GLOBAL EDITION

ELEVENTH EDITION

COLLEGE PHYSICS

SERWAY ◆ VUILLE

EDITION
11

College Physics

Global Edition

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Embry-Riddle Aeronautical University

WITH CONTRIBUTIONS FROM
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***College Physics*, 11e, Global Edition**
Raymond A. Serway, Chris Vuille

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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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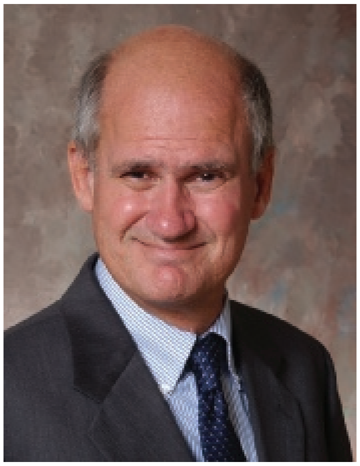
About the Authors

Raymond A. Serway received his doctorate at Illinois Institute of Technology and is Professor Emeritus at James Madison University. In 2011, he was awarded 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 the Rome Air Development Center from 1961 to 1963 and at the 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 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 at the University of Florida in 1989. While he has taught courses at all levels, including postgraduate, his primary interest and responsibility has been the teaching of introductory physics courses. He has received a number of awards for teaching excellence, including the Senior Class Appreciation Award (three times). He conducts research in general relativity, astrophysics, cosmology, 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 in *Analog Science Fiction/Science Fact* magazine. In addition to this textbook, he is the coauthor of *Essentials of College Physics*. Dr. Vuille enjoys playing tennis, swimming, yoga, playing classical piano, and writing science fiction; he is a former chess champion of St. Petersburg and Atlanta and the inventor of x-chess. His wife, Dianne Kowing, is Chief of Optometry at a local VA clinic. He has a daughter, Kira, and two sons, Christopher and James, all of whom love science.

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 tenth edition, analytics gathered from both professors and students, as well as reviewers' suggestions, we have refined the text to better meet the needs of students and teachers. In addition, the text's content is now available on the WebAssign online learning platform.

This textbook, which covers the standard topics in classical physics and twentieth-century physics, is divided into six parts. Part 1 (Topics 1–9) deals with Newtonian mechanics and the physics of fluids; Part 2 (Topics 10–12) is concerned with heat and thermodynamics; Part 3 (Topics 13 and 14) covers wave motion and sound; Part 4 (Topics 15–21) develops the concepts of electricity and magnetism; Part 5 (Topics 22–25) treats the properties of light and the field of geometric and wave optics; and Part 6 (Topics 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 their understanding of them 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. Finally, with the text available on the WebAssign learning platform, we provide a proven online homework solution that keeps students on track for success.

Changes to the Eleventh Edition

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 tenth edition, numerous changes and improvements have been made in preparing the eleventh edition. 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 tenth edition. The features listed here represent the major changes made for the eleventh edition.

Organization by Topics

Our preparatory research for this edition showed that successful students don't just *read* physics, they *engage with* physics. As we created a variety of media, just-in-time-help, and other material to support our activity-based pedagogy, it became clear we were building learning paths and designing assessments around specific *topics*, guided by the fundamental learning objectives of those topics. Consequently, we switched from "chapters" to "topics" to emphasize the textbook's new place as part of an active, fully-integrated learning experience.

Vector Rearrangement

The topic of vectors has been moved to Topic 1 with other preliminary material. This rearrangement allows students to get comfortable with vectors and how they are used in physics well before they're needed for solving problems.

Revision of Topic 4 (Newton's Law of Motion)

A revision to the discussion of Newton's laws of motion will ease students' entry into this difficult topic and increase their success. Here, the common contact forces are introduced early, including the normal force, the kinetic friction force, tension forces, and the static friction force. After finishing these new sections, students will already know how to calculate these forces in the most common contexts. Then, when encountering applications, they will suddenly find that many difficult, two-dimensional problems will reduce to one dimension, because the second dimension simply gives the normal and friction forces that they already understand.

