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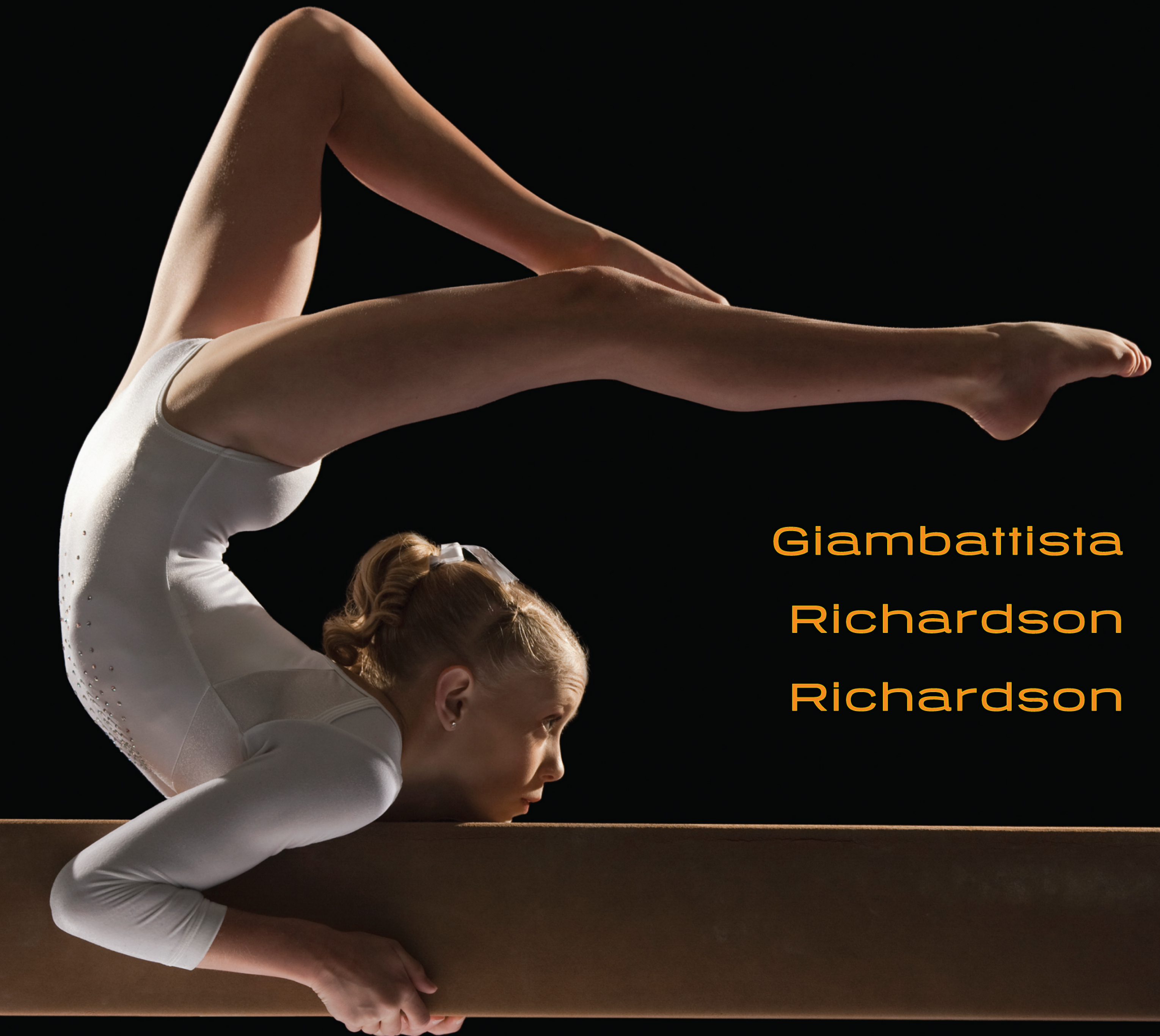

Physics

Third Edition

McGraw Hill Education

THIRD EDITION

Physics

Alan Giambattista

Betty McCarthy Richardson

Robert C. Richardson

Mc Graw Hill Education

PHYSICS, THIRD EDITION

This book is printed on acid-free paper.

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About the Authors

Alan Giambattista grew up in Nutley, New Jersey. Although he started college as a piano performance major, by his junior year at Brigham Young University he decided to pursue a career in physics. He did his graduate studies at Cornell University and has taught introductory college physics ever since. When not found in the classroom or at the computer keyboard working on *Physics*, he can often be found at the keyboard of a harpsichord or piano. He has been a soloist with the Cayuga Chamber Orchestra and has given performances of the Bach harpsichord concerti at several regional Bach festivals. When the long upstate New York winter is finally over, he loves to sail on Cayuga Lake. Alan met his wife Marion in a singing group. They live in an 1824 parsonage built for an abolitionist minister, which is now surrounded by an organic farm. Besides making music and taking care of the house, cats, and gardens, they love to travel together. They also love to spend time with their charming granddaughter, Ivy.

Betty McCarthy Richardson was born and grew up in Marblehead, Massachusetts, and tried to avoid taking any science classes after eighth grade but managed to avoid only ninth grade science. After discovering that physics explains how things work, she decided to become a physicist. She attended Wellesley College and did graduate work at Duke University. While at Duke, Betty met and married fellow graduate student Bob Richardson and had two daughters, Jennifer and Pamela. Betty began teaching physics at Cornell in 1977 with Physics 101/102, an algebra-based course with all teaching done one-on-one in a learning center. From her own early experience of math and science avoidance, Betty has empathy with students who are apprehensive about learning physics. Betty's hobbies include collecting old children's books, reading, enjoying music, travel, and dining with royalty. A highlight for Betty during the Nobel Prize festivities in 1996 was being escorted to dinner on the arm of King Carl XVI Gustav of Sweden. Currently she is spending time enjoying grandsons Jasper (once the 1 m child in Chapter 1), Dashiell and Oliver (the twins of Chapter 12), and Quintin, the later arrival.

Robert C. Richardson was born in Washington, D.C., attended Virginia Polytechnic Institute, spent time in the United States Army, and then returned to graduate school in physics at Duke University where his thesis work involved NMR studies of solid helium-3. In the fall of 1966 Bob began work at Cornell University in the laboratory of David M. Lee. Their research goal was to observe the nuclear magnetic phase transition in solid helium-3 that could be predicted from Richardson's thesis work with Professor Horst Meyer at Duke. In collaboration with graduate student Douglas D. Osheroff, they worked on cooling techniques and NMR instrumentation for studying low-temperature helium liquids and solids. In the fall of 1971, they made the accidental discovery that liquid helium-3 undergoes a pairing transition similar to that of superconductors. The three were awarded the Nobel Prize for that work in 1996. Before his death in 2013, Bob was the Vice Provost for Research, emeritus, and the F. R. Newman Professor of Physics at Cornell. He also enjoyed gardening, photography, and spending time with his grandsons.

Dedication

For Charlotte, Denisha, Ivy, Julia, and Katie

Alan

In memory of daughter Pamela, and husband of 50 years Bob, and for Quintin, Oliver, Dashiell, Jasper, Jennifer, and Jim Merlis

Betty

Brief Contents

Contents

List of Selected Applications

Biology/Life Science

Chemistry

Geology/Earth Science

Astronomy/Space Science

Architecture

Technology/Machines

Transportation

Sports

Everyday Life

Preface

Physics is intended for a two-semester college course in introductory physics using algebra and trigonometry. Our main goals in writing this book are

- to present the basic concepts of physics that students need to know for later courses and future careers,
- to emphasize that physics is a tool for understanding the real world, and
- to teach transferable problem-solving skills that students can use throughout their lives.

