for any key words that will help you interpret the problem and perhaps allow you to make certain assumptions. Your ability to interpret a question properly is an integral part of problem solving. Second, you should acquire the habit of writing down the information given in a problem and those quantities that need to be found; for example, you might construct a table listing both the quantities given and the quantities to be found. This procedure is sometimes used in the worked examples of the textbook. After you have decided on the method you think is appropriate for a given problem, proceed with your solution. Finally, check your results to see if they are reasonable and consistent with your initial understanding of the problem. General problem-solving strategies of this type are included in the text and are highlighted with a surrounding box. If you follow the steps of this procedure, you will find it easier to come up with a solution and will also gain more from your efforts.

Often, students fail to recognize the limitations of certain equations or physical laws in a particular situation. It is very important that you understand and remember the assumptions underlying a particular theory or formalism. For example, certain equations in kinematics apply only to a particle moving with constant acceleration. These equations are not valid for describing motion whose acceleration is not constant, such as the motion of an object connected to a spring or the motion of an object through a fluid.

Experiments

Because physics is a science based on experimental observations, we recommend that you supplement the text by performing various types of "hands-on" experiments, either at home or in the laboratory. For example, the common Slinky™ toy is excellent for studying traveling waves, a ball swinging on the end of a long string can be used to investigate pendulum motion, various masses attached to the end of a vertical spring or rubber band can be used to determine their elastic nature, an old pair of Polaroid sunglasses and some discarded lenses and a magnifying glass are the components of various experiments in optics, and the approximate measure of the free-fall acceleration can be determined simply by measuring with a stopwatch the time it takes for a ball to drop from a known height. The list of such experiments is endless. When physical models are not available, be imaginative and try to develop models of your own.

New Media

If available, we strongly encourage you to use the **Enhanced WebAssign** product that is available with this textbook. It is far easier to understand physics if you see it in action, and the materials available in Enhanced WebAssign will enable you to become a part of that action. Enhanced WebAssign is described in the Preface.

An Invitation to Physics

It is our hope that you too will find physics an exciting and enjoyable experience and that you will profit from this experience, regardless of your chosen profession. Welcome to the exciting world of physics!

To see the World in a Grain of Sand
And a Heaven in a Wild Flower,
Hold infinity in the palm of your hand
And Eternity in an hour.

William Blake, "Auguries of Innocence"

Welcome to Your MCAT Test Preparation Guide

The MCAT Test Preparation Guide makes your copy of *College Physics*, tenth edition, the most comprehensive MCAT study tool and classroom resource in introductory physics. Starting with the Spring 2015 test, the MCAT will be thoroughly revised (see **www.aamc.org/students/applying/mcat/mcat2015** for more details). The new test section that will include problems related to physics is *Chemical and Physical Foundations of Biological Systems*. Of the ~65 test questions in this section, approximately 25% will relate to introductory physics topics from the six content categories shown below:

Content Category 4A: Translational motion, forces, work, energy, and equilibrium in living systems

Review Plan

Motion

- **Chapter 1, Sections 1.1, 1.3, and 1.5**
  Examples 1.1–1.2 and 1.4–1.5
  Chapter problems 1–6 and 15–27
- **Chapter 2, Sections 2.2 and 2.3**
  Quick Quizzes 2.1–2.3
  Examples 2.1–2.3
  Chapter problems 1–25
- **Chapter 3, Sections 3.1 and 3.2**
  Quick Quizzes 3.1–3.3
  Examples 3.1–3.3
  Chapter problems 1–21

Equilibrium

- **Chapter 4, Sections 4.1–4.5**
  Quick Quizzes 4.1–4.6
  Examples 4.1–4.11
  Chapter problems 1–38
- **Chapter 8, Sections 8.1–8.5**
  Quick Quizzes 8.1–8.3
  Examples 8.1–8.11
  Chapter problems 1–41

Work

- **Chapter 5, Sections 5.1 and 5.2**
  Quick Quiz 5.1
  Examples 5.1–5.3
  Chapter problems 1–18
- **Chapter 12, Section 12.1**
  Quick Quiz 12.1
  Examples 12.1–12.2
  Chapter problems 1–10

Energy

- **Chapter 5, Sections 5.2–5.6**
  Quick Quizzes 5.2–5.4
  Examples 5.3–5.14
  Chapter problems 9–58

Content Category 4B: Importance of fluids for the circulation of blood, gas movement, and gas exchange

Review Plan

Fluids

- **Chapter 9, Sections 9.2, 9.4–9.7, and 9.9**
  Quick Quizzes 9.1–9.7
  Examples 9.1, 9.5–9.14, and 9.16–9.19
  Chapter problems 1–7 and 20–72

Gas phase

- **Chapter 9, Section 9.5**
  Quick Quizzes 9.3–9.4
  Chapter problems 20–28
- **Chapter 10, Sections 10.2, 10.4, and 10.5**
  Quick Quiz 10.6
  Examples 10.1–10.2 and 10.6–10.10
  Chapter problems 1–10 and 29–46

Content Category 4C: Electrochemistry and electrical circuits and their elements.