The System Approach Extended to Rotating Systems

The most difficult problems in first-year physics are those involving both the second law of motion and the second law of motion for rotation. Following an insight by one of the authors (Vuille) while teaching an introductory class, it turns out that these problems, involving up to four equations and four unknowns, can often be easily solved with one equation and one unknown! Vuille has put this technique in Topic 8 (Rotational Equilibrium and Dynamics). Not found in any other first-year textbook, this technique greatly reduces the learning curve in that topic by turning the hardest problem type into one of the easiest.

New Conceptual Questions

One hundred and twenty-five of the conceptual questions in the text (25% of the total amount) are new to this edition; they have been developed to be more systematic and clicker-friendly.

New End-of-Topic Problems

Hundreds of new problems have been developed for this edition, taking into account statistics on problem usage by past users.

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 the following pedagogical features to enhance the textbook's usefulness to both students and instructors.

Examples Each example constitutes a complete learning experience, with a strategy statement, a side-by-side solution and commentary, conceptual training, and an exercise. 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 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. The Question at the end of the example usually requires 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. On the next page is an in-text worked example, with an explanation of each of the example's main parts.

Artwork Every piece of artwork in the eleventh edition is in a modern style that helps express the physics principles at work in a clear and 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.

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:

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

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

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?

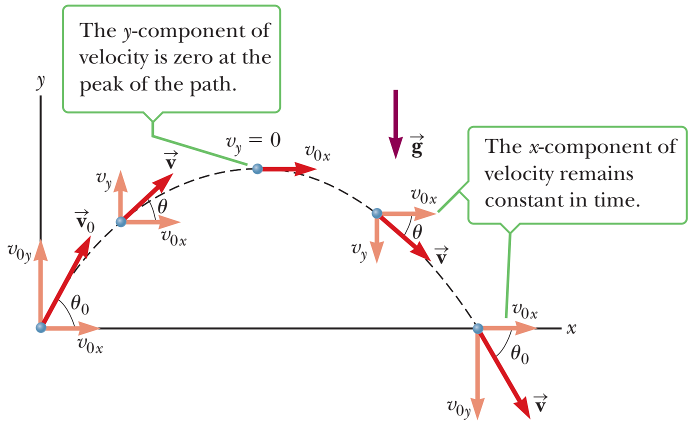
ANSWER 2.04 s

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-topic problems less intimidating.

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 at the bottom of this page.



The y-component of velocity is zero at the peak of the path.

The x-component of velocity remains constant in time.

Figure 3.5
The parabolic trajectory of a particle that leaves the origin with a velocity of $\vec{v}_0$. Note that $\vec{v}$ 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.

Conceptual Questions At the end of each topic are approximately fifteen 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 topic. 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 even-numbered 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 topic (in all, more than 2,100 problems are provided in the eleventh 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 topic. 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**.

There are several other types of problems we think instructors and students will find interesting as they work through the text; these are indicated in the problems set by the following icons:

- BIO **Biomedical problems** deal with applications to the life sciences and medicine.
- 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 $\mu_k = 0.436$. 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 topic, 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:

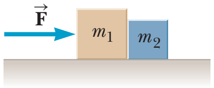


Figure P4.62

> **62.** 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 P4.62. (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?

Quick Quizzes All the Quick Quizzes (see example on the next page) 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 Topic 1. This strategy provides students with a structured process for solving problems. In most topics, 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-topic 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. A list of these applications can be found on pages xxi-xxii.

MCAT Test Preparation Guide Located on pages xxiii and xxiv, this guide outlines the six content categories related to physics on the new MCAT exam that began being administered 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 topic and other scientific disciplines. These examples also serve as models for students when they are assigned the task of responding to the Conceptual Questions presented at the end of each topic. For examples of Applying Physics boxes, see Applying Physics 9.5 (Home Plumbing) on page 292 and Applying Physics 13.1 (Bungee Jumping) on page 433.

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 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 appears on pages xxi and xxii.

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 topics begin with a brief preview that includes a discussion of the topic'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 topics 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 to facilitate location.