We have kept these goals in mind while developing the main themes of the book.

NEW TO THE THIRD EDITION

Although the fundamental philosophy of the book has not changed, detailed feedback from instructors and students using the previous editions has enabled us to continually fine-tune our approach. Some of the most important enhancements in the third edition include:

- Based on a review of the content lists for physics in the *Preview Guide for the MCAT*[2015] *Exam*, coverage of the following topics has been added or expanded: mechanical advantage, turbulence, surface tension, attenuation of sound waves, paramagnetism and diamagnetism, circular polarization, and lens aberrations.
- MCAT review questions have been moved online so actual questions from the 2015 MCAT exams can be made available to students.
- Starting with Chapter 4, Review & Synthesis problems appear at the end of every chapter instead of after related groups of chapters.
- To help students see that the physics they are learning is relevant to their careers, the third edition includes 116 new **biomedical applications** in the end-of-chapter Problems, 12 new biomedical Examples, and 10 new text discussions of biomedical applications.
- A **list of selected biomedical applications** appears on the first page of each chapter.
- Ninety-five new **Ranking Tasks** have been included in the Checkpoints, Practice Problems, and end-of-chapter Problems.
- New **Checkpoints** have been added to the text to give students more frequent opportunities to pause and test their understanding of a new concept.
- Every chapter includes a set of **Collaborative Problems** that can be used in cooperative group problem solving.
- The **Connections** have been enhanced and expanded to help students see the bigger picture—that what may seem like a new concept may really be an extension, application, or specialized form of a concept previously introduced. The goal is for students to view physics as a small set of fundamental concepts that can be applied in many different situations, rather than as a collection of loosely related facts or equations.
- Many of the legends have been expanded to help students learn more from the illustrations.
- Most marginal notes from the previous edition have been incorporated into the text for better flow of ideas and a less cluttered presentation.
- Multiple-Choice Questions that are well-suited to use with **student response systems** are identified with a "clicker" icon. Answers to even-numbered questions are not given, for instructors who track student performance using "clickers."

Some chapter-specific revisions to the text include:

- In **Chapter 1**, the general guidelines for problem solving have been expanded.
- **Chapter 2** introduces motion diagrams earlier and uses them extensively. Students are asked to construct or to interpret motion diagrams in Checkpoints, Examples, Practice Problems, and end-of-chapter Problems.
- **Chapters 3** continues the increased emphasis on motion diagrams. Motion with constant acceleration is now introduced first with motion diagrams, before other representations (graphs and equations).
- In **Chapter 4** the introduction of forces as interaction partners in Section 4.1 now includes an explicit reference to Newton's third law. More prominence is given to the specific identification of forces; the student is asked to state *on* what object and *by* what other object a force is exerted. A Connection has been added to reinforce a central theme in Newton's laws: no matter what *kinds* of forces are acting on an object, we always add them the same way (as vectors) to find the net force.
- **Chapter 6** is enhanced with a new problem-solving strategy box on how to choose between alternative problem-solving approaches (energy vs. Newton's second law). The explanation of why the change in gravitational potential energy is the *negative* of the work done by gravity is simpler and more intuitive. Chapter 6 also uses energy graphs more frequently.
- **Chapter 7** now includes a text discussion of ballistocardiography.
- **Chapter 11** discusses the use of seismic waves by animals to communicate and to sense their environment. The presentation of interference and phase difference has been simplified.
- **Chapter 12** contains an expanded discussion of audible frequency ranges for various animals. The presentation of the (nonrelativistic) Doppler effect is more straightforward, with emphasis on the relative velocities of the wave with respect to source and observer. A new problem-solving strategy box for the Doppler effect has been added.
- **Sections 15.5–15.7** contain improved explanations of heat engines and heat pumps.
- **Chapters 16 and 17** include a description of hydrogen bonds in water, DNA, and proteins. A simplified model of the hydrogen bond as interactions between point charges enables the student to make realistic estimates of the forces involved and of the binding energy of a hydrogen bond. A discussion of gel electrophoresis has also been added to Chapter 16.
- **Chapter 18** includes an enhanced discussion of the resistivity of water and how it depends strongly on the concentrations of ions. An explanation of the microscopic origin of Ohm's law has been added to **Section 18.4**.
- In **Chapter 19**, the visual depiction of the right-hand rule is clearer, and an alternative "wrench rule" is introduced. The explanation of how a cyclotron works is clearer. **Section 19.10** has been rewritten to provide a more complete description of paramagnetism and diagmagnetism.
- **Chapter 20's** treatment of inductance has been streamlined, with the quantitative material on *mutual* inductance moved to the text website.
- **Chapter 22** explains more plainly Maxwell's achievement in unifying the laws of electricity and magnetism, showing that EM waves exist and that electric and magnetic fields are real, not just convenient mathematical tools. The chapter includes discussions of IR detection by animals and the biological effects of UV exposure, as well as an improved explanation of how polarizers work. **Section 22.7** now includes a description of circular polarization.
- **Section 24.3** describes astigmatism of the eye. **Section 24.7** contains a more complete explantion of lens aberrations.
- **Chapter 25** simplifies the discussion of phase differences for constructive and destructive interference.
- **Chapter 29** mentions other modes of radioactive decay such as proton emission and double beta emission. The text discusses the accidents at the Fukushima Daiichi nuclear power plant due to the 2011 Tōhoku tsunami.
- **Chapter 30** now includes brief descriptions of inflation and of the Higgs field.

COMPREHENSIVE COVERAGE

Students should be able to get the whole story from the book. The previous editions have been tested in our nontraditional course, where students must rely on the textbook as their primary learning resource because there are no lectures. Nonetheless, completeness and clarity are equally advantageous when the book is used in a more traditional classroom setting. *Physics* frees the instructor from having to try to "cover" everything. The instructor can then tailor class time to more important student needs—reinforcing difficult concepts, working through Example problems, engaging the students in peer instruction and cooperative learning activities, describing applications, or presenting demonstrations.

A CONCEPTS-FIRST APPROACH

Some students approach introductory physics with the idea that physics is just the memorization of a long list of equations and the ability to plug numbers into those equations. We want to help students see that a relatively small number of basic physics concepts are applied to a wide variety of situations. Physics education research has shown that students do not automatically acquire conceptual understanding; the concepts must be explained and the students given a chance to grapple with them. Our presentation, based on years of teaching this course, blends conceptual understanding with analytical skills. The "concepts-first" approach helps students develop intuition about how physics works; the "formulas" and problem-solving techniques serve as *tools for applying the concepts.* The **Conceptual Examples** and **Conceptual Practice Problems** in the text and a variety of ranking tasks and Conceptual and Multiple-Choice Questions at the end of each chapter give students a chance to check and to enhance their conceptual understanding.

INTRODUCING CONCEPTS INTUITIVELY

We introduce key concepts and quantities in an informal way by establishing why the quantity is needed, why it is useful, and why it needs a precise definition. Then we make a transition from the informal, intuitive idea to a formal definition and name. Concepts motivated in this way are easier for students to grasp and remember than are concepts introduced by seemingly arbitrary, formal definitions.