Review Plan

Electrostatics

- **Chapter 15, Sections 15.1–15.2 and 15.4**
  Quick Quizzes 15.1 and 15.3–15.5
  Examples 15.4 and 15.5
  Chapter problems 17–29
- **Chapter 16, Sections 16.1–16.3**
  Quick Quizzes 16.1–16.7
  Examples 16.1–16.5
  Chapter problems 1–24

Circuit elements

- **Chapter 15, Sections 15.1 and 15.6**
  Chapter problems 30–35
- **Chapter 16, Sections 16.7–16.10**
  Quick Quizzes 16.8–16.11
  Examples 16.6–16.12
  Chapter problems 25–53
- **Chapter 17, Sections 17.1 and 17.3–17.5**
  Quick Quizzes 17.1 and 17.3–17.6
  Examples 17.1 and 17.3–17.4
  Chapter problems 1–32
- **Chapter 18, Sections 18.1–18.3**
  Quick Quizzes 18.1–18.8
  Examples 18.1–18.3
  Chapter problems 1–15

Content Category 4D: How light and sound interact with matter

Review Plan

Sound

- **Chapter 13, Sections 13.6 and 13.8**
  Examples 13.8–13.9
  Chapter problems 41–49
- **Chapter 14, Sections 14.1–14.4, 14.6, 14.9–14.10, and 14.12**
  Quick Quizzes 14.1–14.3 and 14.5–14.6
  Examples 14.1–14.2, 14.4–14.5, and 14.9–14.10
  Chapter problems 1–32, 48–54

Light, electromagnetic radiation

- **Chapter 21, Sections 21.11–21.12**
  Quick Quizzes 21.7 and 21.8
  Examples 21.8 and 21.9
  Chapter problems 49–63
- **Chapter 22, Sections 22.1 and 22.4**
  Example 22.5
  Chapter problems 1–7 and 28–33
- **Chapter 24, Sections 24.1–24.2, 24.4, 24.6–24.9**
  Quick Quizzes 24.1–24.6
  Examples 24.1–24.4 and 24.6–24.8
  Chapter problems 1–61
- **Chapter 27, Section 27.3**
  Chapter problems 15–17

Geometrical optics

- **Chapter 22, Sections 22.2–22.4 and 22.7**
  Quick Quizzes 22.2–22.4
  Examples 22.1–22.6
  Chapter problems 8–44
- **Chapter 23, Sections 23.1–23.4 and 23.6–23.7**
  Quick Quizzes 23.1–23.6
  Examples 23.1–23.10
  Chapter problems 1–46
- **Chapter 25, Sections 25.1–25.6**
  Quick Quizzes 25.1–25.2
  Examples 25.1–25.8
  Chapter problems 1–46

Content Category 4E: Atoms, nuclear decay, electronic structure, and atomic chemical behavior

Review Plan

Atomic nucleus

- **Chapter 19, Section 19.6**
  Quick Quiz 19.4
  Examples 19.5 and 19.6
  Chapter problems 33–42
- **Chapter 29, Sections 29.1–29.4**
  Quick Quizzes 29.1–29.3
  Examples 29.1–29.5
  Chapter problems 1–31

Electronic structure

- **Chapter 19, Section 19.10**
- **Chapter 27, Sections 27.2 and 27.8**
  Examples 27.1 and 27.5
  Chapter problems 9–14 and 33–38
- **Chapter 28, Sections 28.2–28.3, 28.5, and 28.7**
  Quick Quizzes 28.1 and 28.3
  Examples 28.1 and 28.2
  Chapter problems 1–26 and 30–33

Content Category 5E: Principles of chemical thermodynamics and kinetics

Review Plan

Energy changes in chemical reactions

- **Chapter 10, Sections 10.1 and 10.3**
  Quick Quizzes 10.1–10.5
  Examples 10.3–10.5
  Chapter problems 11–28
- **Chapter 11, Sections 11.1–11.5**
  Quick Quizzes 11.1–11.5
  Examples 11.1–11.11
  Chapter problems 1–50
- **Chapter 12, Sections 12.2 and 12.4–12.5**
  Quick Quizzes 12.3–12.5
  Examples 12.3, 12.10–12.12, and 12.14–12.16
  Chapter problems 11–54

John Van Hasselt/Sygma/Corbis

In the eighteenth century, navigators of ocean-going ships could obtain their latitude by observations of the north star, but there was no reliable way of determining longitude. The H1 clock was invented by John Harrison in 1736 in an attempt to address that need. His clock had to remain highly accurate for months at sea while withstanding constant motion, dampness, and changes of temperature. To determine longitude, navigators had only to compare local noon, when the sun was highest in the sky, with the time on the clock, which was Greenwich time. The difference in the number of hours then revealed their longitude.

