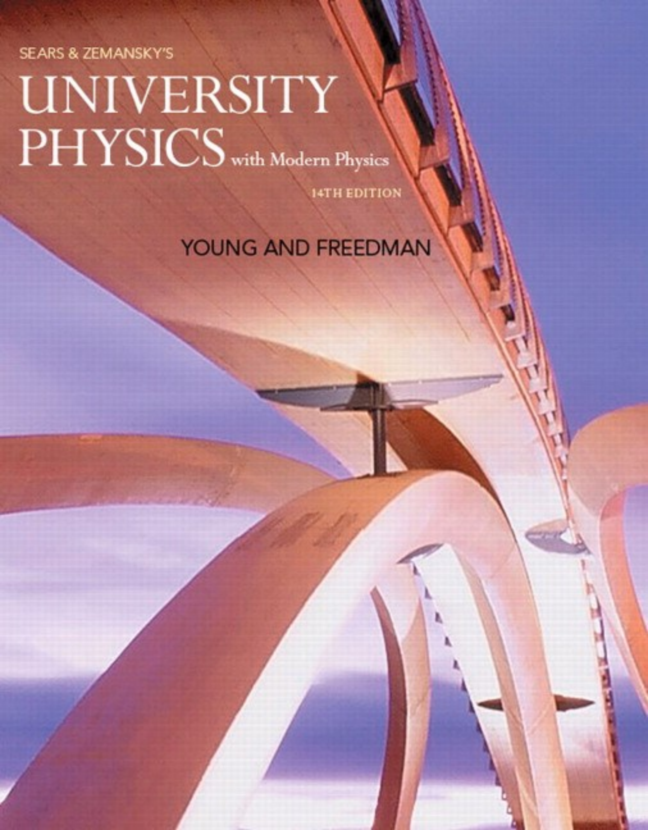
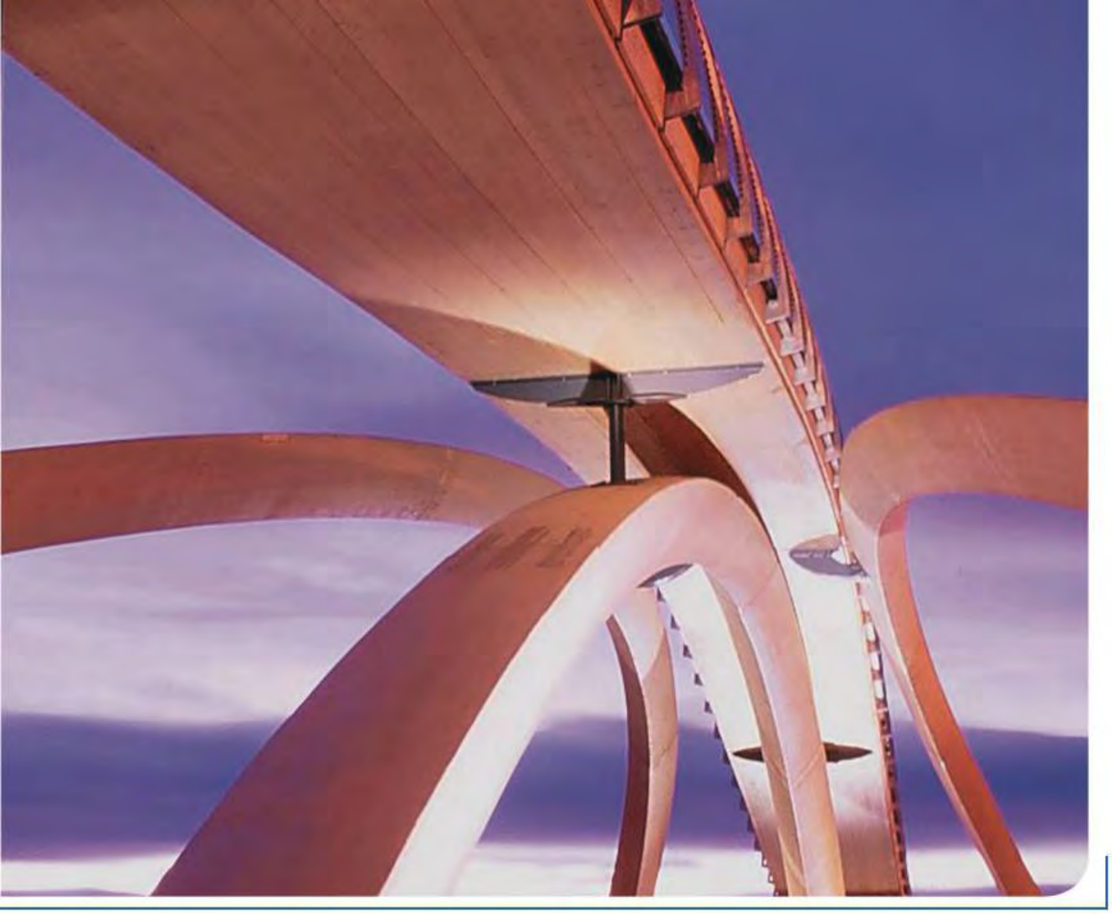
SEARS & ZEMANSKY'S

# UNIVERSITY PHYSICS with Modern Physics

14TH EDITION

YOUNG AND FREEDMAN





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# UNIVERSITY PHYSICS

## WITH MODERN PHYSICS

14TH EDITION


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# BRIEF CONTENTS



VOLUME 1: Chapters 1–20 • VOLUME 2: Chapters 21–37 • VOLUME 3: Chapters 37–44

# THE BENCHMARK FOR CLARITY AND RIGOR

Since its first edition, ***University Physics*** has been renowned for its emphasis on fundamental principles and how to apply them. This text is known for its clear and thorough narrative and for its uniquely broad, deep, and thoughtful set of worked examples—key tools for developing both conceptual understanding and problem-solving skills.

The **Fourteenth Edition** improves the defining features of the text while adding new features influenced by physics education research. A focus on visual learning, new problem types, and pedagogy informed by MasteringPhysics metadata headline the improvements designed to create the best learning resource for today's physics students.

## A FOCUS ON PROBLEM SOLVING

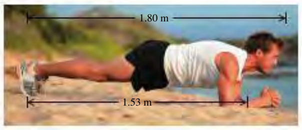
**EXAMPLE 11.2** LOCATING YOUR CENTER OF GRAVITY WHILE YOU WORK OUT

SOLUTION

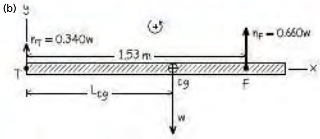
The *plank* (**Fig. 11.8a**) is a great way to strengthen abdominal, back, and shoulder muscles. You can also use this exercise position to locate your center of gravity. Holding plank position with a scale under his toes and another under his forearms, one athlete measured that 66.0% of his weight was supported by his forearms and 34.0% by his toes. (That is, the total normal forces on his forearms and toes were $0.660w$ and $0.340w$, respectively, where $w$ is the athlete's weight.) He is 1.80 m tall, and in plank position the distance from his toes to the middle of his forearms is 1.53 m. How far from his toes is his center of gravity?

**11.8** An athlete in plank position.

(a)




(b)




SOLUTION

**IDENTIFY and SET UP:** We can use the two conditions for equilibrium, Eqs. (11.6), for an athlete at rest. So both the net force and net torque on the athlete are zero. Figure 11.8b shows a free-body diagram, including $x$- and $y$-axes and our convention that counterclockwise torques are positive. The weight $w$ acts at the center of gravity, which is between the two supports (as it must be; see Section 11.2). Our target variable is the distance $L_{cg}$, the lever arm of the weight with respect to the toes $T$, so it is wise to take torques with respect to $T$. The torque due to the weight is negative (it tends to cause a clockwise rotation around $T$), upward normal force at the forearms $F$ is a counterclockwise rotation around $T$).

**EXECUTE:** The first condition for equilibrium $\sum F_x = 0$ because there are no $x$ because $0.340w + 0.660w + (-w) = 0$. equation and solve for $L_{cg}$:

$$\sum \tau_R = 0.340w(0) - wL_{cg} +$$
$$L_{cg} = 1.01 \text{ m}$$

**EVALUATE:** The center of gravity is navel (as it is for most people) and closer his toes, which is why his forearms You can check our result by writing the forearms $F$. You'll find that his center of forearms, or $(1.53 \text{ m}) - (0.52 \text{ m}) =$

◀ A research-based **PROBLEM-SOLVING APPROACH—IDENTIFY, SET UP, EXECUTE, EVALUATE**—is used in every Example and throughout the Student's and Instructor's Solutions Manuals and the Study Guide. This consistent approach teaches students to tackle problems thoughtfully rather than cutting straight to the math.

**PROBLEM-SOLVING STRATEGIES** ▶ coach students in how to approach specific types of problems.

**PROBLEM-SOLVING STRATEGY 3.1** PROJECTILE MOTION

**NOTE:** The strategies we used in Sections 2.4 and 2.5 for straight-line, constant-acceleration problems are also useful here.

**IDENTIFY** *the relevant concepts:* The key concept is that throughout projectile motion, the acceleration is downward and has a constant magnitude $g$. Projectile-motion equations don't apply to *throwing* a ball, because during the throw the ball is acted on by both the thrower's hand and gravity. These equations apply only *after* the ball leaves the thrower's hand.

**ET UP** *the problem* using the following steps:

1. Define your coordinate system and make a sketch showing your axes. It's almost always best to make the $x$-axis horizontal and the $y$-axis vertical, and to choose the origin to be where the body first becomes a projectile (for example, where a ball leaves the thrower's hand). Then the components of acceleration are $a_x = 0$ and $a_y = -g$, as in Eq. (3.13); the initial position is $x_0 = y_0 = 0$; and you can use Eqs. (3.19) through (3.22). (If you choose a different origin or axes, you'll have to modify these equations.)
2. List the unknown and known quantities, and decide which unknowns are your target variables. For example, you might be given the initial velocity (either the components or the magnitude and direction) and asked to find the coordinates and velocity components at some later time. Make sure that you have as many equations as there are target variables to be found. In addition to Eqs. (3.19) through (3.22), Eqs. (3.23) through (3.26) may be useful.
3. State the problem in words and then translate those words into symbols. For example, *when* does the particle arrive at a certain point? (That is, at what value of $t$?) *Where* is the particle when its velocity has a certain value? (That is, what are the values of $x$ and $y$ when $v_x$ or $v_y$ has the specified value?) Since $v_y = 0$ at the highest point in a trajectory, the question "When does the projectile reach its highest point?" translates into "What is the value of $t$ when $v_y = 0$?" Similarly, "When does the projectile return to its initial elevation?" translates into "What is the value of $t$ when $y = y_0$?"

**EXECUTE** *the solution:* Find the target variables using the equations you chose. Resist the temptation to break the trajectory into segments and analyze each segment separately. You don't have to start all over when the projectile reaches its highest point! It's almost always easier to use the same axes and time scale throughout the problem. If you need numerical values, use $g = 9.80 \text{ m/s}^2$. Remember that $g$ is positive!

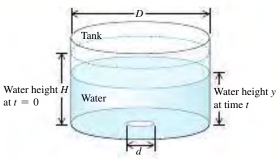
**EVALUATE** *your answer:* Do your results make sense? Do the numerical values seem reasonable?