For example, in Chapter 8, the idea of rotational inertia emerges in a natural way from the concept of rotational kinetic energy. Students can understand that a rotating rigid body has kinetic energy due to the motion of its particles. We discuss why it is useful to be able to write this kinetic energy in terms of a single quantity common to all the particles (the angular speed), rather than as a sum involving particles with many different speeds. When students understand why rotational inertia is defined the way it is, they are better prepared to move on to the more difficult concepts of torque and angular momentum.

We avoid presenting definitions or formulas without any motivation. When an equation is not derived in the text, we at least describe where the equation comes from or give a plausibility argument. For example, Section 9.9 introduces Poiseuille's law with two identical pipes in series to show why the volume flow rate must be proportional to the pressure drop per unit length. Then we discuss why $\Delta V/\Delta t$ is proportional to the fourth power of the radius (rather than to r^2, as it would be for an ideal fluid).

Similarly, we have found that the definitions of the displacement and velocity vectors seem arbitrary and counterintuitive to students if introduced without any motivation. Therefore, we precede any discussion of kinematic quantities with an introduction to Newton's laws, so students know that forces determine how the state of motion of an object changes. Then, when we define the kinematic quantities to give a precise definition of acceleration, we can apply Newton's second law quantitatively to see how forces affect the motion. We give particular attention to laying the conceptual groundwork for a concept when its name is a common English word such as *velocity* or *work.*

WRITTEN IN A CLEAR AND FRIENDLY STYLE

We have kept the writing down-to-earth and conversational in tone—the kind of language an experienced teacher uses when sitting at a table working one-on-one with a student. We hope students will find the book pleasant to read, informative, and accurate without seeming threatening, and filled with analogies that make abstract concepts easier to grasp. We want students to feel confident that they can learn by studying the textbook.

Although we agree that learning correct physics terminology is essential, we chose to avoid all *unnecessary* jargon—terminology that just gets in the way of the student's understanding. For example, we never use the term *centripetal force*, since its use sometimes leads students to add a spurious "centripetal force" to their free-body diagrams. Likewise, we use *radial component of acceleration* because it is less likely to introduce or reinforce misconceptions than *centripetal acceleration.*

ACCURACY ASSURANCE

The authors and the publisher acknowledge that inaccuracies can be a source of frustration for both the instructor and students. Therefore, throughout the writing and production of this edition, we have worked diligently to eliminate errors and inaccuracies. Maureen Ross and her team at diacriTech conducted an independent accuracy check of all new and revised material in the final draft of the manuscript. They then coordinated the resolution of discrepancies between the accuracy check and the end-of-book answers. The page proofs of the text were proofread against the manuscript to ensure the correction of any errors introduced when the manuscript was typeset. The end-of-book answers were then re-checked by Ralph McGrew.

PROVIDING STUDENTS WITH THE TOOLS THEY NEED

Problem-Solving Approach

Problem-solving skills are central to an introductory physics course. We illustrate these skills in the Example problems. Lists of problem-solving strategies are sometimes useful; we provide such strategies when appropriate. However, the most elusive skills—perhaps the most important ones—are subtle points that defy being put into a neat list. To develop real problem-solving expertise, students must learn how to think critically and analytically. Problem solving is a multidimensional, complex process; an algorithmic approach is not adequate to instill real problem-solving skills.

Strategy We begin each Example with a discussion—in language that the students can understand—of the *strategy* to be used in solving the problem. The strategy illustrates the kind of analytical thinking students must do when attacking a problem: How do I decide what approach to use? What laws of physics apply to the problem and which of them are *useful* in this solution? What clues are given in the statement of the question? What information is implied rather than stated outright? If there are several valid approaches, how do I determine which is the most efficient? What assumptions can I make? What kind of sketch or graph might help me solve the problem? Is a simplification or approximation called for? If so, how can I tell if the simplification is valid? Can I make a preliminary estimate of the answer? Only after considering these questions can the student effectively solve the problem.

Solution Next comes the detailed *solution* to the problem. Explanations are intermingled with equations and step-by-step calculations to help the student understand the approach used to solve the problem. We want the student to be able to follow the mathematics without wondering, "Where did that come from?"

Discussion The numerical or algebraic answer is not the end of the problem; our Examples end with a *discussion.* Students must learn how to determine whether their answer is consistent and reasonable by checking the order of magnitude of the answer, comparing the answer with a preliminary estimate, verifying the units, and doing an independent calculation when more than one approach is feasible. When several different approaches are possible, the discussion looks at the advantages and disadvantages of each approach. We also discuss the implications of the answer—what can we learn from it? We look at special cases and look at "what if" scenarios. The discussion sometimes generalizes the problem-solving techniques used in the solution.

Practice Problem After each Example, a Practice Problem gives students a chance to gain experience using the same physics principles and problem-solving tools. By comparing their answers with those provided at the end of each chapter, students can gauge their understanding and decide whether to move on to the next section.

Our many years of experience in teaching the college physics course in a one-on-one setting has enabled us to anticipate where we can expect students to have difficulty. In addition to the consistent problem-solving approach, we offer several other means of assistance to the student throughout the text. A boxed problem-solving strategy gives detailed information on solving a particular type of problem, and an icon for problem-solving tips draws attention to techniques that can be used in a variety of contexts. A hint in a worked Example or end-of-chapter problem provides a clue on what approach to use or what simplification to make. A warning icon emphasizes an explanation that clarifies a possible point of confusion or a common student misconception.

An important problem-solving skill that many students lack is the ability to extract information from a graph or to sketch a graph without plotting individual data points. Graphs often help students visualize physical relationships more clearly than they can with algebra alone. We emphasize the use of graphs and sketches in the text, in worked examples, and in the problems.

Using Approximation, Estimation, and Proportional Reasoning

Physics is forthright about the constant use of simplified models and approximations in solving physics problems. One of the most difficult aspects of problem solving that students need to learn is that some kind of simplified model or approximation is usually required. We discuss how to know when it is reasonable to ignore friction, treat g as constant, ignore viscosity, treat a charged object as a point charge, or ignore diffraction.

Some Examples and Problems require the student to make an estimate—a useful skill both in physics problem solving and in many other fields. Similarly, we teach proportional reasoning as not only an elegant shortcut but also as a means to understanding patterns. We frequently use percentages and ratios to give students practice in using and understanding them.

Showcasing an Innovative Art Program

In every chapter we have developed a system of illustrations, ranging from simpler diagrams to elaborate and beautiful illustrations, that brings to life the connections between physics concepts and the complex ways in which they are applied. We believe these illustrations, with subjects ranging from three-dimensional views of electric field lines to the biomechanics of the human body and from representations of waves to the distribution of electricity in the home, will help students see the power and beauty of physics.

Helping Students See the Relevance of Physics in Their Lives

Students in an introductory college physics course have a wide range of backgrounds and interests. We stimulate interest in physics by relating its principles to applications relevant to students' lives and in line with their interests. The text, Examples, and end-of-chapter problems draw from the everyday world; from familiar technological applications; and from other fields such as biology, medicine, archaeology, astronomy, sports, environmental science, and geophysics. (Applications in the text are identified with a text heading or marginal note. An icon ( ) identifies applications in the biological or medical sciences.)

The **Everyday Physics Demos** give students an opportunity to explore and see physics principles operate in their everyday lives. These activities are chosen for their simplicity and for their effectiveness in demonstrating physics principles.

Each **Chapter Opener** includes a photo and vignette, designed to capture student interest and maintain it throughout the chapter. The vignette describes the situation shown in the photo and asks the student to consider the relevant physics. A reduced version of the chapter opener photo and question indicate where the vignette topic is addressed within the chapter.