Introduction 1

The goal of physics is to provide an understanding of the physical world by developing theories based on experiments. A physical theory, usually expressed mathematically, describes how a given physical system works. The theory makes certain predictions about the physical system which can then be checked by observations and experiments. If the predictions turn out to correspond closely to what is actually observed, then the theory stands, although it remains provisional. No theory to date has given a complete description of all physical phenomena, even within a given subdiscipline of physics. Every theory is a work in progress.

The basic laws of physics involve such physical quantities as force, velocity, volume, and acceleration, all of which can be described in terms of more fundamental quantities. In mechanics, it is conventional to use the quantities of **length** (L), **mass** (M), and **time** (T); all other physical quantities can be constructed from these three.

1.1 Standards of Length, Mass, and Time

Learning Objectives

1. State and use the SI units for length, mass, and time.
2. Give examples of the approximate magnitudes of common measurements.

To communicate the result of a measurement of a certain physical quantity, a *unit* for the quantity must be defined. If our fundamental unit of length is defined to be 1.0 meter, for example, and someone familiar with our system of measurement reports that a wall is 2.0 meters high, we know that the height of the wall is twice the fundamental unit of length. Likewise, if our fundamental unit of mass is defined as 1.0 kilogram and we are told that a person has a mass of 75 kilograms, then that person has a mass 75 times as great as the fundamental unit of mass.

In 1960 an international committee agreed on a standard system of units for the fundamental quantities of science, called **SI** (Système International). Its units of length, mass, and time are the meter, kilogram, and second, respectively.

Length

In 1799 the legal standard of length in France became the meter, defined as one ten-millionth of the distance from the equator to the North Pole. Until 1960, the official length of the meter was the distance between two lines on a specific bar of platinum-iridium alloy stored under controlled conditions. This standard was abandoned for several reasons, the principal one being that measurements of the separation between the lines were not precise enough. In 1960 the meter was defined as 1 650 763.73 wavelengths of orange-red light emitted from a krypton-86 lamp. In October 1983 this definition was abandoned also, and **the meter was redefined as the distance traveled by light in vacuum during a time interval of 1/299 792 458 second**. This latest definition establishes the speed of light at 299 792 458 meters per second.

Definition of the meter ▶

Mass

Definition of the kilogram ▶

The SI unit of mass, the kilogram, is defined as the mass of a specific platinum–iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sèvres, France (similar to that shown in Fig. 1.1a). As we'll see in Chapter 4, mass is a quantity used to measure the resistance to a change in the motion of an object. It's more difficult to cause a change in the motion of an object with a large mass than an object with a small mass.

tip 1.1 No Commas in Numbers with Many Digits

In science, numbers with more than three digits are written in groups of three digits separated by spaces rather than commas; so that 10 000 is the same as the common American notation 10,000. Similarly, $\pi = 3.14159265$ is written as 3.141 592 65.

Time

Before 1960, the time standard was defined in terms of the average length of a solar day in the year 1900. (A solar day is the time between successive appearances of the Sun at the highest point it reaches in the sky each day.) The basic unit of

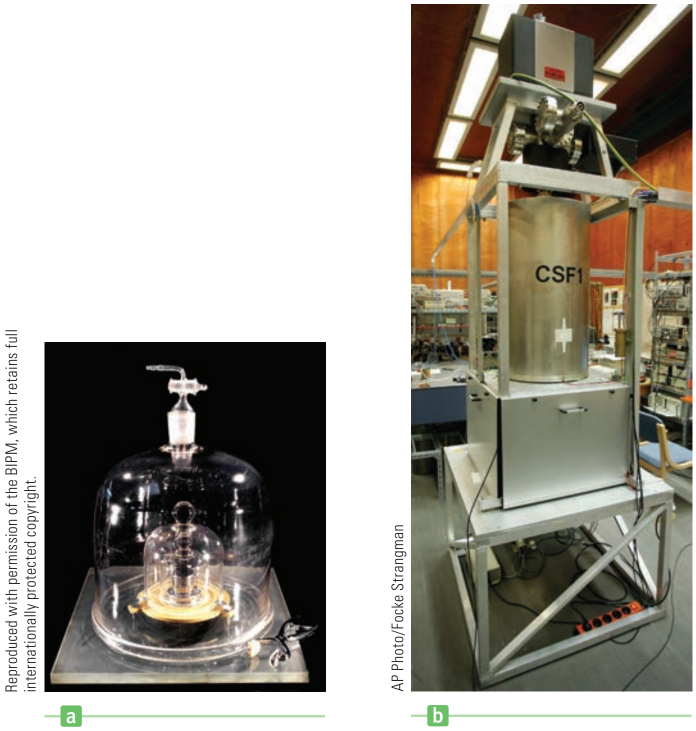

Figure 1.1 (a) International Prototype of the Kilogram, an accurate copy of the International Standard Kilogram kept at Sèvres, France, is housed under a double bell jar in a vault at the National Institute of Standards and Technology. (b) A cesium fountain atomic clock. The clock will neither gain nor lose a second in 20 million years.