**BRIDGING PROBLEM** HOW LONG TO DRAIN?

SOLUTION

A large cylindrical tank with diameter $D$ is open to the air at the top. The tank contains water to a height $H$. A small circular hole with diameter $d$, where $d \ll D$, is then opened at the bottom of the tank (**Fig. 12.32**). Ignore any effects of viscosity. (a) Find $y$, the height of water in the tank a time $t$ after the hole is opened, as a function of $t$. (b) How long does it take to drain the tank completely? (c) If you double height $H$, by what factor does the time to drain the tank increase?

**12.32** A water tank that is open at the top and has a hole at the bottom.




SOLUTION GUIDE

**IDENTIFY and SET UP**

1. Draw a sketch of the situation that shows all of the relevant dimensions.
2. List the unknown quantities, and decide which of these are the target variables.
3. At what speed does water flow out of the bottom of the tank? How is this related to the volume flow rate of water out of the tank? How is the volume flow rate related to the rate of change of $y$?

**EXECUTE**

4. Use your results from step 3 to write an equation for $dy/dt$.
5. Your result from step 4 is a relatively simple differential equation. With your knowledge of calculus, you can integrate it to find $y$ as a function of $t$. (*Hint:* Once you've done the integration, you'll still have to do a little algebra.)
6. Use your result from step 5 to find the time when the tank is empty. How does your result depend on the initial height $H$?

**EVALUATE**

7. Check whether your answers are reasonable. A good check is to draw a graph of $y$ versus $t$. According to your graph, what is the algebraic sign of $dy/dt$ at different times? Does this make sense?

◀ **BRIDGING PROBLEMS**, which help students move from single-concept worked examples to multi-concept problems at the end of the chapter, have been revised, based on reviewer feedback, ensuring that they are effective and at the appropriate difficulty level.

# INFLUENCED BY THE LATEST IN EDUCATION RESEARCH

## PEDAGOGY INFORMED BY DATA AND RESEARCH

### DATA *SPEAKS*

**Gravitation**

When students were given a problem about superposition of gravitational forces, more than 60% gave an incorrect response. Common errors:

- Assuming that equal-mass objects *A* and *B* must exert equally strong gravitational attraction on an object *C* (which is not true when *A* and *B* are different distances from *C*).
- Neglecting to account for the vector nature of force. (To add two forces that point in different directions, you can't just add the force magnitudes.)

◀ **DATA SPEAKS SIDEBARS**, based on MasteringPhysics metadata, alert students to the statistically most common mistakes made in solving problems on a given topic.

Coordinates at time $t$ of a **projectile** (positive $y$-direction is upward, and $x = y = 0$ at $t = 0$)

$$x = (v_0 \cos \alpha_0)t \quad (3.19)$$

$$y = (v_0 \sin \alpha_0)t - \tfrac{1}{2}gt^2 \quad (3.20)$$

Speed at $t = 0$ — Direction at $t = 0$ — Time

Velocity components at time $t$ of a **projectile** (positive $y$-direction is upward)

$$v_x = v_0 \cos \alpha_0 \quad (3.21)$$

$$v_y = v_0 \sin \alpha_0 - gt \quad (3.22)$$

Speed at $t = 0$ — Direction at $t = 0$ — Time

Acceleration due to gravity: Note $g > 0$.

▲ All **KEY EQUATIONS ARE NOW ANNOTATED** to help students make a connection between a conceptual and a mathematical understanding of physics.

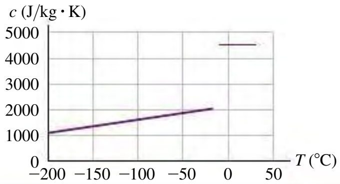
**PASSAGE PROBLEMS**

**BIO PRESERVING CELLS AT COLD TEMPERATURES.** In cryopreservation, biological materials are cooled to a very low temperature to slow down chemical reactions that might damage the cells or tissues. It is important to prevent the materials from forming ice crystals during freezing. One method for preventing ice formation is to place the material in a protective solution called a *cryoprotectant*. Stated values of the thermal properties of one cryoprotectant are listed here:

| | |
|---|---|
| Melting point | $-20°C$ |
| Latent heat of fusion | $2.80 \times 10^5$ J/kg |
| | $4.5 \times 10^3$ J/kg · K |

**17.117** Careful measurements show that the specific heat of the solid phase depends on temperature (**Fig. P17.117**). How will the actual time needed for this cryoprotectant to come to equilibrium with the cold plate compare with the time predicted by using the values in the table? Assume that all values other than the specific heat (solid) are correct. The actual time (a) will be shorter; (b) will be longer; (c) will be the same; (d) depends on the density of the cryoprotectant.

Figure **P17.117**




▲ Each chapter includes three to five **PASSAGE PROBLEMS**, which follow the format used in the MCATs. These problems require students to investigate multiple aspects of a real-life physical situation, typically biological in nature, as described in a reading passage.

**DATA PROBLEMS** appear in each chapter. These data-based reasoning problems, many of which are context rich, require students to use experimental evidence, presented in a tabular or graphical format, to formulate conclusions. ▼

**9.89** •• **DATA** You are rebuilding a 1965 Chevrolet. To decide whether to replace the flywheel with a newer, lighter-weight one, you want to determine the moment of inertia of the original, 35.6-cm-diameter flywheel. It is not a uniform disk, so you can't use $I = \frac{1}{2}MR^2$ to calculate the moment of inertia. You remove the flywheel from the car and use low-friction bearings to mount it on a horizontal, stationary rod that passes through the center of the flywheel, which can then rotate freely (about 2 m above the ground). After gluing one end of a long piece of flexible fishing line to the rim of the flywheel, you wrap the line a number of turns around the rim and suspend a 5.60-kg metal block from the free end of the line. When you release the block from rest, it descends as the flywheel rotates. With high-speed photography you measure the distance $d$ the block has moved downward as a function of the time since it was released. The equation for the graph shown in **Fig. P9.89** that gives a good fit to the data points is $d = (165 \text{ cm/s}^2)t^2$. (a) Based on the graph, does the block fall with constant acceleration? Explain. (b) Use the graph to calculate the speed of the block when it has descended 1.50 m. (c) Apply conservation of mechanical energy to the system of flywheel and block to calculate the moment of inertia of the flywheel. (d) You are relieved that the fishing line doesn't break. Apply Newton's second law to the block to find the tension in the line as the block descended.

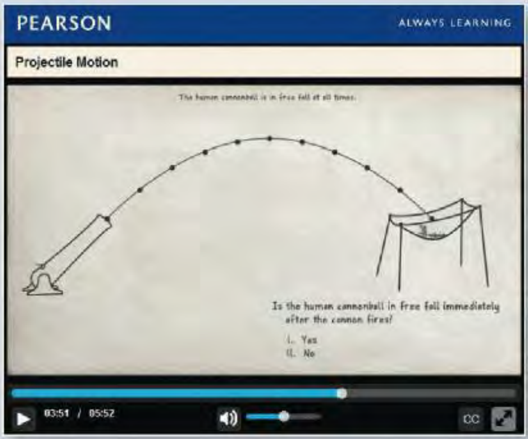
# PERSONALIZE LEARNING WITH MASTERINGPHYSICS

MasteringPhysics® from Pearson is the leading online homework, tutorial, and assessment system, designed to improve results by engaging students before, during, and after class with powerful content. Instructors can now ensure that students arrive ready to learn by assigning educationally effective content before class, and encourage critical thinking and retention with in-class resources such as Learning Catalytics. Students can further master concepts after class through traditional and adaptive homework assignments that provide hints and answer-specific feedback. The Mastering gradebook records scores for all automatically graded assignments in one place, while diagnostic tools give instructors access to rich data to assess student understanding and misconceptions.

Mastering brings learning full circle by continuously adapting to each student and making learning more personal than ever—before, during, and after class.

## BEFORE CLASS

**INTERACTIVE PRE-LECTURE VIDEOS** address the rapidly growing movement toward pre-lecture teaching and flipped classrooms. These videos provide a conceptual introduction to key topics. Embedded assessment helps students to prepare before lecture and instructors to identify student misconceptions.




**PRE-LECTURE CONCEPT QUESTIONS** check familiarity with key concepts, prompting students to do their assigned reading prior to coming to class. These quizzes keep students on track, keep them more engaged in lecture, and help you spot the concepts with which they have the most difficulty. Open-ended essay questions help students identify what they find most difficult about a concept, better informing you and assisting with "just-in-time" teaching.

## DURING CLASS

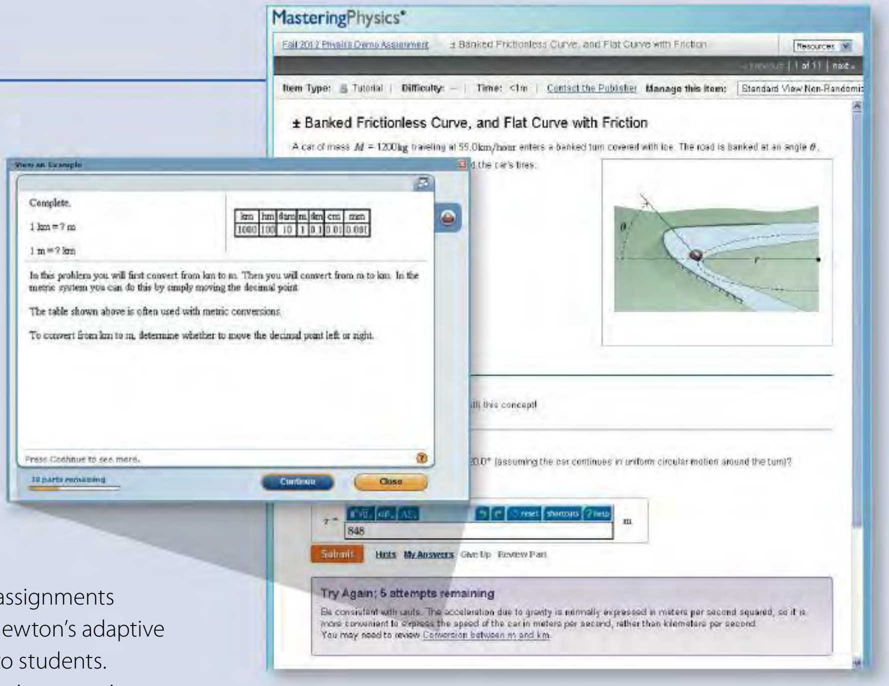
**LEARNING CATALYTICS™** is a "bring your own device" student engagement, assessment, and classroom intelligence system. With Learning Catalytics you can:

- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical-thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