Focusing on the Concepts

By identifying areas where important concepts are revisited, the **Connections** allow us to focus on the basic, core concepts of physics and reinforce for students that all of physics is based on a few, fundamental ideas. A marginal Connections heading and summary adjacent to the coverage in the main text help students easily recognize that a previously introduced concept is being applied to the current discussion.

The exercises in the **Review & Synthesis** sections help students see how the concepts in the previously covered group of chapters are interrelated. These exercises are also intended to help students prepare for tests, in which they must solve problems without having the section or chapter title given as a clue.

Checkpoint questions encourage students to pause and test their understanding of the concept explored within the current section. The answers to the Checkpoints are found at the end of the chapter so that students can confirm their knowledge without jumping too quickly to the provided answer.

Applications are clearly identified as such in the text with a complete listing in the front matter. With Applications, students have the opportunity to see how physics concepts are experienced through their everyday lives.

connect icons identify opportunities for students to access additional information or explanation of topics of interest online. This will help students to focus even further on just the very fundamental, core concepts in their reading of the text.

ADDITIONAL RESOURCES FOR INSTRUCTORS AND STUDENTS

McGraw-Hill SmartBook™

Powered by the intelligent and adaptive LearnSmart engine, SmartBook is the first and only continuously adaptive reading experience available today. Distinguishing what students know from what they don't, and honing in on concepts they are most likely to forget, SmartBook personalizes content for each student. Reading is no longer a passive and linear experience but an engaging and dynamic one, in which students are more likely to master and retain important concepts, coming to class better prepared. SmartBook includes powerful reports that identify specific topics and learning objectives students need to study. These valuable reports also provide instructors insight into how students are progressing through textbook content and are useful for identifying class trends, focusing precious class time, providing personalized feedback to students, and tailoring assessment.

How does SmartBook work? Each SmartBook contains four components: Preview, Read, Practice, and Recharge. Starting with an initial preview of each chapter and key learning objectives, students read the material and are guided to topics for which they need the most practice based on their responses to a continuously adapting diagnostic. Read and practice continue until SmartBook directs students to recharge important material they are most likely to forget so as to ensure concept mastery and retention.

ALEKS® Math Prep for *Physics*

ALEKS Math Prep for *Physics* is a web-based program that provides targeted coverage of critical mathematics material necessary for student success in *Physics.* ALEKS uses artificial intelligence and adaptive questioning to assess precisely a student's preparedness and deliver personalized instruction on the exact topics the student is most ready to learn. Through comprehensive explanations, practice, and feedback, ALEKS enables students to quickly fill individual knowledge gaps in order to build a strong foundation of critical math skills.

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- **Individualized Assessment and Learning:** Ensure student mastery
- **Adaptive, Open-Response Environment:** Avoids multiple-choice questions
- **Dynamic, Automated Reports:** Monitor student and class progress

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McGraw-Hill Connect® Physics

McGraw-Hill Connect® Physics to accompany *Physics* offers online electronic homework, an eBook, and a myriad of resources for both instructors and students. Instructors can create homework with easy-to-assign, algorithmically generated problems from the text. This feature also offers the simplicity of automatic grading and reporting.

- MCAT review materials are available online. These include links to practice tests. After the revised MCATs have been administered in 2015, actual questions from those past tests will be made available online for student practice.
- The end-of-chapter problems and Review & Synthesis exercises appear in the online homework system in diverse formats and with various tools.
- The online homework system incorporates new and exciting interactive tools and problem types: ranking problems, a graphing tool, a free-body diagram drawing tool, symbolic entry, a math palette, and multipart problems.
- Mimicking the interaction with a tutor or professor by providing students with detailed explanations and probing questions, several comprehensive tutorial problems cover the main topics of the course. These give students a way to help learn the concepts in a careful, thoughtful way and guide them to a deeper understanding of the material.

Instructors also have access to PowerPoint lecture outlines, an Instructor's Resource Guide with solutions, suggested demonstrations, electronic images from the text, clicker questions, quizzes, tutorials, interactive simulations, and many other resources directly tied to text-specific materials in *Physics.* Students have access to self-quizzing, interactive simulations, tutorials, selected answers for the text's problems, and more.

See www.mhhe.com/grr to learn more and to register.

Online Physics Education Research Workbook

To help professors integrate new research on how students learn, Drs. Athula Herat and Ben Shaevitz of Slippery Rock University have written a workbook to accompany *Physics.* This workbook contains questions and ideas for classroom exercises that will get students thinking about physics in new and comprehensive ways. Students are led to discover physics for themselves, leading to a deeper intuitive understanding of the material. A group of professors who use new ideas from Physics Education Research in the classroom reviewed the workbook and suggested changes and new problems. By providing the workbook in an online format, professors are free to use as much or little of the material as they choose.

Electronic Book Images and Assets for Instructors

Build instructional materials wherever, whenever, and however you want!

Accessed from the Connect Physics website to accompany *Physics*, an online digital library containing photos, artwork, interactives, and other media types can be used to create customized lectures, visually enhanced tests and quizzes, compelling course websites, or attractive printed support materials. Assets are copyrighted by McGraw-Hill Higher Education, but can be used by instructors for classroom purposes. The visual resources in this collection include

- **Art** Full-color digital files of all illustrations in the book can be readily incorporated into lecture presentations, exams, or custom-made classroom materials.
- **Photos** The photos collection contains digital files of photographs from the text, which can be reproduced for multiple classroom uses.
- **Worked Example Library, Table Library, and Numbered Equations Library** Access the worked Examples, tables, and equations from the text in electronic format for inclusion in your classroom resources.

Also residing on the Connect Physics website are PowerPoint Lecture Outlines, ready-made presentations that combine art and lecture notes for each chapter of the text.

Computerized Test Bank Online

A comprehensive bank of test questions in multiple-choice format at a variety of difficulty levels is provided within a computerized test bank powered by McGraw-Hill's flexible electronic testing program—EZ Test Online (www.eztestonline.com). EZ Test Online allows you to create paper and online tests or quizzes in this easy-to-use program!

Imagine being able to create and access your test or quiz anywhere, at any time without installing the testing software. Now, with EZ Test Online, instructors can select questions from multiple McGraw-Hill test banks or create their own, and then either print the test for paper distribution or give it online. See www.mhhe.com/grr for more information.

Electronic Books

If you or your students are ready for an alternative version of the traditional textbook, McGraw-Hill brings you innovative and inexpensive electronic textbooks. By purchasing E-books from McGraw-Hill, students can save as much as 50% on selected titles delivered on the most advanced E-book platforms available.

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Personal Response Systems

Personal response systems, or "clickers," bring interactivity into the classroom or lecture hall. Wireless response systems give the instructor and students immediate feedback from the entire class. The wireless response pads are essentially remotes that are easy to use and engaging, allowing instructors to motivate student preparation, interactivity, and active learning. Instructors receive immediate feedback to gauge which concepts students understand. Questions covering the content of the *Physics* text (formatted in PowerPoint) are available on the Connect Physics website for *Physics.*

Instructor's Resource Guide

The *Instructor's Resource Guide* includes many unique assets for instructors, such as demonstrations, suggested reform ideas from physics education research, and ideas for incorporating just-in-time teaching techniques. The accompanying Instructor's Solutions Manual includes answers to the end-of-chapter Conceptual Questions and complete, worked-out solutions for all the end-of-chapter Problems from the text. The Instructors Resource Guide is available in the Instructor Resources on the Connect Physics website to accompany *Physics.*

Student Solutions Manual

The *Student Solutions Manual* contains complete worked-out solutions to selected end-of-chapter problems and questions, and to selected Review & Synthesis problems. The solutions in this manual follow the problem-solving strategy outlined in the text's Examples and also guide students in creating diagrams for their own solutions.