Illustrations and Tables The readability and effectiveness of the text material, worked examples, and end-of-topic 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-topic Summary is organized by individual section heading for ease of reference. Most topic summaries also feature key figures from the topic.

Significant Figures Significant figures in both worked examples and end-of-topic 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 topic each week for a class that meets three hours per week. Those sections, examples, and end-of-topic 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 Topic 8 (Rotational Equilibrium and Rotational Dynamics), Topic 21 (Alternating-Current Circuits and Electromagnetic Waves), and Topic 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.

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To register or access your online learning solution or purchase materials for your course, visit **www.cengagebrain.com**.

Lecture Presentation Resources

Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to author, edit, and manage test bank content from multiple Cengage Learning solutions, create multiple test versions in an instant, and deliver tests from your LMS, your classroom, or wherever you want.

Instructor Resource Website for Serway/Vuille *College Physics, Eleventh Edition*

The Instructor Resource Website contains a variety of resources to aid you in preparing and presenting text material in a manner that meets your personal preferences and course needs. The posted *Instructor's Solutions Manual* presents complete worked solutions for all end-of-chapter problems and even-numbered conceptual questions, answers for all even-numbered problems, and full answers with explanations for the Quick Quizzes. Robust PowerPoint lecture outlines that have been designed for an active classroom are available, with reading check questions and Think-Pair-Share questions as well as the traditional section-by-section outline. Images from the textbook can be used to customize your own presentations. Available online via **www.cengage.com/login**.

WebAssign *WebAssign by Cengage* is the most widely used online homework system in higher education. Available for this global edition, WebAssign allows you to assign, collect, grade, and record assignments via the web. This proven homework system includes links to textbook sections, an eBook, video examples, and problem-specific tutorials. WebAssign by Cengage is more than a homework system—it is a complete online learning system for students. Please contact your Cengage representative for details and a demonstration.

Student Resources

To register or access your online learning solution or purchase materials for your course, visit **www.cengagebrain.com**.

***Physics Laboratory Manual*, Fourth Edition** by David Loyd (Angelo State University). Ideal for use with any introductory physics text, Loyd's *Physics Laboratory Manual* is suitable for either calculus- or algebra/trigonometry-based physics courses. Designed to help students demonstrate a physical principle and teach techniques of careful measurement, Loyd's *Physics Laboratory Manual* also emphasizes conceptual understanding and includes a thorough discussion of physical theory to help students see the connection between the lab and the lecture. Many labs give students hands-on experience with statistical analysis, and now five computer-assisted data entry labs are included in the printed manual. The fourth edition maintains the minimum equipment requirements to allow for maximum flexibility and to make the most of preexisting lab equipment. For instructors interested in using some of Loyd's experiments, a customized lab manual is another option available through the Cengage Learning Custom Solutions program. Now, you can select specific experiments from Loyd's *Physics Laboratory Manual*, include your own original lab experiments, and create one affordable bound book. Contact your Cengage Learning representative for more information on our Custom Solutions program. Available with InfoTrac® Student Collections http://gocengage.com/infotrac.

***Physics Laboratory Experiments,* Eighth 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. It also lets instructors determine the appropriate balance of traditional versus 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 Eighth Edition is updated with four new economical labs to accommodate shrinking department budgets and thirty new Pre-Lab Demonstrations, designed to capture students' interest prior to the lab and requiring only widely available materials and items.

WebAssign *WebAssign by Cengage* is the most widely used online homework system in higher education. Available for this global edition and if required by your instructor, WebAssign allows your instructor to assign, collect, grade, and record your assignments via the web. This proven homework system includes links to textbook sections, an eBook, video examples, and problem-specific tutorials. WebAssign by Cengage is more than a homework system—it is a complete online learning system for students.

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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 eleventh 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-topic problems.