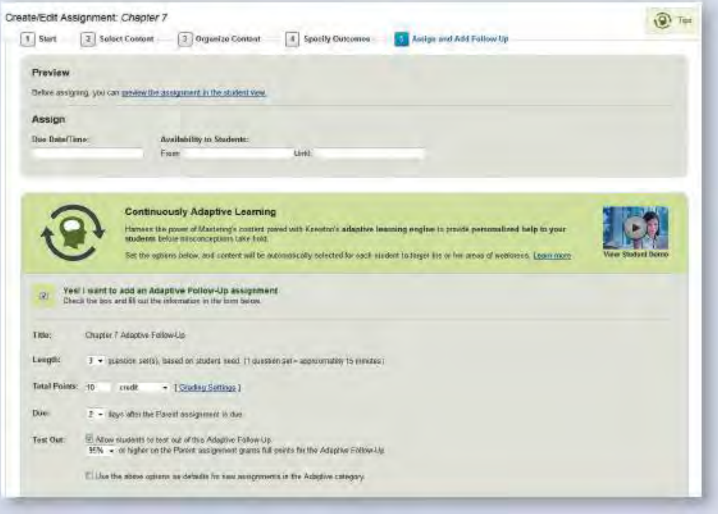
# BEFORE, DURING, AND AFTER CLASS

## AFTER CLASS

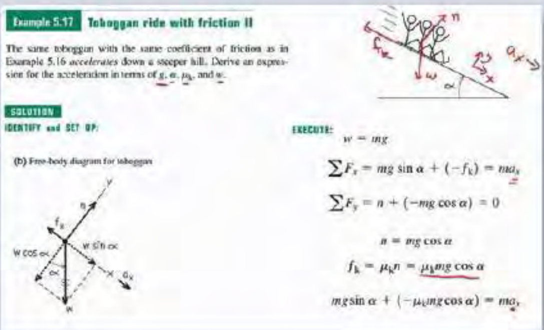
**TUTORIALS** featuring specific wrong-answer feedback, hints, and a wide variety of educationally effective content guide your students through the toughest topics in physics. The hallmark Hints and Feedback offer instruction similar to what students would experience in an office hour, allowing them to learn from their mistakes without being given the answer. ▶




**ADAPTIVE FOLLOW-UPS** are personalized assignments that pair Mastering's powerful content with Knewton's adaptive learning engine to provide personalized help to students. These assignments address common student misconceptions and topics students struggled with on assigned homework, including core prerequisite topics. ▼

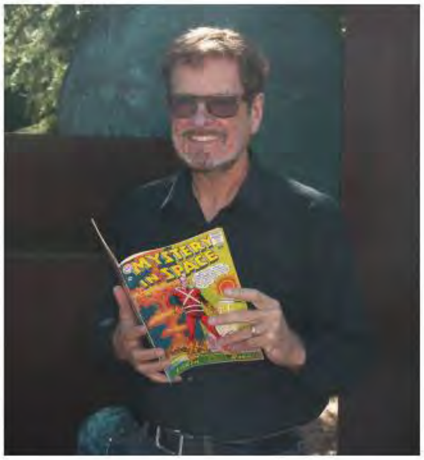



**VIDEO TUTOR DEMONSTRATIONS**, available in the Study Area and in the Item Library and accessible by QR code in the textbook, feature "pause-and-predict" demonstrations of key physics concepts as assessment to engage students actively in understanding key concepts. New VTDs build on the existing collection, adding new topics for a more robust set of demonstrations. ▼




◀ **VIDEO TUTOR SOLUTIONS** are tied to each worked example and Bridging Problem in the textbook and can be accessed through MasteringPhysics or from QR codes in the textbook. They walk students through the problem-solving process, providing a virtual teaching assistant on a round-the-clock basis.

# ABOUT THE AUTHORS




**Roger A. Freedman** is a Lecturer in Physics at the University of California, Santa Barbara. He was an undergraduate at the University of California campuses in San Diego and Los Angeles and did his doctoral research in nuclear theory at Stanford University under the direction of Professor J. Dirk Walecka. Dr. Freedman came to UCSB in 1981 after three years of teaching and doing research at the University of Washington.

At UCSB, Dr. Freedman has taught in both the Department of Physics and the College of Creative Studies, a branch of the university intended for highly gifted and motivated undergraduates. He has published research in nuclear physics, elementary particle physics, and laser physics. In recent years, he has worked to make physics lectures a more interactive experience through the use of classroom response systems and pre-lecture videos.

In the 1970s Dr. Freedman worked as a comic book letterer and helped organize the San Diego Comic-Con (now the world's largest popular culture convention) during its first few years. Today, when not in the classroom or slaving over a computer, Dr. Freedman can be found either flying (he holds a commercial pilot's license) or with his wife, Caroline, cheering on the rowers of UCSB Men's and Women's Crew.

## IN MEMORIAM: HUGH YOUNG (1930–2013)

**Hugh D. Young** was Emeritus Professor of Physics at Carnegie Mellon University. He earned both his undergraduate and graduate degrees from that university. He earned his Ph.D. in fundamental particle theory under the direction of the late Richard Cutkosky. Dr. Young joined the faculty of Carnegie Mellon in 1956 and retired in 2004. He also had two visiting professorships at the University of California, Berkeley.

Dr. Young's career was centered entirely on undergraduate education. He wrote several undergraduate-level textbooks, and in 1973 he became a coauthor with Francis Sears and Mark Zemansky for their well-known introductory textbooks. In addition to his role on Sears and Zemansky's *University Physics,* he was the author of Sears and Zemansky's *College Physics*.

Dr. Young earned a bachelor's degree in organ performance from Carnegie Mellon in 1972 and spent several years as Associate Organist at St. Paul's Cathedral in Pittsburgh. He often ventured into the wilderness to hike, climb, or go caving with students in Carnegie Mellon's Explorers Club, which he founded as a graduate student and later advised. Dr. Young and his wife, Alice, hosted up to 50 students each year for Thanksgiving dinners in their home.

Always gracious, Dr. Young expressed his appreciation earnestly: "I want to extend my heartfelt thanks to my colleagues at Carnegie Mellon, especially Professors Robert Kraemer, Bruce Sherwood, Ruth Chabay, Helmut Vogel, and Brian Quinn, for many stimulating discussions about physics pedagogy and for their support and encouragement during the writing of several successive editions of this book. I am equally indebted to the many generations of Carnegie Mellon students who have helped me learn what good teaching and good writing are, by showing me what works and what doesn't. It is always a joy and a privilege to express my gratitude to my wife, Alice, and our children, Gretchen and Rebecca, for their love, support, and emotional sustenance during the writing of several successive editions of this book. May all men and women be blessed with love such as theirs." We at Pearson appreciated his professionalism, good nature, and collaboration. He will be missed.

**A. Lewis Ford** is Professor of Physics at Texas A&M University. He received a B.A. from Rice University in 1968 and a Ph.D. in chemical physics from the University of Texas at Austin in 1972. After a one-year postdoc at Harvard University, he joined the Texas A&M physics faculty in 1973 and has been there ever since. Professor Ford has specialized in theoretical atomic physics—in particular, atomic collisions. At Texas A&M he has taught a variety of undergraduate and graduate courses, but primarily introductory physics.

## TO THE STUDENT

# HOW TO SUCCEED IN PHYSICS BY REALLY TRYING

***Mark Hollabaugh,*** *Normandale Community College, Emeritus*

Physics encompasses the large and the small, the old and the new. From the atom to galaxies, from electrical circuitry to aerodynamics, physics is very much a part of the world around us. You probably are taking this introductory course in calculus-based physics because it is required for subsequent courses that you plan to take in preparation for a career in science or engineering. Your professor wants you to learn physics and to enjoy the experience. He or she is very interested in helping you learn this fascinating subject. That is part of the reason your professor chose this textbook for your course. That is also the reason Drs. Young and Freedman asked me to write this introductory section. We want you to succeed!

The purpose of this section of *University Physics* is to give you some ideas that will assist your learning. Specific suggestions on how to use the textbook will follow a brief discussion of general study habits and strategies.

## PREPARATION FOR THIS COURSE

If you had high school physics, you will probably learn concepts faster than those who have not because you will be familiar with the language of physics. If English is a second language for you, keep a glossary of new terms that you encounter and make sure you understand how they are used in physics. Likewise, if you are further along in your mathematics courses, you will pick up the mathematical aspects of physics faster. Even if your mathematics is adequate, you may find a book such as Arnold D. Pickar's *Preparing for General Physics: Math Skill Drills and Other Useful Help (Calculus Version)* to be useful. Your professor may assign sections of this math review to assist your learning.

## LEARNING TO LEARN

Each of us has a different learning style and a preferred means of learning. Understanding your own learning style will help you to focus on aspects of physics that may give you difficulty and to use those components of your course that will help you overcome the difficulty. Obviously you will want to spend more time on those aspects that give you the most trouble. If you learn by hearing, lectures will be very important. If you learn by explaining, then working with other students will be useful to you. If solving problems is difficult for you, spend more time learning how to solve problems. Also, it is important to understand and develop good study habits. Perhaps the most important thing you can do for yourself is set aside adequate, regularly scheduled study time in a distraction-free environment.

***Answer the following questions for yourself:***

- Am I able to use fundamental mathematical concepts from algebra, geometry, and trigonometry? (If not, plan a program of review with help from your professor.)
- In similar courses, what activity has given me the most trouble? (Spend more time on this.) What has been the easiest for me? (Do this first; it will build your confidence.)
- Do I understand the material better if I read the book before or after the lecture? (You may learn best by skimming the material, going to lecture, and then undertaking an in-depth reading.)

- Do I spend adequate time studying physics? (A rule of thumb for a class like this is to devote, on average, 2.5 hours out of class for each hour in class. For a course that meets 5 hours each week, that means you should spend about 10 to 15 hours per week studying physics.)
- Do I study physics every day? (Spread that 10 to 15 hours out over an entire week!) At what time of the day am I at my best for studying physics? (Pick a specific time of the day and stick to it.)
- Do I work in a quiet place where I can maintain my focus? (Distractions will break your routine and cause you to miss important points.)

## WORKING WITH OTHERS

Scientists or engineers seldom work in isolation from one another but rather work cooperatively. You will learn more physics and have more fun doing it if you work with other students. Some professors may formalize the use of cooperative learning or facilitate the formation of study groups. You may wish to form your own informal study group with members of your class. Use e-mail to keep in touch with one another. Your study group is an excellent resource when you review for exams.

## LECTURES AND TAKING NOTES

An important component of any college course is the lecture. In physics this is especially important, because your professor will frequently do demonstrations of physical principles, run computer simulations, or show video clips. All of these are learning activities that will help you understand the basic principles of physics. Don't miss lectures. If for some reason you do, ask a friend or member of your study group to provide you with notes and let you know what happened.

Take your class notes in outline form, and fill in the details later. It can be very difficult to take word-for-word notes, so just write down key ideas. Your professor may use a diagram from the textbook. Leave a space in your notes and add the diagram later. After class, edit your notes, filling in any gaps or omissions and noting things that you need to study further. Make references to the textbook by page, equation number, or section number.

Ask questions in class, or see your professor during office hours. Remember that the only "dumb" question is the one that is not asked. Your college may have teaching assistants or peer tutors who are available to help you with any difficulties.

## EXAMINATIONS

Taking an examination is stressful. But if you feel adequately prepared and are well rested, your stress will be lessened. Preparing for an exam is a continuous process; it begins the moment the previous exam is over. You should immediately go over the exam to understand any mistakes you made. If you worked a problem and made substantial errors, try this: Take a piece of paper and divide it down the middle with a line from top to bottom. In one column, write the proper solution to the problem. In the other column, write what you did and why, if you know, and why your solution was incorrect. If you are uncertain why you made your mistake or how to avoid making it again, talk with your professor. Physics constantly builds on fundamental ideas, and it is important to correct any misunderstandings immediately. *Warning:* Although cramming at the last minute may get you through the present exam, you will not adequately retain the concepts for use on the next exam.