table 1.1 Approximate Values of Some Measured Lengths

	Length (m)
Distance from Earth to most remote known quasar	1×10^{26}
Distance from Earth to most remote known normal galaxies	4×10^{25}
Distance from Earth to nearest large galaxy (M31, the Andromeda galaxy)	2×10^{22}
Distance from Earth to nearest star (Proxima Centauri)	4×10^{16}
One light year	9×10^{15}
Mean orbit radius of Earth about Sun	2×10^{11}
Mean distance from Earth to Moon	4×10^{8}
Mean radius of Earth	6×10^{6}
Typical altitude of satellite orbiting Earth	2×10^{5}
Length of football field	9×10^{1}
Length of housefly	5×10^{-3}
Size of smallest dust particles	1×10^{-4}
Size of cells in most living organisms	1×10^{-5}
Diameter of hydrogen atom	1×10^{-10}
Diameter of atomic nucleus	1×10^{-14}
Diameter of proton	1×10^{-15}

time, the second, was defined to be (1/60)(1/60)(1/24) = 1/86 400 of the average solar day. In 1967 the second was redefined to take advantage of the high precision attainable with an atomic clock, which uses the characteristic frequency of the light emitted from the cesium-133 atom as its "reference clock." **The second is now defined as 9 192 631 700 times the period of oscillation of radiation from the cesium atom.** The newest type of cesium atomic clock is shown in Figure 1.1b.

◀ Definition of the second

Approximate Values for Length, Mass, and Time Intervals

Approximate values of some lengths, masses, and time intervals are presented in Tables 1.1, 1.2, and 1.3, respectively. Note the wide ranges of values. Study these tables to get a feel for a kilogram of mass (this book has a mass of about 2 kilograms), a time interval of 10^{10} seconds (one century is about 3×10^{9} seconds), or 2 meters of length (the approximate height of a forward on a basketball team). Appendix A reviews the notation for powers of 10, such as the expression of the number 50 000 in the form 5×10^{4}.

Systems of units commonly used in physics are the Système International, in which the units of length, mass, and time are the meter (m), kilogram (kg), and second (s); the cgs, or Gaussian, system, in which the units of length, mass, and time

table 1.2 Approximate Values of Some Masses

	Mass (kg)
Observable Universe	1×10^{52}
Milky Way galaxy	7×10^{41}
Sun	2×10^{30}
Earth	6×10^{24}
Moon	7×10^{22}
Shark	1×10^{2}
Human	7×10^{1}
Frog	1×10^{-1}
Mosquito	1×10^{-5}
Bacterium	1×10^{-15}
Hydrogen atom	2×10^{-27}
Electron	9×10^{-31}

table 1.3 Approximate Values of Some Time Intervals

	Time Interval (s)
Age of Universe	5×10^{17}
Age of Earth	1×10^{17}
Average age of college student	6×10^{8}
One year	3×10^{7}
One day	9×10^{4}
Time between normal heartbeats	8×10^{-1}
Period[a] of audible sound waves	1×10^{-3}
Period[a] of typical radio waves	1×10^{-6}
Period[a] of vibration of atom in solid	1×10^{-13}
Period[a] of visible light waves	2×10^{-15}
Duration of nuclear collision	1×10^{-22}
Time required for light to travel across a proton	3×10^{-24}

[a]A *period* is defined as the time required for one complete vibration.

table 1.4 Some Prefixes for Powers of Ten Used with "Metric" (SI and cgs) Units

Power	Prefix	Abbreviation
10^{-18}	atto-	a
10^{-15}	femto-	f
10^{-12}	pico-	p
10^{-9}	nano-	n
10^{-6}	micro-	μ
10^{-3}	milli-	m
10^{-2}	centi-	c
10^{-1}	deci-	d
10^{1}	deka-	da
10^{3}	kilo-	k
10^{6}	mega-	M
10^{9}	giga-	G
10^{12}	tera-	T
10^{15}	peta-	P
10^{18}	exa-	E

are the centimeter (cm), gram (g), and second; and the U.S. customary system, in which the units of length, mass, and time are the foot (ft), slug, and second. SI units are almost universally accepted in science and industry, and will be used throughout the book. Limited use will be made of Gaussian and U.S. customary units.

Some of the most frequently used "metric" (SI and cgs) prefixes representing powers of 10 and their abbreviations are listed in Table 1.4. For example, 10^{-3} m is equivalent to 1 millimeter (mm), and 10^3 m is 1 kilometer (km). Likewise, 1 kg is equal to 10^3 g, and 1 megavolt (MV) is 10^6 volts (V). It's a good idea to memorize the more common prefixes early on: femto- to centi-, and kilo- to giga- are used routinely by most physicists.

1.2 The Building Blocks of Matter

Learning Objectives

1. State the fundamental components of matter.
2. Describe qualitatively the levels of structure of matter.

A 1-kg ($\approx$ 2-lb) cube of solid gold has a length of about 3.73 cm ($\approx$ 1.5 in.) on a side. If the cube is cut in half, the two resulting pieces retain their chemical identity. But what happens if the pieces of the cube are cut again and again, indefinitely? The Greek philosophers Leucippus and Democritus couldn't accept the idea that such cutting could go on forever. They speculated that the process ultimately would end when it produced a particle that could no longer be cut. In Greek, *atomos* means "not sliceable." From this term comes our English word *atom*, once believed to be the smallest particle of matter but since found to be a composite of more elementary particles.