For more information, contact a McGraw-Hill customer service representative at (800) 338–3987, or by email at www.mhhe.com. To locate your sales representative, go to www.mhhe.com for Find My Sales Rep.

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REVIEWERS, CLASS TESTERS, AND ADVISORS

This text reflects an extensive effort to evaluate the needs of college physics instructors and students, to learn how well we met those needs, and to make improvements

where we fell short. We gathered information from numerous reviews, class tests, and focus groups.

The primary stage of our research began with commissioning reviews from instructors across the United States and Canada. We asked them to submit suggestions for improvement on areas such as content, organization, illustrations, and ancillaries. The detailed comments of these reviewers constituted the basis for the revision plan.

We then recruited three groups of professors to help guide the updated content. A group of professors who use electronic media and online homework in their classes advised us about updates to the Connect website. Professors who use the latest research in physics education in their courses helped us develop the online workbook and other supplemental materials. Finally, Professors Michael Famiano of Western Michigan University, Todd Pedlar of Luther College, and John Vasut of Baylor University suggested new ways to incorporate applications to biology and medicine throughout the text.

Considering the sum of these opinions, this text now embodies the collective knowledge, insight, and experience of hundreds of college physics instructors. Their influence can be seen in everything from the content, accuracy, and organization of the text to the quality of the illustrations.

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THIRD EDITION

Physics

CHAPTER

1

Introduction

NASA's Mars rover *Curiosity* landed on the surface of Mars in August 2012. One of the mission's primary objectives is to determine whether Mars ever had an environment capable of supporting microbial life. This photo taken by *Curiosity* shows a rock outcrop that contains rounded pieces of gravel. The size, shape, and composition of the gravel led scientists to conclude that a stream once flowed here.

NASA's many successful missions to Mars have sent back a wealth of geologic data. However, in 1998, a simple mistake caused the loss of the *Mars Climate Orbiter* as it entered orbit around Mars. In this chapter, you will learn how to avoid making this same mistake. (See p. 9.)

BIOMEDICAL APPLICATIONS

- Bone density and osteoporosis (Ex. 1.1)
- Surface area of alveoli in the lung (Ex. 1.7)
- Blood flow rates (Probs. 37, 42, 75)
- Mass dependence of metabolic rate (Prob. 5)
- Smallest and largest organisms (Probs. 72, 73)

Concepts & Skills to Review

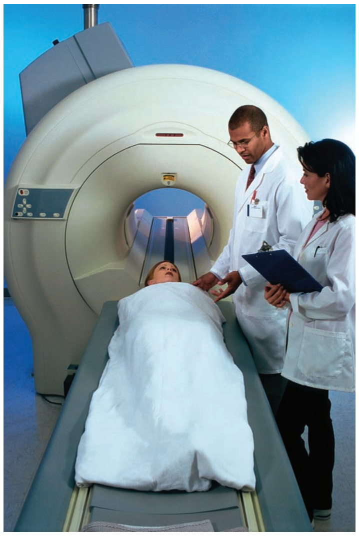
- Algebra, geometry, and trigonometry (Appendix A)
- How to Succeed in Your Physics Class (see the text website connect)

1.1 WHY STUDY PHYSICS?

Physics is the branch of science that describes matter, energy, space, and time at the most fundamental level. Whether you are planning to study biology, architecture, medicine, music, chemistry, or art, some principles of physics are relevant to your field.

Physicists look for patterns in the physical phenomena that occur in the universe. They try to explain what is happening, and they perform experiments to see if the proposed explanation is valid. The goal is to find the most basic laws that describe the universe and to formulate those laws in the most precise way possible.

The study of physics is valuable for several reasons:



A patient being prepared for magnetic resonance imaging (MRI). MRI provides a detailed image of the internal structures of the patient's body.

- Since physics describes matter and its basic interactions, all natural sciences are built on a foundation of the laws of physics. A full understanding of chemistry requires a knowledge of the physics of atoms. A full understanding of biological processes in turn is based on the underlying principles of physics and chemistry. Centuries ago, the study of *natural philosophy* encompassed what later became the separate fields of biology, chemistry, geology, astronomy, and physics. Today there are scientists who call themselves biophysicists, chemical physicists, astrophysicists, and geophysicists, demonstrating how thoroughly the sciences are intertwined.
- In today's technological world, many important devices can be understood correctly only with a knowledge of the underlying physics. Just in the medical world, think of laser surgery, magnetic resonance imaging, instant-read thermometers, x-ray imaging, radioactive tracers, heart catheterizations, sonograms, pacemakers, microsurgery guided by optical fibers, ultrasonic dental drills, and radiation therapy.
- By studying physics, you acquire skills that are useful in other disciplines. These include thinking logically and analytically; solving problems; making simplifying assumptions; constructing mathematical models; using valid approximations; and making precise definitions.
- Society's resources are limited, so it is important to use them in beneficial ways and not squander them on scientifically impossible projects. Political leaders and the voting public are too often led astray by a lack of understanding of scientific principles. Can a nuclear power plant supply energy safely to a community? What is the truth about global climate change, the ozone hole, and the danger of radon in the home? By studying physics, you learn some of the basic scientific principles and acquire some of the intellectual skills necessary to ask probing questions and to formulate informed opinions on these important matters.
- Finally, by studying physics, we hope that you develop a sense of the beauty of the fundamental laws that describe the universe.

1.2 TALKING PHYSICS

Some of the words used in physics are familiar from everyday speech. This familiarity can be misleading, however, since the scientific definition of a word may differ considerably from its common meaning. In physics, words must be precisely defined so that anyone reading a scientific paper or listening to a science lecture understands exactly what is meant. Some of the basic defined quantities, whose names are also words used in everyday speech, include time, length, force, velocity, acceleration, mass, energy, momentum, and temperature.

In everyday language, *speed* and *velocity* are synonyms. In physics, there is an important distinction between the two. In physics, *velocity* includes the *direction* of motion as well as the distance traveled per unit time. When a moving object changes direction, its velocity changes even though its speed may not have changed. Confusing the scientific definition of *velocity* with its everyday meaning will prevent a correct understanding of some of the basic laws of physics and will lead to incorrect answers.

Mass, as used in everyday language, has several different meanings. Sometimes *mass* and *weight* are used interchangeably. In physics, mass and weight are *not* interchangeable. Mass is a measure of inertia—the tendency of an object at rest to remain at rest or, if moving, to continue moving with the same velocity. Weight, on the other hand, is a measure of the gravitational pull on an object. (Mass and weight are discussed in more detail in Chapter 4.)

There are two important reasons for the way in which we define physical quantities. First, physics is an experimental science. The results of an experiment must be stated unambiguously so that other scientists can perform similar experiments and compare their results. Quantities must be defined precisely to enable experimental measurements to be uniform no matter where they are made. Second, physics is a mathematical science. We use mathematics to quantify the relationships among physical quantities. These relationships can be expressed mathematically only if the quantities being investigated have precise definitions.

1.3 THE USE OF MATHEMATICS

A working knowledge of algebra, trigonometry, and geometry is essential to the study of introductory physics. Some of the more important mathematical tools are reviewed in Appendix A. If you know that your mathematics background is shaky, you might want to test your mastery by doing some problems from a math textbook. You may find it useful to visit www.mhhe.com to explore the Schaum's Outline series, especially the Schaum's Outlines of *Precalculus, College Physics,* or *Physics for Pre-Med, Biology, and Allied Health Students*.