## TO THE INSTRUCTOR

# PREFACE

This book is the product of six and a half decades of leadership and innovation in physics education. When the first edition of *University Physics* by Francis W. Sears and Mark W. Zemansky was published in 1949, it was revolutionary among calculus-based physics textbooks in its emphasis on the fundamental principles of physics and how to apply them. The success of *University Physics* with generations of several million students and educators around the world is a testament to the merits of this approach and to the many innovations it has introduced subsequently.

In preparing this new Fourteenth Edition, we have further augmented and developed *University Physics* to assimilate the best ideas from education research with enhanced problem-solving instruction, pioneering visual and conceptual pedagogy, all-new categories of end-of-chapter problems, and the most pedagogically proven and widely used online homework and tutorial system in the world.

## NEW TO THIS EDITION

- **All key equations now include annotations** that describe the equation and explain the meanings of the symbols in the equation. These annotations help promote in-depth processing of information and greater recall.
- **DATA SPEAKS sidebars** in each chapter, based on data captured from thousands of students, alert students to the statistically most common mistakes students make when working problems on related topics in MasteringPhysics.
- **Updated modern physics content** includes sections on quantum measurement (Chapter 40) and quantum entanglement (Chapter 41), as well as recent data on the Higgs boson and cosmic background radiation (Chapter 44).
- **Additional bioscience applications** appear throughout the text, mostly in the form of marginal photos with explanatory captions, to help students see how physics is connected to many breakthroughs and discoveries in the biosciences.
- The **text has been streamlined** with tighter and more focused language.
- **Based on data from MasteringPhysics, changes to the end-of-chapter content** include the following:
  - **25%–30% of problems are new or revised.**
  - Most chapters include **six to ten biosciences-related problems.**
  - The number of **context-rich problems** is increased to facilitate the greater learning gains that they can offer.
  - **Three new DATA problems** appear in each chapter. These typically context-rich, data-based reasoning problems require students to use experimental evidence, presented in a tabular or graphical format, to formulate conclusions.
  - Each chapter now includes **three to five new Passage Problems,** which follow the format that is used in the MCATs. These problems require students to investigate multiple aspects of a real-life physical situation, typically biological in nature, that is described in a reading passage.
- **Looking back at ...** essential past concepts are listed at the beginning of each chapter, so that students know what they need to have mastered before digging into the current chapter.

***Standard, Extended, and Three-Volume Editions***

*With MasteringPhysics:*

- **Standard Edition:** Chapters 1–37 (ISBN 978-0-13-409650-6)
- **Extended Edition:** Chapters 1–44 (ISBN 978-0-321-98258-2)

*Without MasteringPhysics:*

- **Standard Edition:** Chapters 1–37 (ISBN 978-0-13-396929-0)
- **Extended Edition:** Chapters 1–44 (ISBN 978-0-321-97361-0)
- **Volume 1:** Chapters 1–20 (ISBN 978-0-13-397804-9)
- **Volume 2:** Chapters 21–37 (ISBN 978-0-13-397800-1)
- **Volume 3:** Chapters 37–44 (ISBN 978-0-13-397802-5)

## KEY FEATURES OF *UNIVERSITY PHYSICS*

DEMO

- More than 620 **QR codes** throughout the book allow students to use a mobile phone to watch an interactive video of a physics instructor giving a relevant physics demonstration (Video Tutor Demonstration) or showing a narrated and animated worked Example (Video Tutor Solution).

  All of these videos also play directly through links within the Pearson eText as well as the Study Area within MasteringPhysics.
- End-of-chapter **Bridging Problems,** many revised, provide a transition between the single-concept Examples and the more challenging end-of-chapter problems. Each Bridging Problem poses a difficult, multiconcept problem that typically incorporates physics from earlier chapters. A skeleton **Solution Guide,** consisting of questions and hints, helps train students to approach and solve challenging problems with confidence.
- Deep and extensive **problem sets** cover a wide range of difficulty (with blue dots to indicate relative difficulty level) and exercise both physical understanding and problem-solving expertise. Many problems are based on complex real-life situations.
- This textbook offers more **Examples** and **Conceptual Examples** than most other leading calculus-based textbooks, allowing students to explore problem-solving challenges that are not addressed in other textbooks.
- A research-based **problem-solving approach (Identify, Set Up, Execute, Evaluate)** is used in every Example as well as in the Problem-Solving Strategies, in the Bridging Problems, and throughout the Instructor's Solutions Manual and the Study Guide. This consistent approach teaches students to tackle problems thoughtfully rather than cutting straight to the math.
- **Problem-Solving Strategies** coach students in how to approach specific types of problems.
- The **figures** use a simplified graphical style to focus on the physics of a situation, and they incorporate more **explanatory annotations** than in the previous edition. Both techniques have been demonstrated to have a strong positive effect on learning.
- Many figures that illustrate Example solutions take the form of black-and-white **pencil sketches,** which directly represent what a student should draw in solving such problems themselves.
- The popular **Caution paragraphs** focus on typical misconceptions and student problem areas.
- End-of-section **Test Your Understanding** questions let students check their grasp of the material and use a multiple-choice or ranking-task format to probe for common misconceptions.
- **Visual Summaries** at the end of each chapter present the key ideas in words, equations, and thumbnail pictures, helping students review more effectively.
- **Approximately 70 PhET simulations** are linked to the Pearson eText and provided in the Study Area of the MasteringPhysics website (with icons in the printed book). These powerful simulations allow students to interact productively with the physics concepts they are learning. PhET clicker questions are also included on the Instructor's Resource DVD.

## INSTRUCTOR'S SUPPLEMENTS

**Note:** *For convenience, all of the following instructor's supplements (except for the Instructor's Resource DVD) can be downloaded from the Instructor Resources Area accessed via MasteringPhysics (www.masteringphysics.com).*

The **Instructor's Solutions Manual,** prepared by A. Lewis Ford (Texas A&M University) and Wayne Anderson, contains complete and detailed solutions to all end-of-chapter problems. All solutions follow consistently the same Identify/Set Up/Execute/Evaluate problem-solving framework used in the textbook. Download only from the MasteringPhysics Instructor Area or from the Instructor Resource Center (www.pearsonhighered.com/irc).

The cross-platform **Instructor's Resource DVD** (978-0-13-398364-7) provides a comprehensive library of approximately 350 applets from ActivPhysics OnLine as well as all art and photos from the textbook in JPEG and PowerPoint formats. In addition, all of the key equations, problem-solving strategies, tables, and chapter summaries are provided in JPEGs and editable Word format, and all of the new Data Speaks boxes are offered in JPEGs. In-class weekly multiple-choice questions for use with various Classroom Response Systems (CRS) are also provided, based on the Test Your Understanding questions and chapter-opening questions in the text. Written by Roger Freedman, many new CRS questions that increase in difficulty level have been added. Lecture outlines and PhET clicker questions, both in PowerPoint format, are also included along with about 70 PhET simulations and the Video Tutor Demonstrations (interactive video demonstrations) that are linked to QR codes throughout the textbook.

**MasteringPhysics®** (www.masteringphysics.com) from Pearson is the leading online teaching and learning system designed to improve results by engaging students before, during, and after class with powerful content. Ensure that students arrive ready to learn by assigning educationally effective content before class, and encourage critical thinking and retention with in-class resources such as Learning Catalytics. Students can further master concepts after class through traditional homework assignments that provide hints and answer-specific feedback. The Mastering gradebook records scores for all automatically graded assignments, while diagnostic tools give instructors access to rich data to assess student understanding and misconceptions.

Mastering brings learning full circle by continuously adapting to each student and making learning more personal than ever—before, during, and after class.

- **NEW!** The **Mastering Instructor Resources Area** contains all of the contents of the Instructor's Resource DVD—lecture outlines; Classroom Response System questions; images, tables, key equations, problem-solving strategies, Data Speaks boxes, and chapter summaries from the textbook; access to the Instructor's Solutions Manual, Test Bank, ActivPhysics Online—and much more.
- **NEW! Pre-lecture Videos** are assignable interactive videos that introduce students to key topics before they come to class. Each one includes assessment that feeds to the gradebook and alerts the instructor to potential trouble spots for students.
- **Pre-lecture Concept Questions** check students' familiarity with key concepts, prompting students to do their assigned reading before they come to class. These quizzes keep students on track, keep them more engaged in lecture, and help you spot the concepts that students find the most difficult.
- **NEW! Learning Catalytics** is a "bring your own device" student engagement, assessment, and classroom intelligence system that allows you to assess students in real time, understand immediately where they are and adjust your lecture accordingly, improve their critical-thinking skills, access rich analytics to understand student performance, add your own questions to fit your course exactly, and manage student interactions with intelligent grouping and timing. Learning Catalytics can be used both during and after class.
- **NEW! Adaptive Follow-Ups** allow Mastering to adapt continuously to each student, making learning more personal than ever. These assignments pair Mastering's powerful content with Knewton's adaptive learning engine to provide personalized help to students before misconceptions take hold. They are based on each student's performance on homework assignments and on all work in the course to date, including core prerequisite topics.

- **Video Tutor Demonstrations,** linked to QR codes in the textbook, feature "Pause and predict" videos of key physics concepts that ask students to submit a prediction before they see the outcome. These interactive videos are available in the Study Area of Mastering and in the Pearson eText.
- **Video Tutor Solutions** are linked to QR codes in the textbook. In these videos, which are available in the Study Area of Mastering and in the Pearson eText, an instructor explains and solves each worked example and Bridging Problem.
- **NEW!** An **Alternative Problem Set** in the Item Library of Mastering includes hundreds of new end-of-chapter questions and problems to offer instructors a wealth of options.
- **NEW! Physics/Biology Tutorials for MasteringPhysics** are assignable, multipart tutorials that emphasize biological processes and structures but also teach the physics principles that underlie them. They contain assessment questions that are based on the core competencies outlined in the 2015 MCAT.
- **PhET Simulations** (from the PhET project at the University of Colorado) are interactive, research-based simulations of physical phenomena. These tutorials, correlated to specific topics in the textbook, are available in the Pearson eText and in the Study Area within www.masteringphysics.com.
- **ActivPhysics OnLine**™ (which is accessed through the Study Area and Instructor Resources within www.masteringphysics.com) provides a comprehensive library of approximately 350 tried and tested ActivPhysics applets updated for web delivery.
- Mastering's **powerful gradebook** records all scores for automatically graded assignments. Struggling students and challenging assignments are highlighted in red, giving you an at-a-glance view of potential hurdles in the course. With a single click, charts summarize the most difficult problems, identify vulnerable students, and show the grade distribution, allowing for just-in-time teaching to address student misconceptions.
- **Learning Management System (LMS) Integration** gives seamless access to modified Mastering. Having all of your course materials and communications in one place makes life less complicated for you and your students. We've made it easier to link from within your LMS to modified Mastering and provide solutions, regardless of your LMS platform. With seamless, single sign-on your students will gain access to the personalized learning resources that make studying more efficient and more effective. You can access modified Mastering assignments, rosters, and resources and synchronize grades from modified Mastering with LMS.
- The **Test Bank** contains more than 2000 high-quality problems, with a range of multiple-choice, true/false, short-answer, and regular homework-type questions. Test files are provided both in TestGen (an easy-to-use, fully networkable program for creating and editing quizzes and exams) and in Word format. Download only from the MasteringPhysics Instructor Resources Area or from the Instructor Resources Center (www.pearsonhighered.com/irc).