The atom can be naively visualized as a miniature solar system, with a dense, positively charged nucleus occupying the position of the Sun and negatively charged electrons orbiting like planets. This model of the atom, first developed by the great Danish physicist Niels Bohr nearly a century ago, led to the understanding of certain properties of the simpler atoms such as hydrogen but failed to explain many fine details of atomic structure.

Notice the size of a hydrogen atom, listed in Table 1.1, and the size of a proton—the nucleus of a hydrogen atom—one hundred thousand times smaller. If the proton were the size of a ping-pong ball, the electron would be a tiny speck about the size of a bacterium, orbiting the proton a kilometer away! Other atoms are similarly constructed. So there is a surprising amount of empty space in ordinary matter.

After the discovery of the nucleus in the early 1900s, questions arose concerning its structure. Although the structure of the nucleus remains an area of active research even today, by the early 1930s scientists determined that two basic entities—protons and neutrons—occupy the nucleus. The *proton* is nature's most common carrier of positive charge, equal in magnitude but opposite in sign to the charge on the electron. The number of protons in a nucleus determines what the element is. For instance, a nucleus containing only one proton is the nucleus of an atom of hydrogen, regardless of how many neutrons may be present. Extra neutrons correspond to different isotopes of hydrogen—deuterium and tritium—which react chemically in exactly the same way as hydrogen, but are more massive. An atom having two protons in its nucleus, similarly, is always helium, although again, differing numbers of neutrons are possible.

The existence of *neutrons* was verified conclusively in 1932. A neutron has no charge and has a mass about equal to that of a proton. Except for hydrogen, all atomic nuclei contain neutrons, which, together with the protons, interact through the strong nuclear force. That force opposes the strongly repulsive electrical force of the protons, which otherwise would cause the nucleus to disintegrate.

The division doesn't stop here; strong evidence collected over many years indicates that protons, neutrons, and a zoo of other exotic particles are composed of six particles called **quarks** (rhymes with "sharks" though some rhyme it with "forks"). These particles have been given the names *up, down, strange, charm, bottom*, and *top*. The up, charm, and top quarks each carry a charge equal to $+\frac{2}{3}$ that of the proton, whereas the down, strange, and bottom quarks each carry a charge equal to $-\frac{1}{3}$ the proton charge. The proton consists of two up quarks and one down quark (see Fig. 1.2), giving the correct charge for the proton, +1. The neutron is composed of two down quarks and one up quark and has a net charge of zero.

The up and down quarks are sufficient to describe all normal matter, so the existence of the other four quarks, indirectly observed in high-energy experiments, is something of a mystery. Despite strong indirect evidence, no isolated quark has ever been observed. Consequently, the possible existence of yet more fundamental particles remains purely speculative.

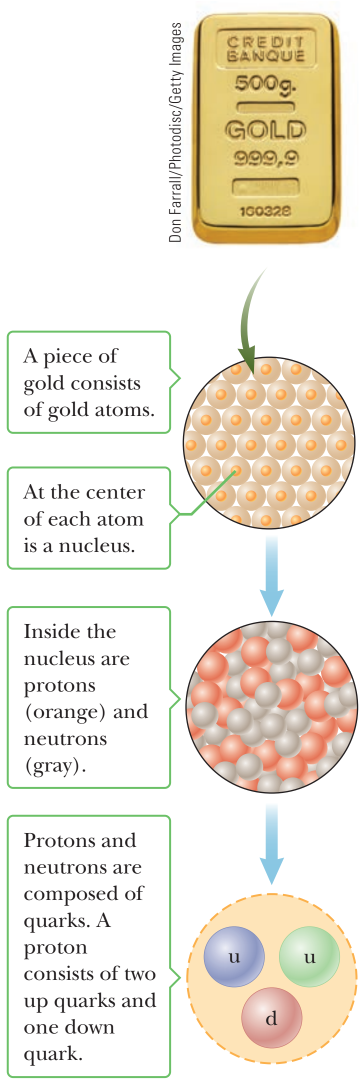

Figure 1.2 Levels of organization in matter.

1.3 Dimensional Analysis

Learning Objectives

1. State the definition of a dimension and give examples of the dimensions of some basic physical quantities.
2. Use dimensions to check equations for consistency.
3. Use dimensions to derive relationships between physical quantities.

In physics the word *dimension* denotes the physical nature of a quantity. The distance between two points, for example, can be measured in feet, meters, or furlongs, which are different ways of expressing the dimension of *length*.