Mathematical equations are shortcuts for expressing concisely in symbols relationships that are cumbersome to describe in words. Algebraic symbols in the equations stand for quantities that consist of numbers *and units*. The number represents a measurement and the measurement is made in terms of some standard; the unit indicates what standard is used. In physics, a number to specify a quantity is useless unless we know the unit attached to the number. When buying silk to make a sari, do we need a length of 5 millimeters, 5 meters, or 5 kilometers? Is the term paper due in 3 minutes, 3 days, or 3 weeks? Systems of units are discussed in Section 1.5.

There are not enough letters in the alphabet to assign a unique letter to each quantity. The same letter V can represent volume in one context and voltage in another. Avoid attempting to solve problems by picking equations that seem to have the correct letters. A skilled problem-solver understands *specifically* what quantity each symbol in a particular equation represents, can specify correct units for each quantity, and understands the situations to which the equation applies.

Ratios and Proportions In the language of physics, the word **factor** is used frequently, often in a rather idiosyncratic way. If the power emitted by a radio transmitter has doubled, we might say that the power has "increased by a factor of 2." If the concentration of sodium ions in the bloodstream is half of what it was previously, we might say that the concentration has "decreased by a factor of 2," or, in a blatantly inconsistent way, someone else might say that it has "decreased by a factor of $\frac{1}{2}$." The *factor* is the number by which a quantity is multiplied or divided when it is changed from one value to another. In other words, the factor is really a ratio. In the case of the radio transmitter, if P_0 represents the initial power and P represents the power after new equipment is installed, we write

$$\frac{P}{P_0} = 2$$

It is also common to talk about "increasing 5%" or "decreasing 20%." If a quantity increases $n\%$, that is the same as saying that it is multiplied by a factor of $1 + (n/100)$. If a quantity decreases $n\%$, then it is multiplied by a factor of $1 - (n/100)$. For example, an increase of 5% means something is 1.05 times its original value, and a decrease of 4% means it is 0.96 times the original value.

Physicists talk about increasing "by some factor" because it often simplifies a problem to think in terms of **proportions**. When we say that A is proportional to B (written $A \propto B$), we mean that if B increases by some factor, then A must increase by the same factor. In other words, the ratio of two values of B is equal to the ratio of the corresponding values of A, expressed as $B_2/B_1 = A_2/A_1$. For instance, the circumference of a circle equals 2π times the radius: $C = 2\pi r$. Therefore $C \propto r$. If the radius doubles, the circumference also doubles. The area of a circle is proportional to the *square* of the radius ($A = \pi r^2$, so $A \propto r^2$). The area must increase by the same factor as the radius *squared*, so if the radius doubles, the area increases by a factor of $2^2 = 4$. Written as a proportion, $A_2/A_1 = (r_2/r_1)^2 = 2^2 = 4$.

Example 1.1

Osteoporosis

Severe osteoporosis can cause the density of bone to decrease as much as 40%. What is the bone density of this degraded bone if the density of healthy bone is 1.5 g/cm^3?

Strategy A decrease of $n\%$ means the quantity is multiplied by $1 - (n/100)$.

Solution $1.5\ \text{g/cm}^3 \times [1 - (40/100)] = 1.5\ \text{g/cm}^3 \times 0.60 = 0.90\ \text{g/cm}^3$

Discussion Quick check: The final density is a bit more than half the original density, as expected for a 40% decrease.

Practice Problem 1.1 Red Blood Cell Count

A hospital patient's red blood count (RBC) is 5.0×10^6 cells per microliter ($5.0 \times 10^6\ \mu\text{L}^{-1}$) on Tuesday; on Wednesday it is $4.8 \times 10^6\ \mu\text{L}^{-1}$. What is the percentage change in the RBC?

Example 1.2

Effect of Increasing Radius on the Volume of a Sphere

The volume of a sphere is given by the equation

$$V = \frac{4}{3}\pi r^3$$

where V is the volume and r is the radius of the sphere. If a basketball has a radius of 12.4 cm and a tennis ball has a radius of 3.20 cm, by what factor is the volume of the basketball larger than the volume of the tennis ball?

Strategy The problem gives the values of the radii for the two balls. To keep track of which ball's radius and volume we mean, we use subscripts "b" for basketball and "t" for tennis ball. The radius of the basketball is r_b and the radius of the tennis ball is r_t. Since $\frac{4}{3}$ and π are constants, we can work in terms of proportions.

Solution The ratio of the basketball radius to that of the tennis ball is

$$\frac{r_b}{r_t} = \frac{12.4\ \text{cm}}{3.20\ \text{cm}} = 3.875$$

The volume of a sphere is proportional to the cube of its radius:

$$V \propto r^3$$

Since the basketball radius is larger by a factor of 3.875, and volume is proportional to the cube of the radius, the new volume should be bigger by a factor of $3.875^3 \approx 58.2$.

Discussion A slight variation on the solution is to write out the proportionality in terms of ratios of the corresponding sides of the two equations:

$$\frac{V_b}{V_t} = \frac{\frac{4}{3}\pi r_b^3}{\frac{4}{3}\pi r_t^3} = \left(\frac{r_b}{r_t}\right)^3$$

Substituting the ratio of r_b to r_t yields

$$\frac{V_b}{V_t} = 3.1875^3 \approx 58.2$$

which says that V_b is approximately 58.2 times V_t.

continued on next page

Example 1.2 continued

Practice Problem 1.2 Power Dissipated by a Lightbulb

The electric power P dissipated by a lightbulb of resistance R is $P = V^2/R$, where V represents the line voltage. During a brownout, the line voltage is 10.0% less than its normal value. How much power is drawn by a lightbulb during the brownout if it normally draws 60.0 W (watts)? Assume that the resistance does not change.

CHECKPOINT 1.3

If the radius of the sphere is increased by a factor of 3, by what factor does the volume of the sphere change?

1.4 SCIENTIFIC NOTATION AND SIGNIFICANT FIGURES

In physics, we deal with some numbers that are very small and others that are very large. It can get cumbersome to write numbers in conventional decimal notation. In **scientific notation**, any number is written as a number between 1 and 10 times an integer power of ten. Thus the radius of Earth, approximately 6 380 000 m at the equator, can be written 6.38×10^6 m; the radius of a hydrogen atom, 0.000 000 000 053 m, can be written 5.3×10^{-11} m. Scientific notation eliminates the need to write zeros to locate the decimal point correctly.

Learn how to use the button on your calculator (usually labeled EE) to enter a number in scientific notation. To enter 1.2×10^8, press 1.2, EE, 8.

In science, a measurement or the result of a calculation must indicate the **precision** to which the number is known. The precision of a device used to measure something is limited by the finest division on the scale. Using a meterstick with millimeter divisions as the smallest separations, we can measure a length to a precise number of millimeters and we can estimate a fraction of a millimeter between two divisions. If the meterstick has centimeter divisions as the smallest separations, we measure a precise number of centimeters and estimate the fraction of a centimeter that remains.

Significant Figures The most basic way to indicate the precision of a quantity is to write it with the correct number of **significant figures**. The significant figures are all the digits that are known accurately plus the one estimated digit. If we say that the distance from here to the state line is 12 km, that does not mean we know the distance to be *exactly* 12 kilometers. Rather, the distance is 12 km *to the nearest kilometer*. If instead we said that the distance is 12.0 km, that would indicate that we know the distance to the nearest *tenth* of a kilometer. More significant figures indicate a greater degree of precision.