MasteringPhysics enables instructors to:

- Quickly build homework assignments that combine regular end-of-chapter problems and tutoring (through additional multistep tutorial problems that offer wrong-answer feedback and simpler problems upon request).
- Expand homework to include the widest range of automatically graded activities available—from numerical problems with randomized values, through algebraic answers, to free-hand drawing.
- Choose from a wide range of nationally pre-tested problems that provide accurate estimates of time to complete and difficulty.
- After an assignment is completed, quickly identify not only the problems that were the trickiest for students but also the individual problem types with which students had trouble.

- Compare class results against the system's worldwide average for each problem assigned, to identify issues to be addressed with just-in-time teaching.
- Check the work of an individual student in detail, including the time spent on each problem, what wrong answers were submitted at each step, how much help was asked for, and how many practice problems were worked.

## STUDENT'S SUPPLEMENTS

The **Student's Study Guide** by Laird Kramer reinforces the textbook's emphasis on problem-solving strategies and student misconceptions. The *Study Guide for Volume 1* (978-0-13-398361-6) covers Chapters 1–20, and the *Study Guide for Volumes 2 and 3* (978-0-13-398360-9) covers Chapters 21–44.

The **Student's Solutions Manual** by A. Lewis Ford (Texas A&M University) and Wayne Anderson contains detailed, step-by-step solutions to more than half of the odd-numbered end-of-chapter problems from the textbook. All solutions follow consistently the same Identify/Set Up/Execute/Evaluate problem-solving framework used in the textbook. The *Student's Solutions Manual for Volume 1* (978-0-13-398171-1) covers Chapters 1–20, and the *Student's Solutions Manual for Volumes 2 and 3* (978-0-13-396928-3) covers Chapters 21–44.

**MasteringPhysics®** (www.masteringphysics.com) is a homework, tutorial, and assessment system based on years of research into how students work physics problems and precisely where they need help. Studies show that students who use MasteringPhysics compared to handwritten homework significantly increase their scores. MasteringPhysics achieves this improvement by providing students with instantaneous feedback specific to their wrong answers, simpler sub-problems upon request when they get stuck, and partial credit for their method(s). This individualized, 24/7 Socratic tutoring is recommended by nine out of ten students to their peers as the most effective and time-efficient way to study.

**Pearson eText** is available through MasteringPhysics either automatically, when MasteringPhysics is packaged with new books, or as a purchased upgrade online. Allowing students access to the text wherever they have access to the Internet, Pearson eText comprises the full text, including figures that can be enlarged for better viewing. With eText, students are also able to pop up definitions and terms to help with vocabulary and the reading of the material. Students can also take notes in eText by using the annotation feature at the top of each page.

**Pearson Tutor Services** (www.pearsontutorservices.com). Each student's subscription to MasteringPhysics also contains complimentary access to Pearson Tutor Services, powered by Smarthinking, Inc. By logging in with their MasteringPhysics ID and password, students are connected to highly qualified e-instructors who provide additional interactive online tutoring on the major concepts of physics. Some restrictions apply; the offer is subject to change.

**TIPERs** (Tasks Inspired by Physics Education Research) are workbooks that give students the practice they need to develop reasoning about physics and that promote a conceptual understanding of problem solving:

- **NEW! TIPERs: Sensemaking Tasks for Introductory Physics** (978-0-13-285458-0) by Curtis Hieggelke, Stephen Kanim, David Maloney, and Thomas O'Kuma
- **Newtonian Tasks Inspired by Physics Education Research: nTIPERs** (978-0-321-75375-5) by Curtis Hieggelke, David Maloney, and Stephen Kanim
- **E&M TIPERs: Electricity & Magnetism Tasks** (978-0-13-185499-4) by Curtis Hieggelke, David Maloney, Thomas O'Kuma, and Stephen Kanim

**Tutorials in Introductory Physics** (978-0-13-097069-5) by Lillian C. McDermott and Peter S. Schaffer presents a series of physics tutorials designed by a leading physics education research group. Emphasizing the development of concepts and scientific reasoning skills, the tutorials focus on the specific conceptual and reasoning difficulties that students tend to encounter.

## ACKNOWLEDGMENTS

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## PLEASE TELL ME WHAT YOU THINK!

I welcome communications from students and professors, especially concerning errors or deficiencies that you find in this edition. The late Hugh Young and I have devoted a lot of time and effort to writing the best book we know how to write, and I hope it will help as you teach and learn physics. In turn, you can help me by letting me know what still needs to be improved! Please feel free to contact me either electronically or by ordinary mail. Your comments will be greatly appreciated.

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# DETAILED CONTENTS

## MECHANICS

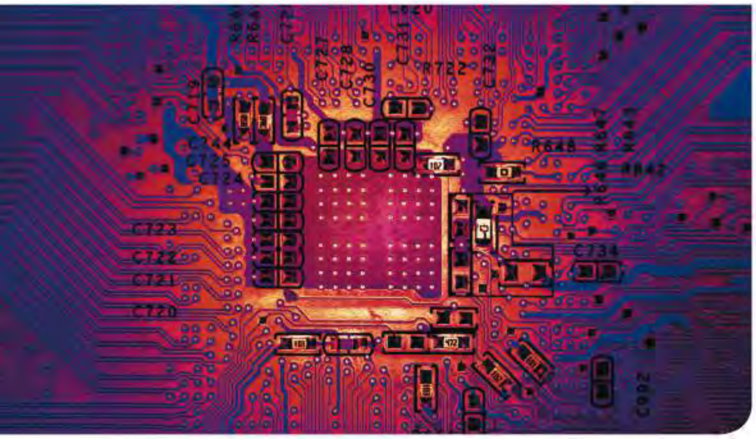


## THERMODYNAMICS



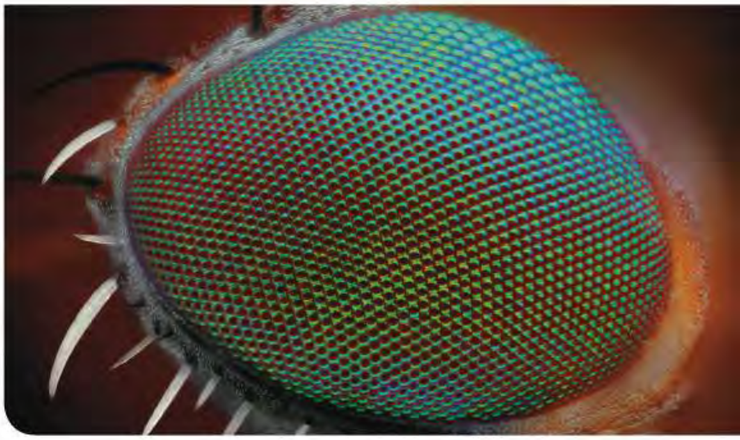


## ELECTROMAGNETISM



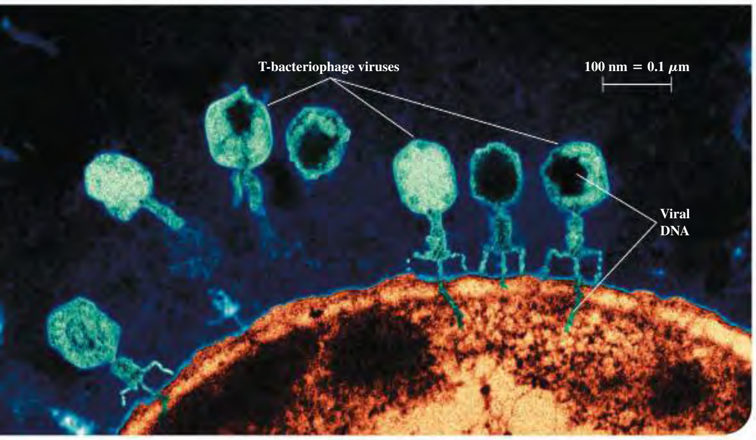
## OPTICS







## MODERN PHYSICS


T-bacteriophage viruses
100 nm = 0.1 μm
Viral DNA

? Tornadoes are spawned by severe thunderstorms, so being able to predict the path of thunderstorms is essential. If a thunderstorm is moving at 15 km/h in a direction 37° north of east, how far north does the thunderstorm move in 2.0 h? (i) 30 km; (ii) 24 km; (iii) 18 km; (iv) 12 km; (v) 9 km.

# 1 UNITS, PHYSICAL QUANTITIES, AND VECTORS

## LEARNING GOALS

*Looking forward at …*

- **1.1** What a physical theory is.
- **1.2** The four steps you can use to solve any physics problem.
- **1.3** Three fundamental quantities of physics and the units physicists use to measure them.
- **1.4** How to work with units in your calculations.
- **1.5** How to keep track of significant figures in your calculations.
- **1.6** How to make rough, order-of-magnitude estimates.
- **1.7** The difference between scalars and vectors, and how to add and subtract vectors graphically.
- **1.8** What the components of a vector are and how to use them in calculations.
- **1.9** What unit vectors are and how to use them with components to describe vectors.
- **1.10** Two ways to multiply vectors: the scalar (dot) product and the vector (cross) product.

Physics is one of the most fundamental of the sciences. Scientists of all disciplines use the ideas of physics, including chemists who study the structure of molecules, paleontologists who try to reconstruct how dinosaurs walked, and climatologists who study how human activities affect the atmosphere and oceans. Physics is also the foundation of all engineering and technology. No engineer could design a flat-screen TV, a prosthetic leg, or even a better mousetrap without first understanding the basic laws of physics.

The study of physics is also an adventure. You will find it challenging, sometimes frustrating, occasionally painful, and often richly rewarding. If you've ever wondered why the sky is blue, how radio waves can travel through empty space, or how a satellite stays in orbit, you can find the answers by using fundamental physics. You will come to see physics as a towering achievement of the human intellect in its quest to understand our world and ourselves.

In this opening chapter, we'll go over some important preliminaries that we'll need throughout our study. We'll discuss the nature of physical theory and the use of idealized models to represent physical systems. We'll introduce the systems of units used to describe physical quantities and discuss ways to describe the accuracy of a number. We'll look at examples of problems for which we can't (or don't want to) find a precise answer, but for which rough estimates can be useful and interesting. Finally, we'll study several aspects of vectors and vector algebra. We'll need vectors throughout our study of physics to help us describe and analyze physical quantities, such as velocity and force, that have direction as well as magnitude.

## 1.1 THE NATURE OF PHYSICS

Physics is an *experimental* science. Physicists observe the phenomena of nature and try to find patterns that relate these phenomena. These patterns are called physical theories or, when they are very well established and widely used, physical laws or principles.

**CAUTION** **The meaning of "theory"** A theory is *not* just a random thought or an unproven concept. Rather, a theory is an explanation of natural phenomena based on observation and accepted fundamental principles. An example is the well-established theory of biological evolution, which is the result of extensive research and observation by generations of biologists.

**1.1** Two research laboratories.

(a) According to legend, Galileo investigated falling objects by dropping them from the Leaning Tower of Pisa, Italy, ...