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Welcome to Your MCAT Test Preparation Guide

The MCAT Test Preparation Guide makes your copy of *College Physics,* eleventh edition, the most comprehensive MCAT study tool and classroom resource in introductory physics. The MCAT was revised in 2015 (see **www.aamc.org/students/applying/mcat/mcat2015** for more details); the test section that now includes problems related to physics is *Chemical and Physical Foundations of Biological Systems.* Of the ~65 test questions in this section, approximately 25% 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

- **Topic 1, Sections 1.1, 1.3, 1.5, and 1.9–1.10**
  Quick Quizzes 1.1–1.2
  Examples 1.1–1.2, and 1.11–1.13
  Topic problems 1–6, 15–27, and 54–71
- **Topic 2, Sections 2.1–2.2**
  Quick Quizzes 2.1–2.5
  Examples 2.1–2.3
  Topic problems 1–25
- **Topic 3, Sections 3.1–3.2**
  Quick Quizzes 3.1–3.5
  Examples 3.1–3.6
  Topic problems 1–19, 47, 50, 53, and 56

Force and Equilibrium

- **Topic 4, Sections 4.1–4.4 and 4.6**
  Quick Quizzes 4.1–4.9
  Examples 4.1–4.12
  Topic problems 1–31, 38, 40, 49, and 53
- **Topic 8, Sections 8.1–8.3**
  Quick Quiz 8.1
  Examples 8.1–8.11
  Topic problems 1–36, 85, 91, and 92

Work

- **Topic 5, Sections 5.1 and 5.2**
  Quick Quiz 5.1–5.2
  Examples 5.1–5.3
  Topic problems 1–18 and 27
- **Topic 12, Section 12.1**
  Quick Quiz 12.1
  Examples 12.1–12.2
  Topic problems 1–10

Energy

- **Topic 5, Sections 5.2–5.7**
  Quick Quizzes 5.2–5.7
  Examples 5.3–5.14
  Topic problems 9–58, 67, 73, 74, and 78

Periodic Motion

- **Topic 13, Sections 13.7–13.9**
  Examples 13.8–13.10
  Topic problems 41–60

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

Review Plan

Fluids

- **Topic 9, Sections 9.1–9.3 and 9.5–9.9**
  Quick Quizzes 9.1–9.2 and 9.5–9.7
  Examples 9.1–9.16
  Topic problems 1–64, 79, 80, 81, 83, and 84

Gas phase

- **Topic 9, Section 9.5**
  Quick Quizzes 9.3–9.4
  Topic problems 8, 10, 14–15, and 83
- **Topic 10, Sections 10.2, 10.4, and 10.5**
  Quick Quiz 10.6
  Examples 10.1–10.2 and 10.6–10.10
  Topic problems 1–10 and 29–50

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

Review Plan

Electrostatics

- **Topic 15, Sections 15.1–15.4**
  Quick Quizzes 15.1 and 15.3–15.5
  Examples 15.1–15.5
  Topic problems 1–39
- **Topic 16, Sections 16.1–16.3**
  Quick Quizzes 16.1–16.7
  Examples 16.1–16.5
  Topic problems 1–24

Circuit elements

- **Topic 16, Sections 16.5–16.8**
  Quick Quizzes 16.8–16.11
  Examples 16.6–16.12
  Topic problems 29–57

- **Topic 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
  Topic problems 1–30 and 32–34
- **Topic 18, Sections 18.1–18.3 and 18.8**
  Quick Quizzes 18.1–18.8
  Examples 18.1–18.3
  Topic problems 1–17

Magnetism

- **Topic 19, Sections 19.1 and 19.3–19.4**
  Quick Quizzes 19.1–19.3
  Examples 19.1–19.4
  Topic problems 1–21

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

Review Plan

Sound

- **Topic 13, Sections 13.7 and 13.8**
  Examples 13.8–13.9
  Topic problems 41–48
- **Topic 14, Sections 14.1–14.4, 14.6, 14.9–14.10, and 14.12–14.13**
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  Examples 14.1–14.2, 14.4–14.5, and 14.9–14.10
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Light, electromagnetic radiation

- **Topic 21, Sections 21.10–21.12**
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  Examples 21.8 and 21.9
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- **Topic 24, Sections 24.1, 24.4, and 24.6–24.9**
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  Examples 24.1–24.4 and 24.6–24.8
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- **Topic 27, Section 27.3–27.4**
  Example 27.2
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Geometrical optics