Rules for Identifying Significant Figures

1. Nonzero digits are always significant.
2. Final or ending zeros written to the right of the decimal point are significant.
3. Zeros written to the right of the decimal point for the purpose of spacing the decimal point are not significant.
4. Zeros written to the left of the decimal point may be significant, or they may only be there to space the decimal point. For example, 200 cm could have one, two, or three significant figures; it's not clear whether the distance was measured to the nearest 1 cm, to the nearest 10 cm, or to the nearest 100 cm. On the other hand, 200.0 cm has four significant figures (see rule 5). Rewriting the number in scientific notation is one way to remove the ambiguity. In this book, when a number has zeros to the left of the decimal point, you may *assume a minimum of two significant figures*.
5. Zeros written between significant figures are significant.

Example 1.3

Identifying the Number of Significant Figures

For each of these values, identify the number of significant figures and rewrite it in standard scientific notation.

(a) 409.8 s
(b) 0.058 700 cm
(c) 9500 g
(d) 950.0×10^1 mL

Strategy We follow the rules for identifying significant figures as given. To rewrite a number in scientific notation, we move the decimal point so that the number to the left of the decimal point is between 1 and 10 and compensate by multiplying by the appropriate power of ten.

Solution (a) All four digits in 409.8 s are significant. The zero is between two significant figures, so it is significant. To write the number in scientific notation, we move the decimal point two places to the left and compensate by multiplying by 10^2: 4.098×10^2 s.

(b) The first two zeros in 0.058 700 cm are not significant; they are used to place the decimal point. The digits 5, 8, and 7 are significant, as are the two final zeros. The answer has five significant figures: 5.8700×10^{-2} cm.

(c) The 9 and 5 in 9500 g are significant, but the zeros are ambiguous. This number could have two, three, or four significant figures. If we take the most cautious approach and assume the zeros are not significant, then the number in scientific notation is 9.5×10^3 g.

(d) The final zero in 950.0×10^1 mL is significant since it comes after the decimal point. The zero to its left is also significant since it comes between two other significant digits. The result has four significant figures. The number is not in *standard* scientific notation since 950.0 is not between 1 and 10; in scientific notation we write 9.500×10^3 mL.

Discussion Scientific notation clearly indicates the number of significant figures since all zeros are significant; none are used only to place the decimal point. In (c), if the measurement was made to the nearest gram, we would write 9.500×10^3 g to show that the zeroes are significant.

Practice Problem 1.3 Identifying Significant Figures

State the number of significant figures in each of these measurements and rewrite them in standard scientific notation.

(a) 0.000 105 44 kg (b) 0.005 800 cm (c) 602 000 s

Significant Figures in Calculations

1. When two or more quantities are added or subtracted, the result is as precise as the *least precise* of the quantities (Example 1.4). If the quantities are written in scientific notation with different powers of ten, first rewrite them with the same power of ten. After adding or subtracting, round the result, keeping only as many decimal places as are significant in *all* of the quantities that were added or subtracted.
2. When quantities are multiplied or divided, the result has the same number of significant figures as the quantity with the *smallest number of significant figures* (see Example 1.5).
3. In a series of calculations, rounding to the correct number of significant figures should be done only at the end, *not at each step*. Rounding at each step would increase the chance that roundoff error could snowball and adversely affect the accuracy of the final answer. It's a good idea to keep *at least two* extra significant figures in calculations, then round at the end.

Example 1.4

Significant Figures in Addition

Calculate the sum 44.560 05 s + 0.0698 s + 1103.2 s.

Strategy The sum cannot be more precise than the least precise of the three quantities. The quantity 44.560 05 s is known to the nearest 0.000 01 s, 0.0698 s is known to the nearest 0.0001 s, and 1103.2 s is known to the nearest 0.1 s. Therefore the least precise is 1103.2 s. The sum has the same precision; it is known to the nearest tenth of a second.

continued on next page

Example 1.4 continued

Solution According to the calculator,

$$44.56005 + 0.0698 + 1103.2 = 1147.82985$$

We do *not* want to write all of those digits in the answer. That would imply greater precision than we actually have. Rounding to the nearest tenth of a second, the sum is written

$$= 1147.8 \text{ s}$$

which has five significant figures.

Discussion Note that the least precise measurement is not necessarily the one with the fewest number of significant figures. The least precise is the one whose rightmost significant figure represents the largest unit: the "2" in 1103.2 s represents 2 tenths of a second. In addition or subtraction, we are concerned with the precision rather than the number of significant figures. The three quantities to be added have seven, three, and five significant figures, respectively, but the sum has five significant figures.

Practice Problem 1.4 Significant Figures in Subtraction

Calculate the difference 568.42 m − 3.924 m and write the result in scientific notation. How many significant figures are in the result?

Example 1.5

Significant Figures in Multiplication

Find the product of 45.26 m/s and 2.41 s. How many significant figures does the product have?

Strategy The product should have the same number of significant figures as the factor with the least number of significant figures.

Solution A calculator gives

$$45.26 \times 2.41 = 109.0766$$

Since the answer should have only three significant figures, we round the answer to

$$45.26 \text{ m/s} \times 2.41 \text{ s} = 109 \text{ m}$$

Discussion Writing the answer as 109.0766 m would give the false impression that we know the answer to a precision of about 0.0001 m, whereas we actually have a precision of only about 1 m.

Note that although both factors were known to two decimal places, our solution is properly given with no decimal places. It is the number of significant figures that matters in multiplication or division. In scientific notation, we write 1.09×10^2 m.

Practice Problem 1.5 Significant Figures in Division

Write the solution to 28.84 m divided by 6.2 s with the correct number of significant figures.

When an integer, or a fraction of integers, is used in an equation, the precision of the result is not affected by the integer or the fraction; the number of significant figures is limited only by the measured values in the problem. The fraction $\frac{1}{2}$ in an equation is *exact;* it does not reduce the number of significant figures to one. In an equation such as $C = 2\pi r$ for the circumference of a circle of radius r, the factors 2 and π are exact. We use as many digits for π as we need to maintain the precision of the other quantities.

Order-of-Magnitude Estimates Sometimes a problem may be too complicated to solve precisely, or information may be missing that would be necessary for a precise calculation. In such a case, an **order-of-magnitude** solution is the best we can do. By *order of magnitude,* we mean "roughly what power of ten?" An order of magnitude calculation is done to at most one significant figure. Even when a more precise solution is feasible, it is often a good idea to start with a quick, "**back-of-the-envelope estimate**" (a calculation so short that it could easily fit on the back of an envelope). Why? Because we can often make a good guess about the correct order of magnitude of the answer to a problem, even before we start solving the problem. If the answer comes out with a different order of magnitude, we go back and search for an error. Suppose a problem concerns a vase that is knocked off a fourth-story window ledge. We can guess by experience the order of magnitude of the time it takes the vase to hit the ground. It might be 1 s, or 2 s, but we are certain that it is *not* 1000 s or 0.00001 s.

CHECKPOINT 1.4

What are some of the reasons for making order-of-magnitude estimates?