... and he studied pendulum motion by observing the swinging chandelier in the adjacent cathedral.

(b) The Planck spacecraft is designed to study the faint electromagnetic radiation left over from the Big Bang 13.8 billion years ago.

These technicians are reflected in the spacecraft's light-gathering mirror during pre-launch testing.

To develop a physical theory, a physicist has to learn to ask appropriate questions, design experiments to try to answer the questions, and draw appropriate conclusions from the results. **Figure 1.1** shows two important facilities used for physics experiments.

Legend has it that Galileo Galilei (1564–1642) dropped light and heavy objects from the top of the Leaning Tower of Pisa (Fig. 1.1a) to find out whether their rates of fall were different. From examining the results of his experiments (which were actually much more sophisticated than in the legend), he made the inductive leap to the principle, or theory, that the acceleration of a falling object is independent of its weight.

The development of physical theories such as Galileo's often takes an indirect path, with blind alleys, wrong guesses, and the discarding of unsuccessful theories in favor of more promising ones. Physics is not simply a collection of facts and principles; it is also the *process* by which we arrive at general principles that describe how the physical universe behaves.

No theory is ever regarded as the final or ultimate truth. The possibility always exists that new observations will require that a theory be revised or discarded. It is in the nature of physical theory that we can disprove a theory by finding behavior that is inconsistent with it, but we can never prove that a theory is always correct.

Getting back to Galileo, suppose we drop a feather and a cannonball. They certainly do *not* fall at the same rate. This does not mean that Galileo was wrong; it means that his theory was incomplete. If we drop the feather and the cannonball *in a vacuum* to eliminate the effects of the air, then they do fall at the same rate. Galileo's theory has a **range of validity:** It applies only to objects for which the force exerted by the air (due to air resistance and buoyancy) is much less than the weight. Objects like feathers or parachutes are clearly outside this range.

## 1.2 SOLVING PHYSICS PROBLEMS

At some point in their studies, almost all physics students find themselves thinking, "I understand the concepts, but I just can't solve the problems." But in physics, truly understanding a concept *means* being able to apply it to a variety of problems. Learning how to solve problems is absolutely essential; you don't *know* physics unless you can *do* physics.

How do you learn to solve physics problems? In every chapter of this book you will find *Problem-Solving Strategies* that offer techniques for setting up and solving problems efficiently and accurately. Following each *Problem-Solving Strategy* are one or more worked *Examples* that show these techniques in action. (The *Problem-Solving Strategies* will also steer you away from some *incorrect* techniques that you may be tempted to use.) You'll also find additional examples that aren't associated with a particular *Problem-Solving Strategy*. In addition, at the end of each chapter you'll find a *Bridging Problem* that uses more than one of the key ideas from the chapter. Study these strategies and problems carefully, and work through each example for yourself on a piece of paper.

Different techniques are useful for solving different kinds of physics problems, which is why this book offers dozens of *Problem-Solving Strategies.* No matter what kind of problem you're dealing with, however, there are certain key steps that you'll always follow. (These same steps are equally useful for problems in math, engineering, chemistry, and many other fields.) In this book we've organized these steps into four stages of solving a problem.

All of the *Problem-Solving Strategies* and *Examples* in this book will follow these four steps. (In some cases we will combine the first two or three steps.) We encourage you to follow these same steps when you solve problems yourself. You may find it useful to remember the acronym ***I SEE***—short for *Identify, Set up, Execute,* and *Evaluate.*

**PROBLEM-SOLVING STRATEGY 1.1 SOLVING PHYSICS PROBLEMS**

**IDENTIFY** *the relevant concepts:* Use the physical conditions stated in the problem to help you decide which physics concepts are relevant. Identify the **target variables** of the problem—that is, the quantities whose values you're trying to find, such as the speed at which a projectile hits the ground, the intensity of a sound made by a siren, or the size of an image made by a lens. Identify the known quantities, as stated or implied in the problem. This step is essential whether the problem asks for an algebraic expression or a numerical answer.

**SET UP** *the problem:* Given the concepts you have identified, the known quantities, and the target variables, choose the equations that you'll use to solve the problem and decide how you'll use them. Make sure that the variables you have identified correlate exactly with those in the equations. If appropriate, draw a sketch of the situation described in the problem. (Graph paper, ruler, protractor, and compass will help you make clear, useful sketches.) As best you can, estimate what your results will be and, as appropriate, predict what the physical behavior of a system will be. The worked examples in this book include tips on how to make these kinds of estimates and predictions. If this seems challenging, don't worry—you'll get better with practice!

**EXECUTE** *the solution:* This is where you "do the math." Study the worked examples to see what's involved in this step.

**EVALUATE** *your answer:* Compare your answer with your estimates, and reconsider things if there's a discrepancy. If your answer includes an algebraic expression, assure yourself that it correctly represents what would happen if the variables in it had very large or very small values. For future reference, make note of any answer that represents a quantity of particular significance. Ask yourself how you might answer a more general or more difficult version of the problem you have just solved.

## Idealized Models

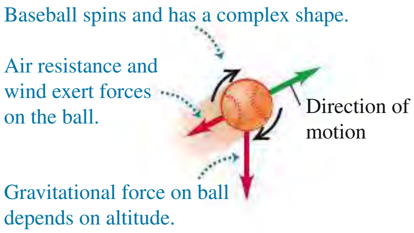
In everyday conversation we use the word "model" to mean either a small-scale replica, such as a model railroad, or a person who displays articles of clothing (or the absence thereof). In physics a **model** is a simplified version of a physical system that would be too complicated to analyze in full detail.

For example, suppose we want to analyze the motion of a thrown baseball (**Fig. 1.2a**). How complicated is this problem? The ball is not a perfect sphere (it has raised seams), and it spins as it moves through the air. Air resistance and wind influence its motion, the ball's weight varies a little as its altitude changes, and so on. If we try to include all these things, the analysis gets hopelessly complicated. Instead, we invent a simplified version of the problem. We ignore the size and shape of the ball by representing it as a point object, or **particle.** We ignore air resistance by making the ball move in a vacuum, and we make the weight constant. Now we have a problem that is simple enough to deal with (Fig. 1.2b). We will analyze this model in detail in Chapter 3.

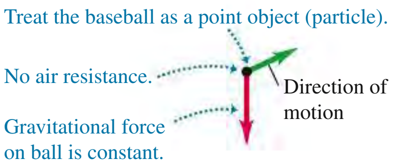
We have to overlook quite a few minor effects to make an idealized model, but we must be careful not to neglect too much. If we ignore the effects of gravity completely, then our model predicts that when we throw the ball up, it will go in a straight line and disappear into space. A useful model simplifies a problem enough to make it manageable, yet keeps its essential features.

**1.2** To simplify the analysis of (a) a baseball in flight, we use (b) an idealized model.

(a) A real baseball in flight




(b) An idealized model of the baseball



The validity of the predictions we make using a model is limited by the validity of the model. For example, Galileo's prediction about falling objects (see Section 1.1) corresponds to an idealized model that does not include the effects of air resistance. This model works fairly well for a dropped cannonball, but not so well for a feather.

Idealized models play a crucial role throughout this book. Watch for them in discussions of physical theories and their applications to specific problems.

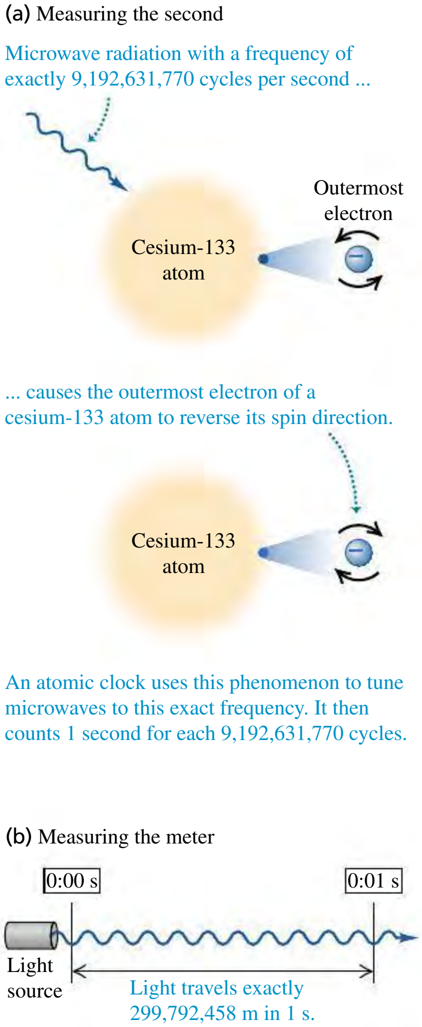
## 1.3 STANDARDS AND UNITS

As we learned in Section 1.1, physics is an experimental science. Experiments require measurements, and we generally use numbers to describe the results of measurements. Any number that is used to describe a physical phenomenon quantitatively is called a **physical quantity.** For example, two physical quantities that describe you are your weight and your height. Some physical quantities are so fundamental that we can define them only by describing how to measure them. Such a definition is called an **operational definition.** Two examples are measuring a distance by using a ruler and measuring a time interval by using a stopwatch. In other cases we define a physical quantity by describing how to calculate it from other quantities that we *can* measure. Thus we might define the average speed of a moving object as the distance traveled (measured with a ruler) divided by the time of travel (measured with a stopwatch).

When we measure a quantity, we always compare it with some reference standard. When we say that a Ferrari 458 Italia is 4.53 meters long, we mean that it is 4.53 times as long as a meter stick, which we define to be 1 meter long. Such a standard defines a **unit** of the quantity. The meter is a unit of distance, and the second is a unit of time. When we use a number to describe a physical quantity, we must always specify the unit that we are using; to describe a distance as simply "4.53" wouldn't mean anything.

To make accurate, reliable measurements, we need units of measurement that do not change and that can be duplicated by observers in various locations. The system of units used by scientists and engineers around the world is commonly called "the metric system," but since 1960 it has been known officially as the **International System,** or **SI** (the abbreviation for its French name, *Système International*). Appendix A gives a list of all SI units as well as definitions of the most fundamental units.

**1.3** The measurements used to determine (a) the duration of a second and (b) the length of a meter. These measurements are useful for setting standards because they give the same results no matter where they are made.




### Time

From 1889 until 1967, the unit of time was defined as a certain fraction of the mean solar day, the average time between successive arrivals of the sun at its highest point in the sky. The present standard, adopted in 1967, is much more precise. It is based on an atomic clock, which uses the energy difference between the two lowest energy states of the cesium atom ($^{133}Cs$). When bombarded by microwaves of precisely the proper frequency, cesium atoms undergo a transition from one of these states to the other. One **second** (abbreviated s) is defined as the time required for 9,192,631,770 cycles of this microwave radiation (**Fig. 1.3a**).

### Length

In 1960 an atomic standard for the meter was also established, using the wavelength of the orange-red light emitted by excited atoms of krypton ($^{86}Kr$). From this length standard, the speed of light in vacuum was measured to be 299,792,458 m/s. In November 1983, the length standard was changed again so that the speed of light in vacuum was *defined* to be precisely 299,792,458 m/s.