- **Topic 22, Sections 22.2–22.4 and 22.7**
  Quick Quizzes 22.2–22.4
  Examples 22.1–22.6
  Topic problems 6–44 and 48
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  Quick Quizzes 23.1–23.6
  Examples 23.1–23.10
  Topic problems 1–46
- **Topic 25, Sections 25.1–25.6**
  Quick Quizzes 25.1–25.2
  Examples 25.1–25.8
  Topic problems 1–40, 59–62, and 66

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

Review Plan

Atomic nucleus

- **Topic 29, Sections 29.1–29.5 and 29.7**
  Quick Quizzes 29.1–29.3
  Examples 29.1–29.5
  Topic problems 1–35, 44–50, and 59

Electronic structure

- **Topic 19, Section 19.10**
- **Topic 27, Sections 27.2 and 27.8**
  Examples 27.1 and 27.5
  Topic problems 9–14 and 35–40
- **Topic 28, Sections 28.2–28.3, 28.5, and 28.7**
  Quick Quizzes 28.1 and 28.3
  Examples 28.1 and 28.2
  Topic problems 1–30 and 37–41

Content Category 5E: Principles of chemical thermodynamics and kinetics

Review Plan

Energy changes in chemical reactions

- **Topic 10, Sections 10.1 and 10.3**
  Quick Quizzes 10.1–10.5
  Examples 10.3–10.5
  Topic problems 11–28
- **Topic 11, Sections 11.1–11.5**
  Quick Quizzes 11.1–11.5
  Examples 11.1–11.11
  Topic problems 1–50
- **Topic 12, Sections 12.1–12.2 and 12.4–12.6**
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TOPIC 1

Units, Trigonometry, and Vectors

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

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.

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.

1.1.1 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

1.1.2 Mass

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 Topic 4, mass is a

◀ Definition of the kilogram

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.

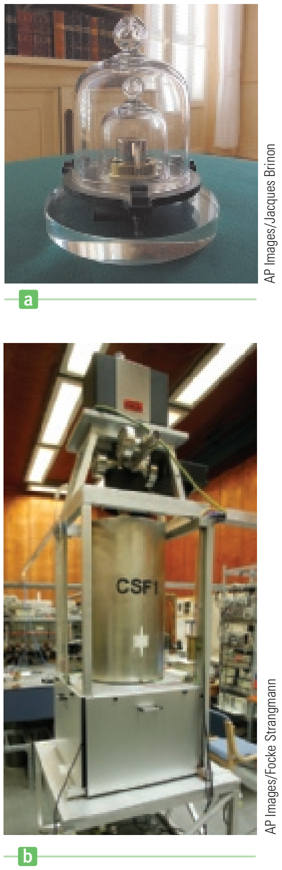
1.1.3 Time

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 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.

1.1.4 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 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.



AP Images/Jacques Brinon

AP Images/Focke Strangmann

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)
Observable Universe	1×10^{26}
Earth to Andromeda	2×10^{22}
Earth to Proxima Centauri	4×10^{16}
One light-year	9×10^{15}
Earth to Sun	2×10^{11}
Earth to Moon	4×10^{8}
Radius of Earth	6×10^{6}
World's tallest building	8×10^{2}
Football field	9×10^{1}
Housefly	5×10^{-3}
Typical organism cell	1×10^{-5}
Hydrogen atom	1×10^{-10}
Atomic nucleus	1×10^{-14}
Proton diameter	1×10^{-15}

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}
Age of college student	6×10^{8}
One year	3×10^{7}
One day	9×10^{4}
Heartbeat	8×10^{-1}
Audible sound wave period[a]	1×10^{-3}
Typical radio wave period[a]	1×10^{-6}
Visible light wave period[a]	2×10^{-15}
Nuclear collision	1×10^{-22}

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

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.

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

1.2 The Building Blocks of Matter

A 1-kg (≈ 2-lb) cube of solid gold has a length of about 3.73 cm (≈ 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.