The symbols used in this section to specify the dimensions of length, mass, and time are L, M, and T, respectively. Brackets [ ] will often be used to denote the dimensions of a physical quantity. In this notation, for example, the dimensions of velocity v are written $[v] = \mathrm{L/T}$, and the dimensions of area A are $[A] = \mathrm{L}^2$. The dimensions of area, volume, velocity, and acceleration are listed in Table 1.5, along with their units in the three common systems. The dimensions of other quantities, such as force and energy, will be described later as they are introduced.

In physics it's often necessary to deal with mathematical expressions that relate different physical quantities. One way to analyze such expressions, called **dimensional analysis,** makes use of the fact that **dimensions can be treated as algebraic quantities.** Adding masses to lengths, for example, makes no sense, so it follows that quantities can be added or subtracted only if they have the same dimensions. If the terms on the opposite sides of an equation have the same dimensions, then that equation may be correct, although correctness can't be guaranteed on the basis of dimensions alone. Nonetheless, dimensional analysis has value as a partial check of an equation and can also be used to develop insight into the relationships between physical quantities.

The procedure can be illustrated by developing some relationships between acceleration, velocity, time, and distance. Distance x has the dimension of length: $[x] = \mathrm{L}$. Time t has dimension $[t] = \mathrm{T}$. Velocity v has the dimensions length over

table 1.5 Dimensions and Some Units of Area, Volume, Velocity, and Acceleration

System	Area (L^2)	Volume (L^3)	Velocity (L/T)	Acceleration ($\mathrm{L/T}^2$)
SI	m^2	m^3	m/s	$\mathrm{m/s}^2$
cgs	cm^2	cm^3	cm/s	$\mathrm{cm/s}^2$
U.S. customary	ft^2	ft^3	ft/s	$\mathrm{ft/s}^2$

time: $[v] = L/T$, and acceleration the dimensions length divided by time squared: $[a] = L/T^2$. Notice that velocity and acceleration have similar dimensions, except for an extra dimension of time in the denominator of acceleration. It follows that

$$[v] = \frac{L}{T} = \frac{L}{T^2}T = [a][t]$$

From this it might be guessed that velocity equals acceleration multiplied by time, $v = at$, and that is true for the special case of motion with constant acceleration starting at rest. Noticing that velocity has dimensions of length divided by time and distance has dimensions of length, it's reasonable to guess that

$$[x] = L = L\frac{T}{T} = \frac{L}{T}T = [v][t] = [a][t]^2$$

Here it appears that $x = at^2$ might correctly relate the distance traveled to acceleration and time; however, that equation is not even correct in the case of constant acceleration starting from rest. The correct expression in that case is $x = \frac{1}{2}at^2$. These examples serve to show the inherent limitations in using dimensional analysis to discover relationships between physical quantities. Nonetheless, such simple procedures can still be of value in developing a preliminary mathematical model for a given physical system. Further, because it's easy to make errors when solving problems, dimensional analysis can be used to check the consistency of the results. When the dimensions in an equation are not consistent, it indicates an error has been made in a prior step.

EXAMPLE 1.1 Analysis of an Equation

GOAL Check an equation using dimensional analysis.

PROBLEM Show that the expression $v = v_0 + at$ is dimensionally correct, where v and v_0 represent velocities, a is acceleration, and t is a time interval.

STRATEGY Analyze each term, finding its dimensions, and then check to see if all the terms agree with each other.

SOLUTION

Find dimensions for v and v_0.

$$[v] = [v_0] = \frac{L}{T}$$

Find the dimensions of at.

$$[at] = [a][t] = \frac{L}{T^2}(T) = \frac{L}{T}$$

REMARKS All the terms agree, so the equation is dimensionally correct.

QUESTION 1.1 True or False. An equation that is dimensionally correct is always physically correct, up to a constant of proportionality.

EXERCISE 1.1 Determine whether the equation $x = vt^2$ is dimensionally correct. If not, provide a correct expression, up to an overall constant of proportionality.

ANSWER Incorrect. The expression $x = vt$ is dimensionally correct.

EXAMPLE 1.2 Find an Equation

GOAL Derive an equation by using dimensional analysis.

PROBLEM Find a relationship between an acceleration of constant magnitude a, speed v, and distance r from the origin for a particle traveling in a circle.

STRATEGY Start with the term having the most dimensionality, a. Find its dimensions, and then rewrite those dimensions in terms of the dimensions of v and r. The dimensions of time will have to be eliminated with v, because that's the only quantity (other than a, itself) in which the dimension of time appears.

SOLUTION

Write down the dimensions of a: $[a] = \frac{\text{L}}{\text{T}^2}$

Solve the dimensions of speed for T: $[v] = \frac{\text{L}}{\text{T}} \quad \rightarrow \quad \text{T} = \frac{L}{[v]}$

Substitute the expression for T into the equation for $[a]$: $[a] = \frac{\text{L}}{\text{T}^2} = \frac{\text{L}}{(\text{L}/[v])^2} = \frac{[v]^2}{\text{L}}$

Substitute $\text{L} = [r]$, and guess at the equation: $[a] = \frac{[v]^2}{[r]} \quad \rightarrow \quad a = \frac{v^2}{r}$

REMARKS This is the correct equation for the magnitude of the centripetal acceleration—acceleration toward the center of motion—to be discussed in Chapter 7. In this case it isn't necessary to introduce a numerical factor. Such a factor is often displayed explicitly as a constant k in front of the right-hand side; for example, $a = kv^2/r$. As it turns out, $k = 1$ gives the correct expression. A good technique sometimes introduced in calculus-based textbooks involves using unknown powers of the dimensions. This problem would then be set up as $[a] = [v]^b[r]^c$. Writing out the dimensions and equating powers of each dimension on both sides of the equation would result in $b = 2$ and $c = -1$.