1.5 UNITS

A **metric system** of units has been used for many years in scientific work and in European countries. The metric system is based on powers of ten (Fig. 1.1). In 1960, the General Conference of Weights and Measures, an international authority on units, proposed a revised metric system called the *Système International d'Unités* in French (abbreviated **SI**), which uses the meter (m) for length, the kilogram (kg) for mass, the second (s) for time, and four more base units (Table 1.1). **Derived units** are constructed from combinations of the base units. For example, the SI unit of force is $kg{\cdot}m/s^2$ (which can also be written $kg{\cdot}m{\cdot}s^{-2}$); this combination of units is given a special name, the newton (N), in honor of Isaac Newton. The newton is a derived unit because it is composed of a combination of base units. When units are named after famous scientists, the name of the unit is written with a lowercase letter, even though it is based on a proper name; the *symbol* for the unit is written with an uppercase letter. The inside front cover of the book has a complete listing of the derived SI units used in this book.

As an alternative to explicitly writing powers of ten, SI uses prefixes for units to indicate power of ten factors. Table 1.2 shows some of the powers of ten and the SI prefixes used for them. These are also listed on the inside front cover of the book. Note that when an SI unit with a prefix is raised to a power, the prefix is *also* raised to that power. For example, $8\ cm^3 = 2\ cm \times 2\ cm \times 2\ cm$.

SI units are preferred in physics and are emphasized in this book. Since other units are sometimes used, we must know how to convert units. Various scientific fields, even in physics, sometimes use units other than SI units, whether for historical or practical

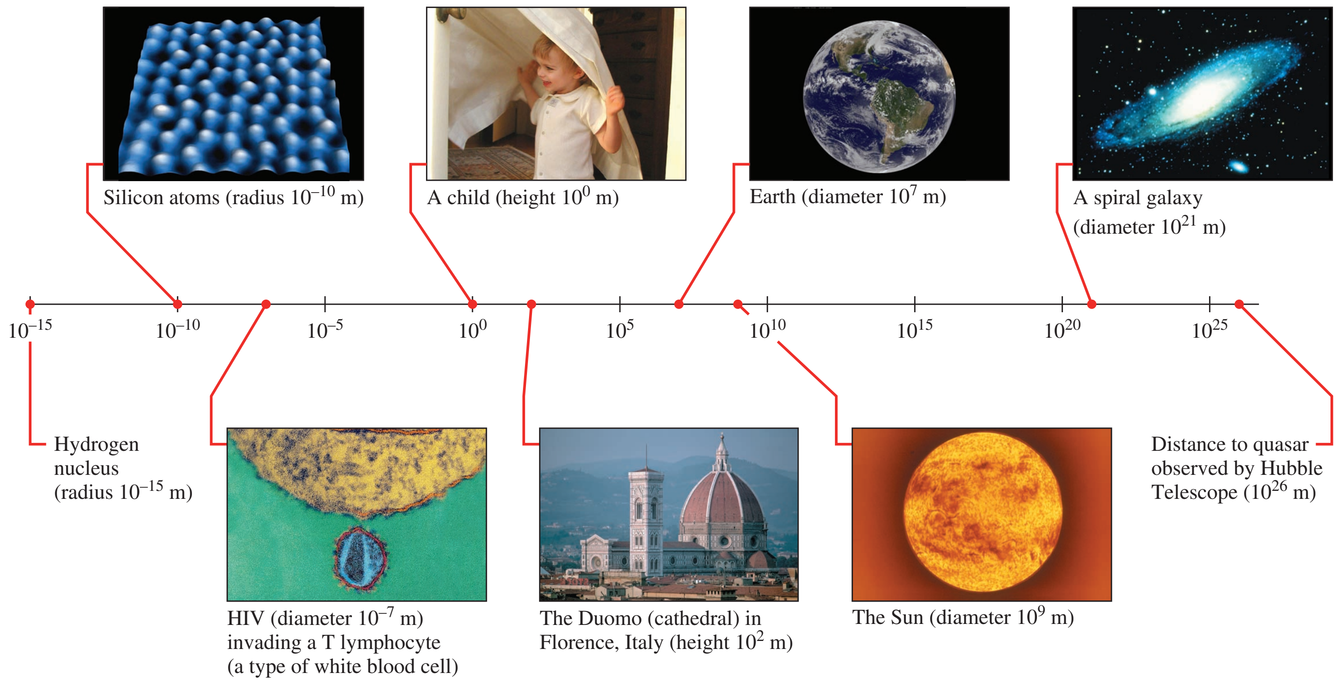


Figure 1.1 Scientific notation uses powers of ten to express quantities that have a wide range of values.

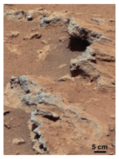
Table 1.1 SI Base Units

Quantity	Unit Name	Symbol	Definition
Length	meter	m	The distance traveled by light in vacuum during a time interval of 1/299 792 458 s.
Mass	kilogram	kg	The mass of the international prototype of the kilogram.
Time	second	s	The duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
Electric current	ampere	A	The constant current in two long, thin, straight, parallel conductors placed 1 m apart in vacuum that would produce a force on the conductors of 2×10^{-7} newtons per meter of length.
Temperature	kelvin	K	The fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
Amount of substance	mole	mol	The amount of substance that contains as many elementary entities as there are atoms in 0.012 kg of carbon-12.
Luminous intensity	candela*	cd	The luminous intensity, in a given direction, of a source that emits radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of 1/683 watts per steradian.

*Not used in this book

reasons. For example, in atomic and nuclear physics, the SI unit of energy (the joule, J) is rarely used; instead the energy unit used is usually the electron-volt (eV). Biologists and chemists use units that are not ordinarily used by physicists. One reason that SI is preferred is that it provides a common denominator—all scientists are familiar with the SI units.

In most of the world, SI units are used in everyday life and in industry. In the United States, however, the U.S. customary units—sometimes called English units—are still used. The base units for this system are the foot, the second, and the pound. The pound is legally defined in the United States as a unit of mass, but it is also commonly used as a unit of force (in which case it is sometimes called *pound-force*). Since mass and force are entirely different concepts in physics, this inconsistency is one good reason to use SI units.



What happened to the *Mars Climate Orbiter?*

In the autumn of 1999, to the chagrin of NASA, a $125 million spacecraft was destroyed as it was being maneuvered into orbit around Mars. The company building the booster rocket provided information about the rocket's thrust in U.S. customary units, but the NASA scientists who were controlling the rocket thought the figures provided were in metric units. Arthur Stephenson, chairman of the *Mars Climate Orbiter* Mission Failure Investigation Board, stated that, "The 'root cause' of the loss of the spacecraft was the failed translation of English units into metric units in a segment of ground-based, navigation-related mission software." After a journey of 122 million miles, the *Climate Orbiter* dipped about 15 miles too deep into the Martian atmosphere, causing the propulsion system to overheat. The discrepancy in units unfortunately caused a dramatic failure of the mission.

Table 1.2 SI Prefixes

Prefix (abbreviation)	Power of Ten
peta- (P)	10^{15}
tera- (T)	10^{12}
giga- (G)	10^{9}
mega- (M)	10^{6}
kilo- (k)	10^{3}
deci- (d)	10^{-1}
centi- (c)	10^{-2}
milli- (m)	10^{-3}
micro- (μ)	10^{-6}
nano- (n)	10^{-9}
pico- (p)	10^{-12}
femto- (f)	10^{-15}

Converting Units If the statement of a problem includes a mixture of different units, the units must be converted to a single, consistent set before the problem is solved. Quantities to be added or subtracted *must be expressed in the same units*. Usually the best way is to convert everything to SI units. Common conversion factors are listed on the inside front cover of this book.

Examples 1.6 and 1.7 illustrate the technique for converting units. The quantity to be converted is multiplied by one or more conversion factors written as a fraction equal to 1. The units are multiplied or divided as algebraic quantities.