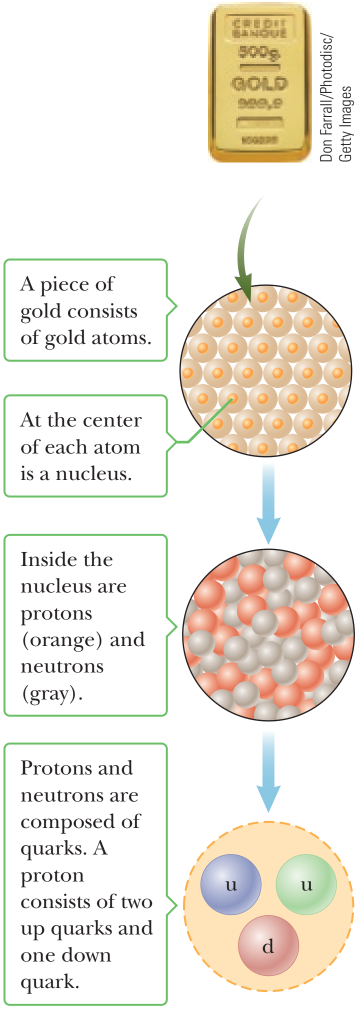
The atom can be naively visualized as a miniature solar system, with a dense, positively charged nucleus occupying the position of the Sun and negatively charged electrons orbiting like planets. This model of the atom, first developed by the great Danish physicist Niels Bohr nearly a century ago, led 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.



Don Farrall/Photodisc/Getty Images

A piece of gold consists of gold atoms.

At the center of each atom is a nucleus.

Inside the nucleus are protons (orange) and neutrons (gray).

Protons and neutrons are composed of quarks. A proton consists of two up quarks and one down quark.

Figure 1.2 Levels of organization in matter.

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.

1.3 Dimensional Analysis

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

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

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

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

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 $x = \frac{1}{2}at^2$.

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	$\mathrm{ft/s^2}$

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.

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

Find the dimensions of at.

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

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:

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

Solve the dimensions of speed for T:

$$[v] = \frac{\mathrm{L}}{\mathrm{T}} \quad \rightarrow \quad \mathrm{T} = \frac{\mathrm{L}}{[v]}$$

Substitute the expression for T into the equation for $[a]$:

$$[a] = \frac{\mathrm{L}}{\mathrm{T}^2} = \frac{\mathrm{L}}{(\mathrm{L}/[v])^2} = \frac{[v]^2}{\mathrm{L}}$$

Substitute $\mathrm{L} = [r]$, and guess at the equation:

$$[a] = \frac{[v]^2}{[r]} \quad \rightarrow \quad \boxed{a = \frac{v^2}{r}}$$

REMARKS This is the correct equation for the magnitude of the centripetal acceleration—acceleration towards the center of motion—to be discussed in Topic 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 $c = -1$.

(Continued)

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 Topic 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

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 in a laboratory experiment we measure the area of a rectangular plate with a meter stick. Let's assume 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 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 cm)

(4.5 cm) = 73.35 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 ±2 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]

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.

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 to the correct number of significant figures.

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 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, or between a nonzero number and before 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-topic 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

---

[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.

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:

$$14.71 \text{ m} \rightarrow 4 \text{ significant figures}$$
$$7.46 \text{ m} \rightarrow 3 \text{ significant figures}$$

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

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

(b) Compute the area of the meeting room.

Count significant figures:

$$4.822 \text{ m} \rightarrow 4 \text{ significant figures}$$
$$5.1 \text{ m} \rightarrow 2 \text{ significant figures}$$

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

$$4.822 \text{ m} \times 5.1 \text{ m} = 24.59 \text{ m}^2 \rightarrow \boxed{25 \text{ m}^2}$$

(c) Compute the area of the dining room.

Count significant figures:

$$13.8 \text{ m} \rightarrow 3 \text{ significant figures}$$
$$9 \text{ m} \rightarrow 1 \text{ significant figure}$$

To find the area, multiply the numbers keeping only one digit:

$$13.8 \text{ m} \times 9 \text{ m} = 124.2 \text{ m}^2 \rightarrow \boxed{100 \text{ m}^2}$$

(d) Calculate the total area of carpet required, with the proper number of significant figures.