Hence the new definition of the **meter** (abbreviated m) is the distance that light travels in vacuum in 1/299,792,458 second (Fig. 1.3b). This modern definition provides a much more precise standard of length than the one based on a wavelength of light.

**1.4** The international standard kilogram is the metal object carefully enclosed within these nested glass containers.

## Mass

The standard of mass, the **kilogram** (abbreviated kg), is defined to be the mass of a particular cylinder of platinum–iridium alloy kept at the International Bureau of Weights and Measures at Sèvres, near Paris (**Fig. 1.4**). An atomic standard of mass would be more fundamental, but at present we cannot measure masses on an atomic scale with as much accuracy as on a macroscopic scale. The *gram* (which is not a fundamental unit) is 0.001 kilogram.

Other *derived units* can be formed from the fundamental units. For example, the units of speed are meters per second, or m/s; these are the units of length (m) divided by the units of time (s).

## Unit Prefixes

Once we have defined the fundamental units, it is easy to introduce larger and smaller units for the same physical quantities. In the metric system these other units are related to the fundamental units (or, in the case of mass, to the gram) by multiples of 10 or $\frac{1}{10}$ Thus one kilometer $(1\text{ km})$ is 1000 meters, and one centimeter $(1\text{ cm})$ is $\frac{1}{100}$ meter. We usually express multiples of 10 or $\frac{1}{10}$ in exponential notation: $1000 = 10^3$, $\frac{1}{1000} = 10^{-3}$, and so on. With this notation, $1\text{ km} = 10^3\text{ m}$ and $1\text{ cm} = 10^{-2}\text{ m}$.

The names of the additional units are derived by adding a **prefix** to the name of the fundamental unit. For example, the prefix "kilo-," abbreviated k, always means a unit larger by a factor of 1000; thus

$$\begin{aligned}
1\text{ kilometer} &= 1\text{ km} = 10^3\text{ meters} = 10^3\text{ m}\\
1\text{ kilogram} &= 1\text{ kg} = 10^3\text{ grams} = 10^3\text{ g}\\
1\text{ kilowatt} &= 1\text{ kW} = 10^3\text{ watts} = 10^3\text{ W}
\end{aligned}$$

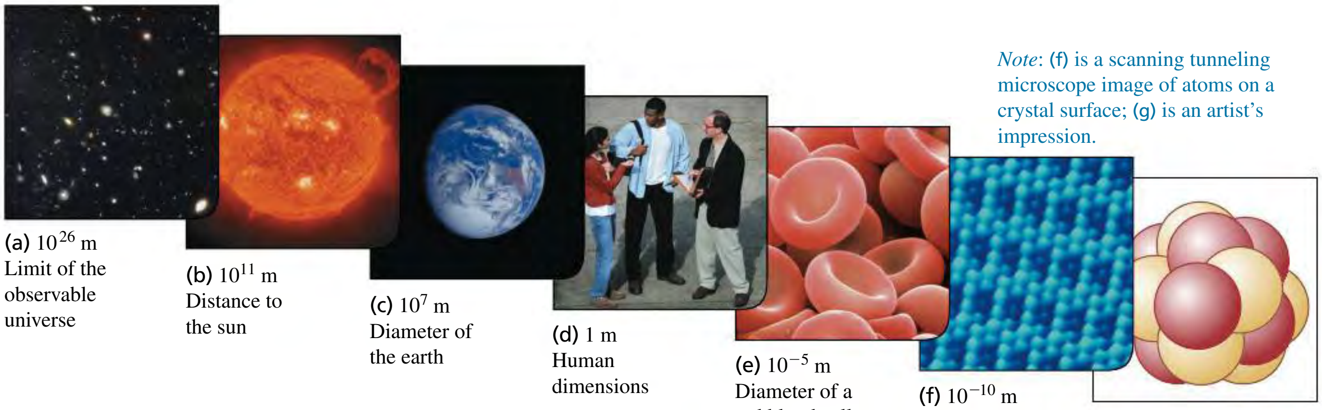
A table in Appendix A lists the standard SI units, with their meanings and abbreviations.

**Table 1.1** gives some examples of the use of multiples of 10 and their prefixes with the units of length, mass, and time. **Figure 1.5** (next page) shows how these prefixes are used to describe both large and small distances.

**TABLE 1.1** Some Units of Length, Mass, and Time

| Length | Mass | Time |
|---|---|---|
| 1 nanometer $= 1\text{ nm} = 10^{-9}\text{ m}$ (a few times the size of the largest atom) | 1 microgram $= 1\ \mu\text{g} = 10^{-6}\text{ g} = 10^{-9}\text{ kg}$ (mass of a very small dust particle) | 1 nanosecond $= 1\text{ ns} = 10^{-9}\text{ s}$ (time for light to travel 0.3 m) |
| 1 micrometer $= 1\ \mu\text{m} = 10^{-6}\text{ m}$ (size of some bacteria and other cells) | 1 milligram $= 1\text{ mg} = 10^{-3}\text{ g} = 10^{-6}\text{ kg}$ (mass of a grain of salt) | 1 microsecond $= 1\ \mu\text{s} = 10^{-6}\text{ s}$ (time for space station to move 8 mm) |
| 1 millimeter $= 1\text{ mm} = 10^{-3}\text{ m}$ (diameter of the point of a ballpoint pen) | 1 gram $= 1\text{ g} = 10^{-3}\text{ kg}$ (mass of a paper clip) | 1 millisecond $= 1\text{ ms} = 10^{-3}\text{ s}$ (time for a car moving at freeway speed to travel 3 cm) |
| 1 centimeter $= 1\text{ cm} = 10^{-2}\text{ m}$ (diameter of your little finger) | | |
| 1 kilometer $= 1\text{ km} = 10^3\text{ m}$ (distance in a 10-minute walk) | | |

**1.5** Some typical lengths in the universe.



(a) $10^{26}$ m Limit of the observable universe

(b) $10^{11}$ m Distance to the sun

(c) $10^{7}$ m Diameter of the earth

(d) 1 m Human dimensions

(e) $10^{-5}$ m Diameter of a red blood cell

(f) $10^{-10}$ m Radius of an atom

(g) $10^{-14}$ m Radius of an atomic nucleus

*Note*: (f) is a scanning tunneling microscope image of atoms on a crystal surface; (g) is an artist's impression.

**1.6** Many everyday items make use of both SI and British units. An example is this speedometer from a U.S.-built automobile, which shows the speed in both kilometers per hour (inner scale) and miles per hour (outer scale).


## The British System

Finally, we mention the British system of units. These units are used in only the United States and a few other countries, and in most of these they are being replaced by SI units. British units are now officially defined in terms of SI units, as follows:

*Length:* 1 inch = 2.54 cm (exactly)

*Force:* 1 pound = 4.448221615260 newtons (exactly)

The newton, abbreviated N, is the SI unit of force. The British unit of time is the second, defined the same way as in SI. In physics, British units are used in mechanics and thermodynamics only; there is no British system of electrical units.

In this book we use SI units for all examples and problems, but we occasionally give approximate equivalents in British units. As you do problems using SI units, you may also wish to convert to the approximate British equivalents if they are more familiar to you (**Fig. 1.6**). But you should try to *think* in SI units as much as you can.

## 1.4 USING AND CONVERTING UNITS

We use equations to express relationships among physical quantities, represented by algebraic symbols. Each algebraic symbol always denotes both a number and a unit. For example, $d$ might represent a distance of 10 m, $t$ a time of 5 s, and $v$ a speed of 2 m/s.

An equation must always be **dimensionally consistent.** You can't add apples and automobiles; two terms may be added or equated only if they have the same units. For example, if a body moving with constant speed $v$ travels a distance $d$ in a time $t$, these quantities are related by the equation

$$d = vt$$

If $d$ is measured in meters, then the product $vt$ must also be expressed in meters. Using the above numbers as an example, we may write

$$10\text{ m} = \left(2\,\frac{\text{m}}{\cancel{\text{s}}}\right)(5\ \cancel{\text{s}})$$

Because the unit s in the denominator of m/s cancels, the product has units of meters, as it must. In calculations, units are treated just like algebraic symbols with respect to multiplication and division.

CAUTION **Always use units in calculations** Make it a habit to *always* write numbers with the correct units and carry the units through the calculation as in the example above. This provides a very useful check. If at some stage in a calculation you find that an equation or an expression has inconsistent units, you know you have made an error. In this book we will *always* carry units through all calculations, and we strongly urge you to follow this practice when you solve problems.

## PROBLEM-SOLVING STRATEGY 1.2 SOLVING PHYSICS PROBLEMS

**IDENTIFY** *the relevant concepts:* In most cases, it's best to use the fundamental SI units (lengths in meters, masses in kilograms, and times in seconds) in every problem. If you need the answer to be in a different set of units (such as kilometers, grams, or hours), wait until the end of the problem to make the conversion.

**SET UP** *the problem* and **EXECUTE** *the solution:* Units are multiplied and divided just like ordinary algebraic symbols. This gives us an easy way to convert a quantity from one set of units to another: Express the same physical quantity in two different units and form an equality.

For example, when we say that 1 min = 60 s, we don't mean that the number 1 is equal to the number 60; rather, we mean that 1 min represents the same physical time interval as 60 s. For this reason, the ratio (1 min)/(60 s) equals 1, as does its reciprocal, (60 s)/(1 min). We may multiply a quantity by either of these factors (which we call *unit multipliers*) without changing that quantity's physical meaning. For example, to find the number of seconds in 3 min, we write

$$3\text{ min} = (3\ \cancel{\text{min}})\left(\frac{60\text{ s}}{1\ \cancel{\text{min}}}\right) = 180\text{ s}$$

**EVALUATE** *your answer:* If you do your unit conversions correctly, unwanted units will cancel, as in the example above. If, instead, you had multiplied 3 min by (1 min)/(60 s), your result would have been the nonsensical $\frac{1}{20}$ min$^2$/s. To be sure you convert units properly, include the units at *all* stages of the calculation.

Finally, check whether your answer is reasonable. For example, the result 3 min = 180 s is reasonable because the second is a smaller unit than the minute, so there are more seconds than minutes in the same time interval.

## EXAMPLE 1.1 CONVERTING SPEED UNITS

SOLUTION

The world land speed record of 763.0 mi/h was set on October 15, 1997, by Andy Green in the jet-engine car *Thrust SSC*. Express this speed in meters per second.

### SOLUTION

**IDENTIFY, SET UP, and EXECUTE:** We need to convert the units of a speed from mi/h to m/s. We must therefore find unit multipliers that relate (i) miles to meters and (ii) hours to seconds. In Appendix E we find the equalities 1 mi = 1.609 km, 1 km = 1000 m, and 1 h = 3600 s. We set up the conversion as follows, which ensures that all the desired cancellations by division take place:

$$763.0\text{ mi/h} = \left(763.0\frac{\cancel{\text{mi}}}{\cancel{\text{h}}}\right)\left(\frac{1.609\ \cancel{\text{km}}}{1\ \cancel{\text{mi}}}\right)\left(\frac{1000\text{ m}}{1\ \cancel{\text{km}}}\right)\left(\frac{1\ \cancel{\text{h}}}{3600\text{ s}}\right)$$
$$= 341.0\text{ m/s}$$

**EVALUATE:** This example shows a useful rule of thumb: A speed expressed in m/s is a bit less than half the value expressed in mi/h, and a bit less than one-third the value expressed in km/h. For example, a normal freeway speed is about 30 m/s = 67 mi/h = 108 km/h, and a typical walking speed is about 1.4 m/s = 3.1 mi/h = 5.0 km/h.