QUESTION 1.2 True or False: Replacing v by r/t in the final answer also gives a dimensionally correct equation.

EXERCISE 1.2 In physics, energy E carries dimensions of mass times length squared divided by time squared. Use dimensional analysis to derive a relationship for energy in terms of mass m and speed v, up to a constant of proportionality. Set the speed equal to c, the speed of light, and the constant of proportionality equal to 1 to get the most famous equation in physics. (Note, however, that the first relationship is associated with energy of motion, and the second with energy of mass. See Chapter 26.)

ANSWER $E = kmv^2 \quad \rightarrow \quad E = mc^2$ when $k = 1$ and $v = c$.

1.4 Uncertainty in Measurement and Significant Figures

Learning Objectives

1. Identify the number of significant figures in a given physical measurement.
2. Apply significant figures to estimate the proper accuracy of a combination of physical measurements.

Physics is a science in which mathematical laws are tested by experiment. No physical quantity can be determined with complete accuracy because our senses are physically limited, even when extended with microscopes, cyclotrons, and other instruments. Consequently, it's important to develop methods of determining the accuracy of measurements.

All measurements have uncertainties associated with them, whether or not they are explicitly stated. The accuracy of a measurement depends on the sensitivity of the apparatus, the skill of the person carrying out the measurement, and the number of times the measurement is repeated. Once the measurements, along with their uncertainties, are known, it's often the case that calculations must be carried out using those measurements. Suppose two such measurements are multiplied. When a calculator is used to obtain this product, there may be eight digits in the calculator window, but often only two or three of those numbers have any significance. The rest have no value because they imply greater accuracy than was actually achieved in the original measurements. In experimental work, determining how many numbers to retain requires the application of statistics and the mathematical propagation of uncertainties. In a textbook it isn't practical to apply those sophisticated tools in the numerous calculations, so instead a simple method, called ***significant figures,*** is used to indicate the approximate number of digits that should be retained at the end of a calculation. Although that method is not mathematically rigorous, it's easy to apply and works fairly well.

Suppose that in a laboratory experiment we measure the area of a rectangular plate with a meter stick. Let's assume that the accuracy to which we can measure a particular dimension of the plate is ± 0.1 cm. If the length of the plate is measured to be 16.3 cm, we can only claim that it lies somewhere between 16.2 cm and 16.4 cm. In this case, we say the measured value has three significant figures. Likewise, if the plate's width is measured to be 4.5 cm, the actual value lies between 4.4 cm and 4.6 cm. This measured value has only two significant figures. We could write the measured values as 16.3 ± 0.1 cm and 4.5 ± 0.1 cm. In general, **a significant figure is a reliably known digit** (other than a zero used to locate a decimal point). Note that in each case, the final number has some uncertainty associated with it, and is therefore not 100% reliable. Despite the uncertainty, that number is retained and considered significant because it does convey some information.

Suppose we would like to find the area of the plate by multiplying the two measured values together. The final value can range between $(16.3 - 0.1 \text{ cm})(4.5 - 0.1 \text{ cm}) = (16.2 \text{ cm})(4.4 \text{ cm}) = 71.28 \text{ cm}^2$ and $(16.3 + 0.1 \text{ cm})(4.5 + 0.1 \text{ cm}) = (16.4 \text{ cm})(4.6 \text{ cm}) = 75.44 \text{ cm}^2$. Claiming to know anything about the hundredths place, or even the tenths place, doesn't make any sense, because it's clear we can't even be certain of the units place, whether it's the 1 in 71, the 5 in 75, or somewhere in between. The tenths and the hundredths places are clearly not significant. We have *some* information about the units place, so that number is significant. Multiplying the numbers at the middle of the uncertainty ranges gives $(16.3 \text{ cm})(4.5 \text{ cm}) = 73.35 \text{ cm}^2$, which is also in the middle of the area's uncertainty range. Because the hundredths and tenths are not significant, we drop them and take the answer to be 73 cm^2, with an uncertainty of $\pm 2 \text{ cm}^2$. Note that the answer has two significant figures, the same number of figures as the least accurately known quantity being multiplied, the 4.5-cm width.