Sum all three answers without regard to significant figures:

$$1.10 \times 10^2 \text{ m}^2 + 25 \text{ m}^2 + 100 \text{ m}^2 = 235 \text{ m}^2$$

The least accurate number is 100 m^2, with one significant figure in the hundred's decimal place:

$$235 \text{ m}^2 \rightarrow \boxed{2 \times 10^2 \text{ m}^2}$$

REMARKS Notice that the final answer in part **(d)** has only one significant figure, in the hundred's place, resulting in an answer that had to be rounded down by a sizable fraction of its total value. That's the consequence of having insufficient information. The value of 9 m, without any further information, represents a true value that could be anywhere in the interval [8.5 m, 9.5 m), all of which round to 9 when only one digit is retained.

QUESTION 1.3 How would the final answer change if the width of the dining room were given as 9.0 m?

EXERCISE 1.3 A ranch has two fenced rectangular areas. Area A has a length of 750 m and width 125 m, and area B has length 400 m and width 150 m. Find **(a)** area A, **(b)** area B, and **(c)** the total area, with attention to the rules of significant figures. Assume trailing zeros are not significant.

ANSWERS **(a)** 9.4×10^4 m^2 **(b)** 6×10^4 m^2 **(c)** 1.5×10^5 m^2

In performing any calculation, especially one involving a number of steps, there will always be slight discrepancies introduced by both the rounding process and the algebraic order in which steps are carried out. For example, consider $2.35 \times 5.89/1.57$. This computation can be performed in three different orders. First, we have $2.35 \times 5.89 = 13.842$, which rounds to 13.8, followed by $13.8/1.57 = 8.789\,8$, rounding to 8.79. Second, $5.89/1.57 = 3.751\,6$, which rounds to 3.75, resulting in $2.35 \times 3.75 = 8.812\,5$, rounding to 8.81. Finally, $2.35/1.57 = 1.496\,8$ rounds to 1.50, and $1.50 \times 5.89 = 8.835$ rounds to 8.84. So three different algebraic orders, following the rules of rounding, lead to answers of 8.79, 8.81, and 8.84, respectively. Such minor discrepancies are to be expected, because the last significant digit is only one representative from a range of possible values, depending on experimental uncertainty. To avoid such discrepancies, some carry one or more extra digits during the calculation, although it isn't conceptually consistent to do so because those extra digits are not significant. As a practical matter, in the worked examples in this text, intermediate reported results will be rounded to the proper number of significant figures, and only those digits will be carried forward. In the problem sets, however, given data will usually be assumed accurate to two or three digits, even when there are trailing zeros. **In solving the problems, the student should be aware that slight differences in rounding practices can result in answers varying from the text in the last significant digit, which is normal and not cause for concern.** The method of significant figures has its limitations in determining accuracy, but it's easy to apply. In experimental work, however, statistics and the mathematical propagation of uncertainty must be used to determine the accuracy of an experimental result.

1.5 Unit Conversions for Physical Quantities

Sometimes it's necessary to convert units from one system to another (see Fig. 1.3). Conversion factors between the SI and U.S. customary systems for units of length are as follows:

$$1 \text{ mi} = 1\,609 \text{ m} = 1.609 \text{ km} \qquad 1 \text{ ft} = 0.304\,8 \text{ m} = 30.48 \text{ cm}$$

$$1 \text{ m} = 39.37 \text{ in.} = 3.281 \text{ ft} \qquad 1 \text{ in.} = 0.025\,4 \text{ m} = 2.54 \text{ cm}$$

A more extensive list of conversion factors can be found on the front endsheets of this book. In all the given conversion equations, the "1" on the left is assumed to have the same number of significant figures as the quantity given on the right of the equation.

Units can be treated as algebraic quantities that can "cancel" each other. We can make a fraction with the conversion that will cancel the units we don't want, and

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Figure 1.3 The speed limit is given in both kilometers per hour and miles per hour on this road sign. How accurate is the conversion?