## EXAMPLE 1.2 CONVERTING VOLUME UNITS

SOLUTION

One of the world's largest cut diamonds is the First Star of Africa (mounted in the British Royal Sceptre and kept in the Tower of London). Its volume is 1.84 cubic inches. What is its volume in cubic centimeters? In cubic meters?

### SOLUTION

**IDENTIFY, SET UP, and EXECUTE:** Here we are to convert the units of a volume from cubic inches (in.$^3$) to both cubic centimeters (cm$^3$) and cubic meters (m$^3$). Appendix E gives us the equality 1 in. = 2.540 cm, from which we obtain 1 in.$^3$ = (2.54 cm)$^3$. We then have

$$1.84\text{ in.}^3 = (1.84\text{ in.}^3)\left(\frac{2.54\text{ cm}}{1\text{ in.}}\right)^3$$
$$= (1.84)(2.54)^3\frac{\cancel{\text{in.}^3}\text{ cm}^3}{\cancel{\text{in.}^3}} = 30.2\text{ cm}^3$$

Appendix E also gives us 1 m = 100 cm, so

$$30.2\text{ cm}^3 = (30.2\text{ cm}^3)\left(\frac{1\text{ m}}{100\text{ cm}}\right)^3$$
$$= (30.2)\left(\frac{1}{100}\right)^3\frac{\cancel{\text{cm}^3}\text{ m}^3}{\cancel{\text{cm}^3}} = 30.2\times10^{-6}\text{ m}^3$$
$$= 3.02\times10^{-5}\text{ m}^3$$

**EVALUATE:** Following the pattern of these conversions, can you show that 1 in.$^3$ ≈ 16 cm$^3$ and that 1 m$^3$ ≈ 60,000 in.$^3$?

**1.7** This spectacular mishap was the result of a very small percent error—traveling a few meters too far at the end of a journey of hundreds of thousands of meters.

**TABLE 1.2** Using Significant Figures

**Multiplication or division:**
Result can have no more significant figures than the factor with the fewest significant figures:

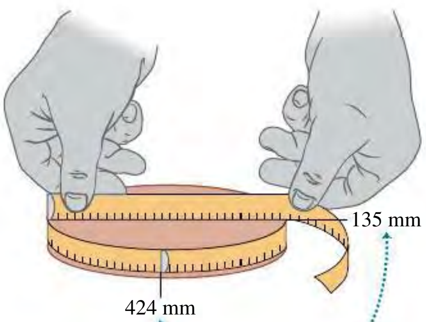
$$\frac{0.745 \times 2.2}{3.885} = 0.42$$

$$1.32578 \times 10^{7} \times 4.11 \times 10^{-3} = 5.45 \times 10^{4}$$

**Addition or subtraction:**
Number of significant figures is determined by the term with the largest uncertainty (i.e., fewest digits to the right of the decimal point):

$$27.153 + 138.2 - 11.74 = 153.6$$

**1.8** Determining the value of $\pi$ from the circumference and diameter of a circle.




## 1.5 UNCERTAINTY AND SIGNIFICANT FIGURES

Measurements always have uncertainties. If you measure the thickness of the cover of a hardbound version of this book using an ordinary ruler, your measurement is reliable to only the nearest millimeter, and your result will be 3 mm. It would be *wrong* to state this result as 3.00 mm; given the limitations of the measuring device, you can't tell whether the actual thickness is 3.00 mm, 2.85 mm, or 3.11 mm. But if you use a micrometer caliper, a device that measures distances reliably to the nearest 0.01 mm, the result will be 2.91 mm. The distinction between the measurements with a ruler and with a caliper is in their **uncertainty;** the measurement with a caliper has a smaller uncertainty. The uncertainty is also called the **error** because it indicates the maximum difference there is likely to be between the measured value and the true value. The uncertainty or error of a measured value depends on the measurement technique used.

We often indicate the **accuracy** of a measured value—that is, how close it is likely to be to the true value—by writing the number, the symbol $\pm$, and a second number indicating the uncertainty of the measurement. If the diameter of a steel rod is given as $56.47 \pm 0.02$ mm, this means that the true value is likely to be within the range from 56.45 mm to 56.49 mm. In a commonly used shorthand notation, the number $1.6454(21)$ means $1.6454 \pm 0.0021$. The numbers in parentheses show the uncertainty in the final digits of the main number.

We can also express accuracy in terms of the maximum likely **fractional error** or **percent error** (also called *fractional uncertainty* and *percent uncertainty*). A resistor labeled "47 ohms $\pm$ 10%" probably has a true resistance that differs from 47 ohms by no more than 10% of 47 ohms—that is, by about 5 ohms. The resistance is probably between 42 and 52 ohms. For the diameter of the steel rod given above, the fractional error is $(0.02 \text{ mm})/(56.47 \text{ mm})$, or about 0.0004; the percent error is $(0.0004)(100\%)$, or about 0.04%. Even small percent errors can be very significant (**Fig. 1.7**).

In many cases the uncertainty of a number is not stated explicitly. Instead, the uncertainty is indicated by the number of meaningful digits, or **significant figures,** in the measured value. We gave the thickness of the cover of the book as 2.91 mm, which has three significant figures. By this we mean that the first two digits are known to be correct, while the third digit is uncertain. The last digit is in the hundredths place, so the uncertainty is about 0.01 mm. Two values with the *same* number of significant figures may have *different* uncertainties; a distance given as 137 km also has three significant figures, but the uncertainty is about 1 km. A distance given as 0.25 km has two significant figures (the zero to the left of the decimal point doesn't count); if given as 0.250 km, it has three significant figures.

When you use numbers that have uncertainties to compute other numbers, the computed numbers are also uncertain. When numbers are multiplied or divided, the result can have no more significant figures than the factor with the fewest significant figures has. For example, $3.1416 \times 2.34 \times 0.58 = 4.3$. When we add and subtract numbers, it's the location of the decimal point that matters, not the number of significant figures. For example, $123.62 + 8.9 = 132.5$. Although 123.62 has an uncertainty of about 0.01, 8.9 has an uncertainty of about 0.1. So their sum has an uncertainty of about 0.1 and should be written as 132.5, not 132.52. **Table 1.2** summarizes these rules for significant figures.

To apply these ideas, suppose you want to verify the value of $\pi$, the ratio of the circumference of a circle to its diameter. The true value of this ratio to ten digits is 3.141592654. To test this, you draw a large circle and measure its circumference and diameter to the nearest millimeter, obtaining the values 424 mm and 135 mm (**Fig. 1.8**). You punch these into your calculator and obtain the quotient $(424 \text{ mm})/(135 \text{ mm}) = 3.140740741$. This may seem to disagree with the true value of $\pi$, but keep in mind that each of your measurements has three significant figures, so your measured value of $\pi$ can have only three significant figures. It should be stated simply as 3.14. Within the limit of three significant figures, your value does agree with the true value.

In the examples and problems in this book we usually give numerical values with three significant figures, so your answers should usually have no more than three significant figures. (Many numbers in the real world have even less accuracy. An automobile speedometer, for example, usually gives only two significant figures.) Even if you do the arithmetic with a calculator that displays ten digits, a ten-digit answer would misrepresent the accuracy of the results. Always round your final answer to keep only the correct number of significant figures or, in doubtful cases, one more at most. In Example 1.1 it would have been wrong to state the answer as 341.01861 m/s. Note that when you reduce such an answer to the appropriate number of significant figures, you must *round,* not *truncate.* Your calculator will tell you that the ratio of 525 m to 311 m is 1.688102894; to three significant figures, this is 1.69, not 1.68.

When we work with very large or very small numbers, we can show significant figures much more easily by using **scientific notation,** sometimes called **powers-of-10 notation.** The distance from the earth to the moon is about 384,000,000 m, but writing the number in this form doesn't indicate the number of significant figures. Instead, we move the decimal point eight places to the left (corresponding to dividing by $10^8$) and multiply by $10^8$; that is,

$$384{,}000{,}000 \text{ m} = 3.84 \times 10^8 \text{ m}$$

In this form, it is clear that we have three significant figures. The number $4.00 \times 10^{-7}$ also has three significant figures, even though two of them are zeros. Note that in scientific notation the usual practice is to express the quantity as a number between 1 and 10 multiplied by the appropriate power of 10.

When an integer or a fraction occurs in an algebraic equation, we treat that number as having no uncertainty at all. For example, in the equation $v_x^2 = v_{0x}^2 + 2a_x(x - x_0)$, which is Eq. (2.13) in Chapter 2, the coefficient 2 is *exactly* 2. We can consider this coefficient as having an infinite number of significant figures (2.000000 . . . ). The same is true of the exponent 2 in $v_x^2$ and $v_{0x}^2$.

Finally, let's note that **precision** is not the same as *accuracy.* A cheap digital watch that gives the time as 10:35:17 A.M. is very *precise* (the time is given to the second), but if the watch runs several minutes slow, then this value isn't very *accurate.* On the other hand, a grandfather clock might be very accurate (that is, display the correct time), but if the clock has no second hand, it isn't very precise. A high-quality measurement is both precise *and* accurate.

## EXAMPLE 1.3 SIGNIFICANT FIGURES IN MULTIPLICATION

SOLUTION

The rest energy $E$ of an object with rest mass $m$ is given by Albert Einstein's famous equation $E = mc^2$, where $c$ is the speed of light in vacuum. Find $E$ for an electron for which (to three significant figures) $m = 9.11 \times 10^{-31}$ kg. The SI unit for $E$ is the joule (J); $1 \text{ J} = 1 \text{ kg} \cdot \text{m}^2/\text{s}^2$.

### SOLUTION

**IDENTIFY and SET UP:** Our target variable is the energy $E$. We are given the value of the mass $m$; from Section 1.3 (or Appendix F) the speed of light is $c = 2.99792458 \times 10^8$ m/s.

**EXECUTE:** Substituting the values of $m$ and $c$ into Einstein's equation, we find

$$\begin{aligned} E &= (9.11 \times 10^{-31} \text{ kg})(2.99792458 \times 10^8 \text{ m/s})^2 \\ &= (9.11)(2.99792458)^2(10^{-31})(10^8)^2 \text{ kg} \cdot \text{m}^2/\text{s}^2 \\ &= (81.87659678)(10^{[-31+(2\times 8)]}) \text{ kg} \cdot \text{m}^2/\text{s}^2 \\ &= 8.187659678 \times 10^{-14} \text{ kg} \cdot \text{m}^2/\text{s}^2 \end{aligned}$$

Since the value of $m$ was given to only three significant figures, we must round this to

$$E = 8.19 \times 10^{-14} \text{ kg} \cdot \text{m}^2/\text{s}^2 = 8.19 \times 10^{-14} \text{ J}$$

**EVALUATE:** While the rest energy contained in an electron may seem ridiculously small, on the atomic scale it is tremendous. Compare our answer to $10^{-19}$ J, the energy gained or lost by a single atom during a typical chemical reaction. The rest energy of an electron is about 1,000,000 times larger! (We'll discuss the significance of rest energy in Chapter 37.)