Calculations as carried out in the preceding paragraph can indicate the proper number of significant figures, but those calculations are time-consuming. Instead, two rules of thumb can be applied. The first, concerning multiplication and division, is as follows: **In multiplying (dividing) two or more quantities, the number of significant figures in the final product (quotient) is the same as the number of significant figures in the *least accurate* of the factors being combined, where *least accurate* means *having the lowest number of significant figures.***

To get the final number of significant figures, it's usually necessary to do some rounding. If the last digit dropped is less than 5, simply drop the digit. If the last digit dropped is greater than or equal to 5, raise the last retained digit by one.[1]

tip 1.2 Using Calculators

Calculators are designed by engineers to yield as many digits as the memory of the calculator chip permits, so be sure to round the final answer down to the correct number of significant figures.

Zeros may or may not be significant figures. Zeros used to position the decimal point in such numbers as 0.03 and 0.007 5 are not considered significant figures. Hence, 0.03 has one significant figure, and 0.007 5 has two.

When zeros are placed after other digits in a whole number, there is a possibility of misinterpretation. For example, suppose the mass of an object is given as 1 500 g. This value is ambiguous, because we don't know whether the last two zeros are being used to locate the decimal point or whether they represent significant figures in the measurement.

Using scientific notation to indicate the number of significant figures removes this ambiguity. In this case, we express the mass as 1.5×10^3 g if there are two significant figures in the measured value, 1.50×10^3 g if there are three significant figures, and 1.500×10^3 g if there are four. Likewise, 0.000 15 is expressed in scientific notation as 1.5×10^{-4} if it has two significant figures or as 1.50×10^{-4} if it has

[1]Some prefer to round to the nearest even digit when the last dropped digit is 5, which has the advantage of rounding 5 up half the time and down half the time. For example, 1.55 would round to 1.6, but 1.45 would round to 1.4. Because the final significant figure is only one representative of a range of values given by the uncertainty, this very slight refinement will not be used in this text.

three significant figures. The three zeros between the decimal point and the digit 1 in the number 0.000 15 are not counted as significant figures because they only locate the decimal point. Similarly, trailing zeros are not considered significant. However, any zeros written after a decimal point are considered significant. For example, 3.00, 30.0, and 300. have three significant figures, whereas 300 has only one. In this book, **most of the numerical examples and end-of-chapter problems will yield answers having two or three significant figures.**

For addition and subtraction, it's best to focus on the number of decimal places in the quantities involved rather than on the number of significant figures. **When numbers are added (subtracted), the number of decimal places in the result should equal the smallest number of decimal places of any term in the sum (difference).** For example, if we wish to compute 123 (zero decimal places) + 5.35 (two decimal places), the answer is 128 (zero decimal places) and not 128.35. If we compute the sum 1.000 1 (four decimal places) + 0.000 3 (four decimal places) = 1.000 4, the result has the correct number of decimal places, namely four. Observe that the rules for multiplying significant figures don't work here because the answer has five significant figures even though one of the terms in the sum, 0.000 3, has only one significant figure. Likewise, if we perform the subtraction $1.002 - 0.998 = 0.004$, the result has three decimal places because each term in the subtraction has three decimal places.

To show why this rule should hold, we return to the first example in which we added 123 and 5.35, and rewrite these numbers as 123.*xxx* and 5.35*x*. Digits written with an *x* are completely unknown and can be any digit from 0 to 9. Now we line up 123.*xxx* and 5.35*x* relative to the decimal point and perform the addition, using the rule that an unknown digit added to a known or unknown digit yields an unknown:

$$\begin{array}{r} 123.xxx \\ +\quad 5.35x \\ \hline 128.xxx \end{array}$$

The answer of 128.*xxx* means that we are justified only in keeping the number 128 because everything after the decimal point in the sum is actually unknown. The example shows that the controlling uncertainty is introduced into an addition or subtraction by the term with the smallest number of decimal places.

EXAMPLE 1.3 Carpet Calculations

GOAL Apply the rules for significant figures.

PROBLEM Several carpet installers make measurements for carpet installation in the different rooms of a restaurant, reporting their measurements with inconsistent accuracy, as compiled in Table 1.6. Compute the areas for **(a)** the banquet hall, **(b)** the meeting room, and **(c)** the dining room, taking into account significant figures. **(d)** What total area of carpet is required for these rooms?

Table 1.6 Dimensions of Rooms in Example 1.3

	Length (m)	Width (m)
Banquet hall	14.71	7.46
Meeting room	4.822	5.1
Dining room	13.8	9

STRATEGY For the multiplication problems in parts (a)–(c), count the significant figures in each number. The smaller result is the number of significant figures in the answer. Part (d) requires a sum, where the area with the least accurately known decimal place determines the overall number of significant figures in the answer.

SOLUTION

(a) Compute the area of the banquet hall.

Count significant figures:

$14.71 \text{ m} \rightarrow$ 4 significant figures

$7.46 \text{ m} \rightarrow$ 3 significant figures

To find the area, multiply the numbers keeping only three digits:

$$14.71 \text{ m} \times 7.46 \text{ m} = 109.74 \text{ m}^2 \rightarrow 1.10 \times 10^2 \text{ m}^2$$

(Continued)